Using Polymer Modified Asphalt Emulsions in Surface Treatments

A Federal Lands Highway Interim Report

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1.0 INTRODUCTION

1.1 Background

Polymer modification of asphalt emulsions offers improvements in performance and durability, mitigation of pavement distress, and reduced life cycle costs when compared to unmodified asphalt emulsions or hot mix asphalt surface dressings. Polymers have exhibited demonstrable reductions in rutting, thermal cracking, and increased resistance to many forms of traffic-induced stress. Conversely, polymer modifiers, when used in chip seal applications, have demonstrated some problems associated with accelerated stripping when placed over a moisture sensitive hot mix. Asphalt emulsions frequently provide a lower cost, efficient, and more environmentally-friendly alternative to hot mixes due to their low energy consumption, reduced hydrocarbon emissions, ease of implementation at remote sites, and preventive maintenance/life-extending benefits when applied to mildly distressed pavements.

Although best-practice manuals and specifications for conventional asphalt emulsions are plentiful, there is no single document available which offers guidance on the proper use, application techniques, and benefits of high-performance polymer modified asphalt emulsions. Similarly, the preponderance of the published research on polymer modifiers has focused primarily upon their use in hot mix asphalt (HMA) applications.

This research includes an exhaustive review of the literature to collect and analyze polymer modified emulsion practices and specifications, coupled with a laboratory testing and verification program designed to validate the findings and recommendations developed from the literature review. Guidance is provided on proper project selection, polymer dosing rates and methods, applicability under varying traffic load and environmental conditions, and contraindications to the use of polymer modifiers.

1.2 Study Objectives

The principal objectives of this study were to:

1. Compile published research on the types of polymer modifiers, dosage rates, and modification methods;
2. Compare and contrast the performance, cost, and benefits of polymer modified versus non-modified asphalt emulsions;
3. Determine the applicability of polymer modified asphalt emulsions to low (i.e., generally < 400 ADT), medium (400 to 1000 ADT), and high (> 1000 ADT) volume roads (as defined by Federal Lands Highway Division), and varying environmental conditions;
4. Evaluate the applicability of polymer modified asphalt emulsions to non-roadway applications such as parking lots, hiking and bike trails;
5. Analyze information obtained from the literature review and develop recommendations and guidelines relating to the proper application, modification, and contraindications of polymer modified asphalt emulsions (PME);
6. Perform laboratory testing and verification to evaluate the recommendations and data gaps identified from the analysis of information obtained from the literature review; and,
7. Prepare a Federal Lands Highway (FLH) manual of best practices for polymer modified asphalt emulsions.

1.3 Scope

Electronic and physical literature searches were performed using a variety of sources, including the National Center for Pavement Preservation (NCPP) on-line library; the Transportation Research Information Service (TRIS) database; the National Technical Information Service (NTIS); the COMPENDEX engineering research database; the Michigan State University College of Engineering Library; the State Library of Michigan; the Asphalt Emulsions Manufacturers Association (AEMA), International Slurry Surfacing Association (ISSA), and the Asphalt Recycling and Reclamation (ARRA) websites; the Asphalt Institute's on-line document collection; the Federal Highway Administration's (FHWA) technical document and reference collection; and the Google™ search engine. Numerous pavement and polymer research publications such as the publications of the Transportation Research Board (TRB) and the Asphalt Paving Technologists (AAPT); the International Journal of Pavement Engineering; the Journal of Materials in Civil Engineering; Polymer Engineering and Science Journal; and the Journal of Applied Polymer Science, were also examined.

Although this review focuses principally on polymer modified asphalt emulsions (PME), literature and research dealing with direct-modified binders (such as those used in hot mix) have also been utilized in cases where the results could reasonably be extrapolated. For example, some polymer modifiers occur only in solid form, and must be added directly to the asphalt regardless of whether the binder will be hot-applied, or emulsified; whereas liquid modifiers may be added either to the soap mix; co-milled; or in some cases, post-added to the emulsion mix either at the plant or in the field. Thus, research dealing with the impact of polymer modification on asphalt binders may have some implications with respect to both hot mix and emulsion applications.

1.4 Report Organization

Section 1 presents an introduction and overview of this report. The results and discussion of the literature review are provided in Section 2. Section 3 presents the recommendations for the laboratory testing program and specifications, and a summary of the recommended application guidelines derived from the literature review and laboratory study will be provided in the final report following completion of the laboratory study.

2.0 LITERATURE REVIEW OF POLYMER MODIFIED ASPHALT EMULSIONS

This section presents the results of the literature review with respect to the types, modification methods, demonstrated performance, surface treatments, environmental applicability, materials selection, and cost-benefit analysis of polymer modifiers. A brief overview of polymer and emulsion chemistry is provided, as is a discussion of the pavement conditions and applications which contraindicate the use of polymer modifiers.

2.1 Basics of Polymers and Asphalt Emulsions

This section introduces and describes some of the basic terms and concepts related to polymers, polymer chemistry, and asphalt emulsions. While the purpose is not to provide a comprehensive narrative of the complexities of polymer chemistry, a grasp of the essential terminology and processes is beneficial in understanding the formulation, advantages, and applications of polymer modified asphalt emulsions.

2.1.1 Polymer Terminology and Chemistry

A polymer is a natural or synthetic high-molecular weight organic compound which consists of a chain of smaller, simpler repeating units known as monomers. For example, the monomer “ethylene” may be “polymerized” (i.e., individual ethylene molecules chained together) to form “polyethylene”. When two or more distinct types of monomers are combined, the resulting compound is termed a “copolymer.”

The structure of copolymers may be random, or may repeat in blocks of polymers (block copolymers) as illustrated in Figure 1. An example of a block copolymer is “polystyrene-b-poly(methyl methacrylate)” or PS-b-PMMA, which consists of blocks of polymerized styrene (a monomer) and polymerized MMA (another monomer). PS-b-PMMA is further categorized as a “diblock” copolymer, because it consists of two different polymerized monomers. Polymer structures include straight, radial, crosslinked, and irregularly branched chains. Factors which can influence the behavior and performance of polymers include chemistry, structure, bonding types, and the manufacturing process.

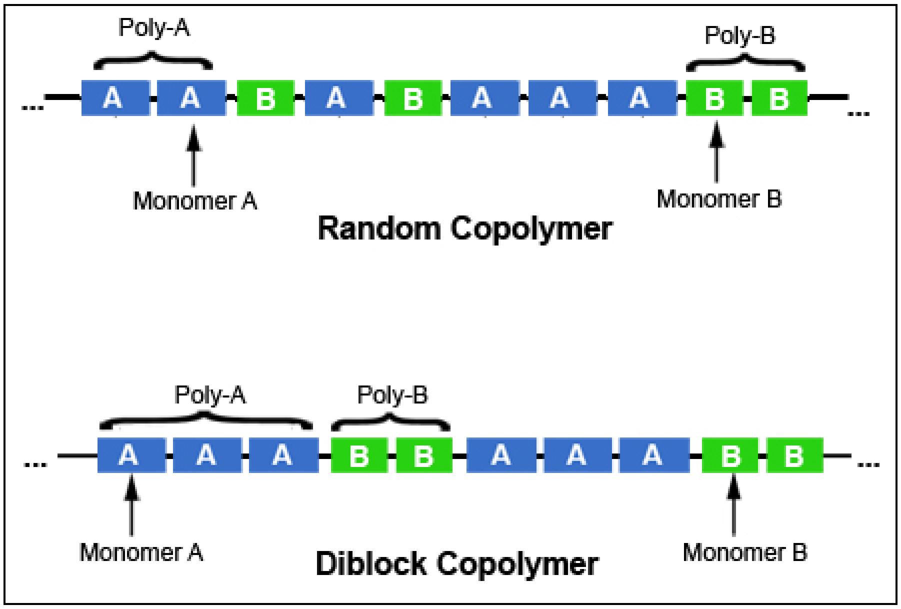


Figure 1: Examples of Copolymers

2.1.2 Asphalt Emulsions

Asphalt emulsions are formed by the milling of raw asphalt into microscopic particles which are dispersed in water with the aid of a chemical emulsifying agent called a “surfactant” (sometimes referred to as “soap”). In such cases, the dispersed asphalt forms discrete droplets which are intrinsically insoluble in water. The emulsion is said to be “stabilized” if the asphalt droplets remain well-dispersed such that phase separation does not occur. Stabilization is achieved through the use of surfactants, which consist of polar molecules comprised of a hydrophilic (water loving) “head” and hydrophobic (water avoiding) “tail.” The tail of the surfactant molecule is attracted to the asphalt particles, forming a coating around each particle which consists of the hydrophilic heads of the emulsifying agent. The hydrophilic portions of these surfactants are very reactive with water, and aid in keeping the droplets dispersed and in suspension.

Surfactants are classified as anionic, cationic, or non-ionic based upon the nature of the charge of the hydrophilic portion of the molecule. Anionic and cationic emulsifiers are the most commonly used in pavement surface treatment applications. The electrical potential that exists between the surface of the surfactant-coated asphalt particles and the emulsion solution is termed the “Zeta potential”. Larger Zeta potentials are indicative of faster droplet movement and greater repulsion between asphalt particles, thus signifying greater stability of the emulsion (i.e., less of a propensity to phase-separate).

In cationic asphalt emulsions, the positively charged layer of surfactants coating the asphalt particles are attracted to the negatively charged aggregate mixed with the emulsion. “Breaking” of the emulsion is said to occur when the asphalt separates from the water phase and coalesces to coat the grains of the mineral aggregate. To achieve breaking in anionic asphalt emulsions, the asphalt and aggregate particles must be sufficiently close to overcome the repulsive forces which exist between the negatively charged outer layer surrounding the asphalt particles and the negatively charged surface of the aggregate. The timing and rate of breaking is controlled by several factors, including the chemistry of the surfactant, the type of aggregate used, the emulsion formulation method, and the temperature of the emulsifying solution.

After the break occurs, the water phase of the applied emulsion evaporates, allowing the residual asphalt to coalesce and achieve its full strength (curing). Factors influencing the quality and performance of asphalt emulsions include (but are not necessarily limited to):

- Chemical properties, particle size, hardness, and concentration of the base asphalt;
- Chemistry, ionic charge, and concentration of the surfactant;
- Manufacturing conditions such as temperature, pressure, milling shear, and the order in which the ingredients are combined;
- The type of manufacturing equipment used;
- The types and amounts of other chemical modifiers (such as polymers) which are added to the emulsion; and,
- Chemistry and quality of the bulk emulsion water solution (1).

2.1.3 Asphalt Composition

Asphalts are generally characterized as colloids containing high molecular weight, relatively insoluble and nonvolatile compounds known as “asphaltenes”, dispersed within a liquid, continuous, lower viscosity phase comprised of low molecular weight compounds called “maltenes”. Asphaltenes are believed to be the component of asphalt that imparts hardness, while maltenes provide ductility and facilitate adhesion. Maltenes consist predominately of oils (aromatics and saturates) and resins (compounds which represent a transition between asphaltenes and oils). Typical asphalts normally contain between 5% and 25% by weight of asphaltenes.

The asphaltene content of asphalt cements is chiefly responsible for influencing the overall viscosity of the composite system – that is, higher asphaltene contents generally lead to higher composite viscosities. In addition, research has shown that maltene phases possessing a comparatively high aromatic content generally result in better dispersal of the asphaltenes, leading to high temperature susceptibilities, high ductility, low complex flows, and lower rates of age-dependent hardening (3).

Conversely, low aromatic maltenes generally lead to the formation of agglomerates of asphaltenes which form a network-like structure and are referred to as “gel-type” asphalt cement. Gel-type asphalt may also be formed from mixtures where the asphaltene to maltene ratio is inordinately high, because maltenes are needed to disperse the asphaltene fractions. Gel-type asphalts are generally characterized by low temperature susceptibilities, low ductility, increased elastic component content, thixotropic behavior, and rapid age-dependent hardening (3). In this sense, the addition of polymer modifiers when used in conjunction with compatible asphalts, can lead to improved high and low temperature performance combined with increased flexibility and resistance to deformation. Compatible asphalts are those that when blended with a polymer modifier, produce a two-phase mixture that is characterized by a well dispersed polymer phase that is stable at high temperatures.

Many of the compounds contained in asphalt are polar molecules due to the presence of alcohol, carboxyl, phenolic, amine, thiol, and other functional groups. As a result of this polarity, the molecules self-assemble to form large, complex structures with molecular weights ranging up to 100,000. The adhesion of asphalt to mineral aggregate particles is also thought to depend on the polar attraction between asphalt particles and the negatively charged surfaces of most aggregates. Although asphalt is not a polymer in the strict sense of the word, it is regarded as a thermoplastic material because it becomes soft when heated and hardens upon cooling. Within a certain temperature range, asphalts also exhibit modest viscoelastic properties which can be improved upon via the addition of polymer modifiers.

2.1.4 Polymer Modified Asphalt (PMA)

In general terms, the addition of polymers to asphalt binders results in the modification of certain key physical properties including the:

- Elasticity;
- Tensile Strength;
- High and Low Temperature Susceptibilities;
- Viscosity; and,
- Adhesion and Cohesion.

Depending upon the form of modification desired, improvements in pavement longevity can be achieved through the reduction of fatigue and thermal cracking, decreased high temperature susceptibility (e.g., rutting and shoving), and enhanced aggregate retention in applications such as chip seals. Polymer modifiers are utilized to extend the lower and/or upper effective temperature operating ranges of pavements, and to add elastic components that allow it to recover from loading stress.

A variety of testing techniques and equipment are available which may be used to evaluate and quantify the performance characteristics of polymer modified binders and emulsion residues. A few of the most common of these include:

- Dynamic Shear Rheometer (DSR) – Used to measure the shear modulus (resistance and phase angle) of asphalt within intermediate to high operational temperature ranges. DSR testing distinguishes between elastic (recoverable) and viscous (non-recoverable) responses of the test material when placed under stress, and is often used as an indicator of rutting resistance, and other forms of permanent deformation.

- Bending Beam Rheometer (BBR) and Direct Tension Test (DTT) – BBR and DTT testing are used to determine the stiffness/flexibility of asphalt binders at low temperatures, and thus, their susceptibility to thermal cracking.
- Ring and Ball Softening Point – Used to determine the temperature at which full penetration of the modified asphalt occurs. This test provides another measure of high temperature susceptibility.
- Direct Tensile Test – A measurement of the force that is required to deform an asphalt sample, tensile strength testing allows the stress applied to the sample to be plotted against its resulting elongation (or strain).
- Elasticity after Ductility Testing – In this test, the sample is elongated into a thread, cut, and the resulting recovery measured. Elasticity measures have important implications related to the resiliency of the pavement under repeated cycles of loading and unloading.
- Rotational Viscometry (RV) – RV is utilized to measure the viscosity of a PMA, and is directly related to the workability of the mixture during field application.

Modified asphalt emulsion testing can be carried out by either testing the binder prior to emulsification, or by obtaining a sample of the properly cured emulsion residue. A more thorough treatment and evaluation of performance testing methodologies and criteria is provided in Section 2.4.

2.2 Types of Polymer Modifiers

2.2.1 Overview and Classification

Polymer modifiers are generally separated into two broad categories: elastomers and plastomers - based upon their strain performance characteristics at low temperatures.

Elastomeric polymers exhibit a low modulus of elasticity which permits the polymer matrix to expand without failure to up to 10 times its undeformed dimensions when stretched (2), but which quickly returns to its original shape once the load has been removed. Typical elastomeric polymer modifiers include natural and synthetic rubbers, styrene-butadiene-styrene (SBS), and reclaimed crumb rubber modifiers (CRM) harvested from scrap tires. Worldwide, elastomeric polymers comprise approximately 75% of all the asphalt polymer modifiers used (not including recycled crumb rubbers).

Unlike the elastomers, plastomeric polymers attain high strength at a rapid rate, but are brittle and resistant to deformation once set. Examples of plastomeric polymer modifiers include low density polyethylene (LDPE), ethylene-propylene-diene-monomer (EPDM), and ethyl-vinyl-acetate (EVA). Plastomeric polymers currently comprise about 15% of the global market for asphalt polymer modifiers.

Elastomeric and plastomeric polymer modifiers are further classified as either "thermoset" or "thermoplastic", based upon their temperature-dependent structural formation and reformation characteristics. When initially heated, thermoset polymers develop a complex, cross-linked structure which is retained upon cooling, but which cannot be reversed when reheated (3). In contrast, thermoplastic polymers also develop a well-defined, linked matrix when cooled, but the resultant structures can be reversed or "reset" with reheating.

Thermoplastic Rubbers (TPR) or Thermoplastic Elastomers (TPE) such as SBS combine the hard, resistant characteristics and re-settable structure of plastics with the elastic recovery of thermoset elastomers like natural or synthetic rubber. TPE's exhibit this unique blend of properties through the structural integration of rigid, generally steric (i.e., styrene-containing) components with rubbery domains such as polybutadiene.

Table 1 presents a summary of the most commonly used polymer modifiers, classified according to their deformational and thermal properties. It is important to note that many of these polymers may be blended with other types to achieve the appropriate combination of thermal and deformational properties.

Table 1: Types and Classifications of Polymer Modifiers

Polymer Type	Examples	Classification	References
Natural Rubber (Homopolymers)	Natural Rubber (NR), Polyisoprene (PI), Isoprene, Natural Rubber Latex (NRL)	Thermoset Elastomers	(4) (5)
Synthetic Latex / Rubber (Random Copolymers)	Styrene-Butadiene (SBR)	Thermoset Elastomers	(4) (5)
	Polychloroprene Latex (Neoprene)	Thermoset Elastomers	(3) (5)
	Polybutadiene (PB, BR)	Thermoset Elastomers	(4)
Block Copolymers	Styrene-Butadiene-Styrene (SBS)	Thermoplastic Elastomers	(5)
	Styrene-Isoprene-Styrene (SIS)	Thermoplastic Elastomers	(5) (7)
	Styrene-Butadiene Diblock (SB)	Thermoplastic Elastomers	(3) (4)
	Acrylonitrile-Butadiene-Styrene (ABS)	Thermoplastic Elastomers	(6)
	Reactive-Ethylene-Terpolymers (RET)	Thermoplastic Elastomers	(8)
Reclaimed Rubber	Crumb Rubber Modifiers	Thermoset Elastomers	(4) (5)
Plastics	Low / High Density Polyethylene (LDPE / HDPE), Other Polyolefins.	Thermoplastic Plastomers	(5)
	Ethylene Acrylate Copolymer	Thermoplastic Plastomers	(3) (5)
	Ethyl-Vinyl-Acetate (EVA)	Thermoplastic Plastomers	(5)
	Ethyl-Methacrylate	Thermoplastic Plastomers	(7)
	Polyvinyl Chloride (PVC)	Thermoplastic Plastomers/ Elastomers	(5)
	Ethylene-Propylene-Diene-Monomer or EPDM	Thermoplastic Elastomers	(5)
	Acrylates, Ethyl methacrylate (EMA), Ethyl butyl acrylate (EBA).	Thermoplastic Plastomers	(10)
Combinations	Blends of Above	Varies	(5)

The following subsections provide detailed discussions of the published literature covering each of these polymer modifiers.

2.2.2 Natural Rubber and Latex

Natural rubber latex (NRL) is an elastic hydrocarbon polymer of the isoprene monomer (polyisoprene) that exists as a milky sap produced by several species of plants. Natural rubber (NR) is produced from NRL by coagulating the latter to form a solid material.

The first commercial process that was developed to modify asphalt emulsions with NRL was the Ralumac® system (9). The Ralumac® process involves mixing naturally anionic NRL with cationic surfactants, and emulsifying the resulting liquid with asphalt using a colloid mill (9). NRL modification performed in this manner must usually be performed as a two-stage process at a continuous-feed emulsion plant to achieve the desired results. However, when compatible NRL is used (with respect to asphalt microstructure) the process can be reduced to a single stage, and the latex added pre- or post-emulsification as shown in Figure 2 (9) (10).

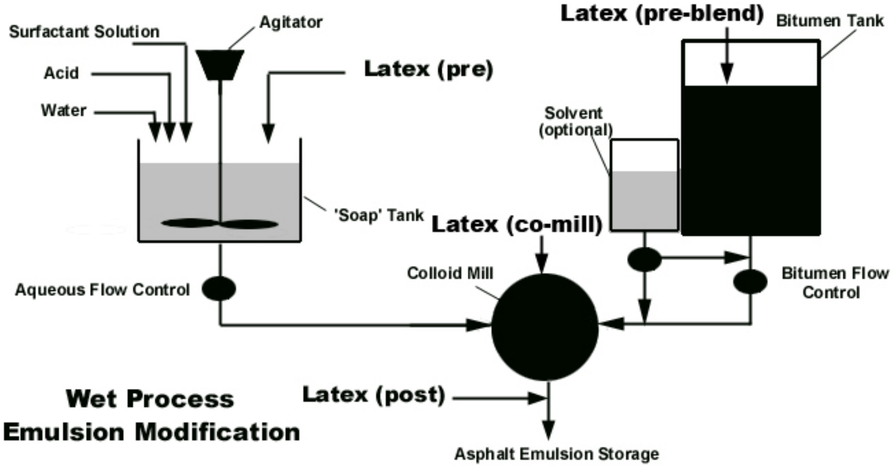


Figure 2: Typical Emulsion Modification Processes (9)

The resulting cationic emulsion is attracted to the anionic surfaces of the aggregate, latex, and filler material; thereby increasing oil-wettability and ensuring better adhesion of the coagulated asphalt to the mineral grains once cured (Figure 3) (11). This process, referred to as “breaking,” is an essential event in ensuring rapid adhesion and strength development. The polymer component of a properly formulated and stabilized emulsion is dispersed throughout the bituminous cement to form an elastic, foam-like lattice once set (Figure 4).

Performance benefits in asphalt emulsions resulting from NRL modification are similar to those obtained in hot mix, and include increased thermal stability, higher resistance to load deformation, and reduced thermal cracking (9). In such applications, the resulting rubberized asphalt acts like an elastic membrane which holds residual asphalt particles together, thereby retarding crack propagation and increasing stone retention (Figure 4).

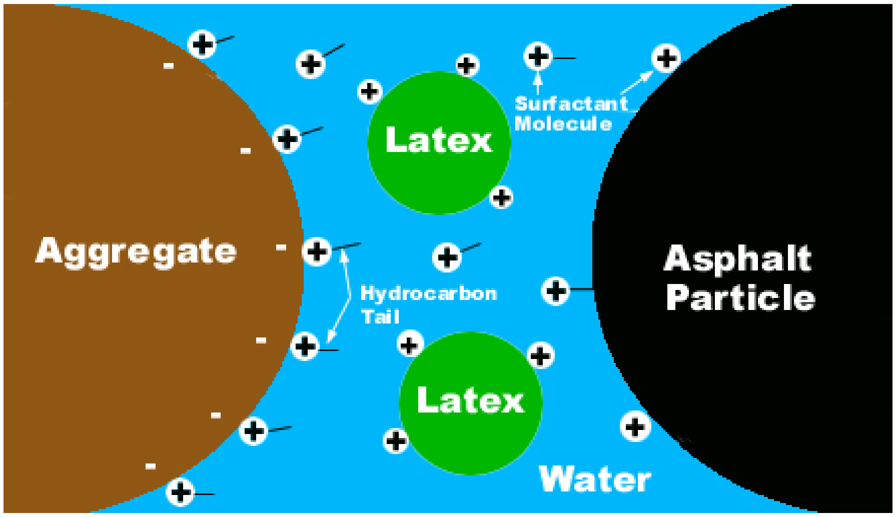


Figure 3: Surfactant Action in NRL Modified Asphalt Emulsion

At higher temperatures, the NRL's lattice resists flow potential in the asphalt matrix, which increases the pavement's resistance to deformation. Treatment applications which may benefit from the use of NRL modified asphalt emulsions include microsurfacing, slurry seals, chip seals, and tack coats. Figure 4 illustrates the distribution of a latex lattice within the asphalt binder used in a typical chip seal.

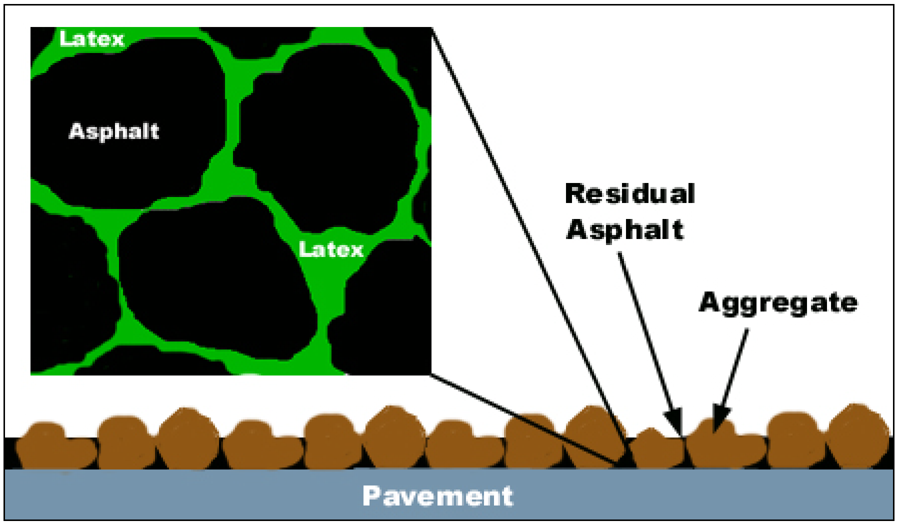


Figure 4: Polymer Modified Chip Seal

2.2.3 Synthetic Rubber and Latex

Synthetic latex is a thermoset elastomer which consists of a mixture of polymer particles dispersed in water. Commonly used varieties of synthetic latex rubber include styrene-butadine rubber (SBR, a random copolymer), polychloroprene (Neoprene), and polybutadiene (PB). Common uses of latex modified asphalt emulsions include microsurfacings, chip seals, and slurry seals. Lubbers and Watson (2005) note that the handling and blending of SBR latex is particularly versatile, and is amenable to a variety of pre- and post-modification methodologies (4). When sufficient quantities of synthetic latex are added to compatible asphalts, the cured mixture is commonly characterized by the existence of a continuous polymer network which envelops the bitumen particles (see Figure 4). Benefits of properly blended latex polymers included improved stone retention, increased skid-resistance, and improved low temperature performance (i.e., less brittleness, better elasticity).

Like NRL, when SBR latex is uniformly dispersed in the emulsion during blending, it forms elastic lattices within the bituminous cement when cured. More specifically, as water within an applied emulsion evaporates, droplets containing SBR coalesce along the surfaces of asphalt particles, which results in the formation of a continuous, honeycombed polymer network which extends throughout the binder (12). In this way, SBR particles form “welds” between asphalt particles, which results in an increase in tensile strength, stone retention, and resistance to cracking (12) (13). SBR modification of asphalt emulsions may be accomplished by co-milling at the colloid mill, post-blending after emulsification, or by mixing at the application site through the distributor (a field variation of the post-blending method) (13). SBR compatibility with the asphalt used should be verified to ensure the success of single-stage mixing methods.

Takamura (2001) has demonstrated the benefits of performing SBR modification of asphalt emulsions and microsurfacing mixes, in which significant increases in rutting resistance were observed with increasing polymer content (14). Takamura notes that as curing time lengthens, the benefits of increased polymer content become more pronounced as shown in Figure 5. Similarly, chip retention has been shown to be more pronounced with longer rates of curing in SBR modified asphalt emulsions as compared to unmodified mixtures (Figure 6).

