Effect of Crumb Rubber Modifiers (CRM) on Performance-Related Properties of Asphalt Binders

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Introduction

Crumb rubber derived from used vehicular tires has been used for a wide variety of industrial applications (1). In the early 1960's, pavement engineers in the United States started experimenting with the use of crumb rubber as a modifier to asphalt cement used in pavement applications (2). Different approaches were used to incorporate crumb rubber modifier (CRM) in road paving materials. In general these approaches are at the present time classified as the dry method and the wet method (3). The wet method involves dispersing the CRM particles into the asphalt cement to produce what is called asphalt rubber (AR) which in turn is used to produce hot-mix asphalt concrete. The dry process involves mixing the CRM with the aggregate before introducing the asphalt cement to the mixture.

Although the use of asphalt rubbers for paving applications is not new, and although there are now a number of paving contractors specialized in AR, only a few studies have been reported on how these binders differ from unmodified binders in general, and how the rubber particles change the properties of the base asphalt cements used in their production (4,5,6,7,8). Furthermore, these few reports were for the most part based on conventional types of binder testing with limited scopes. The asphalt rubber industry is now expanding, in particular following the mandate of recycling used tires included in the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991. The mandate in many ways created a significant dispute about the usefulness of using CRM in asphalt pavements, about whether there are enough data to support the technical soundness of the mandate, and about what is the most efficient approach to satisfy the mandate.

The one point upon which all parties involved are in agreement is the fact that scientific research on the effect of CRM on asphalt binder properties is sparse, and that there are no established procedures for the successful use of CRM in the asphalt pavement industry. This fact has resulted in a confusion on the part of the pavement industry and State agencies as to what type of CRM to use, how to use it, how to construct it, and whether or not the added cost is justified. In November of 1990 there were more than 30 producers of CRM and the number since then is increasing rapidly. Production of CRM can vary significantly and can result in CRM that will affect the asphalt binder or mixtures in a vastly different manner. The few studies reported about CRM have already shown that method by which CRM is produced is of significant consequences on the properties of asphalt rubbers (6). There are now emerging technologies by which CRM properties can be altered or customized to meet application-specific requirements. There are additives that are being introduced to CRM asphalts to better their performance.

The purpose of this paper is to summarize the results of the first phase of a project to evaluate the effect of CRMs produced by different processes on basic rheological, failure, and aging properties of asphalt binders. The evaluation was done using the new testing and aging procedures developed for the Strategic Highway Research Program. Three common types of CRM and four asphalts selected with different compostional properties were used in the testing program. Measurements included rheological properties across a wide range of temperatures covered in the Performance Grade (PG) specification introduced by SHRP. The rotational viscometer was used to measure response at pumping, storage, and construction temperatures; the dynamic shear rheometer was used to measure response at maximum and intermediate pavement temperatures; and the bending beam rheometer and the direct tension device were used to measure response at lowest pavement temperatures. The study also addressed the high-temperature stability of the asphalt rubbers as well as the aging characteristics of these binders as reflected by the Thin Film Oven Test (TFOT) and Pressure Aging Vessel (PAV) aging procedures.

The paper includes analysis of the effect of high-temperature storage on rheological response at high and intermediate temperatures, the effect of rubber on the properties used for grading using the new SHRP specifications, and an evaluation of the change in aging characteristics of the selected asphalts as a result of adding the CRM.

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The oral presentation was made by Professor Bahia

Materials and Experiment Design

There are different types of raw materials and different processes for reduction of CRM. In this study the rubbers were all produced from whole passenger tires. One type of CRM was produced by ambient shredding (AS), a second was produced by cryogenic grinding (CG), and a third was produced by a special extrusion process with the use of some additives (TP). The CRM's were selected to represent the materials that have the potential for dominating the paving market for CRM. The three rubbers were similar in size distribution and had a maximum particle size of approximately 1 mm. Four asphalts selected to cover a wide range in compositional properties were used. The asphalts varied in their asphaltene content, aromatic content, average molecular weight, and in their rheological and failure properties. Table 1 lists the chemical and physical characteristics of the asphalts. The asphalts included two AC-10 grade asphalts, an AR-2000, and a 200/300 pen. asphalt. No additives were used in producing the asphalt rubbers.

Table 1 Properties of Selected Asphalts

	Asphalt Type			
	A	B	C	D
Grade	200/300	AR-2000	AC-10	AC-10
SHRP PG:	46-34	58-16	58-16	58-22
%Asphaltenes	16.2	5	13	4.8
%P. Aromatics	36	51	38.7	50
%N. Aromatics	36.1	35.3	34.6	41.3
%Saturates	11.4	6.6	11.9	3

Mixing was done using a high-speed lab mixer equiped with a heat mantle. Mixing was done in one-quarter gallon (3.8 liter) containers maintained at 160 ± 5C for one hour. The rubber to total mix was kept at 15 percent by weight of total mix for all rubber-asphalt combinations.

