Critical Evaluation of Asphalt Modification Using Strategic Highway Research Program Concepts

HUSSAIN U. BAHIA

With the introduction of the Strategic Highway Research Program (SHRP) binder tests an evaluation of how different additives affect the critical properties of binders was conducted. Testing done as a part of several projects involved asphalt binders modified with three different types of additives: crumb rubber, polymeric additives, and mineral fillers. The testing included rheological and failure characterization at a number of different temperatures. The temperatures were selected to cover those in the climatic regions encountered in the United States and Canada. The measurements included high- and intermediate-temperature measurements with the dynamic shear rheometer at several temperatures, low-temperature creep with the bending beam rheometer, and low-temperature failure strains by the direct tension test. The need for asphalt modification is discussed, a summary of the results of that testing program is presented. The present work includes information on how these modifiers affect the rheological and failure properties at ranges of temperatures and loading frequencies that simulate application conditions. The changes in the performance-related parameters used in the SHRP specifications as a result of these modifications are also discussed. The results indicate that the proposed specification parameters are sensitive to the effects of the modifiers and that different additives can be used to alter the performance-related properties of asphalts. The results also indicate that major improvements in properties can be achieved with certain modifiers and that these improvements in properties are generally achieved at relatively high temperatures.

During the last two decades the paving industry has seen a continuous increase in the use of asphalt modifiers. Many of these modifiers have resulted in the enhanced contribution of asphalt binders to the superior performance of pavements (*1–4*). The selection of modifiers has mainly been done by conventional testing methods to meet the requirements focused around viscosity or penetration grading systems. As a result of the Strategic Highway Research Program (SHRP) a new set of testing techniques and a new grading system have been introduced (*5*). The testing and grading systems are based on measuring fundamental properties that are related in a more rational way to pavement performance.

The purpose of this paper is to discuss the need for asphalt modification, to discuss the main modification targets for paving asphalts, and to show how selected modifiers that are currently used alter the critical properties of asphalt binders. The paper includes results collected during several testing programs conducted to evaluate the roles of different modifiers in changing the rheological and failure properties of asphalt binders.

ASPHALT PRODUCTION AND NEED FOR MODIFICATION

The main source of asphalt for paving applications is crude petroleum of the type with a high specific gravity. Depending on the type of refining process and the source of crude petroleum, the asphalt yield from crude petroleums can vary between 10 and 60 percent (*6*). The chemical composition of an asphalt and, as a consequence, its properties is largely dependent on the crude petroleum's nature and source.

Asphalt production, however, is not one of the main profit-generating processes in the refining industry. Most refineries in the United States deal with asphalt as a by-product of crude fractionation. The production of better-performing asphalts is not considered one of the common strategies in planning refining practices. These facts have left pavement engineers throughout the years with the challenge of selecting the suitable asphalt for their specific application conditions including climate, traffic, and pavement structure. When the asphalt that is produced does not meet the requirements, modification of the asphalt with additives has served as one of the cost-effective engineering solutions. Modification of asphalts has increased steadily within the last decade because modification provides the versatile properties needed to build better-performing roads. Asphalt modification is expected to increase in the future because of the economic barriers involved with improving asphalts through refining processes and because of the logistical difficulties of using crudes that naturally produce better-performing asphalts.

NATURE OF ASPHALT VISCOELASTIC PROPERTIES

At any combination of time and temperature viscoelastic behavior within the linear range is best characterized by two properties: (a) the total resistance to deformation and (b) the relative distribution of that resistance between an elastic part and a viscous part. By using the dynamic (oscillatory) shear loading mode, these properties can be represented by the complex modulus (G^*) and the phase angle (δ). G^* represents the total resistance to deformation under a load, whereas δ represents the relative distribution of this total response between an in-phase component and an out-of-phase component.

The rheological properties of asphalt are very sensitive to temperature and time of loading. Within the range of pavement application (temperature range of −40°C to 80°C and loading rate of static to 100 rad/sec), a typical asphalt changes its modulus by more than 7 orders of magnitude. It changes its phase angle by approximately 90 degrees.

Department of Civil and Environmental Engineering, The University of Wisconsin-Madison, Wis. 53706.