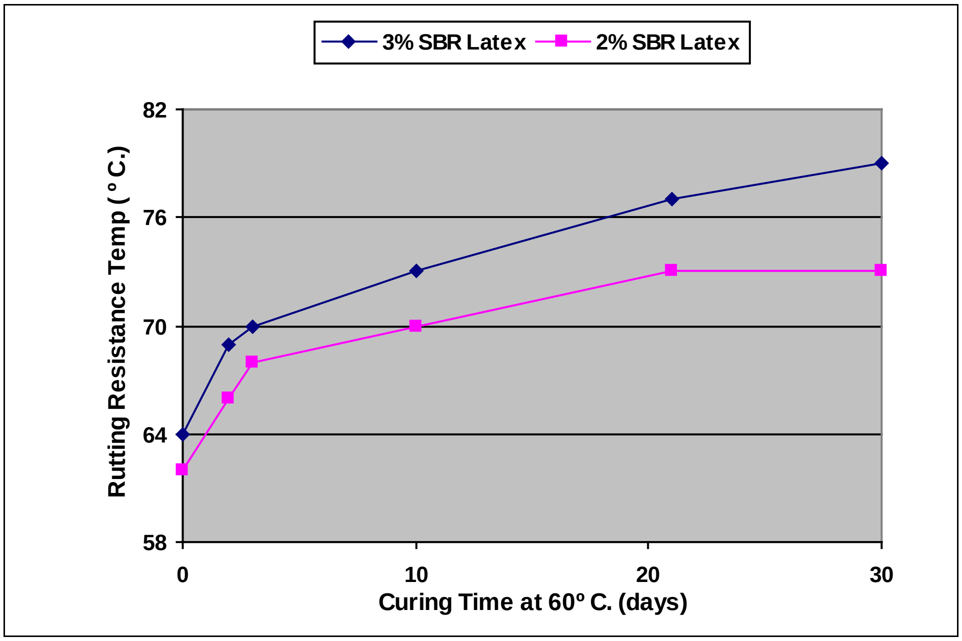


Figure 5: Curing of a CRS-2P Emulsion (14)

Moreover, with respect to wet track abrasion losses and wheel tracked deformation in microsurfacing mixes, results indicate that SBR latex may also provide better stone retention and reduced flow characteristics, respectively, than SBS, EVA, or Neoprene modified samples as shown in Figure 7.

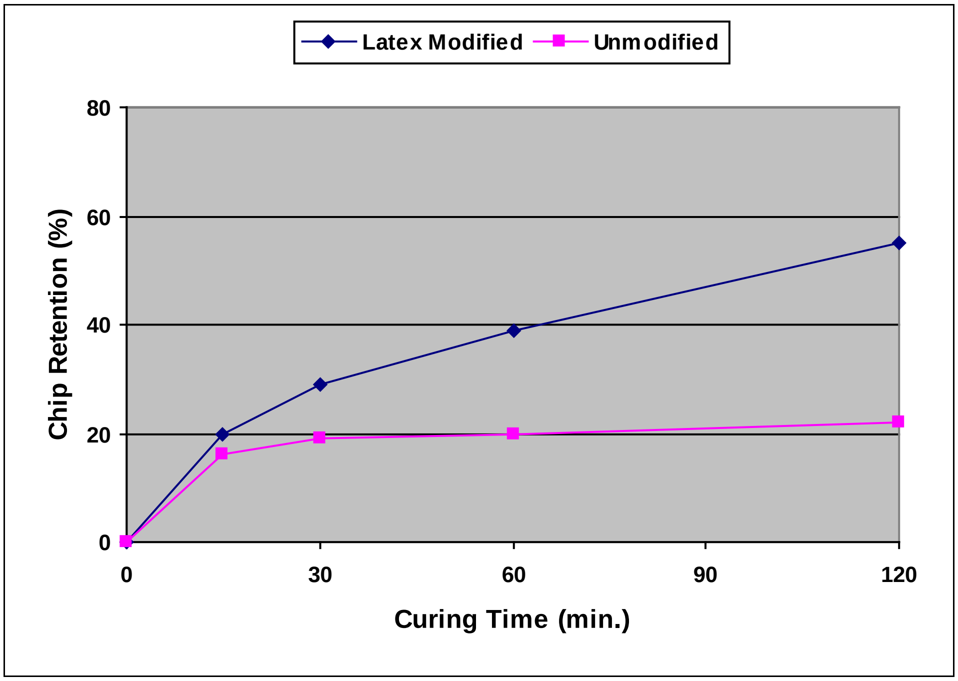


Figure 6: Stone Retention over Curing Time (14)

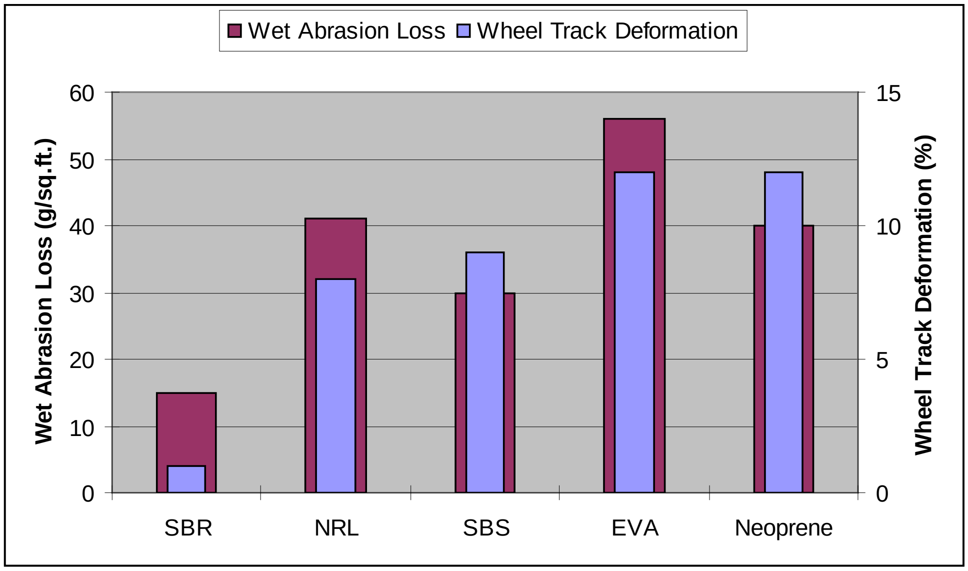


Figure 7: Wet Track Abrasion and Loaded Wheel Test by Polymer Type (14)

2.2.4 Block Copolymers

When hard styrenic polymers (i.e., styrene containing) are co-polymerized with small molecules such as butadiene in structurally discrete connected blocks, the result is a block copolymer (15). Typical examples of block copolymer modifiers include SBS, SIS, SB, ABS, and RET - with the most commonly used among these being SBS (a triblock) owing to its desirable properties and comparatively low cost (16) (17). The elasticity and strength benefits imparted by SBS modifiers are attributable to the molecule's rubbery polybutadiene (PB) "mid-blocks" capped at either end by polystyrene end-blocks which provide strength and rigidity (16). . Most block copolymer modifiers behave as thermoplastic elastomers, returning to their original shape upon removal of the loading stress.

Block copolymers are lower in molecular weight than typical formulations of SBR latex, and generally consist of a comparatively narrow distribution of similar monomer chain lengths. Whereas SBR latex chains are polymerically random in form, block copolymers such as SBS and SB can exhibit a wide variety of regular and well-defined molecular morphologies including linear, star-shaped, and radial structures (4).

When triblock copolymers such as SBS and SEBS are raised above the glass transition temperature of their polystyrene end-blocks, these rigid domains soften, thereby weakening the crosslinked structure of the polymer. At temperatures above 150º C, block copolymers are pliable in molten form in contrast to NRL modifiers which begin to undergo crosslinking at this temperature (3). Work by Wegan (2001) suggests optimal mixing temperatures of approximately 180º C. for SBS modifiers (16). Because block copolymers are workable at higher temperatures, the styrene domains comprising the typical SBS modifier can readily be segregated under shear force during the milling process, promoting the dispersion of individual chains throughout the asphalt binder. Consequently, as the mixture is cooled and begins to break, these styrene domains begin to reform, establishing a pervasive polymer network throughout the residual asphalt matrix (3).

Stroup-Gardiner and Newcomb (1995) report that sufficient quantities of SBS polymer modifiers are required to promote effective crosslinking during the cooling phase to ensure that reactive portions of the styrene domains are close enough together to permit bonding. Termed the "critical concentration" or "c*", Stroup-Gardiner and Newcomb recommend SBS contents of at least 2%, and in some cases > 4% by weight of residual asphalt (3). Additionally, as the swelling of the polymer components of a modified emulsion increase, less polymer additive is needed (by weight) to achieve c*. Polymer swelling is generally believed to be caused via interaction with aromatics contained within maltene fractions, and will eventually lead to the formation of a continuous network (18).

Factors influencing the c* include the quantities of diblock (SB) versus triblock (SBS) copolymer used, mixing temperatures, the chemical compatibility between the asphalt and polymers utilized, and blending time (3). Within this context, “compatibility” refers to the degree of molecular interaction occurring between the asphalt and polymer modifier components of the mixture, with more compatible asphalt being characterized by a higher degree of polymer swelling and increased homogeneity and dispersion of the polymer fractions when mixed. In this regard, block copolymer modifiers must be matched to compatible asphalt which will readily dissolve the end-block styrene domains at typical mixing temperatures, as this ensures thorough dispersion of polymer chains during the emulsification and milling process (3).

Stroup-Gardiner and Newcomb report that the complex modulus of 6% SBS-modified AC-10 decreases significantly with increasing SB diblock content at higher temperatures (3). Moreover, the researchers note that as the concentration of the diblock SB increases within an SBS modifier, the resultant complex modulus decreases substantially, leading to increased pavement rigidity, particularly at higher temperatures (3).

Studies by Serfass et al (1992) show that SBS-modified asphalt emulsions exhibit excellent adhesion properties with a diverse variety of aggregate, and can be applied over a much longer working season than similarly modified hot mixes (19). Moreover, emulsified asphalt applications were also shown to tolerate higher polymer dosing levels than modified hot mixes, resulting in improved stone retention, cohesive, and viscoelastic properties; especially in crack sealing applications.

Investigation into the effects of SBS and SEBS triblock copolymers on asphalt rheology conducted by Gahavari (1997) shows a substantial increase in complex moduli at low to intermediate testing frequencies (via dynamic shear rheometer) as polymer content is increased and when compared to unmodified asphalts (20). Similarly, Gahavari also reports a significant decrease in loss tangent values (i.e., decreased viscous, flow-type behavior) over low to intermediate frequencies with the addition of polymer – an indicator of increased elasticity. However, at higher testing frequencies, it has been shown that the aging condition of modified asphalts may reduce the preferential elastic response effects obtained via the addition of polymer modifiers which were observed at lower frequencies (20).

2.2.5 Reclaimed Rubber

Whereas the abundance of used tires and their associated disposal problems are well-known, the incentive to utilize reclaimed rubber to improve pavement performance and/or as a means of facilitating disposal is undeniable. CRM consists of scrap tire rubber that has been mechanically ground and reduced in size to particles generally less than or equal to 6.35 mm (0.25 inches) in diameter. Although most commonly utilized in HMA applications, reclaimed CRM has been used successfully on a limited basis in asphalt emulsions, particularly in those areas of the world where their lower cost and simplified application in remote locales are viewed favorably as compared to hot mixes.

Reclaimed tire rubbers are not pure polymers, but represent blends of SBR latex, polyisoprene (natural rubber), carbon black, and other additives (21). While CRM can be successfully emulsified if particle size is sufficiently fine or if predigested, the cross-linked structure of the compounds in tire rubber generally result in the formation of two distinct phases upon blending (i.e., asphalt and rubber). This makes stabilization of the final emulsion difficult to achieve. Phase separation in CRM modified asphalt emulsions is characterized by two distinct mechanisms – coalescence and creaming (22). Coalescence occurs when polymer particles aggregate together within the emulsion through the process of molecular diffusion. Creaming occurs when polymer particles rise to the surface of the emulsion due to density differences between the modifier and binder components.

Sabbagh and Lesser (1998) note that the phase stability of CRM modified asphalt emulsions is governed in large part by both particle size and morphology. In unstable modified asphalt emulsions, polymer particles tend to coalesce, gradually increasing in size over time until they become sufficiently large for creaming to occur (22). Sabbagh and Lesser have experimentally determined the critical particle transition radius (between coalescence and creaming) to be approximately 4 µm at 110º C for polyolefin. With respect to morphology, polymer particles in unstable asphalt emulsions are predominately teardrop-shaped, whereas those in stabilized asphalt emulsions are characterized by either spherical and/or long-cylindrical shapes. The irregular, non-spherical shaped polymer particles which characterize unstable modified asphalt emulsions are commonly observed under high shear mixing conditions. Additionally, the use of steric stabilizing copolymers has been shown to promote more thermodynamically stable spherical polymer particle shapes (22). Sabbagh and Lesser have noted that while polymer particle sizes in stabilized asphalt emulsions are generally larger than those in unstable asphalt emulsions, the former are not more susceptible to creaming. This is believed to be due to the increased density of the particles in stabilized asphalt emulsions created by the use of steric stabilizers (22). Thus, stabilized asphalt emulsions are those which are characteristically stable with respect to both creaming and coalescence. Paradoxically, Sabbagh and Lesser have shown comparable increases in fracture toughness and improved high-temperature viscoelastic behavior with increasing polymer content for both stable and unstable asphalt emulsions. This suggests that actual field performance is relatively insensitive to initial polymer particle morphology.

CRM can be added as a dry ingredient to slurry mixes to avoid problems of phase separation, but in such cases it serves primarily as a filler material. When used as filler, CRM fails to form a pervasive matrix or network, and thus does not impart the cohesive and viscoelastic benefits associated with most other forms of polymer modification.

One solution to the phase separation problems associated with CRM modifiers involves the use of solvents to partially predigest the rubber particles prior to their introduction into the emulsion. High boiling point petroleum-based solvents that are high in aliphatic content are generally preferred because they promote swelling and softening of the rubber which improves particle wetting and increases adhesion (21), while also meeting U.S. Environmental Protection Agency (EPA) emissions requirements. “RG-1” represents a mixture of 40-50% CRM dispersed in a petroleum-based solvent, which is post-added to the emulsion through simple mixing. RG-1 modifiers exhibit good stability when blended with either cationic or anionic asphalt emulsions (21), with typical treatment applications including chip seals and slurry surfacing.

Laboratory and short-term field testing of RG-1 modified asphalt emulsions indicate improved crack and rut resistance, higher viscosity, lower thermal susceptibility, better stone retention, and improved elasticity when compared to unmodified asphalt emulsions, though results are generally less impressive than conventional forms of polymer modification (21). In addition, some research shows that the use of RG-1 does not adversely impact setting times for slurries or microsurfacings (21). When used in chip seals, RG-1 costs are approximately 2 to 5 cents per square foot, and for slurry or microsurfacing the cost is about 1.5 to 3 cents per square foot (21). No special equipment is required to add RG-1, and standard batch plant transfer pumps are adequate for the task.

Another use of reclaimed rubber and emulsions involves the direct addition of 15-22% of CRM to the hot asphalt binder used in some chip seals. In such instances, the modified binder is sprayed on top of the pavement surface followed by an overlay of stone, and then rolled. A fog seal of asphalt emulsion (generally, a 1:1 dilution) may then be applied over the top of the chip seal to improve stone retention (23), although this particular type of application does not constitute a direct form of polymer modification of the emulsion per se. Cape seals may be constructed using CRM in a similar fashion, by modifying the chip seal binder coat prior to the application of the overlying microsurfacing or slurry seal.

2.2.6 Plastics

The plastic polymer modifiers are typically thermoplastic plastomers (and sometimes elastomers) which are commonly based upon the polyolefins or copolymers of ethylene. Typically, polyolefin modifiers include polyethylene and its variants such as HDPE and LDPE. Although polypropylenes are also considered part of this group, they are generally not recognized as imparting significant improvements in elasticity or crack resistance in asphalt paving applications (7, 24). Among the ethylene copolymers, ethyl-vinyl-acetate (EVA), ethylene-propylene-diene-monomer (EPDM), ethyl-butyl-acrylate (EBA), and ethyl-methacrylate (EMA) are the most common (10).

Characteristically, the plastomers impart rigidity to asphalt pavements leading to rapid early tensile strength and decreased high temperature susceptibility, but depending upon the formulation, may also fail to exhibit the desired elastic response when deformed (i.e., decreased resistance to strain). Indeed, Strategic Highway Research Program (SHRP) guidelines call for a maximum fatigue resistance value of 5,000 kPa (as tested at standard temperatures) in order to decrease the propensity of the in-place pavement to crack at low ambient temperatures (25). In general, the higher the degree of crystalline structuring possessed by a plastomer, the higher the resulting tensile strength and the lower the elastic response (3). However, additional modifiers may be introduced as copolymers which can serve to partially disrupt this crystalline structure, thereby increasing the ability of the pavement to flow. In this sense, the goal of inducing modest increases in flow potential is to reduce excessive binder stiffness at low (i.e., < 10º C.) temperatures, thereby mitigating the potential for thermal fatigue cracking (25). Moreover, the principal function of plastomeric modifiers is usually not to form a pervasive and continuous elastic network as with the block copolymers or latex - rather it is to produce a dispersal of discrete plastic inclusions throughout the bitumen which can impart increased rigidity that provides better resistance to high temperature (i.e., > 30º C.) rutting, and modest improvements in fatigue cracking caused by repeated loading and unloading at intermediate (i.e., 10º – 30º C.) temperatures (25, 26). In addition, these plastic inclusions can also aid in arresting the propagation of cracks once formed (3).

In laboratory comparisons between unmodified binder and those modified with polyethylene plastomers and various elastomers (e.g., SBR, and CRM) respectively, Morrison et al (1994) have shown that the plastic modifiers in particular provide for substantial increases in the penetration index and measures of rutting resistance (25). These results suggest that the polyethylene-modified binder tested (i.e., Dow Chemical Company's Tyrin® 2552) would offer enhanced rheological performance in those environments and during seasons where pavement temperatures meet or exceed 30º C.

Some of the plastic modifiers, such as EPDM, represent hybrid combinations of elastomeric and thermoplastic characteristics. Indeed, EPDM is often classified as a form of synthetic rubber as well as a plastic, and can be mixed with plastomeric additives such as HDPE to yield pavements that possess high temperature rutting resistance, and sufficient ductility at low temperatures to inhibit thermal cracking (27). [Note: The use of polymer blends will be covered in greater detail in the following section.]

Work with polyolefin modifiers indicates that polyethylene variants frequently suffer from asphalt compatibility problems that result in binder and emulsion instability when stored at temperatures in excess of about 150º C. (28). Perez-Lepe et al (2006) have shown that segregation of the polymer phase occurs at comparatively short storage times in the form of creaming, and that this creaming is immediately preceded by widespread polymer coalescence brought about by the immiscibility between the bitumen and polyethylene fractions. In this regard, Morrison et al (1994) have demonstrated that the use of virgin or recycled tire rubber SB as a steric stabilizer in polyethylene modified asphalt emulsions, does interrupt this coalescence mechanism, and yields a more stabilized mix (29).

Yousefi (2003) suggests that as the melt flow index (MFI) of linear polyethylene polymers (e.g., HDPE) decreases, instability increases, making thorough dispersal within the bitumen problematic (26). Moreover, branched polyethylene modifiers such as LDPE were indicated to be easier to disperse than linearly structured equivalents. While high-MFI polymers are indeed easier to disperse, they have less of an effect on high temperature performance, but were shown to significantly improve low temperature susceptibility (26).

Hesp and Woodhams (1991) note that polyolefin modifiers impart a wide range of beneficial characteristics to applied asphalt emulsions, including decreases in thermal cracking and high temperature rutting, greater fatigue resistance, improved skid-resistance, and increased stone retention (30). However, Hesp also observes that the primary obstacles which inhibit the widespread adoption of polyolefin compounds in PME, are problems related to gross phase separation at elevated storage temperatures. Indeed, the authors note that without the use of a stabilizer, polyolefin-modified asphalt emulsions commonly have stable life-spans of only one hour or less. The findings of Hesp and Woodhams are in general agreement with those of Perez-Lepe, and indicate that the primary mechanism of instability in polyolefin-modified asphalt emulsions is the coalescence of the polymer phase which eventually leads to creaming (28, 30). The most promising and cost-effective method for achieving mixture stability in such cases, is regarded to be the addition of steric stabilizers which are thought to secure emulsion stability by being preferentially absorbed at the polyolefin-asphalt interface (28, 30).

EVA is a commonly used plastomeric modifier which represents a copolymer of ethylene and vinyl acetate. By co-polymerizing ethylene and vinyl acetate, the latter serves to reduce the crystallinity of the former, resulting in increased elasticity and better compatibility with the base asphalt (3). In EMA and ethylene acrylate modifiers, the crystalline structure of polyethylene is similarly reduced via the introduction of acrylic acid (3). Panda and Mazumdar (1999) report decreased penetration and ductility, and improved temperature susceptibility in EVA-modified versus unmodified binders (31). Additionally, EVA modified asphalts have been shown to retain their desirable physical properties even after prolonged periods of storage, and do not appear to be adversely affected by minor variations in mixing methods or temperatures (31).

The use of reclaimed waste plastics such as HDPE and LDPE as modifiers, have been shown to be somewhat effective in improving fatigue resistance, and in reducing penetration (24, 32). However, it is noteworthy that some stability problems with these mixes have also been reported, particularly at higher additive concentrations (24).

Gerard et al (2001) have compared the performance of plastomer-modified, elastomer-modified, and unmodified asphalt binders with respect to fracture toughness and crack propagation characteristics at low (i.e., -20º C.) temperatures (33). It has been demonstrated that generally, the use of polymer modifiers increases the facture toughness of asphalt binders. However, SB- and SBS-based modifiers exhibited substantially better fracture toughness than did comparable EVA and EMA modified mixtures owing to respective differences in crack propagation behavior as shown in Figure 8. More specifically, Gerard et al report that EVA and EMA modified mixes propagate cracks at the interface between the polymer and asphalt phases, leading to brittle behavior and stone pull-out. In contrast, the continuous polymer network formed in binders modified with elastomeric additives tends to stretch as the energy from the crack propagates through the polymer domains – impeding crack development in a phenomenon referred to as "crack-bridging" (33). In summation, the results suggest that SB and SBS modifiers provide for diminished low temperature susceptibilities as compared to similar EVA and EMA mixtures.

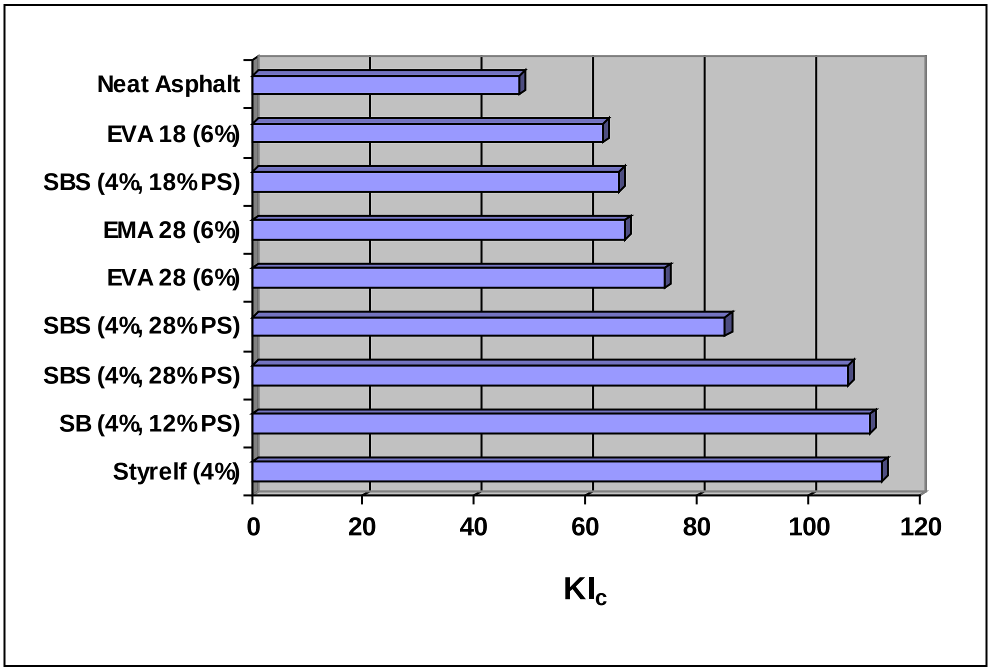


Figure 8: Fracture Toughness at -20º C. (33)

2.2.7 Polymer Blends

Select polymer additives may be blended together to achieve desired composite properties that cannot be obtained from a single polymer modifier alone. Moreover, blending may prove a viable option when the availability and cost of a particular polymer modifier make it attractive for its use, but where the resulting rheological and performance characteristics that it produces may not fully satisfy design requirements. In such cases, the addition of complementary modifiers may provide the means through which design specifications may be satisfied, while permitting the use of the desired primary modifier. Additionally, supplemental modifiers are frequently added to improve the overall compatibility between the polymer and bitumen phases and to improve long-term mixture stability. While practical considerations preclude the exhaustive documentation of the numerous potential polymer combinations, examples of some of the most common blends found within the literature are presented for illustrative purposes.

Applications which utilize polyethylene as the primary modifier are frequently augmented via the addition of elastomers such as PB, in order to achieve better mixture stability (29). Morrison et al (1994) report that polyethylene-modified asphalt emulsions can be effectively stabilized with either virgin PB or lower-cost de-vulcanized CRM (29). In such instances, the mechanism for attaining this increase in stability lies in the attachment of steric stabilizer molecules at the polyethylene-asphalt interface.

Ait-Kadi et al (1996) report that blends of HDPE and EPDM produce improved performance with respect to penetration, the loss of aromatics (aging), and viscosity, when compared to neat asphalt (27). Comparisons of HDPE/EPDM blends to straight HDPE-modified asphalt in this study indicate little performance difference, although microscopic evaluation suggests that the former generally yields a better distribution of the polymer phase than does the latter. This characteristic has important cost and handling implications, since modifiers which are difficult to disperse translate into significantly higher energy requirements and longer mixing times (34). In addition, more thorough and homogeneous dispersal of the polymer phase within the bitumen generally leads to improved mixture stability, which increases potential storage life.

2.3 Polymer Modification Methods and Dosage Rates

The performance of polymer modifiers can be greatly affected by the blending techniques that are utilized, the quantity that is added relative to residual asphalt content, the types of aggregate used, and the methods and temperatures of emulsion storage. This section provides discussions related to the impacts of mixing methodologies and conditions, dosing rates, and storage and handling practices on the demonstrable field and laboratory qualities of polymer modified asphalt emulsions.

2.3.1 Polymer Modification Methodology

Table 2 presents a summary of representative polymer modification methods and recommended dosage rates by polymer type, which have been culled from the available literature. A review of Table 2 reveals that commonly utilized techniques generally include the pre-addition of polymer to either the emulsifying solution or asphalt; post-addition to the finished emulsion product; or “co-milling” of the various component streams at the colloid mill (see Figure 2).

Moreover, of the recommended modification methods presented in Table 2, pre-mixing with the soap solution is the generally preferred method of adding liquid latex to asphalt emulsions, followed by co-milling at the colloid mill. Becker et al (2001) observe that the phase separation and stability problems associated with using solid polymer modifiers generally necessitates the use of a “hot mix” addition method in such cases, whereby the solid polymer is pre-blended with the asphalt prior to emulsification (7).

Post-addition of the modifier to the final emulsion product either at the plant or the application site is sometimes discouraged due to the need for vigorous, continual, and thorough mixing to ensure proper and homogeneous polymer dispersal. One notable exception is the use of CRM-based RG-1, which is predigested with an organic solvent prior to being post-added to the emulsion.

