POLYMER-MODIFIED ASPHALT MIXTURES FOR HEAVY-DUTY PAVEMENTS: FATIGUE CHARACTERISTICS AS MEASURED BY FLEXURAL BEAM TESTING

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INTRODUCTION

Fatigue damage to asphalt pavements is a complex phenomenon occurring from repeated bending that results in microdamage to the asphalt pavement. This microdamage is a competitive process between microcracking and healing, manifested as a reduction in stiffness of the asphalt pavement, degrading the load capacity and ability to resist further damage. Eventually microcracks coalesce into macrocracks that appear in the wheel path. Incorporation of polymers could potentially result in significant increases in fracture toughness of an asphalt pavement. The purpose of this work is to illustrate the significant differences in fatigue and viscoelastic properties between different commercially-available modifiers.

The work described herein demonstrates the differences in fatigue performance (as measured using AASHTO TP-8) for several PMAs. The additives studied here are a chemically modified experimental crumb rubber product (MCR), SBR (a linear random styrene-butadiene latex polymer), reactive SB (an in-situ crosslinked block copolymer), SBS (a linear styrene-butadiene-styrene block copolymer), and a modified SBS (MSBS). All of the above polymers are proprietary materials. The amount of polymer loadings are 3% and 5%, except for MCR which was only tested at 5% and MSBS for which the polymer amount is considered proprietary.

BACKGROUND

Fatigue is not a widely observed distress on military airfield pavements. Asphalt mixtures for airfield pavements are stiff, dense-graded mixtures and in combination with sound structural design results in a pavement that minimizes flexural strain. Multiple-wheel gear configurations, longer rest periods between traffic, and non-linear behavior under heavy loads are important factors in airfield pavement performance. However, stiff asphalt mixtures are typically low in asphalt content and as such can be susceptible to fatigue if the structural base allows significant deformation or is weakened from saturation or freeze-thaw. The addition of polymer to asphalt binder has the potential to improve permanent deformation, fatigue, thermal cracking, and aging resistance.

The relationships between asphalt chemistry, colloidal structure, and mechanical properties are complex even for asphalts containing no additives [1]. Many asphalt additives are polymers and the interactions with asphalts may result in a complex blends. The polymer may have no interaction with the asphalt (phase separate), partial interaction (swollen polymer domains), or strong interaction (thermodynamic dissolution of polymer). Polymer additives differ in molecular weight, shape (linear, branched, star, etc…), repeat unit, etc… Polymer amount, strain and thermal history may alter the morphological and physical properties of the blend [2]. In particular, the relationship of fatigue properties to asphalt chemistry is not well understood and the incorporation of additives only complicates an analysis [3].

The ability of polymer-modified asphalts to improve asphalt pavement resistance to permanent deformation is well documented [4-6]. In cases where high-quality aggregates are used, polymer modification for the purpose of permanent deformation resistance may not be necessary, at least for some airfield asphalt mixtures [6]. However, modified asphalt mixtures may either degrade or enhance asphalt mixture fatigue life as measured by flexural beam tests [5,7,8]. Although the $G^*\sin\delta$ 'fatigue' binder parameter has demonstrated reasonable correlation with mixture tests, it has not been as successful for some unmodified asphalts [9, 10] and, particularly, modified mixtures [5,7]. Studies by Harvey and Monismith have shown that addition of a modifier to certain asphalts may reduce the number of strain cycles to failure. The same modifier mixed with another asphalt produced opposite results in that the fatigue life increased. These studies indicated that the modifiers had different effects on mix stiffness, fatigue life and the cumulative dissipated energy. Stiffness of unmodified asphalt mixtures and cycles to failure in flexural beam tests has been shown to correlate well with fatigue life. Fatigue life estimates using ‘surrogate’ stiffness of asphalt mixtures were developed for cases in which beam testing was not available. However, with polymer-modified asphalt mixtures, fatigue life models were unreliable [7]. Khattak and Baladi have shown significant effects of modifier type and concentration on fatigue and indirect tensile properties [11].