In addition to the prefailure properties of asphalts as measured by rheology, asphalt failure properties need to be characterized. The failure behavior of asphalts is also highly dependent on temperature and time of loading. They are brittle at low temperatures, with a plateau zone showing a strain at failure that is relatively small (limiting value of approximately 1.0 percent strain). As the temperature increases a transition from brittle to ductile failure can be observed; at high temperatures this converts into a flow zone. The most critical part of this behavior for pavement applications is the temperature and loading rate at which the transition from the brittle to the ductile behavior occurs. For many unmodified asphalts there is some correlation between the stiffness measured at small strains (rheological prefailure properties) and this transition. The correlation, however, may not hold for modified asphalts or specially produced asphalts. (*7*).

ASPHALT MODIFICATION STRATEGIES AND TARGETS

For the successful modification of asphalt binders the binders should be engineered to improve one or more of the basic properties of asphalt related to one or more pavement distress modes. These properties can be classified into four main types. For each type SHRP has introduced certain response parameters that can be measured.

- Rigidity: total resistance to deformation that can be measured by complex moduli such as G^* under dynamic loading or by creep stiffness, $S(t)$, under quasistatic loading. Higher rigidity is favorable at high temperatures or low loading rates to resist rutting, whereas lower rigidity is favorable at intermediate and low temperatures to resist fatigue and thermal cracking, respectively.
- Elasticity: recovery of deformation by using the stored energy applied. It can be determined by measuring either the phase angle (δ) or the logarithmic creep rate (m). To resist rutting and fatigue damage more elasticity is favorable. To resist thermal cracking less elasticity and a greater ability to relax stress by flow are favorable.
- Brittleness: failure at low strains, which is the best definition of brittleness. To improve resistance to fatigue and thermal cracking, brittleness should be reduced by enhancing strain tolerance or ductility.
- Durability: oxidative aging, physical hardening, and volatilization, which are key durability properties. Resistance to all of these changes is favorable.

A modifier can be selected to improve one or more of these main properties. Also, different modifiers that affect different properties can be combined to improve several properties. The new test methods introduced by SHRP offer the capability of measuring each of these properties under conditions that simulate the loading and climatic conditions encountered in the field.

MATERIALS AND EXPERIMENTAL DESIGN

For the present study three types of modifiers were used: polymer, crumb rubber, and mineral fillers. Polymer modifiers included styrene-butadiene (SB)-based modifiers and polyethylene-based modifiers (PE1 to PE5). Crumb rubber modifiers (CRM) included ambient shredded crumb rubber (RB3), cryogenic grinded crumb rubber (RB2), and a crumb rubber–plastic composite (RB1). All crumb rubbers were produced from whole tire stock with a maximum particle size of 1.0 mm. Mineral fillers included manufactured quartz and natural calcite with a maximum particle size of 75 µm. The polymer modifiers were preblended by manufacturers at concentrations varying between 3 and 6 percent. The crumb rubber modifiers were mixed at 15 percent by weight of binder in the laboratory by using a blender at 160°C for 1 hr. The mineral fillers were mixed by using the same technique used for the crumb rubber. The mix proportions were kept at a ratio of 0.50 filler to asphalt by volume.

Testing of the base and modified binders included full characterization by the dynamic shear rheometer at different temperatures and frequencies. The binders were characterized by running frequency sweeps of 1 to 100 rad/sec at temperatures ranging between −30°C and 60°C. The testing geometry deviated from the standard geometry later selected for testing neat asphalts. For parallel plate geometry a 2.0−mm gap was used for all binders at high and intermediate temperatures. At temperatures below 5°C torsion bar geometry was used to cover the range of high moduli measured for the different binders.

In addition to the dynamic shear rheometer, the bending beam rheometer was used to measure creep properties at several low temperatures. Also, the direct tension test device was used to measure failure properties at low temperatures. Oxidative aging was done by using the thin film oven test (AASHTO T179) and the pressure aging vessel. No changes were made in the standard procedures for the creep, failure, and aging tests except for taking extra care to prepare specimens and to ensure the uniform dispersion of the additives. Selected data were used in this paper to present the important points observed during the study.

EFFECT OF MODIFICATION ON RHEOLOGY OF ASPHALT

Data collected by using the dynamic shear rheometer were used to develop and compare the master rheological curves of the modified binders with their base asphalts. The following discussion is divided into sections according to the type of modifier or additive used.