Table 2: Polymer Modification Methods and Dosages

Type	Method	% Polymer Solids	Application(s)	Reference(s)
SBR	Soap pre-batching. NO post or field addition.	3 – 4% of residual asphalt content.	Slurry Seals	(36)
SBR	Not Specified	3% of residual asphalt content	Various	(4)
SBR (Ultracoat™)	Dilute with water to 15% latex solids and blend with aggregate at collection hopper.	15% of total emulsion weight	Polymeric anti-strip coating to increase stone retention in chip seals.	(37)
SBR (Butonal LS 198®)	Soap pre-batching. NO post or field addition.	2 - 6% of residual asphalt content, usually 3%.	Various	(9, 38)
SBR	Soap pre-batching.	>=3% of residual asphalt content.	Microsurfacing	(39)
SBR, NRL, Neoprene, SBS, EVA	Pre-blend latex solids with bitumen using a high-shear blender. If latex in form, then use soap pre-batching.	2% of residual asphalt content.	Microsurfacing	(40)
SBR, NRL	Soap pre-batch, co-mill, or post add.	3 – 5% of residual asphalt content.	Various.	(41)
SBS	Pre-blend with asphalt.	5 – 12% of residual asphalt content.	Various	(42)
SBS	Pre-blend with asphalt binder.	> 5% of residual asphalt content (forms continuous polymer matrix).	Various HMA applications.	(17)
SBS, SB	Pre-blend with asphalt.	6% of residual asphalt content.	Various.	(43)
SBS, SB	Pre-blend with asphalt.	4% by weight of asphalt content.	Various low temperature applications.	(33)
CRM (RG-1)	Post-blended in-line directly with emulsion at plant and remixed before application.	5 – 8% of total emulsion weight.	Asphalt Rubber Slurry Surfacing	(44)
NRL (1497C)	Ralumac Process – Soap pre-batching.	4% of total emulsion by weight.	Various	(9)
EGA (Elvaloy®)	Pre-blend directly with binder.	1.5 – 2.0% of residual asphalt content.	Various HMA applications.	(45)
EVA	Pre-blend with binder.	5% by weight of asphalt content.	Various	(31)

Type	Method	% Polymer Solids	Application(s)	Reference(s)
EVA / EVM	Pre-blend with binder.	6% by weight of asphalt content.	Various low temperature applications.	(33)
EPDM, LDPE, HDPE	Pre-blend directly with binder.	5% of residual asphalt content.	Various HMA applications.	(34)
EVA, LDPE	Pre-blend directly with binder.	4 – 8% of asphalt content by weight.	Various	(35)
Any Appropriate	Soap pre-batch or pre-blend with bitumen.	3% of residual asphalt content	Microsurfacings	(46)
Polyethylene (Tyrin® 2552)	Pre-blend directly with binder.	3 – 5% of residual asphalt content.	Various	(25)
Various	Various	2 – 10% of residual asphalt content, 2 - 3% most commonly.	Various	(7)

Forbes et al (2001) (47) examined the effect of four distinct and commonly used polymer modification techniques on asphalt binder microstructure at high temperatures. The emulsion modification techniques tested include:

1. Pre-blending – The polymer modifier is added directly to the bitumen prior to emulsification. This method is required for solid forms of polymer.
2. Co-milling – Separate streams of polymer, bitumen, and emulsifier solution (soap) are co-milled together simultaneously.
3. Soap Pre-batching – The polymer modifier is added to the soap solution (water and emulsifier) prior to milling with the bitumen.
4. Post-Modification – The polymer modifier is added to the final asphalt emulsion either at the plant or in the field.

Properly cured residue from a sample of asphalt emulsions prepared using each of the addition methods enumerated above were examined using laser-scanning microscopy to ascertain the resultant character of the structural network and distribution of polymer within the test samples. Microstructure comparisons were also performed with non-emulsified polymer-modified “hot mix” binders.

Forbes et al found that asphalt emulsions produced using either soap pre-batching or co-milling produced a slightly better distribution of the polymer than did post-modification (47). In these cases, bituminous particles created within the colloid mill were found to be layered around their surfaces by droplets of polymer modifier (Figure 9). When asphalt emulsions are prepared by soap pre-batching or co-milling, latex particles are prevented from coalescing in the presence of the soap solution, but result in the formation of a thin film or matrix around the asphalt particles upon drying (Figure 10).

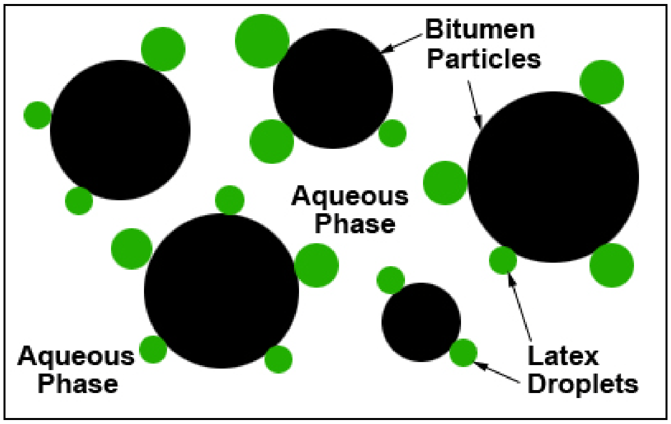


Figure 9: Bi-Phase Modified Emulsion (47)

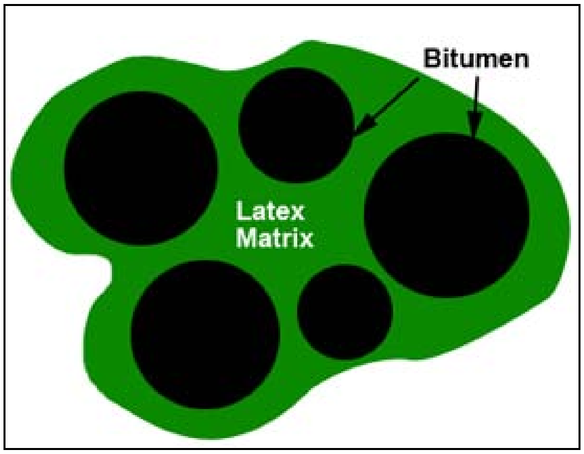


Figure 10: Polymer Network in Cured, Co-Milled Emulsion (47)

Examinations of non-emulsified asphalt binders which have been subjected to direct polymer modification indicate the presence of widely distributed polymer droplets of varying size, and numerous occurrences of “swollen” (i.e., coalesced) polymer – an indication of incompatibility between the polymer and bitumen phases.   However, when pre-blended asphalts are emulsified, the resulting mixture exhibits well-distributed and discrete fine particles of polymer, areas of swollen polymer, and aggregated asphaltenes – characteristics which represent a marked improvement in bitumen-polymer compatibility (47). Thus, whereas co-milling and soap pre-batch modification yield a bi-phase of asphalt and polymer, pre-blending produces a monophase of asphalt and polymer after emulsification as illustrated in Figure 11. Additionally, pre-blending was shown to ultimately yield a much more homogeneous and more thorough distribution of polymer than did modified hot binders, suggesting that pre-blended polymer-modified asphalt emulsions may lead to more consistent cohesive strength performance, better elasticity, and improved stone retention characteristics than modified hot mix asphalt (47). Indeed, when lateral shear stress was applied to a dried pre-blended modified emulsion sample in the Forbes study, the polymer network was found to predictably elongate and resist deformation (47). However, Forbes et al caution that pre-blended asphalt emulsions do not produce a continuous polymer network as seen in co-milling or soap pre-batching mixes, and recommend further investigation to determine if this structural difference might impact performance.

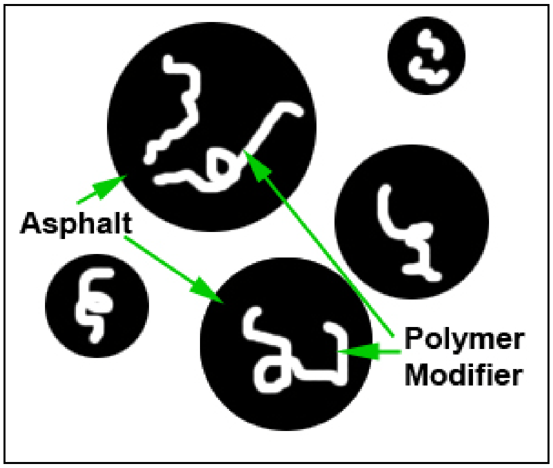


Figure 11: Pre-Blended Asphalt-Polymer Monophase (54)

Lubbers and Watson (2005) present the results of analyses performed at BASF Corporation which employed a form of stress-strain testing developed by Dr. Koichi Takamura (48), to gauge the relative fatigue performance of unmodified, pre-blended, and co-milled asphalt emulsion residues, as well as unmodified hot mixes (4). The testing modality utilized by the BASF researchers consisted of the following steps:

1. Strain sweep from a low of 0.1% to high of 5% applied for 30 minutes.
2. Constant strain of 5% applied for 30 minutes.
3. Strain reduced to 0.1% for 15 minutes to monitor potential recovery.
4. Repeat steps 2 and 3 and measure change in residual strength.

A similar test sequence was also performed on duplicate samples using a maximal stress of 10%. The test results indicate that unmodified asphalt emulsions are substantially weaker than neat hot-mix asphalt, due in large part to the failure of asphalt droplets in the former to fully coalesce, even within a 24-hour period. Conversely, asphalt emulsions modified with 3% SBR latex performed significantly better than did unmodified emulsions or neat non-emulsified asphalt cement. Of particular interest was the performance of the pre-blended SBS-modified emulsion samples, which demonstrated diminished viscoelastic recoveries as compared with conventionally co-milled SBR-modified emulsions. The reduced performance of the pre-blended asphalt emulsion was especially evident at the higher 10% strain level (4). These results suggest that using pre-blended modified asphalts in emulsions may yield reduced residual asphalt performance - perhaps due to the absence of the continuous polymer network which is more characteristically found in emulsions modified using co-milling or soap pre-batching methods. Figure 12 illustrates fatigue resistance test result comparisons between unmodified, conventionally co-milled, and pre-blended modified asphalt emulsion residues (4).

Similarly, an evaluation of pre-blended and co-milled SBR modified asphalt emulsions in chip seals performed by Takamura (2001) indicates that the formation of a honeycombed polymer network around the asphalt particles, results in a 1-2 Performance Grade (PG) improvement in rut-resistance as compared to polymer-asphalt monophase mixtures (12). Figure 13 illustrates a comparison of rutting resistance temperatures for neat asphalt, hot mix, emulsion residue, and cured residue (1 week at 60º C.).

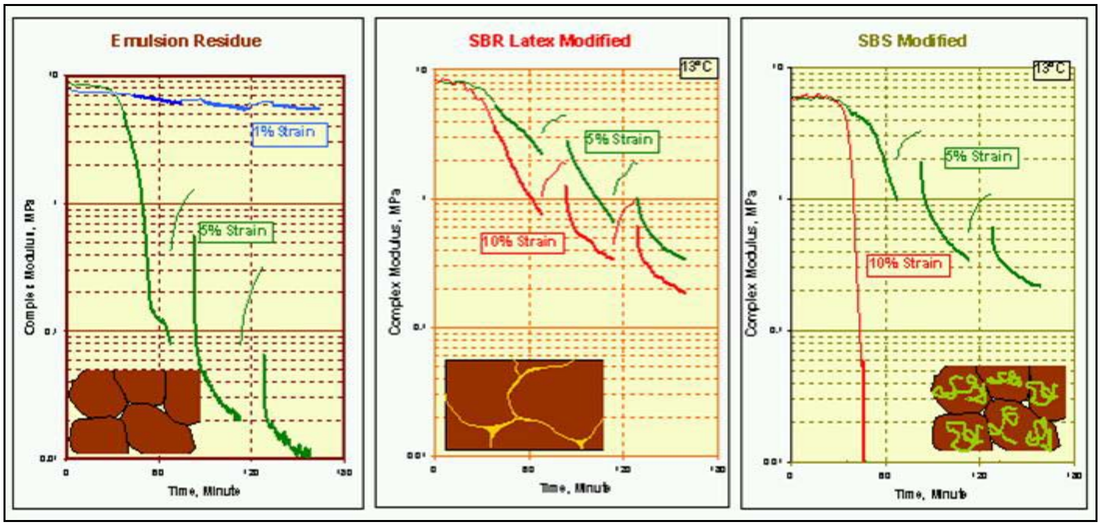


Figure 12: (L to R) Unmodified, Co-Milled, and Pre-Blended Emulsion Test Results (4)

[Note that the hot mix and asphalt emulsion residue results shown in Figure 13 were all modified with 3% SBR latex by weight.]

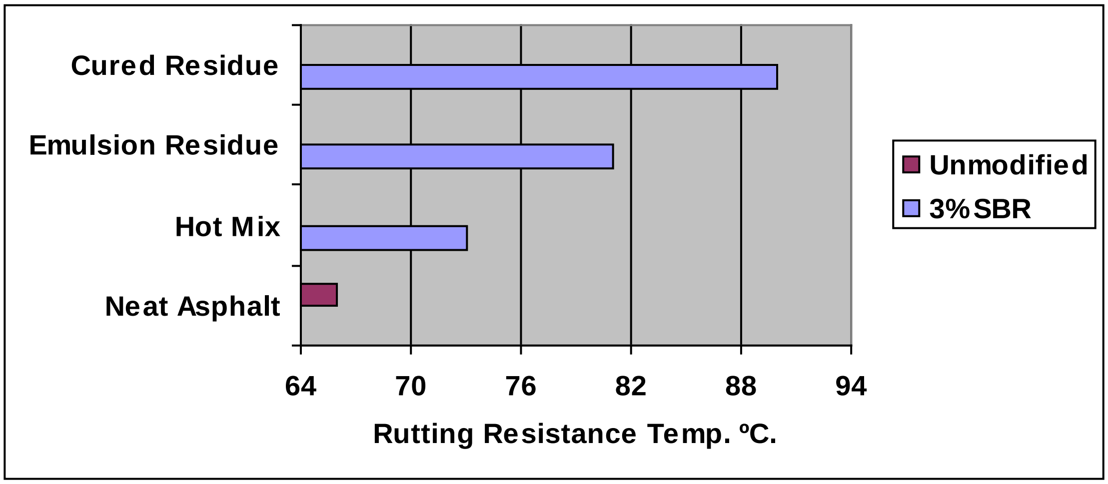


Figure 13: Advantages of SBR Network (12)

Takamura and Heckmann (1999) suggest that SBR latex is preferable in some respects to SBS modifiers because it possesses physical characteristics which make it more flexible by permitting it to be successfully added using co-milling, soap pre-batching, or post modification methods.   The researchers report observing the successful formation of a continuous polymer network in asphalt emulsions prepared with post-added 3% Butonal® NS198 (an SBR modifier), as well as significant improvements in laboratory measures of rutting resistance over unmodified binders – particularly at high (i.e., > 50º C) temperatures (49). However, no comparisons were provided between the performance characteristics of the various polymer mixing methodologies. Takamura and Heckmann further demonstrated that once formed, the resultant polymer network will remain intact, even when reheated to “hot mix” temperatures (i.e., 200º C).

Wegan (2001) (50) examined the impact of different polymer modification techniques, mixing times and temperatures, and filler and aggregate types on the distribution of polymer additives in modified asphalt binders. This study involved the formulation of a variety of mix designs in the laboratory which upon curing, were cut and prepared as ultra-thin sections which were subsequently subjected to UV-light microscopic analysis. Polymer modifiers tested in the Wegan study included EVA, SBS, and a waste product material based on polyethylene (PE). Results indicate that polymer swelling increases substantially in cases where modifiers are pre-blended with the binder, versus those which are added directly to the final bituminous mixture (i.e., post-modification to asphalt and aggregate mix). Pre-blended polymer modified asphalt binders were also shown to provide increased contact and adhesion between polymer components and the surfaces of mineral grains in those mixtures where coarse-grained aggregate was used. Polymer was similarly found be more pervasively distributed and to exhibit better aggregate contact characteristics in cases where mixing times and/or the quantity of the modifier used were increased. Wegan’s temperature-related studies indicated that a mixing temperature of approximately 180º C. provided for more homogeneous polymer distribution than did substantially cooler (i.e., 160º C.) or hotter (i.e., 200º C.) temperatures (50).

In test mixes where 7% EVA was pre-blended with the asphalt binder, Wegan reports observing the formation of a partial, yet distinct polymer network structure. Test samples containing 18% pre-blended EVA exhibited an even greater degree of polymer network formation. These results appear to suggest that in contrast to the findings of the BASF and Forbes studies, modified asphalt binders produced by pre-blending may produce a cross-linked network structure, providing that the polymer content is sufficiently high. However, no information is provided by Wegan with respect to comparing the performance of high polymer content pre-blended binders to conventionally modified lower content mixtures, or whether the increased materials cost of this form of pre-blend justifies its use.

Hussein (2005) has examined the impact of polymer-asphalt blending time on PMA performance for varying molecular weight LDPE and EVA additives. Figure 14 summarizes the change in complex shear modulus for various modified and neat asphalts relative to mixing time. Polymer modified mixes exhibit significant and well-defined increases in complex shear modulus (G*) as mixing time is lengthened, until a critical point is reached where upon these improvements begin to stabilize. For example, the steady-state points for 8% LDPE1, 8% EVA1 and 8% EVA2 are approximately 30, 15, and 20 minutes, respectively. In contrast, neat asphalt exhibits a virtually flat-line G* response over the same period. Hussein proposes that the point which represents stabilization in the magnitude of G*, is indicative of the optimal blending time for that polymer-modified mixture. Results indicate that the optimal blending time for EVA-modified binders was generally less than for LDPE-modified mixtures, owing in part, to the lower weight-average molecular weights of the former (35). Hussein also found that binders containing low vinyl acetate content EVA additives exhibited the best high temperature susceptibility and long-term storage stability of the mixtures tested. However, little if any benefit was identified for these polymer additives at low temperatures.

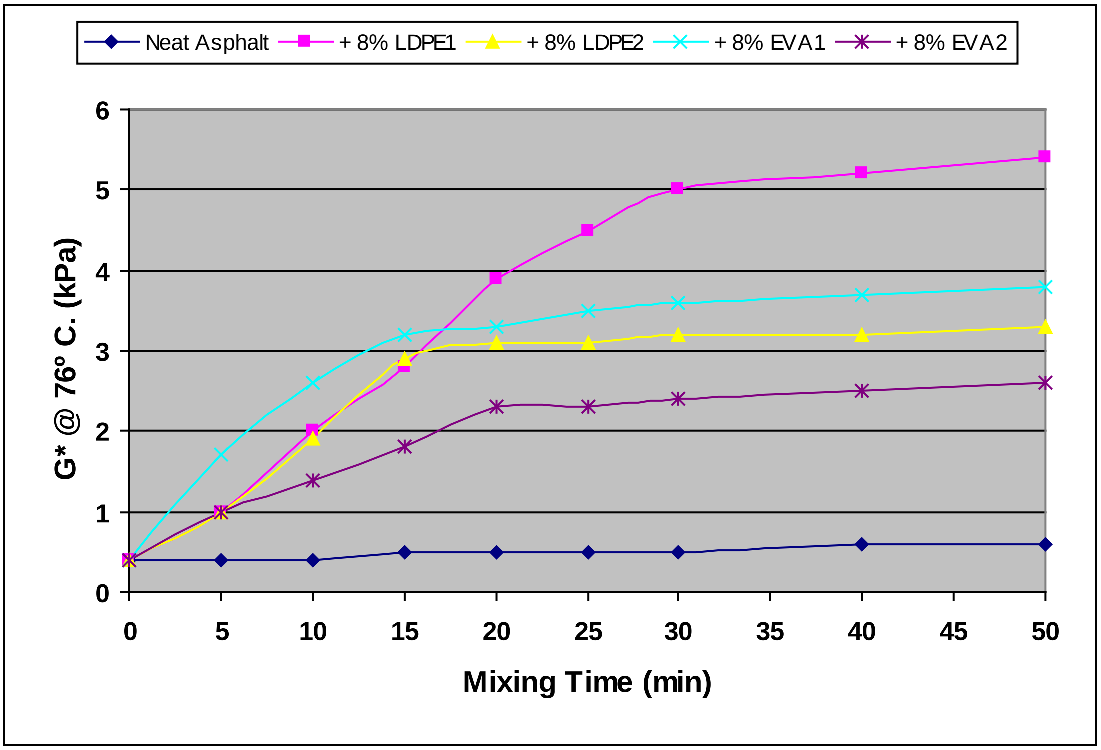


Figure 14: Complex Modulus over Mixing Time (35)

2.3.2 Polymer Dosing

As Table 2 illustrates, the range of polymer content dosing recommended for most applications generally varies between about 2% and 10% by weight of the residual asphalt content with most research, standard, and manufacturer specifications calling for a polymer concentration of approximately 3% to 5%.

Chen et al (2002) have examined the effect of SBS polymer content on laboratory-determined PMA performance. SBS contents were varied from 0% to 9%, and the resulting cured mixtures tested for ring-and-ball softening point, penetration, and complex modulus by dynamic shear rheometer (DSR) (17). In addition, test samples were also subjected to structural analysis via transmission electron microscopy. Results of the Chen et al study reveal that increasing SBS content resulted in increased polymer swelling, which in turn produced increases in asphaltene content (caused by maltene absorption by the polymer phase), leading to a harder matrix. Figure 15 presents the results of the softening point and penetration tests.

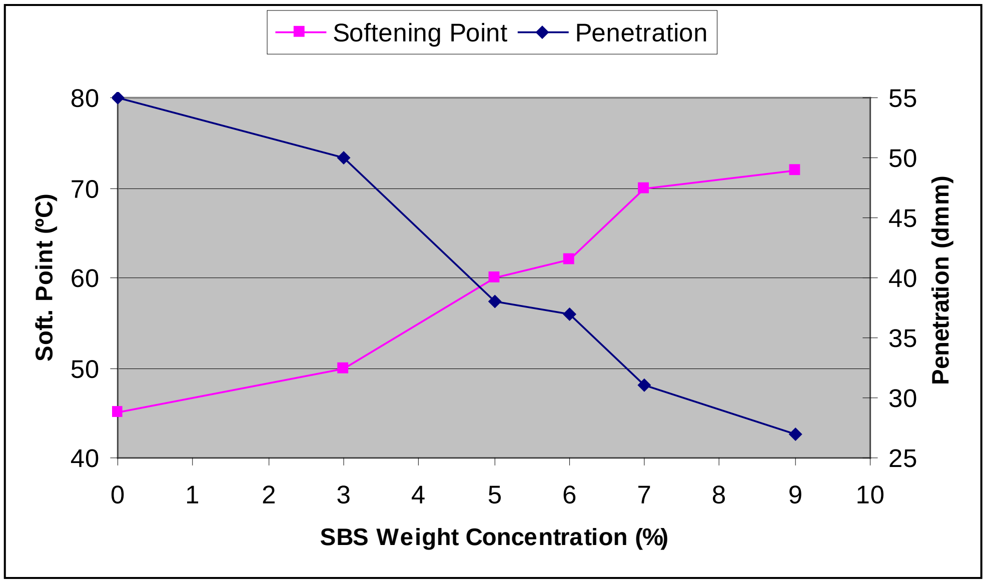


Figure 15: Effect of SBS Concentration on PMA (16)

As Figure 15 illustrates, increasing SBS content resulted in substantially improved softening point and penetration characteristics up to a critical concentration of about 5% to 6%. Chen et al note that as the concentration of polymer reaches about 5%, the asphalt and polymer phases both become continuous – that is, each phase forms an interconnected and interwoven matrix. At polymer concentrations in excess of 5%, the SBS becomes the dominant matrix, forming a continuous film around droplets of almost pure asphalt. Moreover, because improvements in softening point and penetration begin to stabilize at concentrations higher than about 6%, Chen suggests that this level of SBS is optimal for the particular asphalt tested (i.e., AC-30) (17). Figure 16 depicts the effect of SBS content on the complex shear modulus of test samples as measured using the DSR. As Figure 15 illustrates, adding about 5% SBS results in an approximately 6-fold increase in the complex modulus over neat asphalt cement. Furthermore, increasing SBS content from 3% to 5% yields a proportionally larger increase in complex modulus than do increases in excess of 5%.

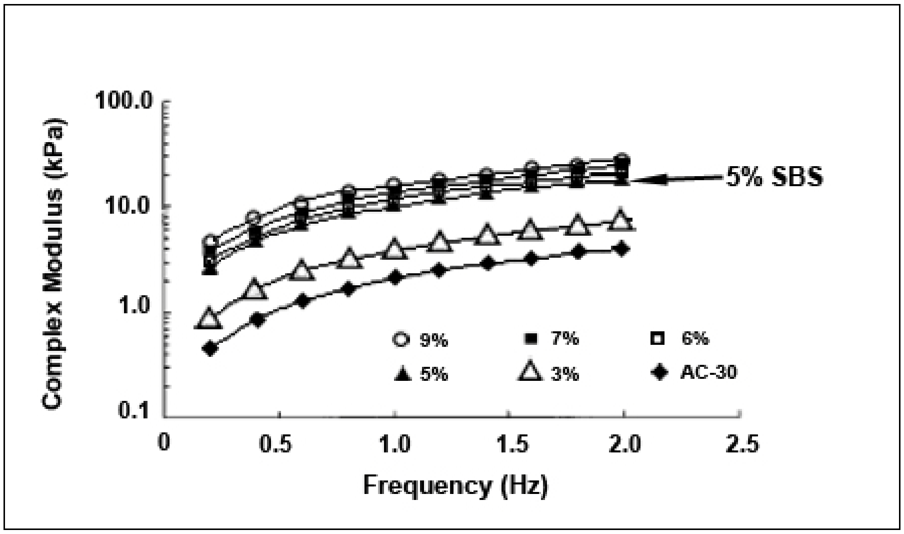


Figure 16: Effect of SBS Concentration on Complex Modulus at 60º C. (16)

Thus, it is suggested that a polymer content of around 6% is required to generate the continuous polymer network which is believed to impart the desirable rubber-like elasticity characteristics associated with polymer modified binders. It should be noted however, that a form of direct bitumen modification (i.e., pre-blending) was utilized to prepare samples for this study. Similar results were obtained by Airey et al (2002), which indicate that SBS concentrations of 4% to 8% are required to establish a continuous polymer network when direct bitumen modification methods are utilized (17). However, as previously discussed, others have shown that pre-blending may fail to result in the formation of a continuous polymer network unless the content of polymer added is sufficiently high to promote phase separation and swelling (4, 12, and 50). Thus, the optimal polymer contents presented in the Chen and Aiery studies might prove to be higher than necessary should a polymer modifier be employed which would permit co-milling or soap pre-batching (e.g., SBR) in an analogous PME application.

Chen et al have also examined the impact of variable SBS concentrations on Brookfield viscosity (ASTM D789, D4878) as shown in Figure 16. In this regard, the researchers note that polymer modified binder pumping generally does not become problematic until mixture viscosities begin to exceed about 3,000 cP (16). Thus, as Figure 17 illustrates, SBS weight concentrations in excess of 6% appear to be contraindicated with respect to the materials handling and placement practicalities for modified AC-10 and A-30 asphalt binders.

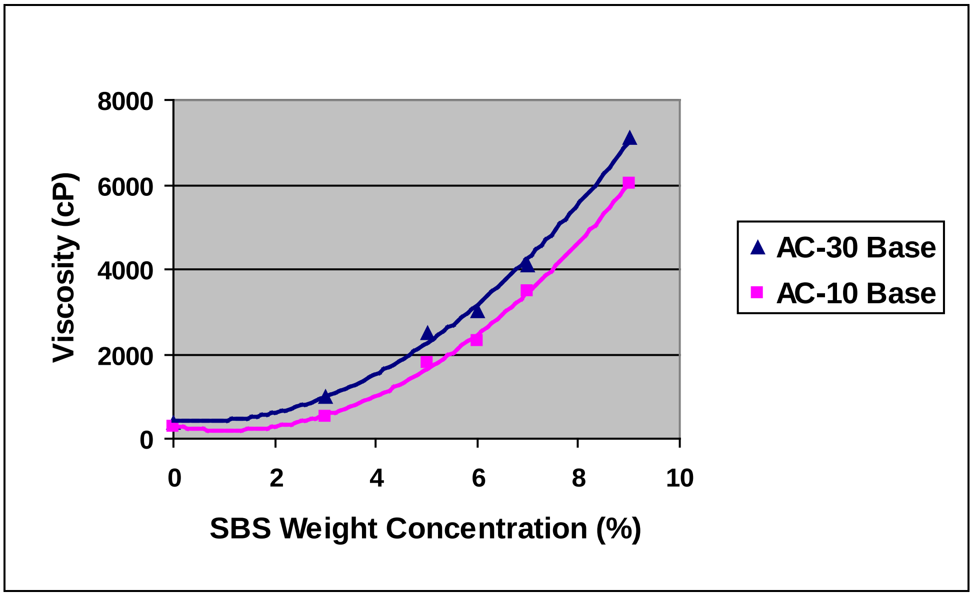


Figure 17: Viscosity as a Function of SBS Concentration (12)

Serfass et al (1992) report that adequate SBS concentrations are required to ensure proper formation of a continuous polymer network, and that it is this network which imparts the most desirable viscoelastic properties to modified asphalt binders. Within this context, the authors note that "adequate" is highly dependent upon asphalt compatibility, but is generally within the range of 3% to 5% by weight of residual asphalt (18).