A detailed study by Bahia *et al*. [5] of modified asphalt systems produced similar results as those by Harvey and Monismith. Poor correlations were found for G*sin δ at 20°C using RTFO-aged (Rolling Thin Film Oven) binder and comparing those values to the number of cycles to failure of modified asphalt mixtures at 20°C. The number of cycles was determined using the flexural beam fatigue test (AASHTO TP-8) with the failure criteria set at 50% of the initial stiffness. However, improved correlations were realized for repetitive load binder tests. In these tests, a ‘time-sweep’ of a repetitive sinusoidal shear load (strain or stress-controlled) is placed on the sample analogous to a mixture fatigue test. The data is interpreted using dissipated energy concepts.

Investigations of microdamage healing have demonstrated that healing is asphalt dependent and may be significantly affected by polymer/asphalt interaction. Addition of low-density polyethylene, SBS, and hydrated lime modifiers reduced the healing ability of the AAM asphalt. Hydrated lime improved the fatigue properties when added to asphalt AAD. AAM and AAD are SHRP ‘core’ asphalts. It was speculated that perhaps the incorporation of polymers in some asphalts selectively adsorbed chemical fractions that resulted in asphaltene-rich domains of low molecular mobility that exhibit poor healing potential [3].

So-called ‘networking’ is the result of entanglement or crosslinking of polymer chains and is manifested as a local minimum for tan δ in mastercurves [12]. Additives that form networks (polymer entanglements) or promote formation of connecting domains would be expected to improve resistance to repetitive strains. It has been shown that some polymer modifiers exhibit classic networking behavior with some asphalts and not others [13].

Fatigue testing of asphalt mixtures has been the focus of numerous studies that have utilized a variety of sample shapes, sizes, and testing apparatus [14,15] An established method of testing asphalt mixtures is the flexural beam fatigue test developed during the SHRP [7,9]. The flexural beam fatigue test provides a measure of the laboratory fatigue life (number of cycles to failure). Beam samples may be prepared by several methods but rolling wheel compaction more closely simulates field compaction. This method of sample preparation and testing has been successfully employed as a performance prediction tool to evaluate the susceptibility of fatigue to both accelerated pavement testing and in-service pavements. [16-20]. Although fatigue has been generally accepted as occurring more often in aged, brittle pavements, studies on aged samples indicate this may be a consequence of accumulated damage and not necessarily related to binder embrittlement [21].

EXPERIMENTAL

Statistical analysis was conducted using SPSS [22]. All significant differences are reported at the 5% level.

Asphalt Binder Testing

Asphalt binder testing was conducted on a Rheologica Viscotec dynamic shear rheometer according to procedures set forth in AASHTO MP1-98 specification for determination of SHRP performance grades [23]. This specification has since been modified, however; at the outset of this work, MP1-98 was the operative standard and, as such, all subsequent binder testing was conducted using this procedure. G*sin δ was measured at 10 rad/sec applied frequency on PAV-aged (Pressure Aging Vessel) samples. All modified asphalt binders containing 3% weight of polymer/weight (w/w) of asphalt and those with 5% w/w MCR and 5% SBS were heated to 175 C prior to hand mixing and pouring. 5% SBR and SB were heated to 180°C. Samples were poured into silicone molds, placed between 8mm plates and heated to 80°C for five minutes to provide good adhesion to the plates. Samples were trimmed at 60°C using a heated trimming tool set at approximately 100°C.

Asphalt Mixture Preparation and Testing

The optimum asphalt content was chosen at 4.7% to achieve 4% air voids based on the Marshall 75 blow mixture design using the aggregate gradation given in Figure 1 with the PG64-22 unmodified asphalt. All subsequent mixtures were prepared at 4.7% asphalt content to allow for a direct comparison of properties between mixtures. The heavy-duty asphalt mixture samples (75 blow Marshall) were tested for response to repeated flexural bending to induce fatigue damage according to AASHTO TP8-93 “Test Method for Determining the Fatigue Life of Compacted Hot-Mix Asphalt Subjected to Repeated Flexural Bending” at 20°C [23]. The fatigue testing was performed on an Industrial Process Controls LTD (IPC) beam fatigue device using an IPC environmental chamber and data collection system. The 5% SB testing was prematurely halted due to a preset software value and the long fatigue life of this binder compared to samples that had been previously tested up to that point.