Polymer Modification

Figure 1 depicts the master rheological curves measured by using a dynamic shear rheometer for an asphalt before and after modification with the SB polymer at two different concentrations (c = 3 percent and $2c$ = 6 percent). Changes in both G^* and δ as a function of temperature are shown. The effects of this modifier show favorable trends of change. At high temperatures G^* is higher, whereas δ is lower. This indicates increases in rigidity and elasticity, which results in better resistance to permanent deformation. At intermediate temperatures (0°C to 30°C) lower values of G^* can be observed, whereas δ values remain indifferent. The reduction in G^* values is favorable for fatigue cracking under strain-controlled conditions, which are typical of conditions for thin pavements. At low temperatures (−20°C to 0.0°C) a more pronounced reduction is observed for G^* and a minor increase in δ is seen. Both of these effects are favorable since they make the binder less rigid and less elastic or more prone to stress relaxation under a load. The changes shown appear to improve the properties with respect to pavement performance at all temperatures. Considering the relative changes in G^*

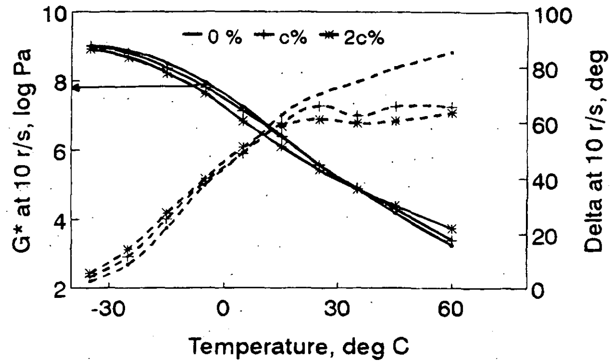

FIGURE 1 Isochronal rheological curves for an asphalt before and after SB modification.

and δ, it is evident that the main effect is the change in the rigidity of the binder as determined by measuring *G**. The data presented in Figure 1 indicate that although the *G** value is increased by 100 to 200 percent at 60°C, the δ value is reduced by approximately 16 to 30 percent. At low temperatures the same trend can be observed; the *G** value is reduced by 40 to 50 percent, whereas the δ value is increased by only few degrees. Similar trends of change were observed for the other types of polymers that were used in the study. Considering the fact that energy dissipation and the rate of relaxation of binders are functions of sin δ or tan δ, it appears that the effects of these commonly used polymeric additives on binders at small strains or stresses are mainly caused by changes in rigidity, whereas only secondary effects are caused by changes in elasticity.

CRM Modification

Figure 2 depicts master rheological curves for an asphalt before and after modification with a CRM at a 15 percent weight concentration. The data in Figure 2 are presented in terms of loading frequency rather than temperature. As discussed earlier frequency and temperature are interchangeable; the effect of high temperature corresponds to that of low frequencies and vice versa. Changes in master curves are similar to the changes observed for polymer modification shown in Figure 1. *G** values increase at low frequencies (high temperatures), whereas they decrease at intermediate and high frequencies (intermediate and low temperatures). The δ values are lower at low frequencies but higher at high frequencies. The relative changes in either parameter are of the same order of magnitude as those for the polymer modification. The effects of CRM can therefore also be described mainly as changes in the rigidity of the asphalt.

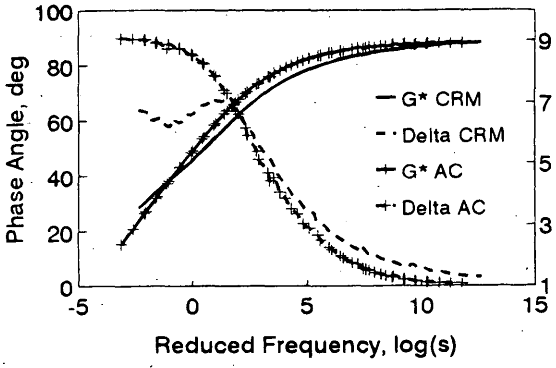

FIGURE 2 Master rheological curve for an asphalt before and after CRM modification (15 percent CRM).