2.3.3 Storage and Handling Considerations

Proper storage conditions represent one of the most common problems associated with the use of PME. The mixing processes used are complex and often proprietary, and as such, modified binders are generally acquired in an already-blended form from the supplier. Once batched, the mixture must be placed in a special holding tank that can be continuously agitated to prevent the phase separation problems which were noted previously and described in some detail. Temperatures during storage must also be strictly controlled to prevent setting, premature breaking (emulsions), and/or thermal destruction of the polymer modifier. As has already been demonstrated, the effective length of storage of polymer modified asphalt emulsions, even under ideal conditions, can vary widely depending upon the modifier and bitumen types, and the degree of polymer-asphalt compatibility. When storing and handling prepared asphalt emulsions, the following general guidelines are recommended:

- In general, store the emulsion between 10º and 85º C. depending upon the intended use and the particular grade of emulsion being utilized;
- Do not heat the emulsion above 85º C. during storage as this may cause excess water evaporation. Similarly, excessive and prolonged temperatures above 100º C. can cause breakdown of the emulsion and/or destruction of its polymer components;
- Avoid prolonged periods of storage, and make sure the mixture is gently and continuously agitated;
- Maintain an accurate temperature history and collect frequent measurements;
- Do not allow the asphalt emulsion to freeze, as this breaks the emulsion and causes phase separation and mixture instability; and,
- Do not use forced air to agitate the emulsion as this too may cause it to break prematurely (1, 51, 52).

DSR testing conducted after simulated aging with a Rolling Thin Film Oven (RTFO-DSR) of properly cured polymer modified emulsion residue indicates that unmodified asphalt emulsion contamination present within storage tanks or product transfer lines may adversely impact performance (52). Similarly, some reductions in RTFO-DSR performance were noted with increasing storage times, which, when combined with product contamination, resulted in even more pronounced degradation of RTFO-DSR results (52, 53).

However, when modified non-emulsified asphalt binders were tested using comparable protocols, results indicate that the impact of prolonged storage, elevated temperatures, and contamination were substantially greater than were found during asphalt emulsion residue trials. It is hypothesized that this performance differential between modified asphalt binders may be due to the evaporation of water from the former, which provides a better barrier to oxidation, and hence aging (52). Therefore, it is suggested that modified asphalt emulsion storage and handling protocols should focus primarily on preventing excessive water loss and phase separation rather than on aging-related problems (53).

2.4 Performance

2.4.1 Performance Criteria

The performance enhancing characteristics of polymer additives are generally twofold - offering increased resistance to permanent forms of deformation such as rutting and shoving (high temperature susceptibility); and providing improved durability with respect to the formation of load-associated types of pavement distress (i.e., fatigue cracking). Polymers can also afford additional benefits by reducing the formation of non-load associated cracks caused by roadway brittleness which often occurs in pavements that become excessively stiff and hard at low temperatures. In this regard, properly modified asphalts demonstrate improved temperature susceptibility characteristics by remaining flexible at low temperatures, while retaining sufficient stiffness at high temperatures to resist permanent deformation.

Some initiatives have been undertaken to develop a “Superpave™-like” specification for surface applied asphalt emulsions. At present, ASTM D977-05 Standard Specification for Emulsified Asphalt utilizes some aspects of Superpave™ in its testing and characterization protocols. Hazlett (1996) asserts that many of the Superpave™ performance criteria, such as rutting resistance, thermal cracking, and RTFO aging, are not applicable to surface applied treatments (55). Moreover, while some forms of Superpave™ testing could be extrapolated to polymer-modified emulsified asphalts, certain specification limits may not be appropriate for pavement surface conditions. However, Clyne et al (2003) utilized Superpave™ specifications to test polymer modified asphalt emulsion residue for cold in-place recycling applications, in a manner similar to that of asphalt binder (56). Comparisons of resulting data trends from emulsified and non-emulsified asphalt binder tests were similar enough to suggest that PG test protocols could be adapted to emulsion characterization, although further investigation is required to establish whether experimental results can be successfully correlated to field performance (56).

Takamura notes that polymer modified asphalt emulsions can be successfully used in microsurfacing applications for filling ruts up to 5 cm deep (54). This contradicts the contention by some that rutting resistance is an inconsequential measurement parameter when assessing polymer modified asphalt emulsion performance. Indeed, rutting resistance should prove a valuable indication of a rut-filling mixture's ability to resist future high temperature deformation.

Epps et al (2001) have developed a Surface Performance Grading (SPG) system for asphalt emulsions based upon the modification of existing test protocols used under the standard PG system for HMA (57). The SPG is designed to take into account the unique forms of distress common to surface course mixes, such as extreme high and low temperature performance, susceptibility to aging, stone loss (e.g., from chip seals), storability, and handling characteristics. Modifications to the standard PG system generally include adjustments to constant limiting values, as well as some changes to the actual testing protocols. For example, the PG procedure specifies that the designed high temperature limit should be determined at a depth of 20 mm below the pavement surface – a depth limitation which is not applicable to surface treatments. Thus, high (and low) design temperatures under the SPG are taken to be directly at the pavement surface.

Determinations of in-place asphalt emulsion performance are dependent upon the identification of key performance variables, and the measurable physical and chemical properties of the asphalt binder or emulsion residue which relate to those variables. An extensive literature review conducted by the Strategic Highway Research Program (SHRP) has identified five (5) key variables for assessing pavement performance. These are:

1. Low Temperature Cracking (low temperature susceptibility);

2. Fatigue Cracking (repetitive loading/unloading);
3. Raveling (stone loss);
4. Rutting (permanent deformation, high temperature susceptibility); and,
5. Aging (58).

Table 3 presents a matrix adapted from the SHRP review, and depicts the reported relationships between various asphalt physical and chemical properties and each of the performance variables enumerated above. The arrows in Table 3 indicate whether the performance criteria increases or decreases in magnitude as the corresponding physical or chemical property increases or decreases. For example, when viscosity increases, so do measured fatigue and low temperature cracking.

Table 3: Asphalt Properties and Pavement Performance (58)

Performance Criteria	**Viscosity**	**Penetration**	**Ductility**	**Temperature Susceptibility**	**Binder or Mix Stiffness**	**Softening Point**	**Asphaltene Content**	**Naphthalene Aromatics**
Low Temp. Cracking	↑	↓	↓	↑	↑			↑
Fatigue Cracking	↑	↓	↓					
Raveling	↓		↓				↑	↓
Rutting				↓			↓	
Aging	↑	↓	↓	↓		↑	↑	↓

However, in developing the SPG, Epps generally discounts the importance of rutting and thermal cracking in surface treatments, focusing instead on:

1. High and low temperature behavior which can lead to aggregate loss;
2. Aging performance;
3. Application and handling characteristics of the prepared emulsion (57).

Conversely, rutting resistance can prove a valuable test parameter when assessing the performance of rut-filling mixes (54). Takamura has observed that the action of radial truck tires actually produces higher than average critical shear stresses on thin surface treatments such as chip seals and microsurfacings, as compared to full or partial thickness HMA (see Figure 18). This underscores the importance and value of estimating the high temperature susceptibility and stone retention capacity of modified surface treatments.

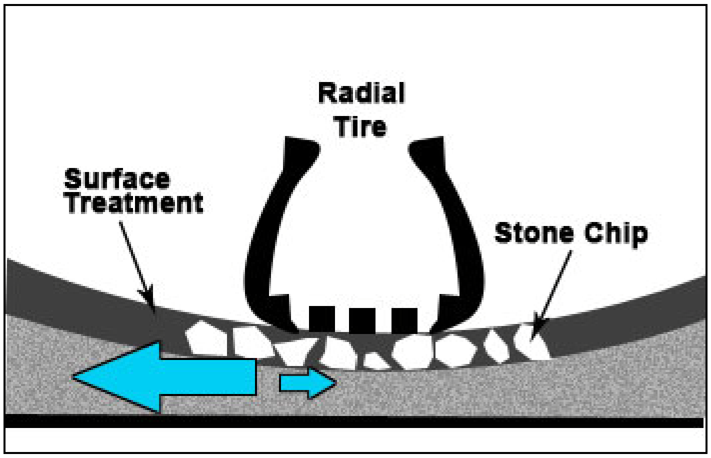


Figure 18: Influence of Radial Tire on Surface Treatment (54)

It is noteworthy that the relationships between laboratory-determined binder physical properties and actual field performance are not always clear, and substantial evidence exists which is often contradictory. For example, it has been shown through stress-controlled fatigue tests that <u>stiffer</u> mixes are more resistant to fatigue cracking, whereas strain-controlled tests indicate that softer mixes are more fatigue resistant (16). Moreover, because polymer modified asphalt binders are used as thinly-applied surface treatments, the physical parameters used to characterize the performance of HMA mixes (such as the PG specification) may not always be applicable.

The search for physical parameters and related laboratory tests which can be used to accurately characterize the performance of PME is on-going. The following section discusses some of the information obtained from the literature review which pertains to the use and adaptation of various innovative and routine testing protocols that have been, or which may be utilized for the analysis of PME residue performance.

2.4.2 Testing Protocols and Considerations

Analysis of asphalt emulsion properties may be accomplished by directly collecting a sample of the non-emulsified binder, or by extracting the properly cured residue from a prepared emulsion sample. Typical residue extraction techniques include:

- Stirred Can Method – A commonly utilized extraction technique, it involves constantly stirring a sample of the emulsion for 170 minutes at a temperature of 163º C. to drive-off the water. A blanket of nitrogen gas is used to dampen the effects of oxidation. Although this method yields abundant quantities of testable residue in fairly short-order, it has been criticized as not accurately representing actual field conditions due to the high continuous temperatures which are used (59).

- RTFO Method – This methodology described by Takamura (2000) is a variation on the RFTO test used to simulate aging (60). Samples of the emulsion are rolled in bottles in a temperature-controlled environment at 85º C. for 75 minutes with a stream of heated nitrogen gas jetted over the emulsion film to facilitate water evaporation. This method has also received criticism because it can lead to incomplete water evaporation in certain asphalt emulsions such as CRS-P2, producing inconsistent follow-up test results (59). However, some suggest that this method may be useful for quality control purposes at emulsion production sites since it permits for the rapid extraction of testable quantities of residue (60).

- Forced Air-Drying Method – This extraction technique utilizes forced air flow at ambient (22º C.) temperatures to facilitate water evaporation. Although this method is generally regarded as being one of the most representative of actual field conditions, it is a lengthy process to complete (i.e., 300 to 360 minutes) and approximately one day is required to prepare the sample for extraction (59).

- Vacuum Distillation Method – The sample is placed into a vacuum distillation unit at a temperature of 115º C. Takamura (2000) has noted that microscopic examinations of samples extracted through distillation exhibit undesirable changes in polymer network morphology including cross-linking and polymer decomposition owing to the application of excessive heat (60). These changes can lead to viscosity inconsistencies and the degradation of other performance measures. Thus, it is suggested that vacuum distillation may only be appropriate for determining the presence of polymer, not for ascertaining the placed network structure.

Key factors which should be considered when selecting a residue extraction methodology include:

- Reproducibility – Residue samples repeatedly extracted from the same emulsion mix should yield statistically similar results when subjected to testing techniques such as DSR, softening point, penetration, etc. Extraction techniques that tend to yield widely divergent physical property test results are not suitable for insuring accurate characterization of modified emulsion performance.

- Time – Various extraction methods have different processing time requirements which must be considered from a logistical standpoint. For example, lengthy extraction techniques may not be appropriate for use at the emulsion production site if accurate test results cannot be obtained in a timely manner prior to field placement.

- Cost – Differences in sample preparation time, extraction time, and equipment requirements can translate into varying costs between methods.

- Accuracy and Representativeness – A balance must be achieved between time/cost considerations, and the testing accuracy that can be realized with an associated extraction methodology. Similar consideration should also be given to how representative an extraction technique is relative to actual field evaporation and curing conditions, and whether a particular method might fundamentally alter the character of the residue in a way that distorts physical property test results.

As discussed previously, extracted residues or samples of non-emulsified binder material may be subjected to a wide variety of testing modalities to estimate field performance. Typical forms of performance testing include (but are not necessarily limited to):

- DSR – to predict rutting resistance and high temperature susceptibility. Useful for polymer modified asphalt emulsions employed in rut-filling applications;
- RTFO – to simulate the effects of aging/oxidation;
- Ductility – to estimate the potential for fatigue and thermal cracking, and/or raveling;
- RV – used to gauge cracking susceptibility, and raveling potential through viscosity measurements;
- BBR – low temperature susceptibility and thermal cracking potential;
- Vialit – measures stone retention characteristics;
- Penetration – to estimate cracking potential and mixture consistency;
- Wheel-Track Test – used to simulate wheel traffic loading and unloading to ascertain rutting-resistance;
- Loaded Wheel Test – used for slurry seals and microsurfacings to compact the sample as a means of assessing the mixture’s susceptibility to flushing;

- Wet Track Abrasion Loss – used to measure the wearing characteristics of slurry seals and microsurfacings under wet track abrasion conditions;
- Ring and Ball – to estimate softening point temperature where full penetration occurs. Usually used as a consistency check on polymer modified asphalts;
- Schulze-Breuer-Ruck – utilized to evaluate the compatibility between bitumen, aggregate, filler and polymer modifier, particularly in microsurfacings;
- Zero Shear Viscosity – proposed as an alternative to G*/sin δ as a measure of rut-resistance. Also used in highly modified mixtures to estimate the degree of polymer network formation;
- Infrared Spectroscopy (IR) and Nuclear Magnetic Resonance (NMR) – used to verify the presence and relative abundance of polymer modifiers (61); and,
- High Performance Gel Permeation Chromatography (HPGPC) – utilized to characterize the molecular weight and physical size of polymer modifiers (61).

Testing of the finished emulsion product may also be performed to verify placed product quality or to estimate storage life. The former can be evaluated using one of the extraction procedures described previously to determine residual asphalt content, and the latter by the Long-Term Asphalt Storage Stability Test (LAST) which is used to estimate thermal degradation and phase separation potential (61).

Typical physical property testing techniques for asphalt binders and emulsion residue have traditionally focused on determinations of viscosity, penetration, ductility, and softening point temperature. However, these tests often fail to accurately and comprehensively characterize the performance characteristics associated with PME (16, 48). In this regard, the use of oscillatory DSR testing has become increasingly advocated as one method through which the viscoelastic properties of modified residue and binders may be assessed (16). Under this procedure, a binder or emulsion residue sample is placed between two plates in a DSR device, and subjected to oscillating shear stress and strain for the purpose of determining the complex modulus (G*, a relative measure of stiffness) and the phase angle (δ, the elastic response) of the material. Takamura (2005) has further proposed a variation on the DSR procedure specifically for modified emulsion residues, which consists of the following sequence of three testing intervals:

1. Strain Sweep - Strain is gradually increased from 0.1 to 5% in 35 minutes, and is used to evaluate rheological properties of the binder at wide strain levels;
2. High-Constant Strain – constant strain (1%, 5%, or 10%) is applied immediately after the first period of strain sweep for a period of 30 minutes;
3. Relaxation – After the end of the second period of high-constant strain, the sample is permitted to relax for a period of 15 minutes with only a minimal strain of 0.1% which is used to observe the recovery of G* (48).

The sequence above is typically repeated at least two more times on the same sample to illustrate the progressive loss of G* as shown in the example provided in Figure 12. The results of this test provide an indication of the relative fatigue resistance of various mixtures under the high-strain deformation forces which might be created by radial truck tires and/or snowplow blades (48).

In contrast, Airey (2004) reports that the phase angle (δ) is usually considered to be much more sensitive to the structure of the binder than is G*, and as such, provides a better indication of the type and extent of polymer modification (16). Within this context, smaller δ values are indicative of a greater elastic (less viscous) response, and thus, suggest a higher degree of polymer network formation, particularly at higher temperatures.

King (1998) notes that at comparatively high polymer levels, viscosity can increase substantially, leading to an over-prediction of rutting resistance, while DSR and Wheel-Tracking test results are generally found to be more representative and in good agreement with one another (61). Moreover, ductility testing on binders modified with elastomeric polymers can exhibit significant variability at low to intermediate temperatures (4º – 25º C.). In this regard, Neoprene and SBR modifiers generally produce comparatively high ductility, while SB and SBS additives yield much lower ductility (61). King characterizes the low ductility of the latter as a function of “too much” rather than “too little” strength, as SB/SBS modified mixes are comparatively thick when elongated and snap much in the way a thick rubber band does when pulled too far (61). This suggests that with some SB and SBS modified mixes, ductility testing could under-predict performance measures of strength.

Desmazes et al (2000) have developed a testing protocol for measuring the zero shear viscosity (ZSV) which the authors assert provides for a more accurate estimate of rut-resistance in binders modified with certain elastomeric polymers (e.g., SBS) (62). Conceptually, ZSV represents the viscosity of a fluid which is at rest. In elastic mixes at very low shear rates, the structures of the fluid deform slowly enough that they can adapt to the point where a form of equilibrium is reached. Measurements are collected at lower and lower shear rates, and the results extrapolated to yield the zero shear viscosity. Demazes observes that rutting is a demonstrably slow process, and as such, the “resting” viscosity of a modified binder more closely approximates its capacity to resist permanent deformation (62). In contrast, studies have shown that conventional DSR testing tends to underestimate high temperature performance in modified binders characterized by high delayed elasticity.

The SPG developed by Epps (2001) uses the following modified testing program:

- <u>Residue Recovery</u> – the researchers utilized the Stirred-Can method;

- <u>Aging</u> – pavements located at the surface are most susceptible to aging. RTFO was disregarded due to the comparatively low application temperatures associated with surface treatment applications. A Pressure Aging Vessel test (PAV) was utilized instead for long-term aging only;

- <u>RV</u> – viscosity was determined for un-aged binders, as this parameter generally reflects how easily the resulting asphalt emulsion can be pumped and sprayed. Multiple temperatures were utilized to simulate the wide-range of typical surface treatment application temperatures, as opposed to the single (135º C.) utilized for HMA binders under the standard PG;

- DSR – DSR testing was performed in accordance with AASHTO TP5 on the un-aged binders to determine G* and δ values to assess early, high temperature performance. With respect to surface treatments, the researchers believe aggregate loss is of greater significance at high temperatures in surface treatments, than are rutting or shoving;

- PAV-DSR – residues were long-term aged using PAV and then tested using the DSR to assess intermediate temperature range performance. More specifically, this test was intended to evaluate the potential for aggregate loss rather than fatigue cracking;

- BBR – BBR testing was performed on long-term aged residues to evaluate low temperature behavior. For this test, the fastest BBR loading time (8 sec.) was used to simulate critical traffic loading conditions, rather than to gauge thermal cracking per se (57).

The final recommended limiting values proposed for the SPG are presented in Table 4.

Table 4: Recommended SPG Limiting Values (57)

Viscosity	DSR	BBR
ASTM D 4402 Max: 0.15; Min: 0.1 Pas	G*/Sin δ , Min: 0.750 kPa Test Temp. @ 10 rad/s, °C	Creep Stiffness, TP1 S, Max: 500 MPa m-value, Min: 0.240 Test Temp., @ 8 s, °C

2.4.3 Evaluation of Existing Federal Lands Standards

The Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects (FP-03) calls for cationic and anionic emulsified asphalts to conform to AASHTO M 208 and AASHTO M 140, respectively (63).

Polymer modified asphalt emulsions used for microsurfacing are further specified to meet the requirements of AASHTO M 208 as well as the following:

- Residue by distillation: 62% minimum;
- Softening point: 57º C. minimum;
- Penetration at 25º C.: 40-90.

Current Federal Lands Highway (FLH) specifications direct that polymer additives are to be blended either into the asphalt directly or the emulsifier prior to emulsification.

Table 5: Summary of M 208/140 Specifications

Emulsion Type	Viscosity, Saybolt at 22º C †	Viscosity, Saybolt at 50º C †	Demuls †	Min. Residue by Distillation †	Penetration at 25º C ‡	Ductility at 25º C ‡ (cm)
Anionic Emulsions and Residues (M 140-86)						
RS-1	20 - 100	--	60	55%	100 - 200	40
RS-2	--	75 - 400	60	63%	100 - 200	40
MS-1	20 - 100	--	--	55%	100 - 200	40
MS-2	100	--	--	65%	100 - 200	40
MS-2h	100	--	--	65%	40 - 90	40
HFMS-1	20 - 100	--	--	55%	100 - 200	40
HFMS-2	100	--	--	65%	100 - 200	40
HFMS-2h	100	--	--	65%	40 - 90	40
HFMS-2s	50	--	--	65%	200	40
SS-1	20 - 100	--	--	57%	100 - 200	40
SS-1h	20 - 100	--	--	57%	40 - 90	40
Cationic Emulsions and Residues (M 208-86)						
CRS-1	--	20 -100	40	60%	100 -250	40
CRS-2	--	100 - 400	40	65%	100 - 250	40
CMS-2	--	50 - 450	--	65%	100 - 250	40
CMS-2h	--	50 - 450	--	65%	40 - 90	40
CSS-1	20 - 100	--	--	57%	100 - 250	40

CSS-1h	20 - 100	--	--	57%	40 - 90	40

† Applies to liquid asphalt emulsion
‡ Applies to asphalt emulsion residue

Table 5 presents the key physical property parameter requirements specified under AASHTO M 208 and M 140 (i.e., ASTM D2397-05 and ASTM D977-05, respectively) for comparison and discussion purposes.

As has already been covered in some detail, the literature review unequivocally illustrates that polymer modified asphalt binders (i.e., PME and PMA) exhibit significant performance benefits over unmodified equivalents (4, 12, 14, 20, 21, 24, 25, 31, 33, 48, 49). Demonstrable benefits include increased rutting resistance, improved chip/stone retention, improved elasticity and ductility, increased fracture toughness, improvements in the penetration index, decreased low and high temperature susceptibility, and improved fatigue resistance. Although polymer blending techniques appear to impact mixture performance, all of the methods examined performed better when compared to unmodified binders.

2.4.4 Modified versus Unmodified Asphalts

Khosla and Zahran (1988) compared the performance of unmodified and Styrelf® polymer modified mixtures of three commonly used asphalt cements: AC-5, AC-10, and AC-20 (64). Styrelf® is a proprietary blended modified asphalt product produced by Total™, which utilizes a cross-linked elastomeric polymer additive. Khosla and Zahran evaluated each asphalt preparation under varying load conditions and operating temperatures using the resilient modulus test, and reported that they were able to predict the fatigue, deformation, and brittleness of each of the binders. These test results were then used to simulate the predicted service life using the VESYS III computer model in each of the four major climatic regions as shown below in Table 6.

Table 6: Predicted Service Life (years) After Khosla (64)

Region	Temp. Range	AC-5	AC-5 Styrelf®	AC-10	AC-10 Styrelf®	AC-20	AC-20 Styrelf®
1	0-90º F	9.83	15.90	11.96	17.13	15.10	19.01
2	40-90º F	6.24	14.39	8.04	16.55	11.94	18.53

3	40-120º F	5.02	12.81	6.04	14.92	10.40	16.39
4	40-140º F	NA	10.32	NA	12.76	6.63	14.21

As Table 6 suggests, in each case the Styrelf® asphalt mixtures appeared to yield significant improvements in overall predicted service life as compared to their unmodified parent asphalts. The performance impacts of polymer modified binders were further evaluated specifically with respect to predicted rut depth, fatigue cracking, and low temperature cracking for various service year benchmarks. Quantitatively, Khosla and Zahran estimated the approximate resulting magnitude of rut depth and the degree of fatigue cracking (using cracking indices) over time. Additionally, low temperature cracking susceptibility was determined by a stiffness value that was formulated based upon creep tests conducted at temperature benchmarks of -20º F, 0º F, 20º F, and 40º F, respectively. Khosla and Zahran conclude that:

1. Styrelf® mixtures have better low temperature susceptibility than their unmodified counterparts, and are thus, less brittle;
2. Styrelf® asphalts are more resistant to low temperature cracking;
3. The Styrelf® samples exhibited a reduced propensity for rutting deformation at higher temperatures than the unmodified asphalts; and,
4. Polymer modification of Styrelf® asphalts results in improved fatigue life (64).

Takamura (n.d.) has compared the rut-resistance performance of unmodified asphalt emulsions in microsurfacing applications as shown in Figure 19 (54). In the early stages of curing, the rutting resistance comparisons between modified and unmodified mixes are unremarkable. However, the modified asphalt emulsion residues show significantly better rut-resistance than unmodified mixtures after just a few days of curing, particularly in mixes where Portland cement is added to the modified emulsion (due to resulting increases in pH). Note also that when compared to unmodified asphalt emulsions, the curing time to achieve optimal rutting resistance is considerably longer in the modified residues (about 20 days versus approximately 7-8 days). This has implications for high volume roadways, where prolonged lane closures needed to achieve the requisite optimal curing period may not prove feasible or practical.

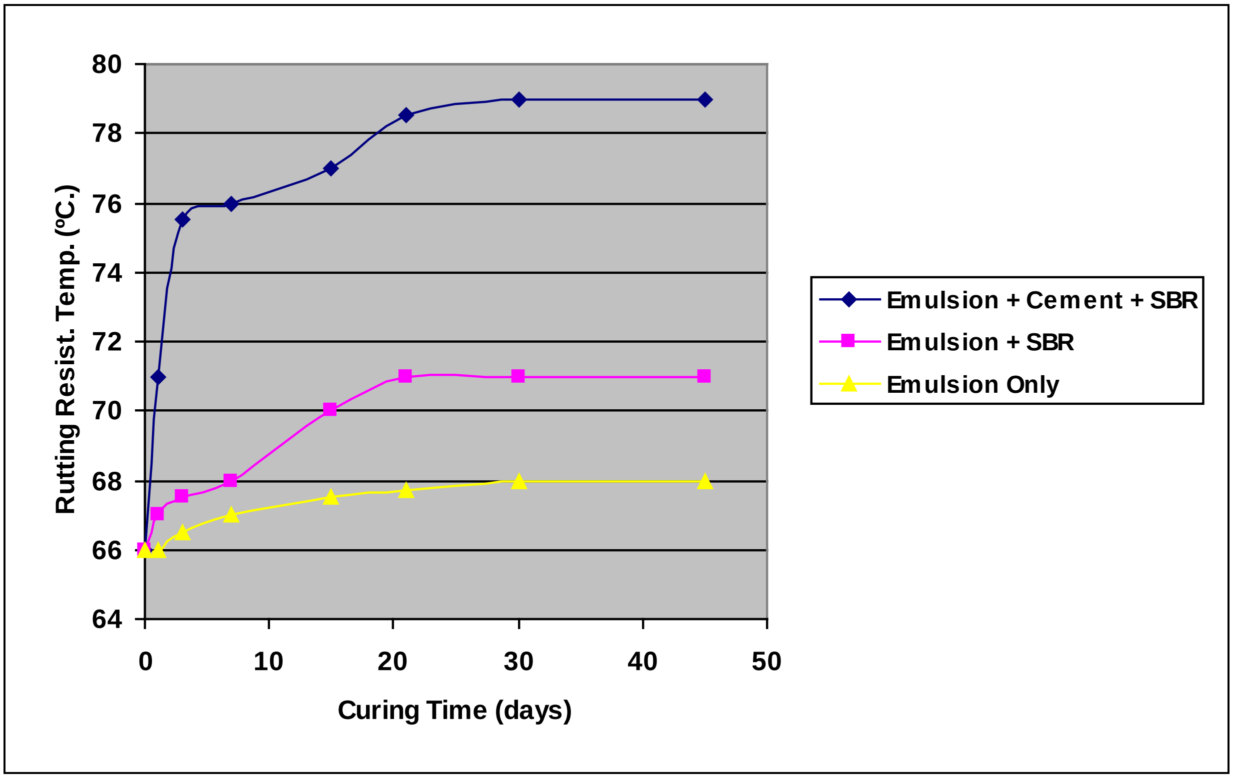


Figure 19: Microsurfacing Emulsion Residue Curing Time (54)

2.4.5 Modified Emulsion versus Modified Hot Mix Binders

Serfass et al (1992) have compared the performance of SBS-modified hot mix and emulsified asphalt in thin surface treatments using laboratory measures of rheological properties, cohesion, stone retention, tensile strength, and durability (18). Results from this study indicate that SBS-modified hot mixes exhibit poor adhesion to aggregate and require the use of an anti-stripping agent. Moreover, the use of anti-stripping agents in SBS-modified hot mixes yields only modest improvements which decline under more adverse climatic conditions (18). In this regard, Serfass et al report that the use of SBS-modified hot mixes is contraindicated in cooler environs, and that SBS-modified asphalt emulsions offer a longer application season – performing well under cool and even damp conditions. The authors also note however, that SBS-modified asphalt emulsions require a much longer set time than do their hot mix counterparts. In addition, Serfass et al report that higher SBS contents may be used in asphalt emulsions, since modified hot mixes exhibit decreased adhesion and problematically high viscosities when higher SBS concentrations are used (18).