Sample Preparation by Rolling Wheel Compaction

The asphalt mixture samples produced by design compaction methods should not be directly compared to avoid a comparison of compaction techniques rather than the properties of field pavements. Studies of different methods of mixture compaction have shown that samples produced by the Marshall hammer, the SHRP Gyratory Compactor (SGC), and kneading compactor generally do not produce samples representative to those in the field. Aggregate orientation and air void size and distribution are likely to very different from field-cored samples [25]. These differences from field-cored samples are manifested in measured physical properties and can have serious consequences for interpretation of laboratory data for performance prediction. For the most reliable prediction of field performance based on laboratory specimens, use of rolling wheel compaction has been shown to produce specimens with properties closest to actual field cored samples [26]. This technique has been employed on several projects to provide performance prediction capabilities for shear and fatigue [16-20].

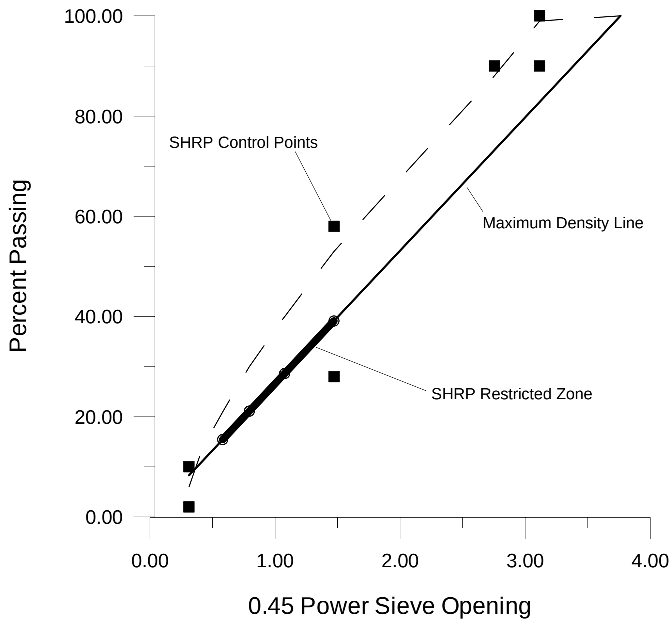

Figure 1. Aggregate blend employed for asphalt mixtures.

Samples for performance-related testing were prepared by means of rolling wheel compaction to simulate field compaction conditions. The procedure was a variation of AASHTO PP3-94 and closely followed compaction methods used at the University of California at Berkeley [23]. Short-term aging of the mixtures was eliminated to reduce possible morphological changes of the PMA during extended heating. A large square steel mold approximately 76 by 622 mm by 622 mm (3 by 24.5 by 24.5 inches) with a slight bevel towards the surface of the mold to facilitate sample removal was constructed. A smaller mold subdividing the volume into three equal sizes approximately 203 by 76 by 610 mm (8 by 3 by 24 inches) was prepared. The surface of the mold was pretreated with a release agent and heated for at least one hour prior to sample placement. Approximately 21 kg (46.1 lbs) of asphalt-aggregate mixture at optimum asphalt content was placed in the mold to achieve a target air void content of between 4.5 and 6%. A small 600kg steel wheel roller operating in static mode with multiple passes was immediately employed to compact the material until flush with the surface of the mold. The finished ingots were allowed to completely cool before removal from the mold. Samples for testing were sawed from the ingot. Mixing and compaction temperatures were according to the particular modifier manufacturer's recommendation.

RESULTS AND DISCUSSION

Asphalt Binders

The SHRP grades of the asphalt binders are listed in Table 1. The grades are given for both the BBR-based (Bending Beam Rheometer) ranking and the DTT (Direct Tension Test). The low temperature SHRP grade differs depending on whether the BBR or DTT is used to determine the ranking. Also, in several cases the RTFO (Rolling Thin-Film Oven Test) value for G*/sin δ controlled the high temperature limit.