Testing was divided into four main parts:

Rotational Viscosity. This part had two objectives: First, to evaluate the change in consistency of binders after mixing the different rubbers; second, to evaluate the storage stability of the AR's. A Brookfield viscometer was used to test each AR at 135, 160, and 185C. The storage stability was evaluated after storage at only one temperature, 160C. Intermittent mixing was done during the storage period of 23 hours starting after the one hour of mixing.

Dynamic Shear Rheometry. As a result of SHRP research two parameters (G^* and $\sin\delta$) were selected to describe the rheological behavior of binders. The objective of this part was to measure the effect of CRM on these two parameters within the range of maximum and intermediate pavement temperatures. The measurements were done in a range of temperatures from 5 to 75C. These temperatures include the temperature ranges used in the current SHRP binder specification.

Flexural Creep and Failure Properties. At low pavement temperatures, SHRP requirements involve using the bending beam rheometer and the direct tension test for evaluating creep and direct-tension characteristics. This part of the study included measuring both responses at several temperatures to evaluate the influence of rubbers on asphalt properties.

Aging Characteristics. The TFOT and the PAV were used to investigate the aging behavior of asphalt rubbers and to compare it with the behavior of the base asphalts. For the evaluation, the dynamic shear rheometer, the bending beam rheometer, and the direct tension test were used to measure properties before and after aging. The PAV aging was done at 100C to simulate moderate climate.

Results and Discussions

Consistency at High Temperatures

Although not a property that affects pavement performance directly, consistency at high temperatures is important to ensure that the binder can be pumped and mixed with aggregates, and that the total mix can be put down and compacted properly. SHRP specifications require that the viscosity at 135C is less than 3 Pa-s. The lower the viscosity, the better is the pumpability and constructability of the binder.

All CRM's, because of their particulate nature and high melting points, are expected to increase the viscosity of the base binder. This increase is, in fact, one of the most commonly reported disadvantages of asphalt rubbers. In addition, several studies have indicated that because of the interaction between asphalt cements and rubbers, a swelling-reaction phenomenon takes place and results in an unacceptable increase in viscosity (6). Asphalt-rubber producers use different approaches to control this phenomenon and produce an acceptable mix. It is well known that this phenomenon is both temperature-and time-dependent, and that if the wrong combination is used, major problems may arise.

Figure 1 depicts the relative increase in viscosities at 135 and 160C for two of the asphalts mixed with the three CRM's. The bar sets on the right represent the measurements after one hour of mixing, while the sets on the left represent the measurements after 23 hours of storage at 160C with intermittent mixing. Several interesting trends can be observed in the figure:

- The increase in viscosity as a result of rubber addition after one hour mixing is very significant and ranges from a minimum of 7 to a maximum of 20 folds.

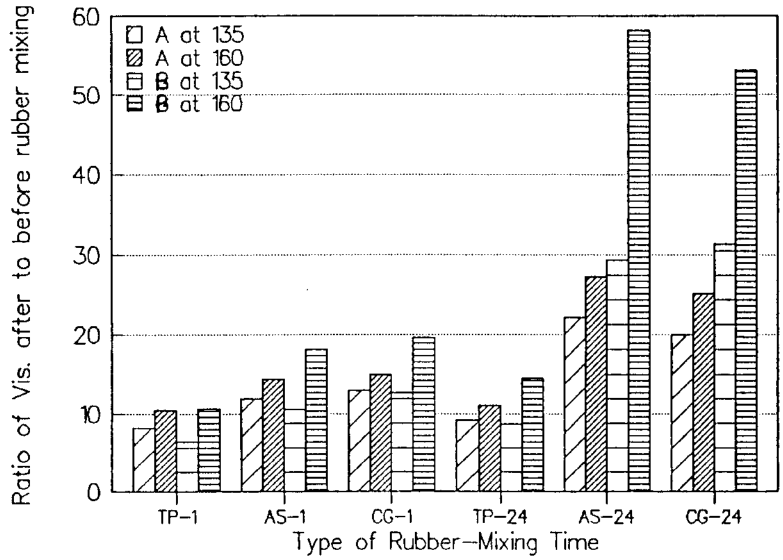


Figure 1 Relative Change in Rotational Viscosity at High Temperature

- For all asphalt-rubber combinations, the relative increase is more at 160C than at 135C. The difference is more apparent for asphalt B than for asphalt A.
- After one hour mixing, the effect on viscosity at 135C is similar for both asphalts regardless of the rubber type.
- The effect of storage at 160C for 23 hours is highly dependent on the rubber type: For rubber TP there is very little change for asphalt A and only a very small increase with asphalt B. For rubbers AS and CG the effect is very significant for both asphalts, but is particularly high for asphalt B.

- The effect of storage is more apparent at 160C than at 135C and is very similar for both the AS and CG rubbers.

The above observations indicate that the influence of rubber on high-temperature consistency is rather complicated. It is changing the viscosity-temperature profile, and it is not only rubber-specific, but also rubber-asphalt combination-specific. The effect of storage is also complicated: while for the TP rubber no effects were observed, for the other rubbers the effects were very dramatic, especially when looked at in terms of the higher temperature viscosity; the storage is further altering the viscosity-temperature profile.