Gransberg and Zaman (2005) examined the relative performance and cost effectiveness of 342 chip seal projects in the State of Texas to compare the efficacy of hot mix binders to asphalt emulsions (65). The results of this study indicate that PME performs at least as well as modified hot mix binders, and that the former does so at a lower cost while offering modest improvements in skid resistance and ride quality (65). The Texas Department of Transportation (TxDOT) generally utilizes asphalt emulsions in their chip seals on lower volume (i.e., < 2,000 ADT) roadways. Moreover, these asphalt emulsions are typically applied to pavements that are generally in poorer condition as compared to hot mix-based chip seal projects. In such cases, TxDOT differentiates between asphalt emulsion and hot mix chip seal applications based primarily on traffic volumes, because the latter requires a shorter curing time and as such, reduces lane closure times and traffic delays.

The importance of asphalt emulsion curing time is further noted by Takamura (n.d.), who observes that in microsurfacing applications, rutting resistance is shown to steadily improve when curing is extended from 1 day to 10 days (2 PG improvement), and from 10 days to 1 month (3 PG additional improvement, 5 PG total). This study suggests an optimal curing time of about 20 days for SBR modified asphalt emulsion residue as shown in Figure 19 (54).

2.5 Surface Application Types

2.5.1 General

This section presents those findings of the literature review specific to common surface treatment applications where polymer modified asphalt emulsions may be employed. Among the treatment applications examined are chip seals, slurry seals / microsurfacing, and cape seals. The benefits and limitations of PME are examined with respect to each specific treatment type, and where applicable, compared to the performance of non-modified asphalt emulsions.

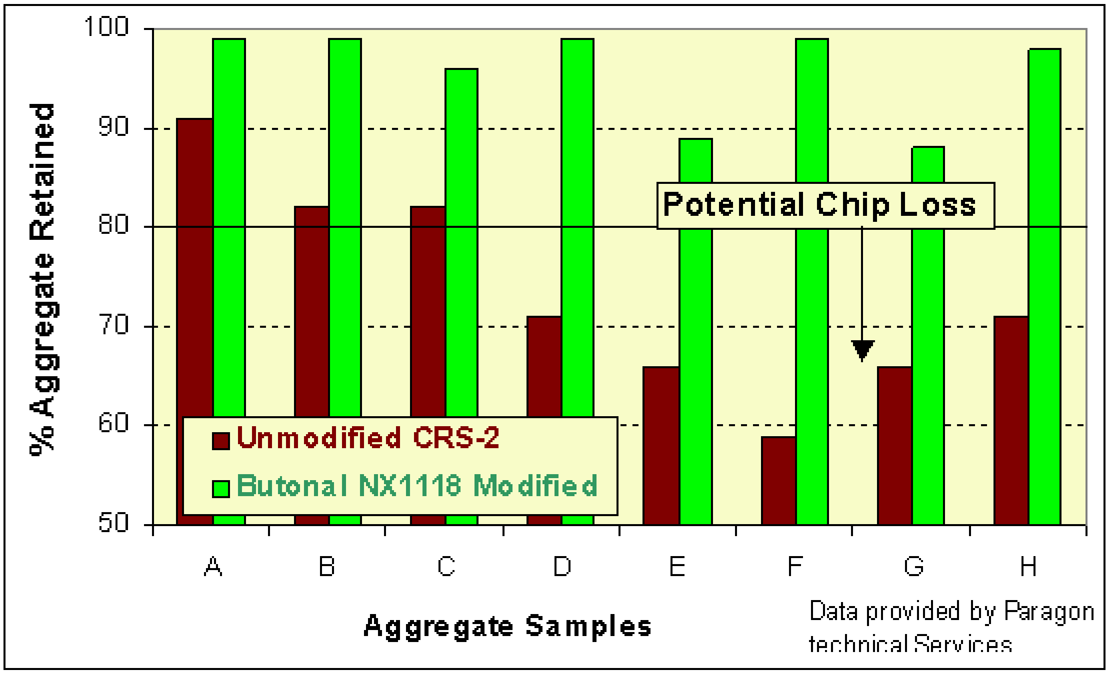
2.5.2 Chip Seals

Chip seals (sometimes called seal coats or bituminous surface treatments) consist of an asphalt emulsion which is applied to the pavement surface which is subsequently overlain by one or more layers of stone chip aggregate up to one-inch in total thickness, and then rolled. Chips seals are commonly employed as an inexpensive treatment for minor forms of pavement surface distress such as cracking or raveling.

The advantages of using polymer modified asphalt emulsions in chip seal applications over non-modified mixtures include:

1. Better stone retention;
2. Projects can usually be opened to traffic sooner;
3. Reduced rates of flushing and bleeding;
4. More effective on higher volume roadways (due to improved stone retention); and,
5. Greater design tolerance for chip and asphalt emulsion quantities and aggregate embedment factor (14).

Takamura (2003) demonstrates the impact of polymer modifiers on improving stone retention in chip seals (66). Figure 20 presents a comparison of retained aggregate percentages between modified and unmodified variants of eight mixtures - each containing different aggregates – from an early strength sweep test. As Figure 20 illustrates, improvements in aggregate retention range from modest to dramatic in the polymer modified (i.e., BASF’s Butonal™ NX1118) chip seal mixes in all eight test cases, with percentages near or above 90%.



Data provided by Paragon technical Services

Figure 20: Chip Seal Aggregate Retention with Polymers (66)

Windshield damage caused by the displacement of stone is perhaps the most widely reported difficulty involved in the use of chip seals. For this reason, many agencies restrict the use of chip seals to relatively low volume (i.e., < 2,000 ADT) roadway pavements. Therefore, because polymers offer demonstrably improved rates of aggregate retention, it is suggested that modified chip seals could provide acceptable performance on higher volume roads.

Moreover, Lubbers and Watson have also shown that Vialit chip retention test results are markedly better in modified chip seals at low temperatures than are comparable unmodified mixtures, indicating polymers may similarly prove valuable in cold weather climates (Figure 21) (4).

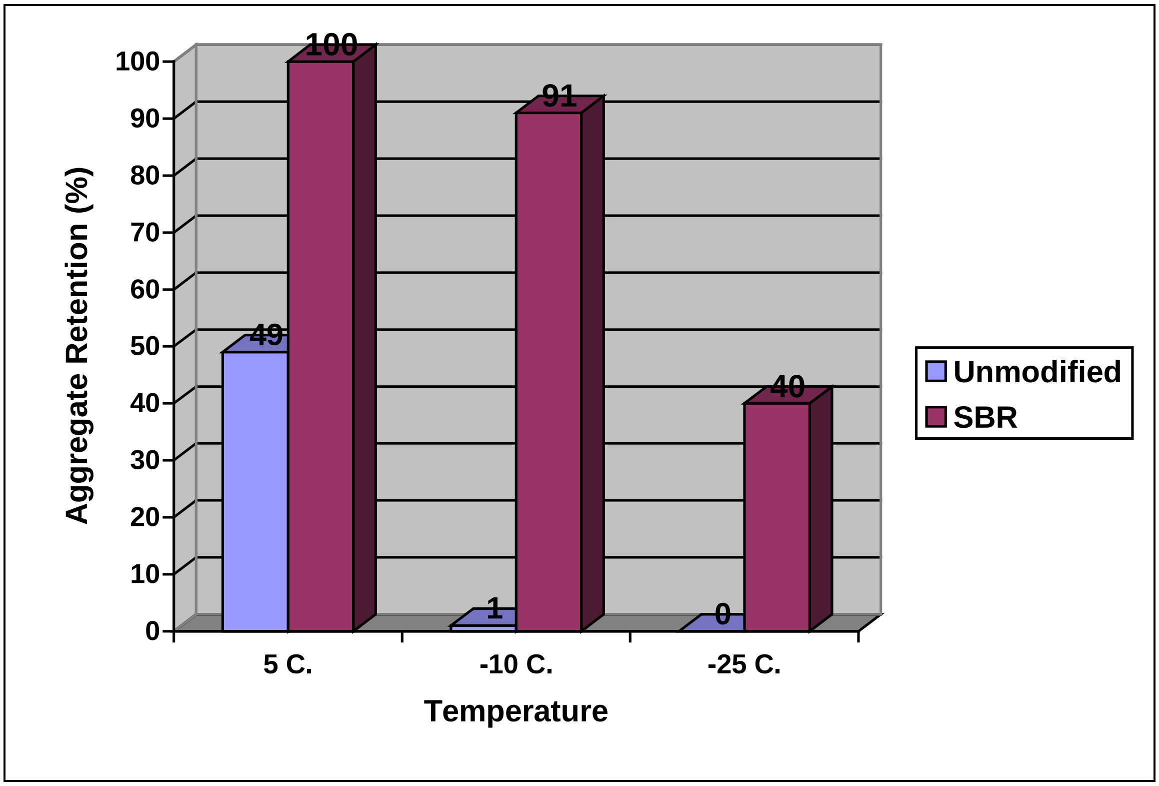


Figure 21: Vialit Chip Retention at low Temperatures Chip Seals (4)

Wegman (1991) notes that the improved early chip retention offered by polymer additives when used in chip seals, allows for greater variation in aggregate and emulsion application rates, and permits earlier sweeping of the applied surface which serves to mitigate windshield damage (67).

A survey of chip seal best practices by Gransberg and James (2005) indicates that early brooming of chip seals immediately after rolling to remove loose stone, is ill-advised since curing at this stage is generally insufficient to permit proper binder to aggregate bonding (68). More specifically, although polymer modifiers can significantly enhance stone retention, research has shown that adequate cure times are needed to realize this benefit (14, 66) (see Figures 6 and 20). Gransberg observes that chip seals can be successfully applied to high volume roads, providing allowances are made for adequate curing time, and that the underlying pavement condition of the roadways selected for treatment are fundamentally sound (68). Moreover, detailed assessment of chip seal performance nationwide indicates that the best performing chip seals are those where design specifications are meticulously prescribed, implemented, and verified by the highway agency (68).

2.5.3 Slurry Seals and Microsurfacing

Slurry seals consist of a homogeneous mix of crushed aggregate and an asphalt emulsion which is applied to the pavement surface as a single-pass monolayer. Curing of the slurry seal coat occurs as the water evaporates, leaving only the residual asphalt to coat the aggregate surfaces. In general, slurry seals contain a high proportion of fines which generally yields a highly skid-resistant surface. In addition, slurry seals also improve water- and skid-resistance, but most are generally applied to only lower-volume (i.e., < 1,000 ADT) roads.

Microsurfacing is a commonly used form of slurry sealing consisting of a combination of mineral aggregate and fillers, a polymer modified asphalt emulsion, and other additives. The primary difference between microsurfacing and most other forms of slurry sealing is the thickness. Slurry seals are generally laid at 1-1.5 inches in thickness, whereas microsurfacings are thickly applied in multiple layers. In addition, the PME used in microsurfacing are broken chemically instead of through evaporation which is used in most other asphalt emulsion applications. This permits the microsurfacing to gain cohesive strength rapidly, thereby minimizing lane closures and traffic delays (69). Microsurfacing is commonly used to correct wheel-path rutting and improve skid-resistance, and can be applied to either high or low volume roadway pavements (40, 70). Takamura (n.d.) reports that polymer enhanced microsurfacings can be used to fill ruts up to 5 cm in depth using a rut-box (54). When applied in rut-filling applications, it is desirable to assess the rut-resistance potential of the PME (at a minimum) through the performance of DSR testing on the extracted asphalt residue (48, 49, and 54).

Takamura (n.d.) also provides comparisons of the effects of microsurfacing curing between mixtures containing varying polymer concentrations (54). Figure 21 illustrates the change in rutting resistance temperature versus curing time for 5% and 3% polymer contents in microsurfacing mixtures. As has been noted previously, increases in rutting resistance are evident in both mixtures as curing time increases. Moreover, note also that although the rutting resistance for the 5% mixture is improved over the 3% mix, the relative rates and patterns of improvement between the two are very similar. This implies that polymer concentration may not be substantially related to the rate of curing time improvements in rut-resistance, although the benefits provided through the use of polymers cannot be fully realized without allotting adequate time for curing regardless of concentration (see Figure 19). Furthermore, it is important to realize that microsurfacing curing times are highly dependent upon a number of factors, including the pH of the asphalt emulsion, the type and amount of surfactant, the type of bitumen and aggregate, and the application temperature (71).

Setting agents such as Portland cement or lime can be added to microsurfacing mixes to control curing time by reducing the rate at which water evaporates and the asphalt emulsion breaks. When used with polymer modifiers, these setting agents aid in promoting the formation of the continuous polymer networks associated with quantifiable improvements in the viscoelastic characteristics of thin surface treatments discussed previously (71). Work by Takamura (2001) proposes substituting aqueous-phase alkali metal hydroxides or salts in place of Portland cement to facilitate independent control of curing and mixing times based upon aggregate and bitumen type (71). In addition, mixing accuracy is improved and handling made much easier owing to the difficulty in metering powdered Portland cement on the paving machine.

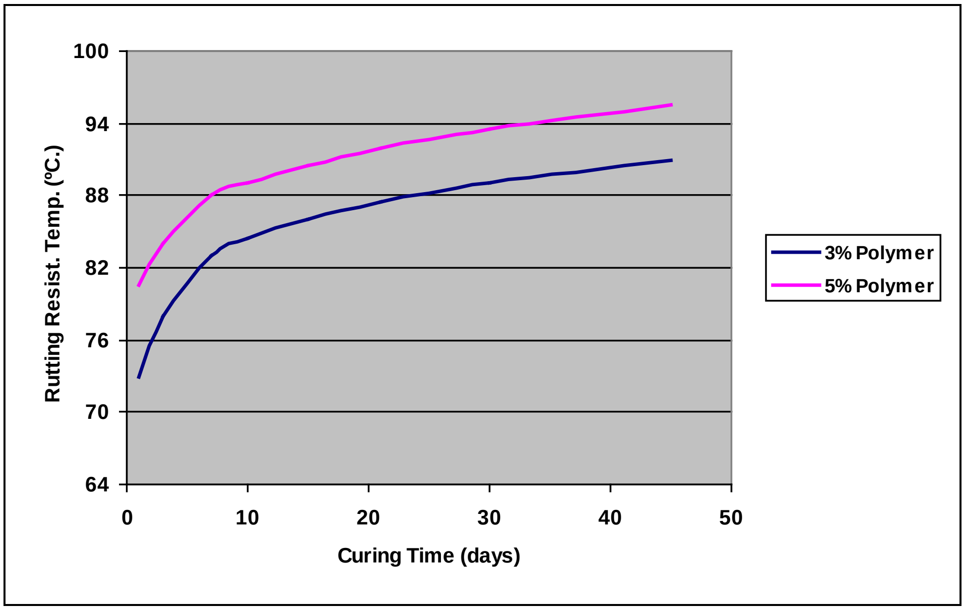


Figure 22 Microsurfacing Curing Time and Rut-Resistance (54)

Holleran (n.d.) recommends using SBR or EVA in microsurfacings at a concentration of 1% to 5% depending upon the application; noting that 3% to 5% polymer concentrations will offer the most significant improvements (70). Figure 23 presents wet track abrasion losses for 3% SBR, SBS, Neoprene, and NRL modified surfacing treatments in comparison to an unmodified asphalt emulsion. A mixture modified with 3% SBR can reduce abrasion losses by up to 67% over unmodified asphalt after a 6 day soaking period. Similarly, Neoprene and SBS modifiers improve abrasion losses by 40% to 50%. These results indicate that PME offers significantly increased adhesion (translating into better stone retention) and water resistance than unmodified asphalt emulsions in slurry seal applications.

With respect to flushing, Holleran has shown that loaded wheel test results produce significant improvements in vertical displacement for 3% PME over neat asphalt - particularly for SBR and EVA modified mixtures (Figure 24) (70).

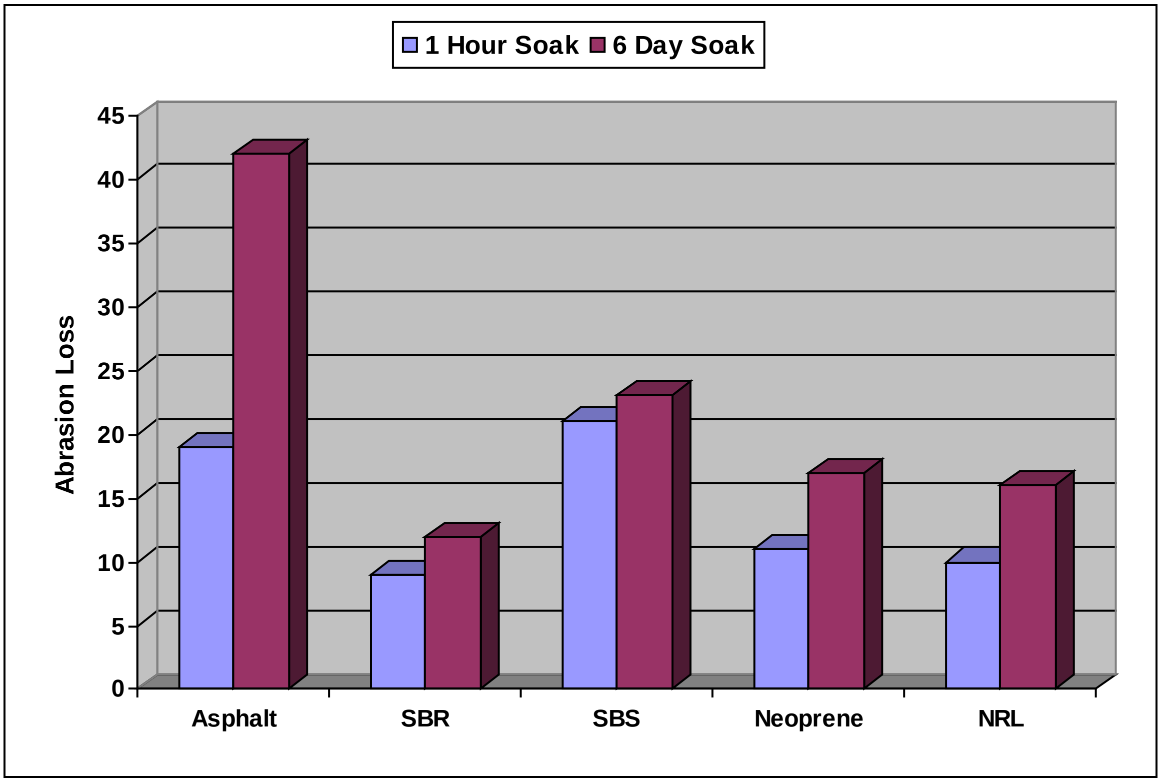


Figure 23: Wet Track Abrasion Losses (70)

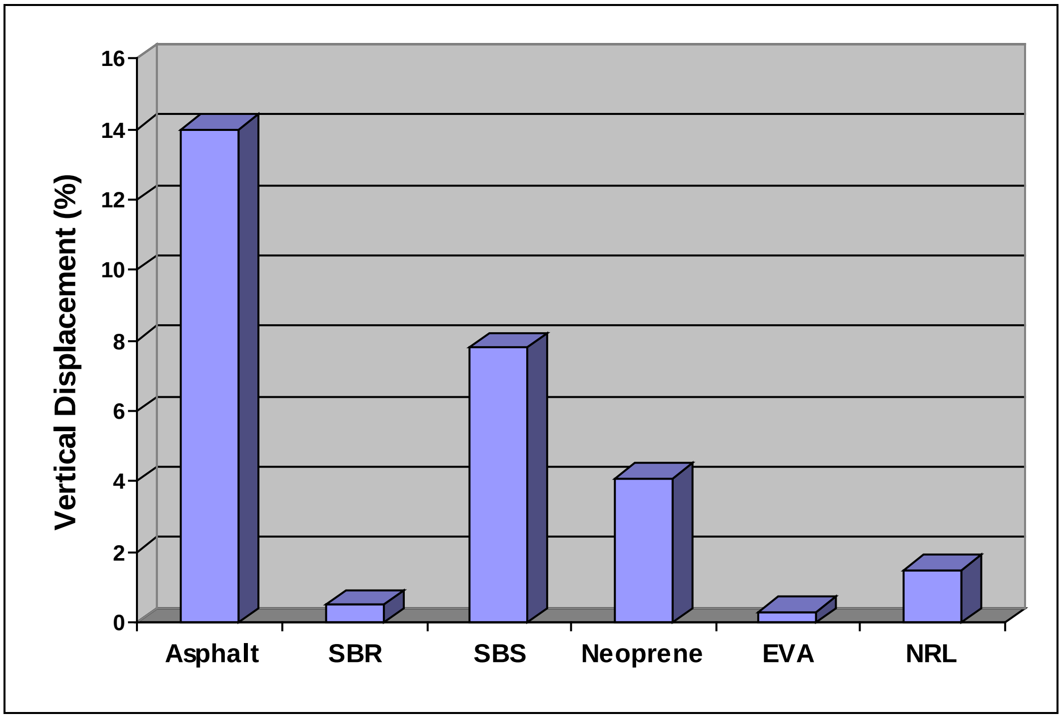


Figure 24: Loaded Wheel Test Results (70)

Jones and Ng (1989) have demonstrated similar results, with SBR, NRL, and SBS modifiers offering the greatest improvement in vertical displacement for microsurfacing emulsions as shown in Figure 25 (40). Jones further subjected these same mixtures to the Schulze-Breuer-Ruck abrasion test, which provides estimates of water absorption (soaking), loss (rotary tumbling), adhesion (water boiling), and integrity (largest remaining fragment after tumbling). Measurement parameters from Schulze-Breuer-Ruck are used to derive an overall numerical grade or rating for each test sample, with higher values representing greater compatibility (and thus better adhesion) between the aggregate, binder, filler, and polymer components. Schulze-Breuer-Ruck results from the Jones study are provided in Table 7. As Table 7 illustrates, SBR and SBS modifiers provide for the most significant improvements in abrasion loss. Moreover, SBR demonstrates the highest degree of integrity and the highest overall grade for the microsurfacing mixtures tested.

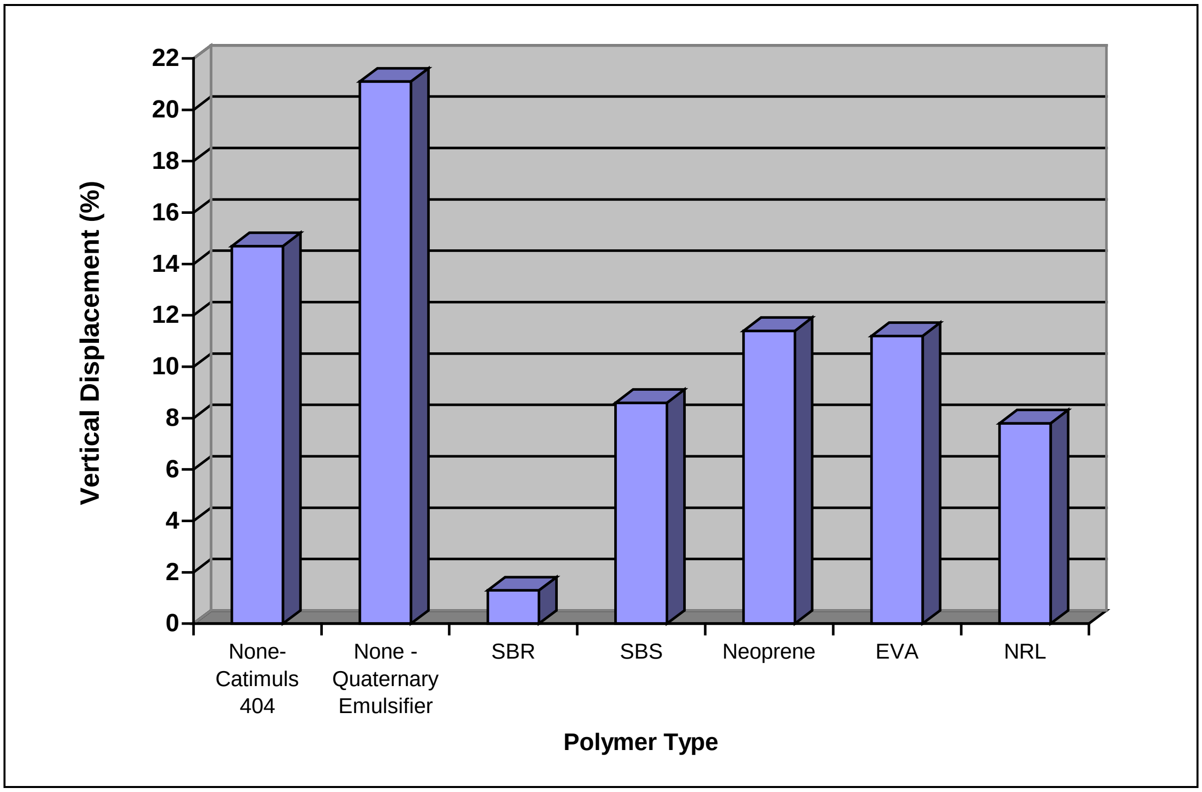


Figure 25: Loaded Wheel Test Results (40)

Table 7: Schulze-Breuer-Ruck Test Results (40)

Polymer	Absorption (g)	Loss (g)	Adhesion (g)	Integrity (%)	Rating
SBR	1.25	0.96	99	98	11
NRL	2.30	1.49	99	95	9
SBS (Fina 416)	2.18	0.82	99	40	8
EVA (150W)	1.64	1.13	99	67	8
Neoprene (671 A)	2.06	1.51	99	96	9
None Catimuls 404	1.35	1.97	99	62	7
None EM26	1.59	2.01	99	33	5

Jones concludes that among the modifiers tested, SBR offers the best laboratory and long-term field performance in microsurfacing applications (40). While the Schulze-Breuer-Ruck test appears to be a promising method of assessing the performance of polymer modifiers, it is noted that resulting measures of adhesion and absorption provide little or no correlation or distinction between modified and unmodified mixes (Table 7). Jones also notes that latex modifiers were generally found to outperform solid polymers in microsurfacings. This likely relates both to the necessitated differences in mixing methodology (i.e., pre-blending for solids), and the manner and relative efficiency with which latex may be dispersed relative to bituminous fractions (4, 7, 12, 47, 54). In addition, it has been shown that pre-blending of solid polymers may necessitate the addition of higher polymer concentrations than in soap batching or co-milling in order to achieve the formation of a continuous polymer network.