The results for the G*sin δ parameter at 19°C for each of the PAV-aged binders are presented in Figure 2. The data were collected as part of the normal procedures for SHRP performance grading. For each additive, G*sin δ was significantly lower than the unmodified asphalt. Analysis of Variance (ANOVA) of the means followed by Tukey's HSD (honest significant difference) classification indicates that all of the modifiers are significantly different from the unmodified asphalt. Several of the modifier G*sin δ are significantly different from one another. In Figure 1, values of G*sin δ having similar means are given classes A-G indicating significant difference in overlap of means.

Table 1.
SHRP binder grades for unmodified and modified asphalts by BBR and DTT.

Binder Type	SHRP PG-BBR	SHRP PG -DTT	Notes
Unmodified	64-22	64-22	
3% MCR	64-22	64-22	
5% MCR	64-22	64-22	
3% SBR	58-22	58-22	Failed RTFO at 64°C
5% SBR	64-22	64-28	Failed RTFO at 70°C
3% SB	64-22	64-22	
5% SB	64-22	64-28	Failed RTFO at 70°C
3% SBS	64-22	64-22	
5% SBS	64-22	64-28	Failed RTFO at 70°C
MSBS	70-22	70-28	

Binders with SB and MSBS exhibit the lowest values of G*sin δ with the unmodified asphalt exhibiting the highest value for G*sin δ. All of the modifiers reduced G*sin δ to some extent. 3 and 5% SB, and MSBS had the lowest values for G*sin δ followed by 5% SBS. 5% MCR and 5% SBR were not significantly different from one another but had greater G*sin δ than 5% SBS. 5% MCR and 3% MCR were not significantly different from one another. 5% SBR exhibited higher G*sin δ than 3% MCR but not 5% MCR. 3% SBR had higher G*sin δ than 5% SBR but not 3% MCR. 3% SBS had higher G*sin δ than 3% SBR and 3% MCR but lower G*sin δ than the unmodified asphalt.

Asphalt Mixtures

ANOVA of the means and subsequent classification by Tukey's HSD indicate significant differences for modulus, phase angle, cycles to failure (defined as 50% of initial stiffness), and cumulative dissipated energy. Cycles to failure, N_{50}, have been previously utilized as an important determinator of fatigue life, especially when used as a function of strain. The tabulated data for cycles to failure and initial flexural modulus are presented in Table 2.

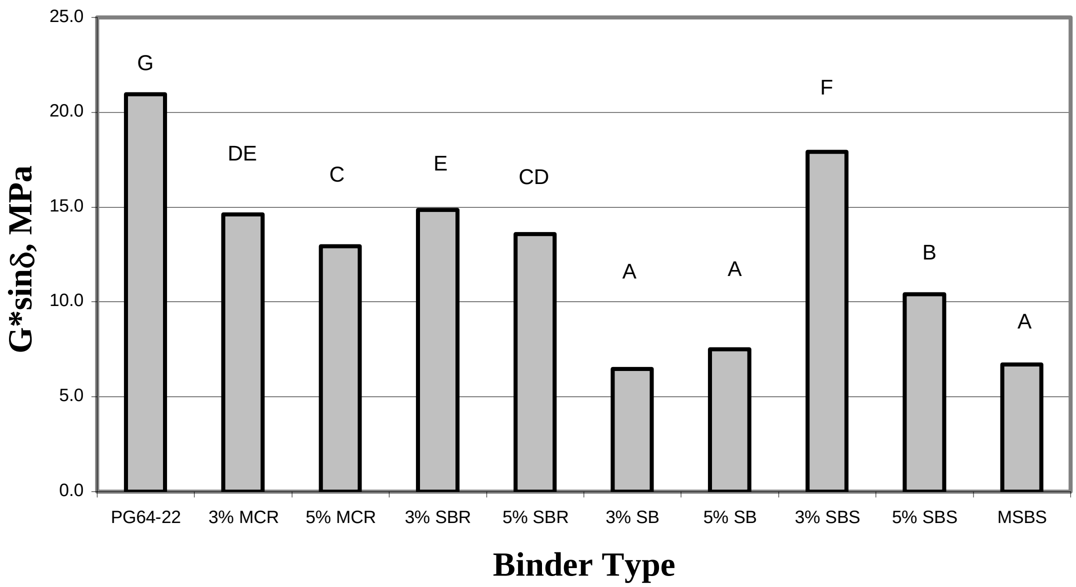

Figure 2. Values for G*sin δ for modified asphalts.