The mechanism by which CRM changes properties is, however, different. Although the polymer is dispersed in the asphalt and causes changes in the molecular structure of the asphalt, CRM is observed to keep its physical identity and to behave as a flexible particulate filler in the asphalt. The overall effect of CRM on the master rheological curve is a reduction of the dependencies of *G** and δ on frequency. This effect is similar in nature to the effect of polymer modification, despite the difference in the nature of the material. Polymer modification usually results in a more homogeneous binder that is more favorable than the nonhomogeneous CRM modification. The trade-off, however, is the relatively higher cost of the polymer modifiers compared with the cost of CRM.

Mineral Fillers

Figure 3 depicts master rheological curves for an asphalt before and after the addition of two mineral fillers. Unlike the previous modifiers the effect of mineral fillers results in increasing the *G** value and decreasing the δ value at all frequencies (temperatures). This distinct change is expected because of the rigid nature of the mineral fillers. Although some polymers and CRMs have moduli that are lower than those of typical asphalts at low or intermediate temperatures, mineral fillers have moduli that are much higher than those of asphalts. This is true even at very low temperatures where asphalts reach their glassy modulus. Furthermore, since mineral fillers lack the viscoelastic nature, they do not impart any significant changes in δ. The upward shift in the *G** curves seen in Figure 3 is simply the effect of the addition of these rigid particles that increases the moduli at all temperatures. The increase is larger at high temperatures (low frequencies), at which the asphalt moduli are lower. The effect at low temperatures (high frequencies) is not favorable since it indicates an increase in modulus and a decrease in the ability of relaxing stresses. At high temperatures the effect is favorable and, for the fillers shown, much more pronounced than the effect for the modifiers considered earlier.

One of the similarities between the effects of fillers and the other modifiers is the reduction in the dependency of *G** and δ on

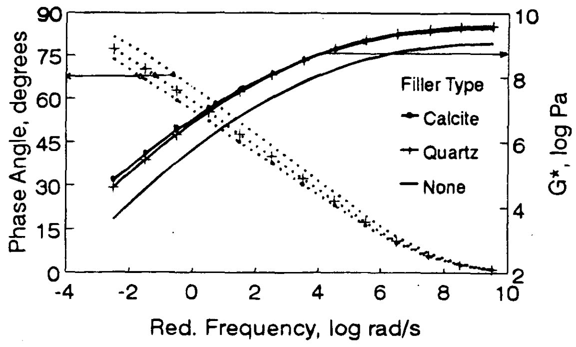

FIGURE 3 Master rheological curves for an asphalt before and after addition of mineral.

temperature or loading frequency. Also, it is evident that the rheological behaviors of binders with fillers as well as the two other modifiers remain relatively simple in nature: At low temperatures a glassy modulus asymptote is reached, at which the response is mainly elastic, and at high temperatures a viscous asymptote is reached, at which behavior is mainly if not completely viscous.

EFFECTS OF MODIFICATION ON FAILURE PROPERTIES

By using the direct tension test developed by SHRP the binders modified with the different additives were tested at temperatures ranging between −30°C and 0.0°C. The tests were conducted at a deformation rate of 1.0 mm/min in three replicates, and the stress and strain at failure were calculated. To evaluate the effects of the modifiers the failure stress and failure strain values of the base and the modified binders are compared.

Polymer Modification

Figure 4 shows strain-at-failure and stress-at-failure plots as a function of temperature for an asphalt before and after modification with 3 and 6 percent SB-based polymer. The strain curves show that the polymer increases the strain at failure within the brittle and the brittle–ductile zone but converge to the same values as the flow zone is approached. The effect can be considered to be shifting the strain-at-failure curve horizontally to lower temperatures without significantly changing the shape of the curve. The effect of polymer addition is favorable because it tends to increase the strain at failure within the critical region. The results also indicate that the effect is more favorable with higher concentrations of the polymer. The stress-at-failure curves are similar for all binders, which indicates that use of the polymer does not result in significant changes in the strengths of the binders.