2.5.4 Cape Seals

Cape seals represent a combination of a large-aggregate chip seal topped by a slurry seal coat (or microsurfacing) which is applied approximately 4 to 10 days later. Cape seals provide a dense, water-resistant surface which exhibits superior ride quality and skid resistance.

Solaimanian and Kennedy (1998) evaluated the field performance and design characteristics of 20 cape seal projects in the State of Texas over a period of one year (72). During this study, bleeding, shoving, and flushing were identified as the most significant forms of distress in cape seals. Insufficient binder stiffness and failure at the interface between the chip seal and underlying pavement surface were generally found to the primary causes of permanent deformation. Moreover, the infiltration and entrapment of water were indicated to be substantially involved in early cape seal failure.

It has been demonstrated that resistance to deformation can be increased significantly through the addition of polymer modifiers to surface-applied asphalt emulsion treatments (12, 14, 47, 48, 54). This indicates that the use of polymers in the surface seal or microsurfacing overlays of cape seals can increase pavement life and high temperature performance. PME slurry seal overlays are also useful to increase chip seal stone retention, and to provide a more water-resistant, smoother riding surface. Polymer modifiers in general have been shown to improve water resistance (69, 70). However Solaimanian notes that microsurfacing cannot be used to correct an underlying water problem present in an incorrectly constructed chip seal or deficient base pavement. Indeed, in such cases the use of polymers in surface treatments can actually exacerbate underlying deficiencies, by entrapping water which can lead to stripping and freeze-thaw related damage (72).

2.6 Polymers and Traffic Volumes

The Context Sensitive Roadway Surfacing Selection Guide (2005) specifies roadway volume classifications based upon ADT which are used in practice by the FLH Division (73). Table 8 presents this classification system for reference.

Table 8: Federal Lands Traffic Volume Classification (73)

Design Volume (vehicles/day)	Suggested Descriptive Term	Design Speed (mph)	
		Preferred	Minimum
< 200	Very Low	40	30
200 -400	Low	50	40
400 – 1,000	Medium	50	40
1,000 – 4,000	High	55	45
4,000 – 8,000		60	50
> 8,000		60	50

A survey of chip seal best practices performed by Gransberg and James (2005) reveals that many U.S. highway agencies restrict their use of chip seals to roadways with maximum traffic volumes of < 2,000 ADT (68). The primary reason cited for confining chip seal applications to lower volume roads, is the loss of stone which can result in inordinately high levels of windshield damage. In this regard, it has been well-established that when properly formulated, applied, and cured; polymer modifiers can substantially increase stone retention and allow for earlier brooming without excessive losses (4, 12, 13, 14, 23, 30, 51, 66, 68). This suggests that polymer modifiers are an essential (though not the only) component in the successful application of chip seals to high volume roads. Table 9 presents a summary of the maximum ADT volumes used for chip seal construction projects which were reported by U.S. and select international highway agencies surveyed during the Gransberg study.

Table 9: Chip Seal Maximum Traffic Volumes (68)

Maximum ADT	U.S.	Canada	Australia	New Zealand	South Africa	U.K.
< 500	2	1	0	0	0	0
< 1,000	1	1	0	0	0	0
< 2,000	12	2	0	0	0	0
< 5,000	11	2	0	0	0	0
< 20,000	12	3	3	1	0	0
> 20,000	7	0	1	1	1	1
Agencies Reporting:	45	9	4	2	1	1

Of the U.S. state agencies surveyed, approximately 64% specify the use of polymer modified emulsions in all chip seal applications. Moreover, Gransberg indicates that of the states self-reporting “excellent” levels of chip seal performance (32% for in-house, 17% for contractors), all were found to use polymer modifiers (including CRM), and all generally prescribe chip seals for only those roads attaining a pavement condition rating (PCR) of “fair” or better (68). With respect to this latter point, chip seals are indicated to work best when they are applied as part of the regular pavement maintenance cycle, and are not a suitable replacement for roads requiring rehabilitation even when polymer modifiers are used.

Microsurfacing applications by definition always include the use of polymer modifiers and are widely regarded as appropriate for use on medium to high volume traffic (i.e., > 1,000 ADT) roadway pavements (40, 70). Because microsurfacing treatments are augmented with setting additives such as Portland cement, breaking can be controlled even at significant layer depths of up to 5 cm. This chemically-controlled curing mechanism allows microsurfacing to be used for comparatively “deep” treatment applications such as rut-filling, and permits expedited opening of the roadway to vehicular traffic (54, 71).

The South African National Roads Agency (SANRA) states that traffic volumes are important to ensuring proper stone embedment, and in keeping the binder “alive and flexible”, particularly in chip seal applications (74). In this regard, it is noted that since polymers impart increased rigidity to the binder, the demands for an appropriate level of traffic loading are even higher in PME based surface treatments and base pavements. However, SANRA also observes that polymer modified binders offer superior stone retention in the early stages of seal placement, thereby having the additional benefit of reducing asphalt bleeding. This latter benefit of PME is especially relevant on steep grades and at intersections where bleeding problems are most frequently encountered (74).

2.7 Non-Roadway Applications

Among the objectives of this FLH study, was the desire to identify existing research which would establish the efficacy of utilizing polymer modifiers in non-roadway applications such as parking areas, hiking trails, or bike paths. Although no pertinent literature was identified by this study that would permit direct analysis, the potential effectiveness of polymer modifiers in non-roadway applications can be informally deduced based upon the forms of distress commonly found in parking areas and on recreational trails; and by utilizing the findings of roadway pavement research which can be reasonably correlated to addressing those distress conditions.

For example, prevalent forms of pavement distress, deformation, and weathering observed in FLH parking areas include:

- Block Cracking;
- Rutting (caused by high pavement temperatures in combination with tight, relatively stationary wheel turns); and
- Oxidation.

Cracking and oxidation are also found on hiking trails and bike paths, with the former representing the most common and problematic form of distress.

FLH reports that slurry seals in particular, are the favored preventive maintenance treatment applied to parking lot pavements, owing to their ability to waterproof the underlying base pavement while reducing closed-to-traffic times, reducing energy consumption, and minimizing environmental impacts.

As the research presented elsewhere in this report clearly illustrates, the use of PME in thin surface treatments does appear to enhance stone retention, improve low temperature susceptibility, and reduce the effects of high temperature deformation (i.e., rutting). Moreover, PME-based slurry has been anecdotally found to cure at a somewhat faster rate than its non-modified counterparts (thereby reducing closed-to-traffic times). Thus, it is reasonable to conclude that the use of PME could be expected to provide similar benefits in non-roadway applications, although it is not possible at this time to assess the resulting cost-benefit implications.

2.8 Climate, Environmental and Timing Considerations

Serfass et al (1992) have examined the impact of climate on stone retention in surface dressings using SBS-modified hot mixes and emulsified asphalt (18). In modified hot mixes, the researchers note that an adequate period of warm weather is required to facilitate the evaporation of aromatics to allow aggregate to “firm” into its final position. The researchers recommend an application period extending from late May to late August in northern or mountainous climates, and mid-May to mid-September in southern regions for modified hot mix asphalt binders (18). Conversely, SBS-modified emulsions were found to exhibit good stone retention characteristics even at relatively cool temperatures and high humidity as determined through Vialit cohesive testing.

Thus, the cohesive properties of SBS-modified emulsions appear to offer a longer application season when used for surface dressings, although Serfass does not provide a specific application calendar.

With respect to chip seals, minimum ambient air and pavement application temperatures of at least 10º C. and 21º C., respectively, are generally accepted standards to prevent against excessive and prolonged stone loss (75, 68). Indeed, early stone loss as a result of late season application under cool temperatures is perhaps the most common reason for chip seal failure. In general, low application ambient and/or pavement temperatures can result in high binder viscosity which hampers bitumen-to-aggregate adhesion (68). Conversely, excessively high ambient or pavement temperatures may produce viscosities which are too low to permit in-place fixation of the stone. There is little consensus concerning maximum pavement temperatures for chip seal application projects, but most recommendations vary between approximately 54º C. and 60º C. (68). Typically, a maximum ambient air temperature of approximately 43 º C. is recommended for most chip seals (68).

In hot climates, the primary issues that impact bituminous pavements and surface dressings are 1) deformation caused by high temperature susceptibility; and 2) binder aging (76). Vonk and Hartemink (2004) have shown that when comparing the accuracy of ring-and-ball softening point and zero shear viscosity (ZSV) test results, the latter produces a much more reliable measure of high temperature deformation potential in modified binders than does the former, as illustrated in Table 10 (76).

Table 10: Physical Properties and Deformation Results (76)

Binder	**Ring & Ball Temp. ºC.**		**ZSV Pa.s**		**Deformation Rate in Test Road**	
Test Temp.:	**40º C.**	**50º C.**	**40º C.**	**50º C.**	**40º C.**	**50º C.**
100 pen	45.5	45.5	2.5×10^3	6.3×10^2	24.0	56.2
100 pen + 3% SBS	49.5	49.5	3.2×10^5	1.0×10^4	4.0	12.6
60 pen	51.0	51.0	7.9×10^3	2.0×10^3	10.1	23.6

In this regard, the test result data provided in Table 10 reveal the following:

1. Noting that the Ring & Ball test results for the unmodified binders are equivalent to, or better than the modified binder, and considering the deformation rate results, it appears that softening point is not a good indicator of high temperature deformation potential in polymer modified binders;
2. The ZSV results correlate well with the deformation rate test results, suggesting this may be a preferable method for assessing rutting resistance; and,
3. The improved high temperature susceptibility imparted by polymer modifiers extends to higher temperatures.

In high temperature applications, Vonk recommends SBS concentrations of at least 5% to insure that the polymer phase forms a resilient and continuous network throughout the mixture (76). As has been suggested previously, it is this network that ultimately imparts the elastic response desired to resist permanent forms of deformation (4, 12, and 14). Vonk's work focuses primarily on the modification of asphalt binder cements, and as such, the implications for desirable polymer concentrations in soap pre-batched or co-milled emulsions are uncertain. However, this research undoubtedly has valid implications in emulsion applications where the bitumen is subjected to direct forms of modification (i.e., pre-blending) prior to emulsification (one example would be the use of SBS). Moreover, the interplay between polymer concentration, ZSV, and the measurement of high temperature deformation potential, have significance in emulsion treatments such as microsurfacing which are commonly used to fill wheel rut paths.

Vonk (2004) and Demazes et al (2000) note that the measurement of ZSV in modified binders containing a substantial polymer network is inaccurate because one requirement of this test is the development of steady-state viscosity under constant stress – a state which the elastic components of such a mix cannot attain (i.e., viscosity appears to grow infinitely) (62, 76). Although Desmazes offers an extended ZSV testing protocol that may yield improved accuracy and reliability, Vonk suggests that this phenomenon could be utilized to evaluate proper polymer dosing. More specifically, as ZSV begins to trend toward infinity, this provides a solid indication that a pervasive, 3-

dimensional polymer network is present within the mixture, thereby insuring that the optimal modifier content has been achieved.

Vonk notes that accelerated binder aging in hot climates is dominated by the following characteristics:

- The binder becomes harder and less compatible; and,
- The occurrence of polymer-polymer cross-linking, polymer chain-scission, and reactions with bituminous components (76).

With respect to these characteristics, Vonk observes that even in cases where polymer chains are shortened through age-related scission, the smaller polymer segments still contribute to maintaining elastic flexibility, albeit to a lesser degree than in un-aged modified binders. Indeed, work by Davies and Laitinen (1995) demonstrates that aged SBS modified binders harden less than unmodified / differently-modified mixtures as measured via the wheel tracking test (77).

In chip seal applications, Vonk asserts that SBS-modified binders also offer demonstrable benefits in hot climates – specifically increased stone retention, and high ZSV which indicates the presence of a continuous polymer network which retards permanent deformation and aggregate displacement (76).

In arid climates however, the potential for hydrogenesis can pose a significant challenge to the use of PME. Hydrogenesis is defined as “the upward migration of water vapor in the road pavement which, under certain climatic conditions, condenses under the road surfacing” (78). In such cases, ambient air which penetrates through the roadway shoulders into the pavement aggregate layer, may transfer water to the stone surfaces via condensation to form a thin film. Although the full implications of hydrogenesis are not yet fully understood, anecdotal evidence provided by state highway agency (SHA) practitioners suggests that PME used in thin surface treatments may inhibit this trapped water from evaporating, thereby hastening the development of surface distress and/or structural failure.

2.9 Impact of Materials Selection

The literature review failed to yield significant available research into the compatibility and selection of materials used in conjunction with PME based systems. Indeed, thin surface treatment research in general was found to be lacking overall in this area, with most investigators concentrating on individual component impacts, or “whole system” performance (e.g., chip seals).

2.9.1 Polymer Type

A review of the available research indicates no clear empirical evidence that one type of polymer modifier is inherently superior to another with respect to performance, at least between the most commonly used types (i.e., SBR and SBS). A recent study of stone retention in chip seals performed by Kucharek et al (2006) indicates that while latex-based PME may require more curing time than pre-blended PME to fully achieve the aggregate retention benefits associated with polymer modification, performance between the two binder types is comparable after only 24 hours (80). Moreover, Kucharek concludes that “no special benefit has been observed so far from having the SBR polymer both inside and around the asphalt binder;” citing the need for additional research (80).

2.9.2 Surfactants & Emulsion Type

Surfactant chemistry is a complex and multifaceted area of study and as such, is well beyond the scope of the current review. Although published literature on the variation in PME thin surface treatment performance with respect to surfactant types is relatively scant (much of these data are proprietary in nature), a few researchers have attempted to identify high level differences between modified anionic and cationic emulsions.

Kucharek et al (2006) assessed the chip retention characteristics of a variety of anionic and cationic emulsions modified with different polymers (80). In this study, emulsion and whole system (i.e., chip seal) performance evaluations were accomplished using DSR, the Frosted Marble Cohesion Test, and the Sweep Test for Thin Surface Treatments. Overall, cationic PME mixes demonstrated considerably higher moduli during the first few hours of curing than did similarly modified anionic preparations.

Moreover, although the moduli of the anionic group did gain some ground on the cationic test samples as curing progressed, the modulus values of the anionic mixes were not found to reach the same levels as the cationic group, even after a 24 hour cure period (80).

Kucharek reports that cationic emulsions consistently demonstrated better chip retention characteristics (as measured in the sweep tests) than anionic emulsions for all the aggregate types studied. Cationic mixes also showed less sensitivity towards the varying chemical composition of the aggregates tested than did those prepared using anionic emulsions (80).

2.9.3 Aggregates

One of the few issues identified during the literature review with respect to aggregate-polymer interactions pertains to the use of moisture-sensitive aggregate in thin surface treatments. In this regard, aggregates such as moisture-sensitive gravels may exacerbate the effects of hydrogenesis in arid climates, leading to water film buildup beneath a relatively impermeable polymer modified surface treatment (78). Moreover, in cooler climates pre-existing excess water retention problems can lead to freeze-thaw damage (72). Arguably, these potentially negative interactions are representative of an indirect relationship between aggregates and polymers. That is, the use of PME in certain climates - when placed atop a base course containing moisture-sensitive aggregate or one that already has a pre-existing water retention problem - may be contraindicated.

Overall, the impact of polymers on moisture sensitivity is not well understood at this time. Moreover, chemical sensitivity issues between aggregate and various types of polymers could also present some challenges in certain cases. But the literature review presented herein turned-up little to no information regarding chemically sensitive aggregates and the use of PME. Indeed, the available research points overwhelmingly toward the ability of polymers to impede moisture penetration, enhance stone retention, and increase overall pavement durability. However, caution should be used to determine whether the base course has a fundamental water retention problem prior to the application of any PME-based thin surface treatment.

2.9.4 Fillers

Airey et al (2002) present the findings of a laboratory investigation into the effects of mixing SBS modifier with CRM to produce impact absorbing asphalt (IAA) surfaces (17). The results of this study show that the polymeric viscoelastic characteristics of the SBS are lost due to precipitation and phase-separation caused by the absorption of light aromatics contained within the maltene fractions by the CRM particles. In properly mixed SBS PMA which does not contain CRM, the SBS latex particles absorb these light maltene fractions, which results in the swelling of the polymer phase, thereby producing a continuous elastic network.

The availability of literature covering interactions between polymer modifiers and other types of fillers was scant.

2.10 Surface Treatments, Distress, and Cost-Effectiveness

The selection of appropriate surface treatments and the decision on whether or not to utilize polymer modifiers are dependent upon a number of factors, including:

- The effectiveness of a given treatment in rectifying a particular form of pavement distress;
- The cost-effectiveness of a particular treatment relative to the benefits and cost of other alternatives;
- The environmental conditions under which the treatment is to be applied;
- The functional classification and/or traffic loading conditions of the roadway to be treated;
- The current condition of the underlying roadway, the type of pavement involved, and its construction and maintenance history; and,
- The availability of appropriate materials and well-trained maintenance forces to insure proper placement.

Numerous decision tools and best practices have been developed by state highway agencies and industry trade organizations for matching the type and degree of pavement distress with the appropriate form of surface treatment. Hicks et al (2000) provide a review of some of the best known of these practices, and present a framework which can be used to determine the most cost-effective treatment alternative (79). This section of the report focuses on those treatments which are regularly employed using PME including chip, slurry, and cape seals; and microsurfacing.

One of the simplest and best known approaches to determining cost-effectiveness is the Equivalent Annual Cost method or EAC. EAC is determined as follows:

EAC = (unit cost of treatment) / (expected life of treatment in years).

Table 11 presents examples of the EAC cost-effectiveness of various treatment types.

Table 11: Examples of EAC Cost-Effectiveness

Treatment	Approx. Average Cost per s.y. (1)	Avg. Longevity (years)		EAC
		< 100 ADT	100 – 500 ADT	(100-500 ADT)
Chip Seal	$1.30	8	5	$0.26
Chip Seal Modified	$1.69	--	6.5 (2)	$0.26
Slurry Seal	$1.08	7	5	$0.22
Slurry Seal Modified	$1.40	--	6.5 (2)	$0.22
Cape Seal	$2.08	11	7	$0.30
Cape Seal Modified	$2.70	--	9 (2)	$0.30
Microsurfacing	$1.40	11	6	$0.23

(1) Costs may vary widely depending on materials used, location, etc.

(2) Number of years of longevity needed to achieve EAC break-even point assuming average cost increase of 30% for PMA emulsions.

Other forms of determining cost-effectiveness include life-cycle costing, longevity cost index, and cost-effectiveness analysis using pavement performance curves.

As Table 11 suggests, the increased longevity realized through the appropriate use of PME in thin surface treatments, can offset somewhat higher initial material costs associated with the addition of polymer modifiers.

In 2007 and 2008, the FHWA developed the Transportation System Preservation (TSP) Research Roadmap by garnering the input of numerous SHAs, private industry, and academia at three workshops held across the U.S. Several of the resulting problem statements generated by the Roadmap working groups were specifically targeted at identifying research needs that would better quantify the cost-effectiveness of preventive maintenance treatments in general, and of specific material components more specifically. The literature review contained herein serves to further emphasize the need for additional research in the area of assessing the cost-benefit relationships between polymer modifiers and thin surface treatments. However, it is worthwhile to note that the comparatively small cost of polymer modifiers relative to overall material and construction costs, coupled with the demonstrable benefits of polymer modification illustrated throughout this report, indicate that the benefits of PME likely far outweigh its additional cost.

3.0 LABORATORY TESTING AND SPECIFICATION RECOMMENDATIONS

Task 2 in the Statement of Work articulated four areas for recommendations. Following the literature search, there were several industry outreach initiatives to collect information from current practitioners. Presently, there are several other in-progress research projects addressing some of the same issues as this work, and the principal investigators of those projects were contacted for idea sharing and possible coordination of on-going and future efforts.

There is a general consensus that current test methods and specifications can be greatly improved, and there are several performance-related protocols and methods currently being evaluated that look very promising. Because the proposed performance tests are not yet ASTM or AASHTO approved, and because there are still major data gaps, these protocols are not yet ready for full implementation by FLH.

Based on the findings of this investigation, it is recommended that FLH continue to use the best practices of existing specifications for acceptance and pay supplemented with the “report only” performance tests listed in Table 12. It is further recommended that the data thus reported be combined with field performance evaluations, and that those results be used to gain statistical validation and acceptance as AASHTO/ASTM standards. More detailed information on the background for these recommendations is given in the following sections.

3.1 Industry Outreach Initiatives

3.1.1. Initial Discussions with Industry Representatives

Asphalt emulsion material suppliers, study participants from the NCPP, and FLH representatives participated in an initial information gathering session on September 25, 2006 in St. Louis, Missouri. Koichi Takamura and Chris Lubbers of BASF Corporation (BASF); Joe Thrasher and Barry Baughman of Ultrapave; Dennis Muncy and Jon Wingo of SemMaterials; Paul Morris of Ergon; and Roger Hayner of Terry Industries represented the industry viewpoint. Gary Evans, Scott Saunders and Mike Voth represented FLH, and the NCPP participants were Larry Galehouse and John Johnston.

Following this meeting, Gayle and Helen King were brought into the project as consultants to contribute asphalt emulsion materials expertise and a better understanding of supplier needs and concerns. Several teleconference calls and meetings have followed since the initial meeting in St. Louis to garner relevant input from other industry representatives, academics and FHWA personnel. A summary list of these meetings includes:

- September 2006 Meeting in St. Louis, Missouri;
- March 2008 Meeting in Okemos, Michigan;
- Teleconference Calls with Industry and FLH in October, November, and December 2007; and July 2008.

Discussions of the input received during these meetings are presented in the following subsections, and detailed meeting minutes are provided in Appendix A.

3.1.2 Findings from the Survey and Follow-up Communication

Based on comments gathered from the previously referenced meetings, the study participants developed a survey for the industry at large. Invitations were sent to members of the Binder Expert Task Group (ETG); the Transportation Research Board (TRB) committee AFK20 (Asphalt Binders); the TRB Pavement Preservation Task Force; and the International Technical Committees of the American Emulsion Manufacturers Association (AEMA), the Asphalt Recycling and Reclaiming Association (ARRA), and the International Slurry Surfacing Association (ISSA) to respond to a web-based questionnaire. Appendix B contains a PowerPoint™ summary presentation as well as the full survey results. In support of the survey, numerous research resources and proposed test procedures were posted on the NCPP website. These documents can be found in Appendix C. While a majority of the 33 survey respondents were technical people, there was a good cross-section of industry leaders and experts representing SHAs, suppliers, contractors, academics, and consultants involved in regulatory, technical, construction, marketing, management and business roles. Industry had previously opposed innovative ideas for polymer modified emulsion testing and performance-related specifications - often because of concerns about shipping and payment delays or extensive testing requirements. The survey indicates that the private sector of the asphalt emulsion industry would be willing to accept more performance-based methods and specifications, so long as emulsion suppliers and contractors are included in the change process and their existing operations can continue to produce and place products efficiently. To make this happen, emulsion suppliers generally support a standardized certified pre-compliance testing program and acceptance. Overall, there was a good mandate for contractor, supplier, and lab certification, but not individual certification. Specific comments on test protocols included:

PME Emulsion Test Methods and Specifications

All of the experts consulted agreed that the ASTM D-244 specification covering test procedures for asphalt emulsions needs to be updated. Changes discussed in the survey include:

- **Emulsion Viscosity – Lab Tests:** Experts agree the Saybolt-Furol method for measuring asphalt emulsion viscosity is antiquated and unable to measure shear rate. Brookfield rheometers are used to determine asphalt viscosities at high temperatures for prediction of HMA mix and compaction temperatures, and are therefore standard equipment in asphalt laboratories. Although asphalt emulsion viscosity can be measured with this same rheometer, survey comments revealed that recent work by Salomon (81) indicates some problems with Brookfield testing that might be overcome with a Paddle Rheometer as used by the paint industry. Survey comments on the Paddle Method were generally favorable, but a follow-up phone call indicated that one lab (Flint Hills Resources) conducting work in support of the ASTM committee on asphalt emulsion test methods had problems with temperature control and suggested that additional work is required to validate the method. Improving the method for measuring asphalt emulsion viscosity in the lab remains a data gap. Although not critical for the improvement of FLH PME specifications as outlined in this study, it would be appropriate to include any new viscosity test methods under review by ASTM in the report-only field study.

- **Asphalt Emulsion Viscosity – Field Test:** Asphalt emulsion viscosity as measured in an agency laboratory at some time well after project application is not necessarily informative, because particle size and resulting emulsion viscosity changes with storage and agitation, particularly when asphalt emulsions are kept at ambient temperatures. Another data gap recognized by many experts is the need for a field viscosity test to be run on an asphalt emulsion at the time of delivery to the project. Wyoming DOT has already implemented such a field test, which is available on the project website (82). The Wyoming procedure should be considered for the report-only field study.

- **Optimizing Emulsion Viscosity:** Respondents from cooler climates don't want chip seal emulsion viscosities raised from the standard 100-400 SSF, but a number of agency and industry representatives from hot climates expressed concern that the 100-400 SSF minimum is too low. Other comments referenced problems with lower viscosity asphalt emulsions on pavements with steep slopes. It is important for the viscosity to be such that the asphalt emulsion sprays uniformly through the distributor and stays in a thick enough film on the pavement for optimal chip embedment. Another data gap revealed by the literature review is that optimum seal coat emulsion viscosity may need to vary with climate and pavement slope.

Residue Recovery

- **Residue Recovery Method:** Support for low-temperature asphalt emulsion residue recovery was strong, but significantly increasing the testing time for product certification may only be practical in combination with a delayed-acceptance or a pre-certification program to overcome shipping delays. The need to eliminate distillation methods with recovery temperatures of 177°C (350°F) and higher was emphasized in a recent presentation by Kadrmas to the 2008 AEMA Annual Meeting (83). He showed that binder moduli for PME microsurfacing residues as recovered using a Forced Draft Oven Procedure at 60°C (140°F) were consistently twice as high as the moduli for the same residues as recovered using 177°C (350°F) distillations. This data shows conclusively that asphalt emulsion residue performance specifications must not be based on current residue recovery practices. This conclusion is consistent with findings obtained from several European studies. During follow-up discussions, Dr. Didier Lesueur, an asphalt emulsion research manager for Eurovia and participant on European Normalization Committees for asphalt emulsion specification, shared new European Community for Standardization (CEN) standards for residue recovery (84) and a framework for cationic emulsion specifications based on performance parameters (85). CEN also has a third relevant specification for recovery of emulsion residues which contain solvent (86). The CEN standard for emulsion recovery is very similar to the Forced Draft Oven Procedure that Takamura and Kadrmas plan to submit at the next ASTM meeting.

Both methods first evaporate the asphalt emulsion at ambient temperature for 24 hours, and then place the residue in a forced draft oven for another 24 hours. The only major difference is that the CEN standard uses an oven temperature of 50°C (122°F), whereas the ASTM proposal will use 60°C (140°F). Although many lower temperature recovery methods have been proposed, the Forced Draft Oven procedure has the advantage of curing materials at conditions that most closely simulate conditions on the pavement. Furthermore, residue can be removed from the silicone mold without reheating. Although other potential recovery methods such as Stirred Can, Vacuum Recovery, Microwave Moisture Analyzer and others may be faster or may yield more emulsion residue, Forced Draft Oven will remain the method of choice until other methods are proven to match all residue performance properties resulting there from.

Residue Testing Using Superpave Binder Technology

There is strong support for utilization of Superpave binder tools to specify performance properties of asphalt emulsion residues, with an accompanying climate driven grading system. However, legitimate concerns were expressed regarding additional equipment costs, extended testing time, lack of aging protocols, and the need for a residue recovery method that yields a binder consistency equal to that of a pavement-cured material. More importantly, there is little consensus regarding the definition of performance parameters and specific testing conditions for PME chip seal and PME microsurfacing/slurry applications. Unfortunately, current practice is only loosely tied to variability in climate and traffic. For example, the penetration range for a binder in current microsurfacing specifications is 40 to 90 dmm, a range that would typically represent three full grades in the PG grading system for HMA binders (i.e., PG 58, PG 64, & PG 70). Implementation of performance specifications is a huge data gap. Virtually every expert believes it should be done, but no one knows how.