Table 2.
Fatigue Results for Polymer-Modified Asphalt Concrete.

Sample	Air Voids, %	Cycles to Failure	Initial Flexural Modulus, MPa
A – PG64-22	5.8	31,995 ± 5,091	3,580 ± 290
B – 3% MCR	4.8	38,690 ± 13,214	4,248 ± 480
C – 3% SBR	5.3	60,457 ± 30,912	3,731 ± 312
D – 3% SB	5.3	429,560 ± 63,689[a]	3,613 ± 631
E – 3% SBS	5.6	42,283 ± 10,001	4,176 ± 175
F – 5% MCR	5.9	31,040 ± 12,007	3,114 ± 608
G – 5% SBR	5.0	88,380 ± 8,156[a]	3,620 ± 431
H – 5% SB	5.1	3,737,890 ± 3,260,260	2,131 ± 123
I – 5% SBS	5.0	41,990 ± 19,233	4,114 ± 446

[a] Three samples

In Figures 3 and 4, the mixture flexural modulus and phase angle are presented, respectively. 5% MCR and 5% SB reduced the modulus, SBR had no effect, and SBS and MSBS increased the modulus. The modified mixture with MSBS exhibited the highest modulus values. The effect on the phase angle was as follows: the SB modifier increased the phase angle the most with 3% MCR having a significantly higher phase angle than the unmodified mixture. 5% SBR, 3 and 5% SBS, and MSBS were significantly different from the SB modifier but not from the unmodified control.

Values for N_{50} (50% of initial stiffness), cycles to failure at 20°C, for each of the modified asphalts with limestone aggregate are presented in Figure 5. The N_{50} nomenclature is adopted from Bahia *et* a*l*. [5]. Values ranged from approximately 30,000 cycles for the unmodified asphalt to over 3,500,000 cycles for the SB mixture. The variances were large for some mixtures. It is helpful to note that overall the N_{50} testing resulted in coefficient of variation of approximately 40%. This similar to other reported values for error for rolling wheel compacted samples [7].

For N_{50}, SB > MSBS > SBR, SBS, MCR, PG64-22 in terms of modifier effect. These rankings have poor correlation with modulus, as has been previously observed for modified asphalts [5,7]. The phase angle for the modified asphalts, although related to the ability of the binder to dissipate strain energy, also has poor correlation with N_{50}. The MSBS mixture had a low phase angle and the SB mixtures had high phase angle, yet both displayed significantly higher N_{50}.

The mechanism for the increases in fatigue life is likely to be related to several factors such as polymer crosslinking and chain entanglement, the rate of microdamage healing induced by polymer chain mobility or polymer/asphalt interactions, adhesion of binder to aggregates, and changes to the mechanisms of crack pinning, etc., during fracture. One can imagine that a crack can easily be interrupted when encountering a distinct polymer domain [27].

The formation of continuous colloidal structures, crosslinking, and/or and entanglement of polymer chains would contribute to the resistance of the asphalt binder to fracture (fracture toughening). This is consistent with the observations of increasing N_{50} for 5% SBR over 3% SBR, and is similar for SB. However, an increase in N_{50} was not observed for the SBS modified mixtures. Previous rheological studies of SB and SBR binder exhibit an overall flattening of tan δ (Figure 1, reference [13]). This behavior of tan δ is not consistent with crosslinking or entanglement of polymer chains [12].

The increases in N_{50} for the PMAs could be a result of increases in the rate of microdamage healing. The SBR, SBS, and SB polymers all have considerable molecular mobility with portions of the polymer chains having low glass transition temperatures, T_g, (in relation to the temperature at which the fatigue tests were conducted). An increase in polymer content may have a significant effect on the rate of microdamage healing, dependent upon polymer chain mobility and asphalt/polymer interactions (3). In most cases, assuming no complex interactions of asphalt and polymer, addition of a polymer with a lower T_g than the base asphalt would be expected to increase molecular mobility. The bulk modulus should also decrease. The changes in fatigue life for the SB polymers are consistent with this mechanism as lower flexural moduli are observed at the 5% SB level.