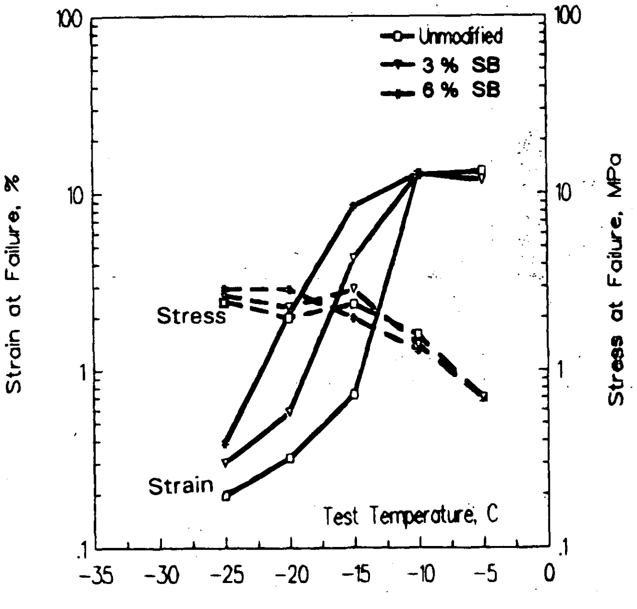

FIGURE 4 Failure strain isochronal curves for an asphalt before and after SB modification.

The results shown in Figure 4 may not apply to all types of polymer modifiers. The effects of different polymers on failure properties are expected to depend largely on the type of interaction between the asphalt and the polymer, on the molecular nature of the polymer additives, and on the way the polymer is dispersed in the asphalt. The effects of polymers on failure properties can be hypothesized in different ways. One hypothesis is that polymers form some kind of molecular network inside the asphalts, resulting in more strain-tolerant material. Another hypothesis is that the dispersed polymer particulates may serve as reinforcements, arresting microcrack propagation and increasing the toughness of the binders. The typical trend observed from a review of polymer modification work, however, is that not many of the currently used polymers improve low-temperature failure properties. This may be attributed to the fact that there has been no simple technique that can be used to measure the brittle failure of asphalt. It can also be attributed to the fact that none of the binder specifications that are now used addresses the brittleness of asphalt in a rational and fundamental form. These issues did not encourage many polymer modifier producers to concentrate on designing a modifier to mainly enhance low-temperature failure properties.

CRM Modification

Figure 5 depicts failure plots for an asphalt before and after modification with crumb rubber at concentrations of 10 percent (CRM1) and 20 percent (CRM2) by weight of total binder. The effect of the CRM modification is similar to that of the polymer modification with respect to the strain-at-failure values; higher strains are observed at low temperatures, but similar strains are observed as the flow region is reached by the binders. The effect also represents a shift of the failure curve along the temperature scale toward lower temperatures. The shift is larger for the higher CRM content. The stress-at-failure curves for the CRM modification, however, show a trend different from that for the polymer modification. The CRM

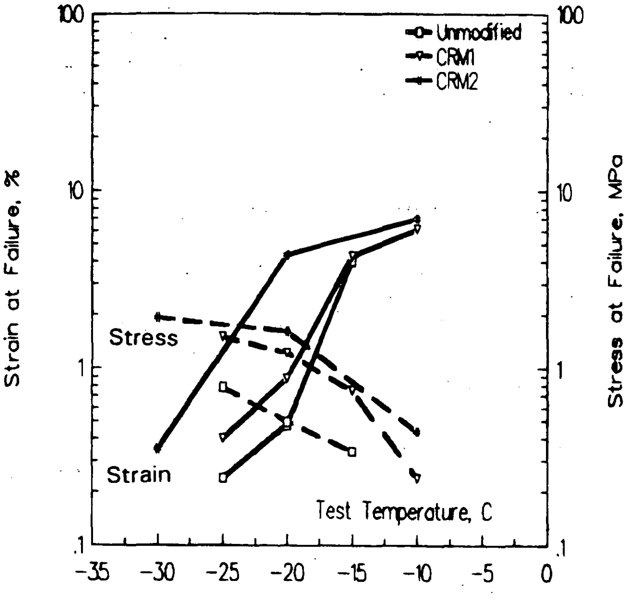

FIGURE 5 Failure strain isochronal curves for an asphalt before and after CRM modification.

modification results in stress values that are significantly higher than those for unmodified asphalt at all temperatures. This behavior can be attributed to the reinforcing effect of the rubber particles. The crumb rubber particles do not dissolve in asphalt; the particles maintain their integrity and tend to swell in asphalts, resulting in effective volumes that are larger than their initial volume (*8–10*). It is speculated that the swelling results in the selective absorption or adsorption of certain components of the asphalt. Such interactions are expected to reinforce the matrix of the binder and result in higher strength, as observed in Figure 5. The increases in strain and stress at failure are favorable for paving-grade asphalts, particularly when they are accompanied by a reduction in stiffness, as shown in Figure 2.