- **Basic Requirements and Preferred Outcomes for Residue Testing**: Although many issues remain to be resolved before asphalt emulsion residues can be characterized with reliable performance tests, a number of guidelines for future research can be established based on input received during the survey and related discussions:

    1. Residue performance properties to be characterized:
        - High temperature grade based upon climate, traffic, and appropriate failure parameters (rutting, bleeding)
        - Low temperature grade based upon climate and appropriate failure parameters (cracking, aggregate loss)
        - Polymer identifier which is able to rank performance at different levels of polymer modification
        - High Float gel identifier
        - Aging Protocol: RTFO was definitively rejected, since hot mix plants are not used for cold emulsion applications. The Pressure Aging Vessel (PAV) is clearly the aging tool of choice, but has a number of limitations as described below.

- Polymer/Asphalt Compatibility and Stability During Aging: It is known that certain polymer/asphalt blends are incompatible, such that the polymer will tend to separate or loose its elastic network over time. For modified HMA binders, such unstable systems are typically eliminated by specifying heat stability tests such as the Long-Term Asphalt Stability (LAST) test or the Separation Test. Because there is no heated storage of emulsion residue, experts reject these methods as performance indicators. Another good indication of compatibility comes from various microscopic methods such as fluorescence or scanning electron microscopy. Again, experts suggest such methods are useful to the formulator, but should not be adopted for specifications. As another data gap, a method is needed to insure polymer network stability under the conditions experienced by aging emulsion residues on the pavement surface.

2. PME residues should not be exposed to elevated temperatures during recovery or sample preparation. Any procedure requiring curing or reheating temperatures above 60ºC (140°F) must be validated by showing performance properties comparable to those from Forced Draft Oven Residues.

3. Minimize the quantity of residue needed for performance testing, ideally completing all residue tests with the recovered binder from a single silicone mold as cured in the Forced Draft Oven Recovery Method.

4. Minimize equipment costs and testing time, using common tools wherever possible. Survey comments and AEMA discussions emphasized the concern that there are many small companies supplying emulsion from one or two plants, and those facilities only manufacture approximately 10-20% of volumes shipped by refineries or liquid asphalt terminals supplying

PG-graded binders. Amortizing expensive laboratory equipment and testing costs over small volumes can significantly increase product cost and disadvantage smaller producers.

- Maximize Utilization of the Dynamic Shear Rheometer. DSR appears to be a critical tool for defining performance standards based upon rheology. One goal of the planned FLH report-only field study will be to maximize the capabilities of this instrument. Conversations with other research teams lead project leaders to believe it may be possible to use DSR to meet each of the four critical residue performance properties, as well as determine polymer-asphalt compatibility after aging. DSR also offers other important advantages including small sample size and no reheating for sample prep. As discussed later in this report, the DSR methods developed by the Binder ETG and adapted by Kadrmas (87) will be used for high temperature residue properties and for polymer identification. Although most experts consider it logical to use the BBR for low temperature performance testing, several disadvantages make its use problematic for asphalt emulsion residues. For example, BBR would necessitate reheating recovered residue to pour relatively large test specimens. The equipment itself is costly, requires significant lab space for testing and temperature control units, and needs volatile solvents that often require access to fume hoods or vents.

  An ongoing field-aging study led by Harnsberger and Huang at the Western Research Institute (WRI) encountered similar problems with the need to reduce sample size and so developed DSR protocols that include rheological measurements around 0-20°C (32-68°F) (87). The WRI researchers then fit and extrapolate rheological CAM models (88) to predict binder modulus and phase angle at the lowest pavement temperatures. Full details of Harnsberger's and Huang's work have not yet been published. WRI has significant funding within their current FHWA "Fundamental Properties" contract for development of rheological methods. Discussions are ongoing with project managers to determine whether WRI work plans and resources can be modified to develop specific DSR methods for testing emulsion residues at low temperatures. With the recent addition of a second rheologist to their staff, WRI may also be willing to take on the task of developing a DSR test method to characterize the non-linear gel-like characteristics of anionic high float residues. WRI also has broad experience with asphalt aging, and could be asked to adapt PAV protocols for emulsion residues. If WRI work plans can be altered accordingly, the report-only format of the FLH projects will be used to validate their findings.

- **Defining polymer content:** Industry experts overwhelmingly favor physical performance tests over analytical chemistry methods to define the amount of polymer in various PME residues. Elastic Recovery in a Ductilometer (ER), the most common method used by FLH and most AASHTO agencies, received lukewarm support as the preferred method. However, there was no strong support for other currently available alternatives such as force ductility, toughness and tenacity, torsional recovery, or DSR phase angle. Most industry experts would prefer DSR testing - if equipment costs could be controlled and the right parameters were selected. Most of the survey comments favored utilization of a strain recovery parameter from the newly developed DSR Multi-Step Creep Recovery (MSCR) Procedure as recommended by the Binder Expert Task Group and recently adopted as AASHTO test method 7405-08 (89). Kadrmas' research presented to AEMA in February 2008 outlines a path forward that should satisfy the many comments received in this area. His results also showed the importance of physical testing rather than polymer quantification to assure equal performance (83). This study was discussed in some detail at the Okemos, Michigan meeting, and further testing plans to identify polymer for the FLH report-only study will be based on Kadrmas' recommendations (83).

- **Polymer/Asphalt Compatibility:** Although widely used by suppliers as a formulation tool, there was very little support for the use of microscopy in product specifications to verify polymer network formation or asphalt/polymer compatibility. Among the primary objections to utilizing microscopy were the increased equipment acquisition and training costs, as well as potential delays in testing. If such a tool were to be included, it should be used as part of product qualification in a certified supplier program rather than as a PME specification tool.

- **PAV Tests to Simulate Field Aging of Emulsion Residues:** It is easy to reject RTFO since this laboratory aging procedure is meant to simulate oxidation occurring at elevated temperatures in the hot mix plant. The Pressure Aging Vessel (PAV) is clearly the tool of choice for asphalt emulsion residue aging, but the direct translation of PAV procedures from asphalt concrete (AC) binders to PME residues is not as straightforward as most experts might expect. Issues to be considered include:

    - Residue recovery for PAV testing: In order to avoid reheating the recovered residue to pour the sample into the PAV pan, it would be preferable to pour asphalt emulsion directly into the PAV pan and then cure the pan using methods established for the Forced Draft Oven. The cured residue would then be placed into the PAV oven for a defined time and temperature. Although seemingly straightforward, such a method has not yet been developed.

    - PAV aging time & temperature: It would be ideal to hold PAV temperatures to 60°C (140°F) so that polymer modified residues would never be damaged by temperature. The problem is that oxidation reaction rates double for each 10°C increase in temperature. Therefore the rate of oxidation in the PAV should be approximately 16 times slower at 60°C than at the 100°C (212°F) condition used for most Superpave binders. To reach an equivalent level of oxidation, the PAV testing time would have to be increased from 20 hours to 320 hours if temperature were reduced to 60°C. Extensive time-temperature PAV aging studies were conducted at WRI during SHRP. Such data would be valuable in evaluating alternatives for asphalt emulsion residues. Further research will be needed to determine the maximum temperature to which residues can be heated without damaging latex-induced polymer networks.

- Performance tests to be run on PAV-aged residues should include:
  - Low Temperature Performance Specification: As asphalt ages, it becomes more brittle and prone to cracking at low pavement temperatures. Hence, low temperature physical properties should ideally be measured on appropriately aged residues. For surface applications such as slurry/micro or chip seals, the level of asphalt oxidation should be comparable to that observed near the surface of HMA. Physical tests on the aged residue should report both a hardness parameter and a relaxation parameter. For example, low temperature specifications could be based upon Stiffness (S) and "m-value" as measured by the Bending Beam Rheometer (BBR), or dynamic modulus (G*) and phase angle as measured by a DSR.
  - PAV Aging to Control Polymer Compatibility/Degradation: Because standard test methods which control polymer/asphalt compatibility have been removed, there is some risk that unstable polymer/asphalt blends might prematurely degrade or separate. One possible means to control this could be to evaluate the polymers contribution to physical properties both before and after

aging. For example, if the strain recovery in the MSCR test falls off rapidly with PAV aging, there would be some concern that the polymer system is unstable. Such a test method has not been considered in the literature, and this issue remains a data gap yet to be defined.

Aggregate Specifications

It is clear from the survey responses that aggregate requirements must fit the asphalt emulsion application. For example, chip seal experts typically prefer to specify fines by assigning a maximum P200%, while microsurfacing designers want a methylene blue test to control the surface activity of those fines. Although survey respondents generally favor LA Abrasion over MicroDeval, the few who have actually used the latter think it is a much better test, particularly for surface applications where more moisture is present. It is also generally believed that more aggregate and aggregate/emulsion compatibility testing will yield better performance. A recent study by Kim has shown how to optimize aggregate gradation for surface treatments (90).

Although the primary objective of this study relates to the use and specification of polymer modified emulsions, some effort was also directed towards reviewing FLH aggregate specifications for chip seal and slurry/micro applications. Tables 12 through 19 show how current FLH standards compare to other agency specifications (specifically, TxDOT and CALTRANS), as well as to recommendations coming from active research projects and unique industry sources. A quick inspection indicates that FLH aggregate specifications use ASTM/AASHTO standard versions of common test procedures. Overall aggregate quality requirements are consistent with or exceed those of most state agencies. Specification of the Adherent Coating test to control the quantity of P-200 washed from the aggregate is particularly notable as a less common procedure that plays a very important role for insuring early aggregate adhesion to the emulsion residue.

Because the industry survey and other discussions led to a consensus belief that aggregate quality should be tied to traffic, some effort was made to identify aggregate quality standards that might be used to differentiate such use of materials.

- Aggregate specifications for PME chip seals:

  Table 12 presents a comparison of current and proposed chip seal aggregate quality specifications for five (5) different source agencies / organizations.

Table 12: Comparison of Chip Seal Aggregate Quality Specs

Agency / Organization	**FLH (703.10)**	**Caltrans**	**TxDOT** **(Not AASHTO Standards)**	**Colorado State Study**	**RoadArmor® recommendations (High Performance)**
General Specifications	Furnish hard, durable particles or fragments of crushed stone, crushed slag, or crushed gravel. Use only one type of aggregate on a project.	Screenings shall consist of broken stone, crushed gravel or both. At least 90 percent by weight of the screenings shall consist of crushed particles as determined by California Test 205. Screenings shall be clean and free from dirt and other deleterious substances.	Uncontaminated materials of uniform quality throughout that meet the requirements of the plans and specifications. Special requirements for lightweight ag: pressure slaking, freeze-thaw loss, water absorption		
Gradation	Table 703-7	See below	See below		1/2 inch 100 - 100 3/8 inch 100 - 100 #4 0 - 12 #200 0 - 1
Los Angeles abrasion, AASHTO T 96	40% max.		35 max* 40 max*LRA	<25 for high volume traffic	
Los Angeles Rattler, CA 211 Loss at 100 Rev. Loss at 500 Rev.		10% max 40% max			
Sodium sulfate soundness loss, AASHTO T 104	12% max.				
Mg sulfate soundness, 5 cycle, %, Tex-411-A			25 max		

Agency / Organization	**FLH (703.10)**	**Caltrans**	**TxDOT** **(Not AASHTO Standards)**	**Colorado State Study**	**RoadArmor® recommendations (High Performance)**
Fractured faces, one or more, ASTM D 5821	90% min.		2 faces, >85%		1 face >98% 2+ >95%
Flat and elongated particles, 1:3 ratio. +⅜ inch sieve, calculated by mass, weighted average, ASTM D4791	10% max.				
Clay lumps and friable particles, AASHTO T 112	1.0% max.				
Deleterious Materials Tex-217-F P-200			2.0 max*		0.5 % max. 1.0 % max.
Cleanness Value, CA 227		80 min			
Decantation, %, Tex-406-A			1.5 max		
Adherent coating, ASTM D 5711	0.5% max.				
Film Stripping CA 302		25% max			
	Do not use lightweight aggregate according to AASHTO M 195.	Samples for the aggregate grading and Cleanness Value tests will be taken from the conveyor belt of the spreader prior to application.			
Micro-Deval			For screening, not for acceptance		17% max
Flakiness index Tex-224-F			17 max		17 max.
Absorption					2% max.

Size, grade, and combine the aggregate fractions in mix proportions conforming to the following criteria listed below in Tables 13, 14 and/or 15.

Table 13: FL Table 703-7 Target Value Ranges for Single and Multiple Course Surface Treatment Aggregate Gradation

Sieve Size	Percent by Mass Passing Designated Sieve (AASHTO T 27 & T 11)					
	Grading Designation					
	A	B	C	D	E	F
1½ inch	100 (1)					
1 inch	90 – 100 (3)	100 (1)				
¾ inch	0 – 35 (5)	90 – 100 (3)	100 (1)			
½ inch	0 – 8 (3)	0 – 35 (5)	90 – 100 (3)	100 (1)		
⅜ inch	---	0 – 12 (3)	0 – 35 (5)	85 – 100 (3)	100 (1)	100 (1)
No. 4	---		0 – 12 (3)	0 – 35 (5)	85 – 100 (3)	85 – 100 (1)
No. 8	---			0 – 8 (3)	0 – 23 (4)	---
No. 200	0 – ½ (½)	0 – ½ (½)	0 – ½ (½)	0 – ½ (½)	0 – ½ (½)	0 - 10 (1)

(1) Statistical procedures do not apply.
( ) The value in parentheses is the allowable deviation (±) from the target value.

Table 14: CALTRANS Chip Seal Screenings Sizing

Seal Coat Types	Size of Screenings
Fine	1/4" x No. 10
Medium fine	5/16" x No. 8
Medium	3/8" x No. 6
Coarse	1/2" x No. 4
Double	
1st application	1/2" x No. 4
2nd application	1/4" x No. 10

Sieve Size	Percentage Passing			
	Coarse 1/2" x No. 4	Medium 3/8" x No. 6	Medium Fine 5/16" x No. 8	Fine 1/4" x No. 10
3/4"	100	—	—	—
1/2"	95-100	100	—	—
3/8"	50-80	90-100	100	100
No. 4	0-15	5-30	30-60	60-85
No. 8	0-5	0-10	0-15	0-25
No. 16	—	0-5	0-5	0-5
No. 30	—	—	0-3	0-3
No. 200	0-2	0-2	0-2	0-2

Table 15: TxDOT Aggregate Gradation Requirements (Cumulative % Retained[1])

Sieve Size	Grade								
	1	2	3S2	3		4S2	4	5S2	5
				Non-lightweight	Lightweight				
1"	–	–	–	–	–	–	–	–	–
7/8"	0–2	0	–	–	–	–	–	–	–
3/4"	20–35	0–2	0	0	0	–	–	–	–
5/8"	85–100	20–40	0–5	0–2	0–2	0	0	–	–
1/2"	–	80–100	55–85	20–40	10–25	0–5	0–5	0	0
3/8"	95–100	95–100	95–100	80–100	60–80	60–85	20–40	0–5	0–5
1/4"	–	–	–	95–100	95–100	–	–	65–85	–
#4	–	–	–	–	–	95–100	95–100	95–100	50–80
#8	99–100	99–100	99–100	99–100	98–100	98–100	98–100	98–100	98–100

1. Round test results to the nearest whole number.
2. Single-size gradation.

Aggregate specifications for chip seals vary widely, and not all agencies differentiate aggregate quality for traffic. Even the definition of high-volume traffic for chip seals varies markedly, with experts somewhat arbitrarily choosing anywhere from 1,000 ADT to 10,000 ADT as a minimum level which might require higher quality materials. A high volume chip seal study by Shuler elected to construct field test sections with ADTs exceeding 7,500 ADT. Recommendations from that study, and the new NCHRP project also led by Shuler (Manual for Emulsion-Based Chip Seals for Pavement Preservation: NCHRP 14-17) should be considered. Since FLH has graciously agreed to support this latter NCHRP project with field trials, Shuler's results and recommendations should be available and pertinent to FLH needs. Although the study is ongoing, Shuler has already made some recommendations to the FLH research team based upon earlier work. One example of note is to reduce the LA Abrasion maximum from 40% to 25% for high volume traffic.

As another example, SemMaterials (formerly Koch Materials) developed a high performance chip seal system under the trademark RoadArmor® for higher volume traffic. This system includes a new piece of construction equipment which applies both emulsion and then aggregate in a single pass. It also includes upgraded emulsion and aggregate specification recommendations consistent with faster curing and longer wear. RoadArmor® was actually developed for chip seal applications that need a quick return to traffic, a concept which may be more appropriate than ADT to FLH needs on pavements such as narrow mountain roads or isolated areas where detours are unavailable and traffic control is difficult. Hence, RoadArmor® guidelines do not define high volume traffic with a specific ADT. However, the aggregate guidelines supplied with this system offer some insight as to recent trends applicable to differentiating material quality. As can be seen on the comparative table for chip seal aggregates (Table 12), RoadArmor® guidelines reduce P-200 fines and deleterious materials and require more crushed faces than most agency specifications. Interestingly, this guideline specification also appears to be the first in the U.S. to replace LA Abrasion with Micro-Deval.

Although the industry survey received more favorable votes for LA Abrasion, the respondents who actually had experience with using Micro-Deval to screen aggregate durability strongly favored it. Since FLH has the Micro-Deval apparatus available in the Denver lab, it is recommended that Micro-Deval be required in the report-only portion of the experimental materials testing plan. Results should be compared against the RoadArmor guideline of 17% maximum loss to determine whether similar limits might fit FLH needs on higher volume chip sealed pavements.

- Aggregate specifications for PME microsurfacing/slurry:

  ISSA offers separate aggregate quality guidelines for slurry seal and microsurfacing applications. The industry survey indicated that ISSA guidelines represent best current practice, and should be adopted where possible as minimum requirements. More recent research for CALTRANS led by Fugro Consultants proposes that all slurry systems be redefined in essentially three categories based upon traffic, climate, and application. These three classifications should provide better definition for use of microsurfacing, Polymer

Modified Emulsion (PME) slurry, and conventional slurry emulsions. Aggregate and mix design guidelines should be adjusted accordingly for these three distinct uses. Preliminary information on aggregate quality guidelines was provided by Fugro on the CALTRANS study for slurry seals and microsurfacing. These data are compared to both the ISSA guidelines and existing FLH specifications in Tables 16 and 17.

Table 16: Comparison of Slurry Seal Aggregate Quality Specifications

Test Method	FLH	ISSA	FUGRO / CALTRANS Study
General	Furnish natural or manufactured sand, slag, crushed fines, or other mineral aggregate conforming to AASHTO M 29 and the following:	The mineral aggregate used shall be the type and grade specified for the particular use of the slurry seal. The aggregate shall be manufactured crushed stone such as granite, slag, limestone, chat, or other high-quality aggregate, or combination thereof. To assure the material is totally crushed, 100 percent of the parent aggregate will be larger than the largest stone in the gradation to be used.	
Los Angeles abrasion, AASHTO T 96	35% max.	35 % max. Abrasion test run on aggregate before it is crushed	30% max. high traffic 35% max. low traffic
Sand equivalent value, AASHTO T 176, alternate method no. 2, reference method	45 min.	45 min.	45 min. low traffic 65 min. high traffic
Smooth textured sand with < 1.25% water absorption content by weight of total combined aggregate	50% max.		
Soundness, AASHTO T104		15% max using Na_2SO_4 25% max using $MgSO_4$	20% max using $MgSO_4$
Polishing		Meet approved polishing values	
Gradation	See below	See below	See below

Table 17: Comparison of Microsurfacing Aggregate Quality Specifications

Test Method	FLH	ISSA	FUGRO / CALTRANS Study	TxDOT
General	Furnish natural or manufactured sand, slag, crushed fines, or other mineral aggregate conforming to AASHTO M 29 and the following:	The mineral aggregate used shall be of the type and grade specified for the particular use of the Micro-Surfacing. The aggregate shall be a manufactured crushed stone such as granite, slag, limestone, chat, or other high-quality aggregate, or combination thereof. To assure the material is totally crushed, 100 percent of the parent aggregate will be larger than the largest stone in the gradation to be used.		
Los Angeles abrasion, AASHTO T 96	30% max.	30% max. To be run on parent aggregate	30% max. high traffic 35% max. low traffic	
Sand equivalent value, AASHTO T 176, alternate method no. 2, reference method	65 min.	65 min.	45 min. low traffic 65 min. high traffic	70 min.
Sodium sulfate soundness, AASHTO T 104	15 max. Using NA_2SO_4 25 max. Using $MgSO_4$	15 max. Using NA_2SO_4 25 max. Using $MgSO_4$	20 max Using $MgSO_4$	30 max.
Polishing		Meet state-approved polishing values		
		Proven performance may justify the use of aggregates that may not pass all of the above tests.		
Gradation, type II or III	Table 703-8 (See below)	See below	See below	

Recommended aggregate gradation comparisons for slurry seals and microsurfacing applications are provided below in Tables 18 and 19.

Table 18: Comparison of Slurry Seal & Microsurfacing Aggregate Gradation & Application Rates

Sieve Size	Percent by Mass Passing Designated Sieve (AASHTO T 27 & T 11)					
	Slurry Seal Type					
	I (Slurry Only)		II		III	
	FL	ISSA	FL	ISSSA	FL	ISSA
3/8 inch	—	100	100	100	100	100
No. 4	100	100	90-100	90-100	70-90	70-90
No. 8	90-100	90 – 100	65-90	65-90	45-70	45-70
No. 16	65-90	65 – 90	45-70	45-70	28-50	28-50
No. 30	40-65	40 – 65	30-50	30-50	19-34	19-34
No. 50	25-42	25 – 42	18-30	18-30	12-25	12-25
No. 100	15-30	15 – 30	10-21	10-21	7-18	7-18
No. 200	10-20	10 – 20	5-15	5-15	5-15	5-15
Application rate(2) pounds per square yard	6 - 10	8-12	10 - 15	10–18 slurry 10-20 micro	15 or more	15-22 slurry 15-30 micro

Note: Statistical procedures do not apply to gradations. Application rates are based on the dry mass of the aggregate.

Table 19: TxDOT Microsurfacing Aggregate Gradation Requirements
Tex-200-F, Part II (Washed)

Sieve Size	Cumulative % Retained
1/2 in.	0
3/8 in.	0–1
#4	6–14
#8	35–55
#16	54–75
#30	65–85
#50	75–90
#100	82–93
#200	85–95

TxDOT Microsurfacing JMF Requirements have been provided for comparison purposes below in Table 20.

Table 20: TxDOT Microsurfacing JMF Requirements

Property	Test Method	Requirements
Wet track abrasion, g/sq. ft., max. wear value	Tex-240-F, Part IV	75
Gradation (aggregate and mineral filler)	Tex-200-F, Part II (Washed)	Table 1
Mix time, controlled to 120 sec.	Tex-240-F, Part I	Pass

Emulsion/Aggregate Performance Tests

It is widely recognized that asphalt emulsion and residue properties alone cannot define performance. Similarly, mixture performance parameters as typically measured using Superpave mix design and performance tools are not sufficient to describe most Pavement Preservation applications. As pointed out by Leach and Blankenship (91), asphalt emulsions require time to cure. Therefore, one critical performance issue is establishing the amount of time an asphalt emulsion system must cure before a road can be reopened to traffic.

- **Sweep Test - Chip Seal Curing Time for Traffic – ASTM 7000** (92): The survey indicated some concerns with the Sweep Test, particularly with respect to repeatability of the standard ASTM method. Takamura has investigated this test in some detail, and reports that three minor revisions to the procedure can reduce variability from 20% to 5% (93). Such improvement would almost certainly overcome expressed concerns if these results can be duplicated in multi-lab round-robin studies. The survey also indicates that confusion exists as to the performance characteristics being measured. As originally developed by Barnat, the sweep test was intended to rank emulsion/aggregate systems for curing time before a chip seal can be opened to traffic (94, 95). Since temperature and humidity play an important role in curing, the predictive value of this test is only accurate when the conditioning protocol is able to simulate field conditions at the time of placement. However, when conditioning occurs under the constant environmental conditions designated by the ASTM procedure, the test does seem to provide a reasonably correct rank-ordering of curing times as needed for purchase specifications. It is important to further clarify that the sweep test might predict aggregate loss or potential for windshield damage as the emulsion cures, but it is not intended to be a predictive tool for long term chip loss.

- **Chip Seal – Long Term Aggregate Loss**: There was no expert agreement on a good test for evaluating long-term chip loss. Suggestions from Davidson at McAsphalt included the Vialit Plate Shock Test (96) and the Frosted Marble Test

(80, 97), whereas French experts recommended the Vialit Pendulum Test (98). The best tool to date appears to be the MMLS3 procedures as developed by Dr. Richard Kim's group at N.C. State for the North Carolina DOT (99, 100). Although too expensive to advance for specification purposes, it remains an excellent research tool against which the predictive capabilities of less expensive performance tests can be compared. This subject remains a significant data gap, with no specific project recommendations at this time.

- **Microsurfacing vs. Polymer Modified Slurry:** Microsurfacing is formulated to provide significantly higher performance than Slurry Seals either with or without polymer. From a use perspective, Microsurfacing should be used for rut-fill applications and for high-traffic pavements with ADT exceeding 1000. Microsurfacing also contains emulsifier packages that break quickly, so that traffic can usually be returned in one hour or less. Where traffic control is a problem due to urban traffic, narrow roads or long detours, the faster curing microsurfacing might even be specified for lower volume roads.

- **Microsurfacing Performance Tests:** The ISSA document A143 "Recommended Performance Guidelines for Micro-Surfacing" was cited by survey respondents as the best available current practice for performance-related test procedures (39). Performance tests include Wet cohesion, Excess Asphalt by LWT Sand Adhesion, Wet Stripping, and Wet Track Abrasion Loss after one day soak and after six day soak. These tests should be used as pay items.
  - **Newly proposed tests for mix design and performance**: At a recent ETG meeting, Jim Moulthrop of Fugro, Inc. provided an update of a soon-to-be-completed research study updating mix design methods for Microsurfacing (101). Significant contributions from this study include an automated test for cohesion, a German method to predict mixing time by measuring mixer torque, and a French adaptation of the wet track abrasion test using wheels in place of the rubber tube. It is recommended

the FLH report-only format be used to evaluate new tools as ultimately recommended by the Fugro study.

- **Polymer Modified Slurry:** Since polymer modified slurry asphalt emulsions will only be used on roads carrying lower traffic levels (<1000 ADT), the wet-track abrasion test is probably sufficient as a pay item for mixture performance testing. However, it will be important to insure an adequate amount of polymer has been added for PME slurry applications. This can best be done with a residue polymer identification test. Elastic Recovery should remain in formal specifications for now, but Kadrmas' DSR MSCR protocol reporting recoverable strain (83) appears to be the best choice for report-only criteria. The ultimate strain recovery for a PME slurry residue would be significantly less than that expected for microsurfacing. From limited data, Kadrmas recommends the following test conditions and specification limits to differentiate microsurfacing from PME slurry as shown in Table 12.

Table 21: Report Only Performance Tests (83)

Testing Protocol	**Specification Latex/Polymer Modified**	**Specification Microsurfacing**
Original DSR, G*/sin δ	3 (minimum)	5 (minimum)
Original DSR, Phase Angle	80 (maximum)	75 (maximum)
MSCR, % Recovery At 3200 Pa	15 (minimum)	25 (minimum)

Manufacturing and Construction

- **Construction Controls on Climate/Weather:** Because of problems with curing when asphalt emulsions are applied at lower temperatures, the application window should be carefully restricted. Pavement temperatures continue to be important until the emulsion residue is fully cured.