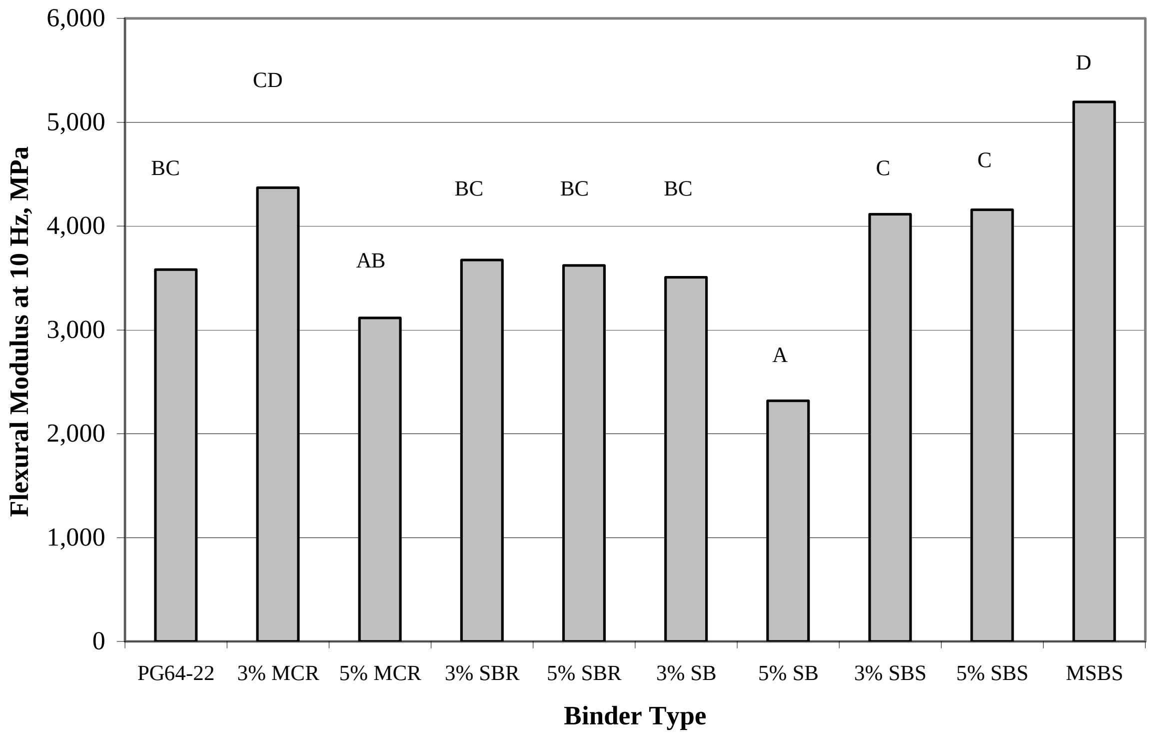

Figure 3. Flexural modulus of modified mixtures at 20°C and 450 microstrain.