Mineral Fillers

Limited data were collected for the failure properties of asphalts modified with mineral fillers. The data, discussed in a later section, show significant increases in strain at failure at all temperatures. The data also show equal or higher stress-at-failure values. Although the fillers may be considered less reactive with asphalt than the other additives, their presence appears to result in an important reinforcing effect. From a fracture mechanics consideration the fillers may serve to arrest cracks or result in longer crack paths. From the limited data that have been collected, however, it appears that the improvements are highly dependent on asphalt type and test temperature. Because of the different natures of mineral fillers, their effects continue to be important even within the ductile flow region. The rigid filler particles are expected to enhance resistance to flow within the ductile region and to increase the peak stress and strain under these conditions.

EFFECT OF MODIFICATION ON SHRP GRADING PARAMETERS

The research efforts of the SHRP binder program have resulted in the introduction of several response parameters that are indicators of the contribution of binders to pavement performance. Three failure modes were identified as critical pavement distress modes in which the binder plays an important role: rutting, fatigue cracking, and thermal cracking (*11*).

Effect of Polymers on SHRP Parameters

Figure 6 depicts the ratios of the SHRP parameters. The ratios represent the relative changes in parameters for an asphalt after modification with the SB-based polymer at three concentrations. The data in Figure 6 indicate that there is a favorable trend in the changes of all performance parameters: $G^*/\sin\delta$ ratios range between 1.2 and 3.4, indicating a favorable increase in the value of the parameter. $G^*/\sin\delta$ ratios range between 0.1 and 0.5, and $S(60)$ ratios range between 0.25 and 0.5, indicating favorable decreases in both of these parameters. The ratios for $m(60)$ range between 1.1 and 1.2, which is a limited but favorable increase. For this class of polymers the modification is also extended to the strain at failure, which has ratios of between 3.4 and 6.0.

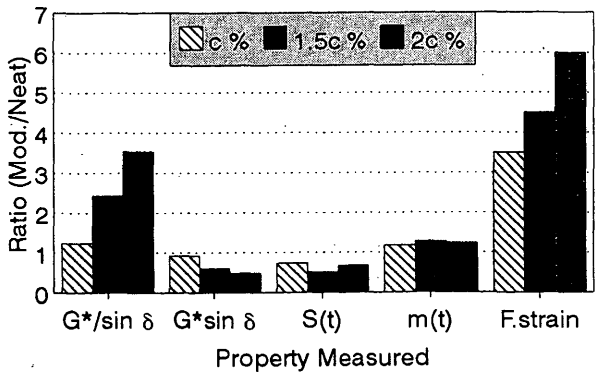

FIGURE 6 Relative change in SHRP performance-related parameters after modification with SB-based modifiers ($c = 3$ percent).

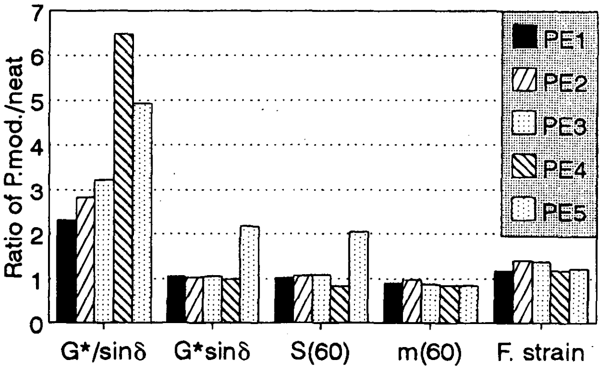

FIGURE 7 Relative change in SHRP performance-related parameters after modification with polyethylene-based modifiers.