In relation to the SHRP specification, Figure 2 depicts the viscosity values for the six asphalt rubbers after one hour of mixing and after 24 hours of storage. As depicted for the TP rubber the viscosities are well within the 3 Pa-s limit at both stages. For the other two rubbers, however, this is not the case; after the 23 hours storage, the rubbers with both asphalts show values ranging between 4.2 and 5.5 Pa-s, which are not acceptable.

To further investigate the unique behavior of the TP rubber, it was mixed with two other asphalts (C and D) and the same measurements were performed. As shown in Figure 3, the effect of the rubber on the other two asphalts was also stable and no increase was observed after the 23 hours storage period.

The above observations raise many questions about the nature of the interaction between asphalts and CRM's. The results indicate that the AS and CG rubbers behave in a very similar fashion with both asphalts. This finding contradicts the claims that the interaction of asphalts is significantly more with ambient shredded rubber due to its large surface area. The results also raise the question of why the interaction is a function of asphalts type. Asphalt B has a lower consistency at 160C than asphalt A. If the interaction mechanism is mainly a diffusion phenomenon, then asphalt B is expected to show a more effective interaction, which is the case here.This hypothesis, however, does not

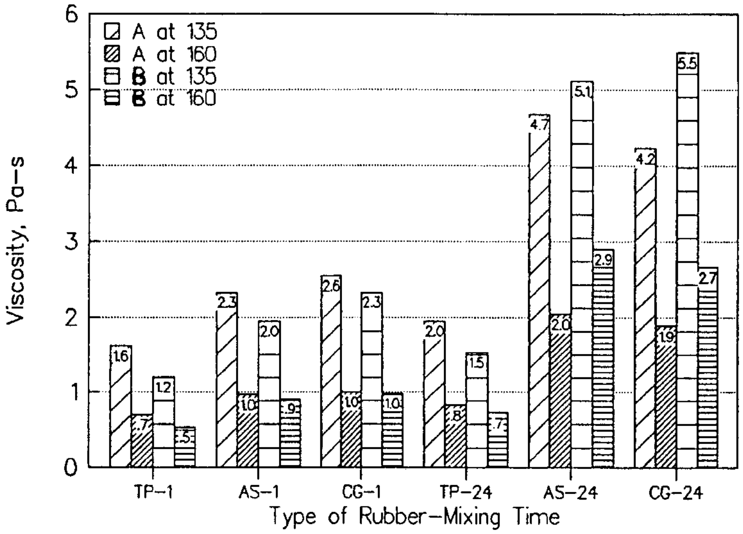


Figure 2 Viscosity of CRM Asphalts at High Temperature Before and After Storage

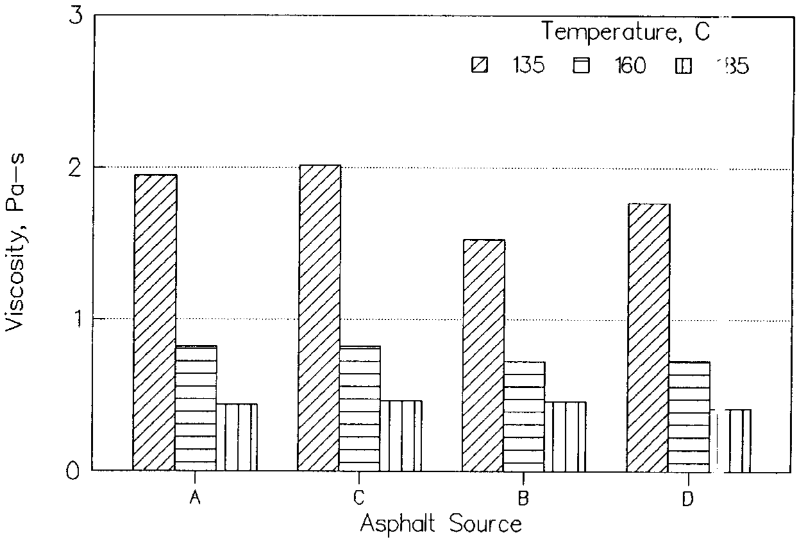


Figure 3 High Temperature Viscosity of Different Asphalts Mixed with Ruber TP After 24 h Storage at Elevated Temperatures

explain why asphalts A and B show the same behavior with rubber TP. It appears that the effect of storage and the interaction between asphalt and rubber at elevated temperatures is a phenomenon that needs more in-depth study. The kinetics of such changes are probably most important from an application point of view.

Rheological Properties at High and Intermediate Pavement Temperatures

Rheological Master Curves

Figure 4 depicts changes in the shape of G^* and phase angle of asphalt B due to addition of the AS rubber. As the figure shows the G^* curve is flattening indicating less dependency of modulus on shear rate. The two G^* curves intersect, resulting in higher G^* values for the asphalt rubber at lower frequencies and lower values at high frequencies. At very low frequencies, where both binders reach their glassy state, the binders show the same asymptotic value. The δ curves also intersect each other; at low frequencies the asphalt rubber exhibits δ values that are significantly lower than the base asphalt while at higher frequencies it shows higher δ values. Figure 5 depicts the temperature shift functions ($\log(a_T)$) and indicates that the addition of the rubber does not alter the temperature shift function curves significantly.