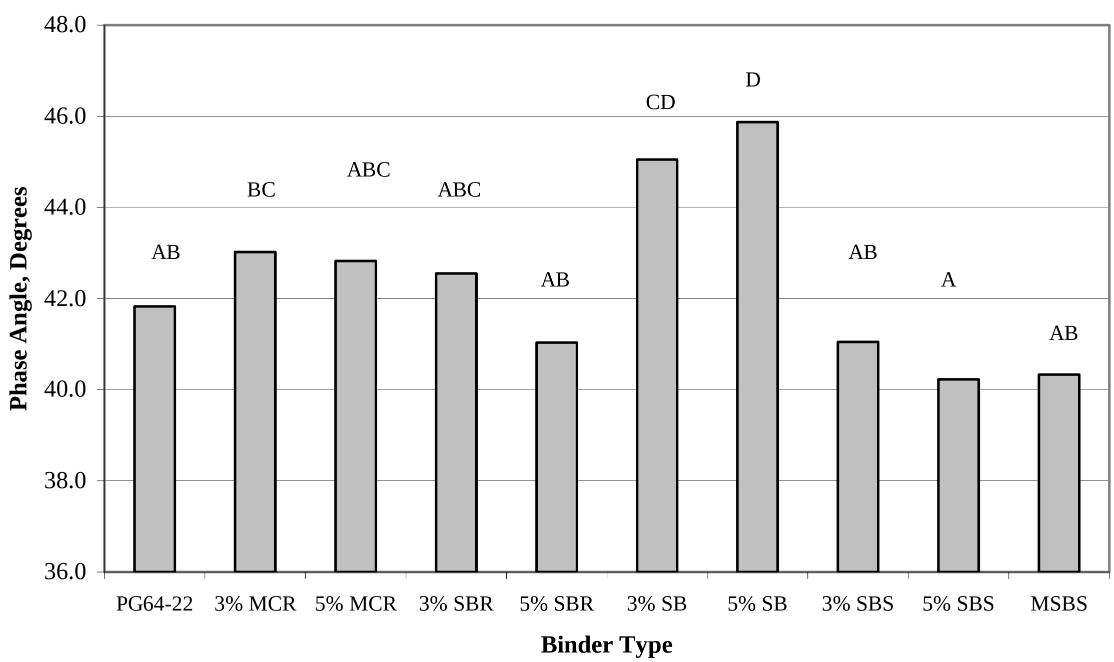

Figure 4. Phase angle of modified mixtures at 20°C and 450 microstrain.

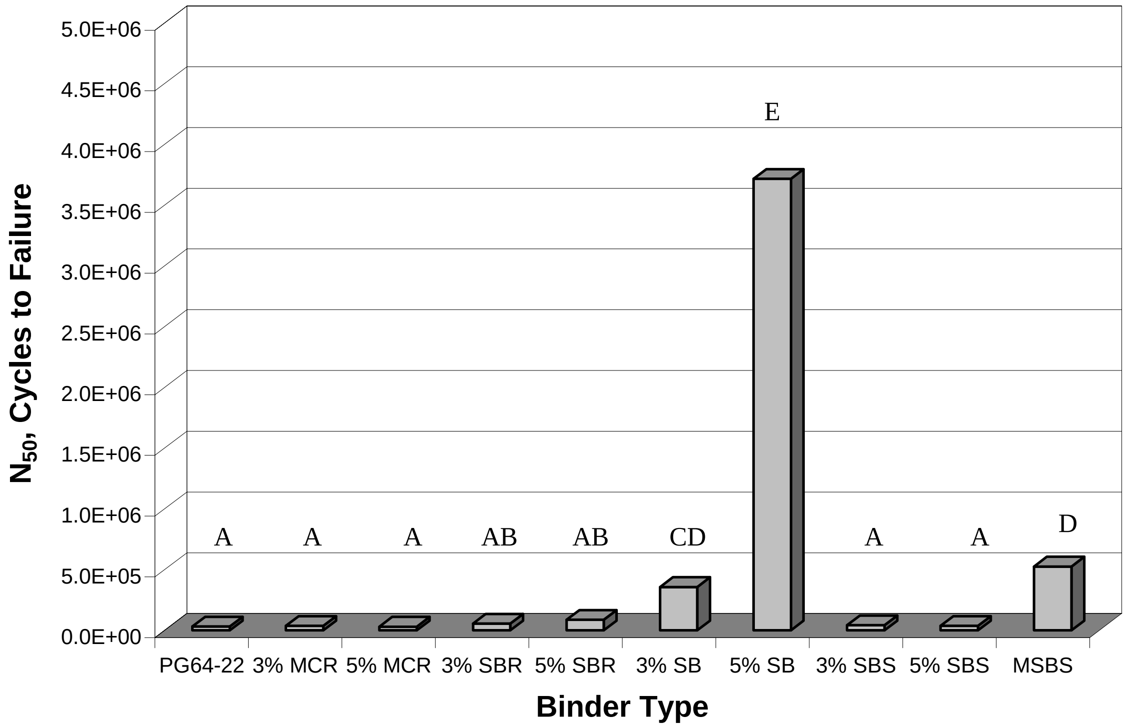

Figure 5. Cycles to failure, N_{50}, of modified mixtures at 20°C and 450 microstrain.