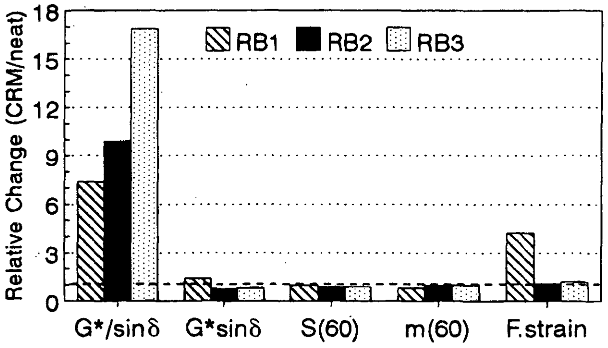

FIGURE 8 Relative change in SHRP performance-related parameters after modification with CRM.

Figure 7 depicts the ratios of SHRP parameters for five types of polyethylene-based polymers (PE1 to PE5). At the high temperatures the $G^*/\sin\delta$ ratios show favorable values ranging between 2.2 and 6.3. At intermediate and low temperatures, however, the ratios of $G^*\sin\delta$, $S(60)$, and $m(60)$ do not show significant changes, and for some of these polymers an unfavorable change can even be seen. The strain at failure also shows only minor changes.

The data shown in Figures 7 and 8 indicate that polymer modification can have major effects on the rutting parameter at high temperatures. The changes in the parameters related to fatigue cracking and thermal cracking are, however, relatively small except for the strain at failure for the SB-based modifier. The effects on strain at failure should not be exaggerated; Figures 4 and 5 indicate that strain at failure is very sensitive to temperature, and the transition from brittle to ductile failure occurs over a narrow temperature range. Thus, a minor shift in the strain curve as a result of modification may show very high strain ratios. The conclusion that can be drawn here is that the polymer modification appears to be very effective at high temperatures but may have limited effects at intermediate and low temperatures. The trend observed in the present study agrees with previous experience reported for polymers (*12,13*).

Effect of Crumb Rubber on SHRP Parameters

Figure 8 depicts bar charts for the CRMs used in the study similar to those in Figure 7 for polyethylene based polymers. The difference between the CRMs used is the process by which they are manufactured. The parameters' ratios show the same trend as the polymer modification (Figures 6 and 7), but they differ in magnitude. The ratios for the rutting parameter ($G^*/\sin\delta$) are higher than those for the polymer modification, whereas the ratios for the fatigue parameter ($G^* \sin\delta$) are lower. $S(60)$ ratios are also lower, whereas the ratios of $m(60)$ and strain at failure are very close to 1.0 (no change). The data in Figure 8 indicate that, similar to polymer modification, crumb rubber modification shows its main effects at high temperatures. This is expected because of the nature of the CRMs. Crumb rubber acts mainly as a flexible filler. At high temperatures it is stiffer than the asphalt and thus contributes significantly to the increased moduli. With decreasing temperatures the asphalt becomes stiffer, whereas the properties of the crumb rubber do not change significantly. At a certain temperature the asphalt may become stiffer than the crumb rubber, and thus, a reduction in stiffness can be observed for the modified binder. Crumb rubber at moderate concentrations that are used in practice (10 to 20 percent), however, cannot reduce the stiffness by large margins because of its own relatively high stiffness at low temperatures. It is therefore expected that the main effects of crumb rubber remain to be seen at higher temperatures and to affect mainly the rutting parameter.

Effect of Mineral Fillers on SHRP Parameters

Figure 9 depicts ratios for two asphalts after modification with two types of fillers. Ratios of $G^*/\sin\delta$ range between 6.5 and 12 for a filler volume concentration of 50 percent. The increases in $G^*/\sin\delta$ are favorable and indicate that the addition of mineral fillers can increase the contribution of binder to resistance to pavement rutting. The ratios of $G^* \sin\delta$, however, do not show a favorable trend; ratios of 3.1 to 4.7 are shown, which indicate that fillers can be detrimental with respect to fatigue damage under strain-controlled loading conditions. The effects are even more detrimental with respect to low-temperature properties; $S(60)$ ratios range between 4.5 and 6.7, and $m(60)$ ratios are all less than 1.0. Strain ratios show some improvements for certain combinations, but a value of 0.3 is shown for one of the modified binders. As mentioned earlier fillers are not expected to modify intermediate- and low-temperature properties, for which a softer binder is more favorable. Mineral fillers are rigid particles with stiffness values that far exceed those of conventional asphalt cements, even at very low temperatures. They are therefore expected to always result in stiffer binders that may not meet the needs for paving applications.