The changes in rheological behavior for the other asphalt-rubber combinations were observed to be following the same trend shown in Figures 4 and 5. Basically, if one assumes that at very low frequency (low temperatures) the binders are similar, the rubbers are decreasing the dependency of both parameters (G^* and δ) on the frequency of loading (shear rate). The changes are significant and should result in a change in the contribution of the binder to the pavement performance, as will be discussed in the following sections.

G^* and Sin δ Isochronal Curves

Using rheological master curves to examine changes in properties related to pavement performance is very difficult. Instead, using temperature isochronal plots of the parameters related to performance may give a much better picture. Figure 6 depicts isochronal curves for the base asphalts A and B and for the six asphalt rubbers produced by mixing the three rubbers with each of the asphalts. The curves are in terms of G^* at 10 rad/s as a function of temperature. As depicted, the addition of the rubber increases the total resistance to deformation (G^*) by a large margin at high temperatures, but as the temperature drops the rubber effect is diminishing.The point at which the asphalt rubbers are demonstrating

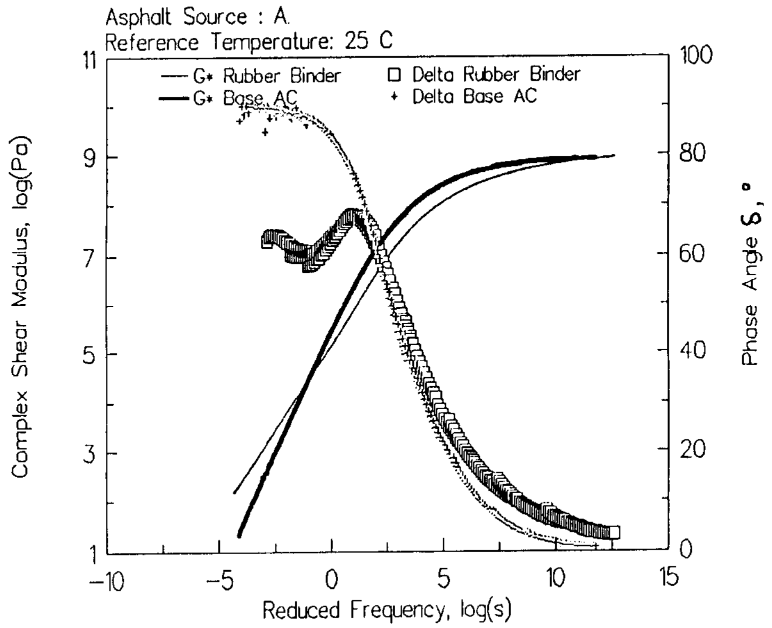


Figure 4 Rheological Master Curves Before and After Mixing with Rubber

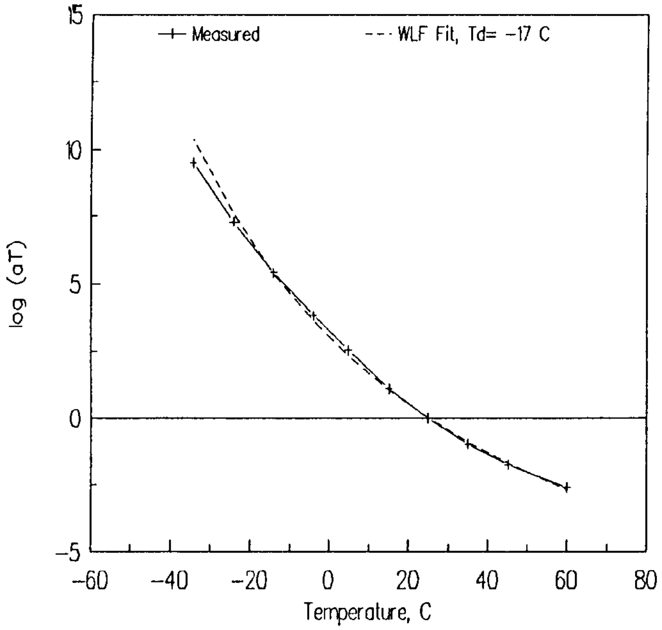


Figure 5 Temperature Shift Functions Before and After Rubber Mixing

lower G^* values is at the low end of the temperature range, depending on the asphalt type. The other important observation is the variation in rubber effects, particularly for asphalt B. The curves for the asphalt rubbers intersect each other, with rubber AS showing the highest G^* values at temperatures above 50C and the lowest values below that temperature. In terms of contribution to pavement performance, the latter behavior is favorable.