  - Chip seals frequently fail if freezing occurs while the moisture content within the binder is still high. Controlling pavement temperature at time of application may not be sufficient to insure full curing. Given improvements in weather forecasting, it might be more appropriate to stop projects based upon predicted freezing temperatures for a few succeeding nights rather than raising pavement temperature requirements or narrowing seasonal limits for construction.

  - Because excess water dilutes and displaces emulsions, break time should be tied to requirements to stop construction for pending inclement weather.

  - It is also known that sealing high concentrations of moisture into a pavement can result in catastrophic stripping failures. Therefore, entrapped water resulting from recent rainfall before construction or other sources of subsurface moisture can lead to unexpectedly poor performance of sealed pavements.

  - Use of fog seals over new chip seals can improve short and long-term aggregate retention; perhaps even to the point of extending the construction season modestly.

  - Each of these observations, although obvious to the experienced practitioner, represent data gaps needing further research so that effective construction controls can be objectively managed.

- **Rolling/Compaction:** Recent research by Kim evaluated the effect of compactor type and roller pattern on the performance of chip seals (100). Recommendations from this work should be included in FLH guidelines.

- **Controls on Polymer Addition:** Good support was noted in the survey for pre-blending/co-milling polymers at the emulsion plant. Almost no one indicated support for adding polymer latex to the emulsion distributor or field tanks, with comments noting viscosity drop, polymer latex separation, and lack of uniformity leading the negatives. If post-blending latex is to be allowed at all, specification language should insure controlled metering and complete blending of latex and asphalt emulsion at the supplier's plant to attain a uniform consistency that continues to meet minimum viscosity requirements.

3.1.3. Follow-up Discussions with Larger Industry Audience

The goals of the FLH project and the need for industry response to the survey were introduced to several Transportation Research Board (TRB) committees at the January 2008 annual meeting in Washington, D.C., including the following:

- AFK10 – General Issues in Asphalt Technology
- AFK20 – Asphalt Binders
- Task Force on Roadway Pavement Preservation
- AHD20 – Pavement Maintenance

Survey results and suggested specification test methods were presented to several groups who were then solicited for their comments. These groups included:

- Joint Annual Meeting of the Asphalt Emulsion Manufacturers Association (AEMA), The Asphalt Recycling and Reclaiming Association (ARRA) and the International Slurry Seal Association (ISSA) in February, 2008;
    - Two presentations and a 1-hour breakfast meeting with the International Technical Committee;
    - By the end of the AEMA meeting, industry response was sufficiently positive for Jim Sorenson of the FHWA Office of Asset Management to form the ETG Emulsions Task Force;
- Asphalt Binder Expert Task Group in February, 2008;
- Emulsion Task Force of the FHWA Pavement Preservation ETG in April, 2008 (see discussion in Section 3.3.3.4),;

- TRB Committee AFK10 (General issues in Asphalt) in April 2008;
- Discussions with Dr. Scott Shuler, principal investigator of NCHRP Project 14-17, “Manual for Emulsion-Based Chip Seals for Pavement Preservation”;
- Discussions with Drs. Hussein Bahia and Peter Sebaaly of the Asphalt Research Consortium;
- Discussions with Dr. Richard Kim, Principal Investigator of an on-going chip seal performance study for the North Carolina DOT (Project HWY 2004-04);
    - Dr. Kim summarized his research at the project review meeting in Okemos, Michigan. He reported that many NC DOT districts are already converting all chip seals to polymer modified asphalt emulsions based upon their own experience and Dr. Kim’s findings to date, even though research is not complete and no state mandate requiring polymers has been published.
- Discussions with European emulsion experts and Standards Committee members, including Didier Lesueur of Eurovia and Francois Chaignon of Colas;
- Discussions with Darren Hazlett (TXDOT) and Dr. Amy Epps (Texas Transportation Institute, TTI) on their efforts to develop Superpave PG-type performance-related emulsion specifications;
- Discussions with Jim Moulthrop regarding progress with Fugro’s pooled-fund microsurfacing mix design study;
- Discussions with McGraw (MnDOT), Maurer (PennDOT), Hosseinzadeh (CALTRANS) and other SHA personnel on the status of delayed acceptance for certified asphalt emulsion suppliers and modified asphalt emulsion performance specification development;
- Discussion with Roger Olson (MnDOT) regarding an upcoming pooled-fund pavement preservation study for MnROAD that may provide a second

opportunity to evaluate performance testing protocols as recommended for this FLH study.;

- Discussions with Dr. Jack Youtcheff, Leader of FHWA's asphalt research team at Turner-Fairbanks. [Note: Dr. Youtcheff oversaw the asphalt chemistry research and the development of Superpave binder specs as a member of the SHRP staff, and now has responsibility for approving research projects and work plans developed by the WRI "Fundamental Properties" Study and by the Asphalt Research Consortium, as well as defining asphalt research to be conducted at Turner-Fairbanks. He is also a member of the Binder ETG and the Emulsions Task Forces.]

  Dr. Youtcheff states that he is interested in funding studies that would advance performance-based asphalt emulsion specifications. He has some ideas as to how the WRI and ARC work plans can be reworked to fit identified research needs, and is prepared to pursue money to support some related activities within FHWA's labs at Turner-Fairbanks. However, Youtcheff feels it is important that any defined research needs for asphalt emulsion applications come from the newly-formed FHWA ETG Emulsions Task Force, rather than from individuals or single projects. Dr. King chairs the emulsion residue testing subcommittee of the Emulsions Task Force (ETF), and will initiate efforts accordingly. Further discussions with Dr. Youtcheff, WRI/ARC investigators, and ETF subcommittee members are planned for the Association of Asphalt Paving Technologists (AAPT) meeting scheduled for late April 2008.

- Recommendations from the FHWA/FP^2 "Spray Applied Polymer Surface Seals Study." The recently completed FHWA/FP^2 study "Spray Applied Polymer Surface Seals" recommends that new chip seals be fog-sealed immediately after brooming if problems from windshield damage or long term chip loss are anticipated (102). Roger Olsen of MnDOT reports that they now fog seal almost all new chip seals, and as a result, windshield and snowplow damage have been reduced, and customer acceptance is unusually high because the black color leads to a perception among the driving public that a new HMA overlay has just been placed. To maintain optimal embedment, the initial application of CRS-2P chip seal emulsion should be reduced by the amount of asphalt to be applied during the ensuing fog seal.

3.2 Specific Recommendations

To specifically address the four items enumerated in the Statement of Work, recommendations are made in the following subsections.

3.2.1 Task 2A. Use of Modified vs. Unmodified Asphalt Emulsions

Polymer modified asphalt emulsions should be used for chip seal and slurry seal / microsurfacing applications for all traffic and climate conditions. While non-modified materials are less expensive than modified products, the construction, mobilization, traffic control costs; and the improved initial and long-term performance of PME usually justify the higher costs of using elastomeric PME.

Moreover, specifications for traffic conditions should be differentiated as follows:

- **Microsurfacing vs. PME Slurry:** Microsurfacing is polymer modified slurry seal with additives which result in a much faster chemical cure rather than atmospheric evaporation emulsion break. This study recommends microsurfacing for rut-filling, high traffic areas (>1000 ADT), roads that require quick return to traffic, and for high durability needs. PME slurry specifications typically require less polymer, but still significantly upgrade the performance above that expected from conventional slurry. PME slurry emulsions are recommended for low-volume roads (<1000) for which microsurfacing is not otherwise justified.

- **PME Chip Seals:** As mentioned above, cationic or anionic polymer modified chip seal asphalt emulsions are justified regardless of traffic level, as demonstrated by recent studies performed by the Ontario Good Roads Association (OGRA) and Gransberg et al. (2005) on the cost-effectiveness of CRS-2P on low volume roads (65), as well as Dr. Kim’s research results discussed previously. Traffic levels and speed should be considered when selecting aggregates and performance criteria. A quick cure and return to traffic, as potentially differentiated by the sweep test, are particularly desirable for high traffic areas, as are durable, polish-resistant aggregates. It is common to have individual asphalt emulsion specifications for cationic (CRS-2P), anionic (RS-2P) and high float anionic (HFRS-2P) PMEs. Local agency names for these emulsions will vary throughout the country.

For climate considerations, it is recommended that strict windows for application temperatures be specified, but this area also needs further investigation as there is clear evidence that curing, shelling and bleeding of chip seals are associated with climatic conditions occurring well after the time of application. Superpave PG-type specifications for HMA are based on climatic temperature ranges, which may also be useful for asphalt emulsion surface treatments, especially microsurfacing. Although the concept of 6°C grade increments based upon LTPPBind climate maps is attractive to practitioners, failure properties have not yet been defined and failure limits have not been established. For this reason, the FLH report-only lab testing format will only be useful if measured physical properties can be tied to actual performance on the pavement. It will be important to have longer-term pavement management data and frequent video tapes of pavement condition so that field performance can ultimately be used to set specification limits on promising laboratory performance measures.

As discussed in the literature review, polymers are believed to be advantageous for use on hiking or biking trails and parking lots because of resistance to permanent deformation, raveling surface aggregate and damage caused in parking lots when front wheels are turned with no concurrent forward motion. Polymer modified materials have also been shown to retard cracking, particularly the block cracking typically seen in older parking areas. Bikers prefer microsurfacing/slurry seals over rougher chip seals for trails. Small-sized aggregates should be used, and loose chips avoided. Although microsurfacing and slurry seals are not typically compacted for paving applications, they are compacted on airport runways and taxiways to eliminate FOD damage caused by raveling surface aggregate.

If loose aggregate is perceived to be a problem on trails, evaluate the use of small rollers on slurry/microsurfacing applications. Also, polymerized seals generally cure faster, meaning faster reopening for its intended use. However, there is not much data in the literature on the use of polymerized asphalt emulsions on trails and parking lots as noted previously.

3.2.2 Task 2B. Identifying and Specifying Polymer Percentages

Experience has shown that specifying polymer percentage does not necessarily result in the expected performance because of differences in compatibilities between asphalt and polymers from different sources. Moreover, feedback received from industry participants at the St. Louis meeting in 2006 clearly indicates that suppliers view polymer quantity specifications as a practice which serves to inhibit innovation – a problem which can be remedied with the adoption of appropriate performance specifications.

Thus, performance testing rather than recipe specifications should result in the longest lasting, most cost-effective treatments, by affording suppliers the opportunity to prescribe the polymer types, formulation methods, and mix design flexibility to meet agency and end-user requirements. Specific methods which are currently under consideration are discussed elsewhere in this report. Because of the importance of uniformity and compatibility to performance, it is recommended that the polymer not be post-blended with the asphalt emulsion in the field, particularly since both SHA and industry stakeholders have openly discouraged this practice.

Low temperature recovery of asphalt emulsion residues will simulate emulsion curing much more effectively than current recovery methods which are performed at temperatures that are far higher than these products will ever experience in the field. The high temperatures associated with currently used recovery methods have been shown to change the residue rheological properties, as the modulus is usually cut in half by heating the sample to 350º C, as opposed to using a low temperature Forced Draft Oven Method. Also, phase angles from high temperature distillation suggest that heating can cause cross-linking and damage to polymer additives. Therefore, it is recommended that a low-temperature method be adopted which is more representative of field curing conditions. Several such methods are under investigation by various researchers, with the leading candidate being a Forced Draft Oven Procedure similar to a recent European standard which is expected to be presented to ASTM later this year.

Rheological performance tests on the residue should identify the polymeric properties as well as high-float gel structures. While there is some concern that performance testing will be more time-consuming and result in shipping, construction and acceptance delays; a supplier pre-certification or delayed-acceptance program should facilitate the process.

3.2.3 Task 2C. Projected Performance and Cost

Costs vary significantly from region to region, depending upon the local costs and local availability of emulsified asphalt and aggregate materials, contractors and expertise. Section 2.10 and Table 11 above give more information on the projected cost-effectiveness and extended performance of PME.

3.2.4 Task 2D. Further Investigation

There are several data gaps in the available information. Nearly everyone in the industry believes that specifications for PME chip and slurry seals need to be changed so that they better predict field performance. While Superpave greatly improved the specifications for HMA, the tests and specifications developed are not necessarily the same criteria needed to specify performance for PME applications, but the tools may prove useful, albeit in some modified form. In fact, there are several studies independently investigating these. A “PG-type” system consistent with the base asphalts used by the binder industry and dependent upon binder rheology and climatic and traffic conditions would be generally acceptable, if it does not disrupt the supply and truly relates to PME surface treatment performance.

The “Strawman” specification given in Table 12 suggests a promising series of protocols, but data gaps are significant. When collected for “report only”, these data will be used to validate or adjust these methods as related pavement performance dictates. Most suppliers indicate they would be willing to pay for or perform these tests on upcoming FLH projects. Two or three commercial laboratories (PRI, Paragon, perhaps

Asphalt Institute) have committed to run the tests (as specified by FLH but paid for by the suppliers) for those suppliers that currently don’t have the in-house testing capability. FLH routinely evaluates pavements as part of its Pavement Management System. The laboratory data and field performance information collected will be evaluated at a later time to prescribe tests that are effective, repeatable, and have definable physical properties that can be tied to pavement performance. Hence, there will be an ongoing need for project oversight beyond the conclusion of the current study.

Delayed Acceptance - Approved Supplier Certification

The length of testing time has been one of the main obstacles to implementation of low temperature residue recovery and rheological testing (low temperature recovery procedures can take two or more days). Suppliers, contractors and agencies are all concerned that a lengthy test procedure would greatly disrupt the current way asphalt emulsions are manufactured and shipped. Suppliers also do not want different specifications and pre-certification requirements for different geographic regions or markets. Similar concerns during the development of Superpave resulted in an Approved Supplier Certification Program to allow shipping from authorized suppliers before testing is completed. AEMA and FHWA have been contacted, and FHWA’s ETG Emulsion Task Force has assigned a sub-committee to develop such a program for emulsions.

Due to unique purchasing requirements for FLH, this program would be written under guidelines for “Delayed Acceptance” rather than in the format of an Approved Supplier Program as preferred by AASHTO.

Strawman “Report Only” Draft Specification

To simulate field performance all protocols will ideally not call for heating to temperatures above possible field conditions. That means a low-temperature recovery method should be used, and the residue recovered should not be reheated for further testing. A Forced Draft Oven procedure using a silicone mold is preferred, because the residue can be easily removed from the mold without reheating.

Table 13 illustrates a draft Strawman “report only” testing protocol for recovery and eventual specification of PME residues. It includes rheological testing using a DSR for a minimum G*/sin δ and a maximum phase angle to determine polymer properties. The DSR is further used in the MSCR mode to determine recoverable strain and j_{nr}. High temperature testing will be done at the T_h grade for the base asphalt if known, and two additional temperatures in 6º C increments above that. It is suggested that new DSR test methods be developed to predict low temperature physical properties so that the BBR would not be needed for specification of asphalt emulsion residues. One logical approach to this problem is to use cone and plate geometry in the DSR to evaluate G* and phase angle at temperatures ranging from 0-20º C, and then use the CAM model to predict low temperature properties.

If DSR extrapolation methods cannot achieve sufficient accuracy, then new sample preparation procedures would be needed to make BBR a viable tool for classifying asphalt emulsion residues. High-float gel characteristics will be captured through some yet-to-be-determined method of defining non-linear pseudo-plastic behavior. DSR plots of ln(G*) versus shear rate or determination of a yield stress should be able to replace the antiquated float test with more quantitative measures of gel strength. For long-term residue aging, the PAV is believed to be the best alternative.

Although questions remain as to a specific aging protocol, rheological tests on PAV residue should characterize low-temperature behavior after aging (brittleness, raveling potential) and answer the question of what happens to the modified binder as it ages. Other research teams at WRI and ARC have been approached regarding the possibility of altering their 2nd year work plans to develop methods for the DSR low-temperature specifications, the gel characterization, and PAV aging of asphalt emulsion residues. Discussions with project principal investigators and FHWA project managers are on-going. The expectation would be that the ongoing FLH report-only field study would be used to evaluate proposed methods and specifications that might come from that research.

It is expected that samples will be collected and tested from three FLH field projects during the summer of 2008 as a test run of the report-only concept.

Table 22: Strawman “Report Only” Draft Specification - PME Residue

Purpose	**Test**	**Conditions**	**Report**
Residue Recovery	Forced Draft Oven	24 hrs @ambient + 24 hrs @60ºC	✓ % Residue
Tests on Residue from Forced Draft Oven			
High Temperature (Rutting/Bleeding)	DSR-MSCR DSR freq sweep	T_h T_h	✓ Jnr ✓ G* & phase angle
Polymer Identifier (Elasticity/Durability)	DSR-MSCR	T_h @3200 Pa	✓ % Recoverable Strain
High Float Identifier (Bleeding)*	DSR – non-linearity	T_h	✓ *Test to be developed*
Tests on PAV (run on emulsions evaporated in the PAV pan using the Forced Draft Oven procedure)			
Low Temperature (Aged Brittleness)*	DSR freq sweep	10ºC & 20ºC Model Low Temperature	✓ G* ✓ Phase Angle
Polymer Degradation (Before/After PAV)*	DSR-MSCR	T_h @3200 Pa	✓ Recoverable Strain Ratio

Design and Performance Testing

This section presents guidance on design and performance testing. Covered areas include aggregate-asphalt interactions, and laboratory design procedures.

Aggregate-Asphalt Interactions

Both the short and long term performance (curing time, adhesion, skid resistance, long term chip retention and durability) are dependent upon the aggregate physical properties and the asphalt-aggregate compatibility as well as the physical properties of the emulsion. Performance testing is needed on both aggregates and the combination of PME and aggregate.

There are several well-accepted performance tests for aggregates. It is clear that cleanliness, shape and durability (as tested by MicroDeval or LA abrasion) are directly related to performance. Aggregate surface chemistry becomes increasingly more important when cure-time-to-traffic is critical to performance.

Laboratory Design Procedures

- **Chip Seals:** The literature review mentions a few of the many design procedures for chip seals, most of which have evolved from McCloud's original work. Dr. Kim's recent studies for NCDOT specifically address aggregate quality, evaluate various design procedures for chip seals, and offer excellent recommendations that should be considered for FLH guidelines (103). Although the current ASTM method needs modest revision, the Sweep Test is viable for ranking curing time, and should be included in the FLH field study. While there are several laboratory test methods for long-term chip seal performance, none has universal acceptance. This is an area where further study is needed, and that is currently being investigated by other research projects such as NCHRP 14-17. If possible, the FLH report-only study should remain flexible to include recommendations from such projects as they become available. The MMLS3, as developed in S. Africa and as investigated by Dr. Kim and Dr. Epps, remains a valuable performance testing tool (100). It can be run wet or dry and its rubber tires simulate uni-directional traffic loading on samples. At approximately $100,000, the machine cost is prohibitive as a specification tool, but it can serve as an accelerated simulator for field performance to accelerate validation of other methods.

- **Microsurfacing / PME Slurry:** Current ISSA mix design and performance testing guidelines offer acceptable performance standards for microsurfacing (39). However, better residue specifications and improved mix design protocols are still needed. As discussed elsewhere, the Fugro pooled-fund study should serve as a source for new tests and methods applicable to microsurfacing mix design.

Leveraging Resources and Information Sharing

This project has begun leveraging available knowledge and pooling information (test methods, data, pavement performance) with suppliers, and other researchers and agencies (Federal, State, City and County). The recently released "TSP Preservation Research Roadmap" also recognizes the need for improved, performance-related specifications for asphalt emulsions. Because of the high interest by several entities in developing improved emulsion test methods and specifications, an ETF of the Pavement Preservation ETG has been formed by FHWA, with the first meeting held in April 2008. By cooperating on testing procedures and round robin testing, researchers from several projects will be more effective in developing standard procedures. Because funding for the current FLH study ends in September 2008, it is hoped that the ETG ETF in combination with these other ongoing research efforts will continue to monitor and update the report-only testing program and eventually recommend pertinent performance specifications to FLH and to the broader paving industry. It is further expected that the Guide delivered by this FLH project will be applicable not only to FLH personnel, but to the industry as a whole.

Other Data Gaps and Future Work

Specific areas identified as currently needing more investigation include:

- Develop performance and specification recommendations for hiking, biking trails; and parking lots;
- Provide clearer differentiation of material performance given variability in climate (temperature, humidity) and traffic;
- Update asphalt emulsion test methods in ASTM D-244, including measures for laboratory and field viscosity and low-temperature residue recovery;
- Develop standard asphalt emulsion residue test methods and specifications that correlate with performance;
- Develop rheological methods to insure the presence of optimum levels of polymer modification or gel (high float) formation in the residue;
- Develop aging procedures and polymer/asphalt compatibility or stability tests for asphalt emulsion residues;
- Improve materials selection, including aggregate specifications and mix-design procedures;

- Develop/improve performance methods for PME applications to include interactions between modified asphalt emulsion and aggregate. Efforts to include curing tests establishing time-to-traffic, moisture damage, and longer term performance under specified traffic and environmental conditions;
- Improve controls on environmental and pavement conditions at time of construction;
- Create Delayed-Acceptance or Certified Supplier Programs for Asphalt Emulsions; and,
- Conduct formal cost-benefit analyses with and without modifiers for specific asphalt emulsion applications.

It is hoped that an ongoing FLH field study continuing under the report-only format can be used to support some of these research needs. There are several FLH chip seals scheduled for the summer of 2008. The materials used should be tested using the suggested Strawman protocols presented herein. As the laboratory data are collected, it must be correlated with field performance.

Although problems with curing might be visible shortly after construction, ultimate performance cannot be analyzed until many years later. FLH collects video pavement management data every three years. More frequent field inspection may be needed as the Strawman tests are run. Tying the field performance information over time to the test results should be an on-going process. A Materials Library of the tested materials should also be maintained, so that materials may be retested as the test methods are perfected and pavement performance is known.

4.0 PME Testing Plan and Strawman Specification

4.1 Strawman Specification for Emulsion Residues

With input from a number of researchers and users and approbation from Federal Lands Highway, the a suggested Strawman Specification was developed with is provided below in Table 23. Note that the BBR will be replaced by low temperature parameters modeled from intermediate temperature DSR results.

Table 23: Strawman Emulsion Residue Performance-Related Specification

PURPOSE	TEST	CONDITIONS	REPORT
Residue Recovery	Forced Draft Oven	24 hrs @ambient + 24 hrs @60ºC	✓ % Residue
Tests on Residue from Forced Draft Oven			
High Temperature (Rutting/Bleeding)	DSR-MSCR DSR freq sweep	T_h T_h	✓ Jnr ✓ G* & phase angle
Polymer Identifier (Elasticity/Durability)	DSR-MSCR	T_h @3200 Pa	✓ % Recoverable Strain
High Float Identifier (Bleeding)*	DSR – non-linearity	T_h	✓ *Test to be developed*
Tests on PAV (run on emulsions evaporated in the PAV pan using the Forced Draft Oven procedure)			
Low Temperature (Aged Brittleness)*	DSR freq sweep	10ºC & 20ºC Model Low Temperature	✓ G* ✓ Phase Angle
Polymer Degradation (Before/After PAV)*	DSR-MSCR	T_h @3200 Pa	✓ Recoverable Strain Ratio

4.2 Testing Plan

To verify the format of the Strawman specification, a testing plan was developed as part of this study for use as report-only for several Federal Lands Highway field projects scheduled for completion in the Summer of 2008. Additional tests will be run during this time to better define the test conditions and limits. Laurand Lewandowski of PRI Asphalt has worked closely with the FLH / NCPP research team to develop the proposed testing plan presented herein.

PRI will be equipped to run all proposed tests for those suppliers or agencies that do not currently have the capability. Several suppliers have indicated that they do have the test equipment and expertise needed. While the testing during this evaluation has an estimated cost of $2,000 to $3,000 per asphalt emulsion, it is expected that the final specification tests will cost approximately $1,000. The full list of PME Testing Plan protocols for the 2008 evaluations is provided below in Table 24.

Table 24: Testing Plan Protocols for 2008 Evaluations

PROPERTY	TEST METHOD		SPEC.	RESULT
Asphalt Emulsion as Received				
Standard AASHTO or ASTM tests:	AASHTO M-140 Emulsified Asphalt or AASHTO M-208 Cationic Emulsified Asphalt			
Field Viscosity Test	WYDOT 538.0		Report	
Evaporative Method Residue (24 hours @ 25°C, 24 hours @ 60°C, Forced Draft Oven)				
Frequency Sweep (25 mm, 0.1 – 100 rad/sec, 10% Strain)	HTG*	AASHTO T 315	Report	Frequency Sweep (G*, □, etc…)
Multiple Stress Creep Recovery (100, 1000, 3200 & 10,000Pa)		TP 70-08		% Recovery & Jnr at each stress level
Frequency Sweep (25 mm, 0.1 – 100 rad/sec, 10% Strain)	HTG - 6°C	AASHTO T 315		Frequency Sweep (G*, □, etc…)
Multiple Stress Creep Recovery (100, 1000, 3200 & 10,000Pa)		TP 70-08		% Recovery & Jnr at each stress level
Frequency Sweep (25 mm, 0.1 – 100 rad/sec, 10% Strain)	HTG -12°C	AASHTO T 315		Frequency Sweep (G*, □, etc…)
Multiple Stress Creep Recovery (100, 1000, 3200 & 10,000Pa)		TP 70-08		% Recovery & Jnr at each stress level
Test Strain Sweep, 1 – 50% strain, 10 rad/s	25ºC			• Resistance to Deformation: G*/sind @ 12% Strain • Strain Tolerance: Strain Level at which G* < 90% G* initial • Failure Properties: Strain Level at which G* <50% G* initial
Pressure Aging Residue (100°C, 300 psi, 20 hours) R 28 (PAV run on residue obtained by Forced Draft Oven Method run in PAV pan)				
Frequency Sweep (25 mm, 0.1 – 100 rad/sec,1% Strain)	HTG*	AASHTO T 315	Report	Frequency Sweep (G*, □, etc…)
Multiple Stress Creep Recovery (100, 1000, 3200 & 10,000Pa)		TP 70-08		% Recovery & Jnr at each stress level
Frequency Sweep (25 mm, 0.1 – 100 rad/sec,1% Strain)	HTG - 6°C	AASHTO T 315		Frequency Sweep (G*, □, etc…)
Multiple Stress Creep Recovery (100, 1000, 3200 & 10,000Pa)		TP 70-08		% Recovery & Jnr at each stress level
Frequency Sweep (25 mm, 0.1 – 100 rad/sec,1% Strain)	HTG -12°C	AASHTO T 315		Frequency Sweep (G*, □, etc…)
Multiple Stress Creep Recovery (100, 1000, 3200 & 10,000Pa)		TP 70-08		% Recovery & Jnr at each stress level
Frequency Sweep (8 mm, 0.1-100 rad/sec, % Strain (TBD))	0°C	AASHTO T 315		Frequency Sweep (G*, □, etc…)
Frequency Sweep (8 mm, 0.1-100 rad/sec, % Strain (TBD))	10°C			Frequency Sweep (G*, □, etc…)
Frequency Sweep (8 mm, 0.1-100 rad/sec, % Strain (TBD))	20°C			Frequency Sweep (G*, □, etc…)
Test Strain Sweep, 1 – 50% strain, 10 rad/s	25ºC			• Resistance to Deformation: G*/sind @ 12% Strain • Strain Tolerance: Strain Level at which G* < 90% G* initial • Failure Properties: Strain Level at which G* <50% G* initial

PROPERTY	TEST METHOD		SPEC.	RESULT
Bending Beam Rheometer	-12°C + -18°C	AASHTO T 313		Stiffness + m-value
Performance tests for Chip Seals				
Sweep Test	Modified ASTM D-7000		Report	
Performance tests for Polymer Modified Slurry Seals and Micro-Surfacing				
Recommended Performance Guidelines for Emulsified Asphalt Slurry Seal Surfaces			ISSA A105	ISSA
Recommended Performance Guidelines for Polymer Modified Micro-Surfacing			ISSA A143	ISSA
Tests recommended by Caltrans Slurry/Micro-Surface Mix Design Procedure Project /Contract 65A0151			TBD	

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