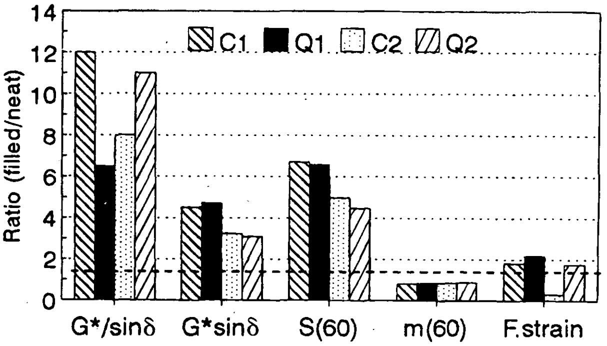

FIGURE 9 Relative change in SHRP performance-related parameters after addition of mineral fillers.

SUMMARY OF FINDINGS

In the present study the effects of polymeric additives, crumb rubber additives, and mineral fillers on the performance-related properties of asphalt cements have been analyzed by using data collected for a number of binders. The analysis included rheological and failure properties measured by using new characterization techniques developed by SHRP. The findings were as follows.

1. Polymer modification of paving-grade asphalts can result in improved rheological and failure properties. The effects are highly dependent on asphalt properties and polymer type. The polymer modifiers reduce the sensitivity of rheological properties (G^* and δ) to temperature and loading frequency. The main effects are observed at high temperatures (low frequencies), at which the polymers result in a higher stiffness and a lower phase angle. At intermediate and low temperatures the effects are less pronounced and can be unfavorable.
2. Crumb rubber modification has effects similar to those of polymer modification. The improvement at high temperatures can be higher than the levels normally achieved by polymers. CRMs also result in a reduction in the dependency on temperature and loading frequency. Effects at intermediate and low temperatures are small but favorable, depending on the properties of the asphalt. CRMs remain as particulates after mixing with asphalts. They mainly function as interactive fillers.
3. Mineral fillers also reduce the dependency of asphalt rheology on temperature and loading frequency. However, they result in increased stiffness at all temperatures and frequencies. This indicates that although their effects at high temperatures are favorable, their effects at intermediate and low temperatures are not favorable and can be detrimental with respect to fatigue and thermal cracking.
4. By using the performance parameters introduced by SHRP, the effects of the different additives on the contribution of binders to resistance to distress mechanisms can be summarized as follows:

- Rutting resistance. Polymers, crumb rubbers, and mineral fillers result in significant increases in G^* and decreases in $\sin\delta$.

These effects are favorable for rutting resistance because they indicate higher levels of resistance to total deformation under a load and a higher elasticity of response.

- Resistance to fatigue damage. Polymers and crumb rubbers can result in marginal improvements by reducing G^* and sin δ. These effects are considered favorable because they indicate a softer and more elastic response. Such a response results in less energy dissipated under strain-controlled fatigue. Mineral fillers, however, result in significantly higher G^* values, which is not favorable for strain-controlled fatigue.
- Thermal cracking resistance. Certain polymers result in lower $S(t)$ values, higher $m(t)$ values, and higher strains at failure. Such favorable effects were not observed for all polymers evaluated in the present study. Crumb rubbers generally have $S(t)$ values that are less than the $S(t)$ values of most conventional asphalts at critical low temperatures. They can therefore result in a reduction in $S(t)$ values. The effects of crumb rubber on $m(t)$ are not significant. Crumb rubbers are observed to cause significant increases in strain at failure and stress at failure. Mineral fillers are not expected to have favorable effects on thermal cracking resistance; higher $S(t)$ and low $m(t)$ values were observed for all systems tested in the present study. Mineral fillers can, however, increase the strain at failure and stress at failure, depending on the properties of asphalt and filler characteristics.

ACKNOWLEDGMENTS

This work was supported by SHRP and by a grant from the Ben Franklin Technology Center of Pennsylvania. The author expresses gratitude for that support. The assistance of the staff of the Pennsylvania Transportation Institute in performing the SHRP binder characterization and the assistance of David Anderson are acknowledged. The assistance of Koch Materials Company and TYREPLEX Corporation in providing the modified binders or the modifiers is appreciated.

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