Figure 7 depicts sin δ isochronal curves for the same set of binders. The curves indicate a general decrease in sinδ throughout the whole temperature range, but more so at lower temperatures. Again, the effect of the rubbers varies, with rubber AS showing the most changes. Reducing the sinδ values indicates less dissipation of energy per loading cycle and thus a more elastic response. Such an effect is considered favorable at high and intermediate pavement temperatures.

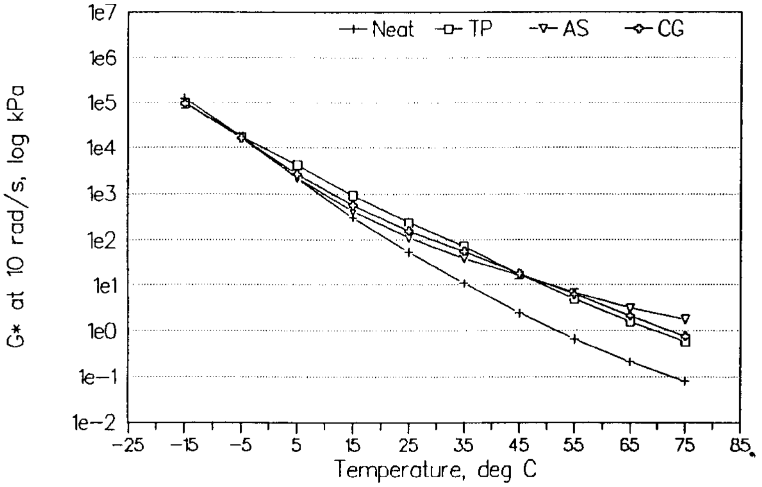


Figure 6a Effect of Different Rubbers on Shear Response of Asphalt A

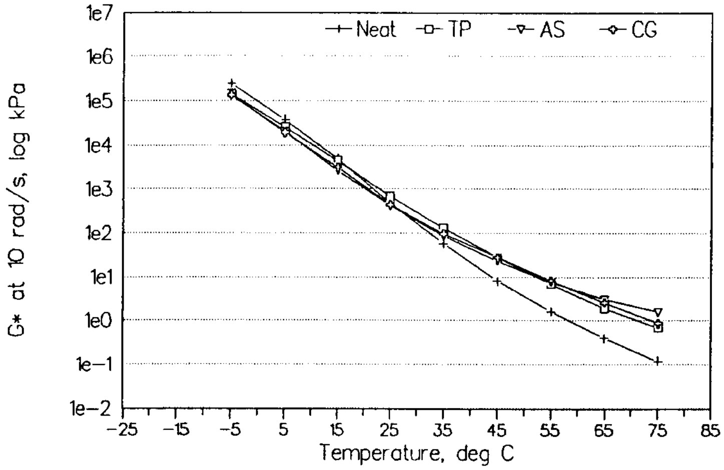


Figure 6b. Effect of Different Rubbers on Shear Response of Asphalt B.

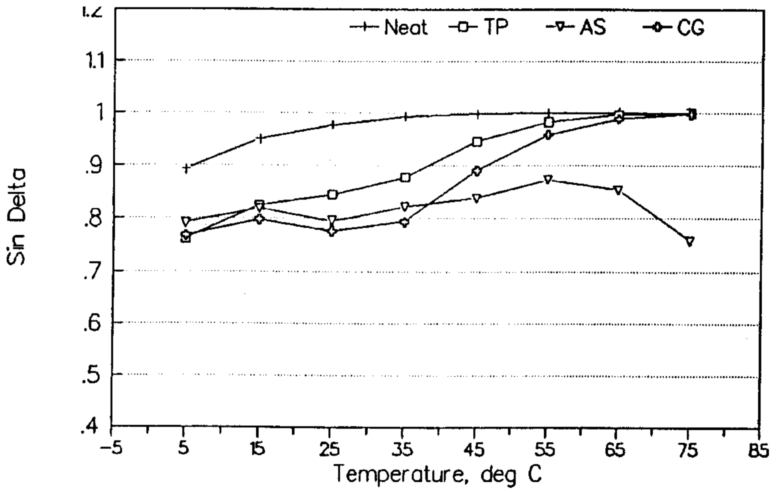


Figure 7a. Effect of Different Rubbers on Phase Angle of Asphalt A.

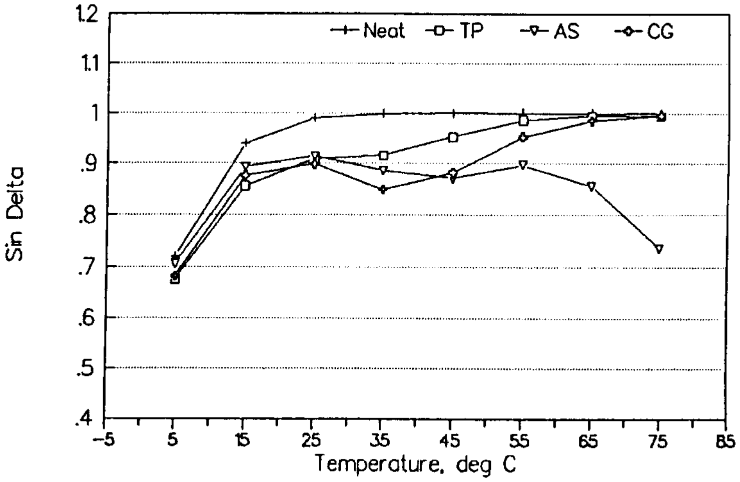


Figure 7b. Effect of Different Rubbers on Phase Angle of Asphalt B.