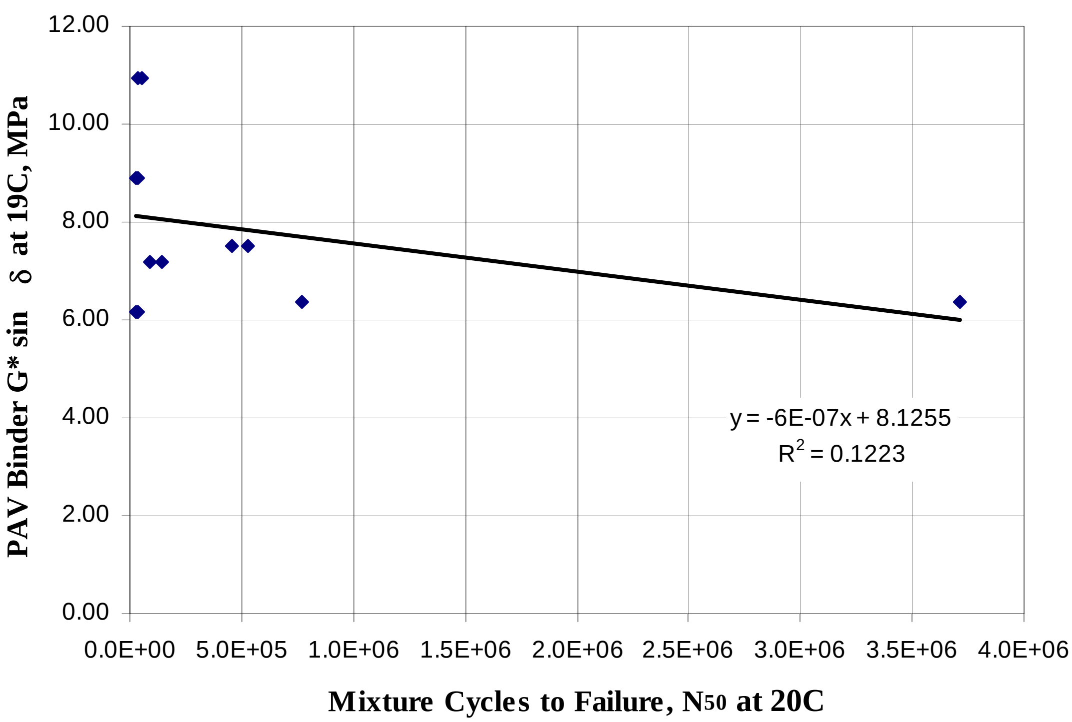

Figure 6. Comparison of G*sin δ and N_{50} for binders and modified mixtures, respectively.

Similar to Bahia *et al*. [5], the values for G*sin δ (at 19°C) were compared to N_{50} at 20°C (Figure 6). The correlation for G*sin δ and N_{50} yielded an $R^2 = 0.12$. This is much lower than observed by Bahia [5] and I to those from the original SHRP fatigue studies for unmodified asphalts [7]. However, an important difference from the work done by Bahia is the temperatures at which the testing was conducted. Testing the validity of the G*sin δ value was incumbent upon conducting the experiments at an equivalent G*sin δ. Fatigue testing at constant temperatures and constant strain reflects the effects of modulus to a much greater degree. Obviously, the G*sin δ parameter is not a useful indicator of fatigue for polymer-modified asphalts.

CONCLUSIONS

The choice of a polymer modifier for a particular project can depend on many factors including cost, construction ability, availability, and expected performance. The expected performance is difficult to quantify and needs to be done on a case-by-case basis. Bahia *et al*. [5] has demonstrated that for many modified asphalt binders, mixture testing must be performed to provide a reasonable expectation of performance.

The fatigue properties of the asphalt mixtures presented in this work demonstrate that the choice of a modifier may have significant bearing on the ultimate performance of the mixture in the field under repetitive traffic. Although typically not a widely observed distress for military airfields, fatigue damage nevertheless occurs and should be minimized, especially for airfield critical to mobilization.

For the particular asphalt used in this study, SB, SBR at higher loadings, and MSBS significantly affect the number of cycles to failure and would be expected to provide an increased level of protection against cracking due to repetitive loads.

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