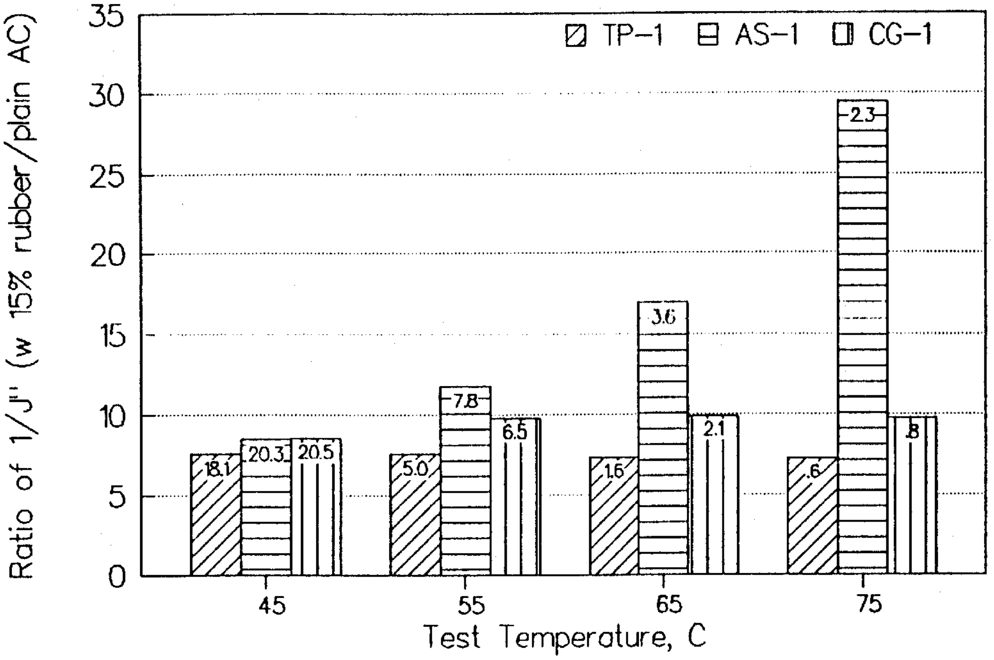
Changes in Fundamental Parameters Used in SHRP Specification

SHRP researchers selected $G^*/\sin\delta$ (1/J") to measure the contribution of binder to rutting performance. For contribution to fatigue cracking performance, $G^*\sin\delta$ (G") was selected. For low-temperature cracking, three parameters were selected: creep stiffness, S(t), logarithmic creep rate, m(t), and strain at failure, ϵ_f. The effects of the CRM's on each of these parameters are addressed next.

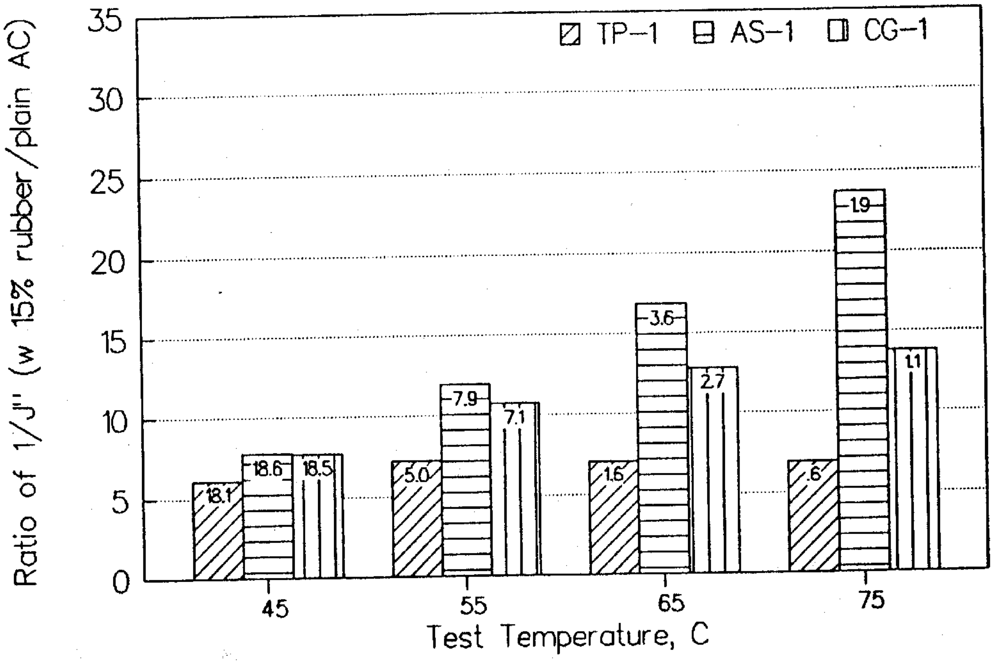
Changes in 1/J" at Maximum Pavement Temperatures

Figures 8 and 9 depict bar charts in terms of the ratio of 1/J" values after to before mixing the CRM (for 1 h, and 24 h), for asphalts A and B, respectively. The ratios at four temperatures for the three rubbers are shown in each figure. The ratios vary between 4 and 29 depending on the temperature, the asphalt source, and the rubber type. Several trends could be observed in the results:

- On average, for all rubbers and both asphalts,the higher the temperature the higher is the relative increase in 1/J" values. This indicates a change in the 1/J" temperature profile in the favorable direction with respect to the contribution of the binder to rutting resistance.
- After one hour of mixing, asphalt A is more affected by the three rubbers (ratios range between 8 and 29) than asphalt B (ratios range between 4 and 18). This is consistent with the rotational viscosity data at 135 to 160C.

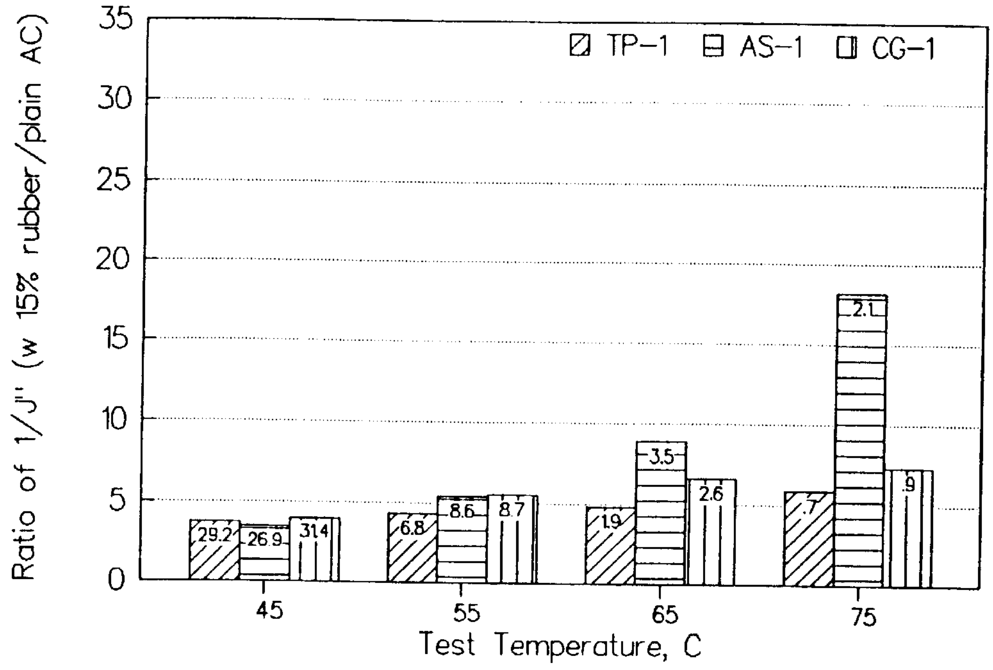


(a) After 1 h mixing at 160°C

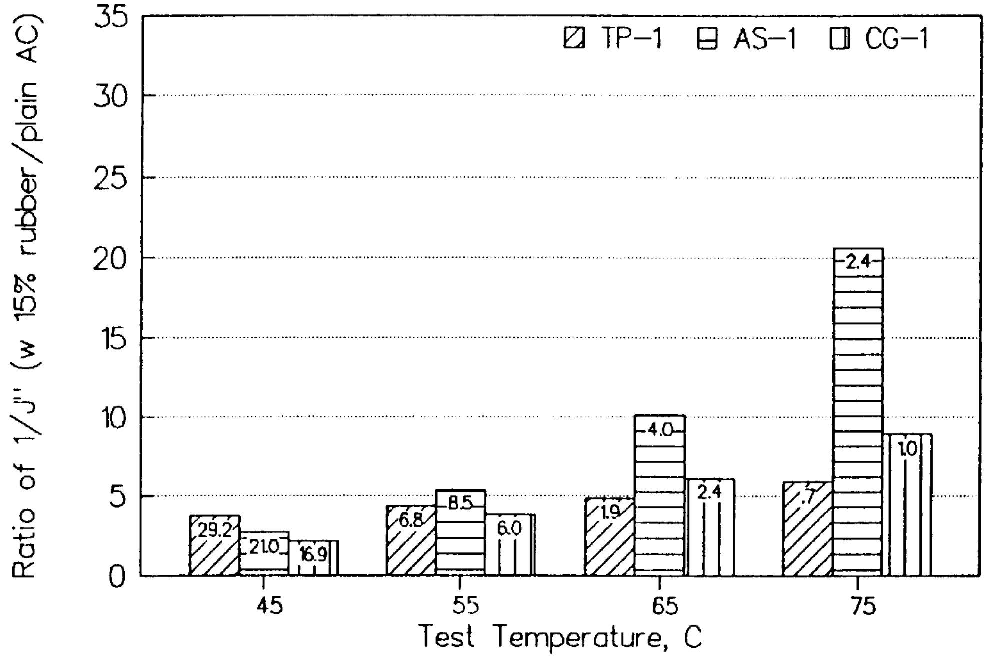


(b) After 24 h storage

Figure 8. Effect of Different Rubbers on $G^*/\sin\delta$ Values for Asphalt A.



(a) After 1 h mixing at 160°C



(b) After 24 h storage

Figure 9. Effect of Different Rubbers on $G^*/\sin\delta$ Values for Asphalt B.

- Rubber AS has the largest effects at all temperatures for both asphalts. It also shows the largest change in the 1/J" temperature profile. Rubber TP shows the smallest changes followed by rubber CG. The ratios for the TP and CG rubber do not show a significant increase with temperature, which indicates that these two rubbers do not significantly change the 1/J" temperature profile.
- After 23 hours storage at 160C the ratios do not show any significant increase for any of the rubbers. On the contrary, at certain combinations of temperature-rubber-asphalt, a decrease in the ratio is observed. This finding is in contradiction with the large increase in the rotational viscosity at high temperatures discussed earlier (see Figure 1). It indicates that the swelling-reaction phenomenon, although exhibited at high temperatures (135 to 185C), does not have an effect on properties at maximum pavement temperature.

The above findings suggest that the effects of rubbers on asphalt properties are very favorable for enhancement of rutting resistance of pavements, particularly at the high end of the pavement temperature spectrum. They also indicate that the effect is rubber- and asphalt-specific and that storage time does not change the properties by any significant amount. Looking at the G^* and sinδ plots in Figures 6 and 7, it is clear that the main changes in 1/J" values come from a change in G^* values, while the changes in sinδ are only secondary. The values of 1/J" for the asphalt rubbers are shown at the top of the bars in the charts. The values indicate that although base asphalts were soft (A is a 200/300 pen. and B is an AR-2000), after mixing with rubber, they both show an average 1/J" value, at 75C that exceeds the limit of 1 kPa selected by SHRP. The temperature of 75C is 5C higher than the highest maximum pavemnet temperatures used in the SHRP specification.

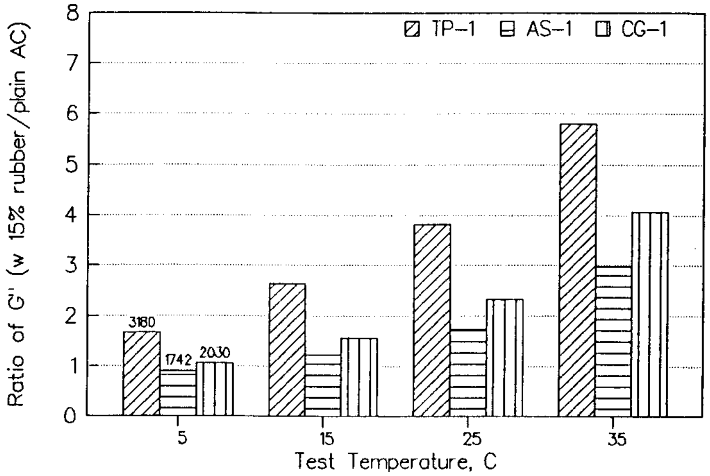


Figure 10. Effect of Different Rubbers on G^* sinδ Values for Asphalt A at Intermediate Temperatures

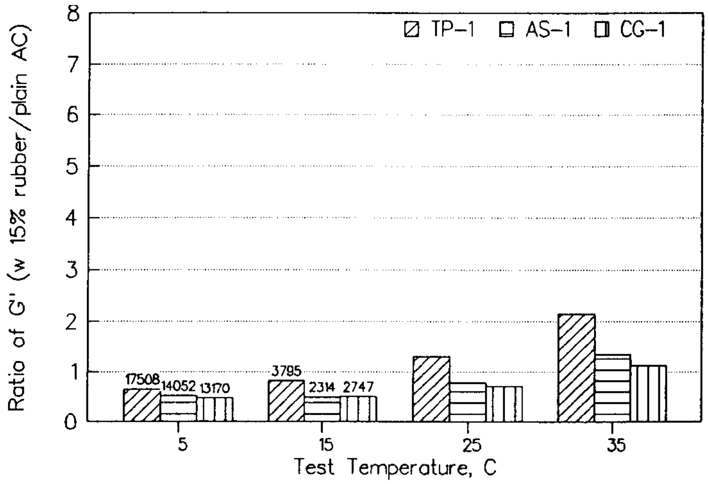


Figure 11. Effect of Different Rubbers on G^* sinδ Values for Asphalt B at Intermediate Temperatures.

Changes in G" at Intermediate Pavement Temperatures

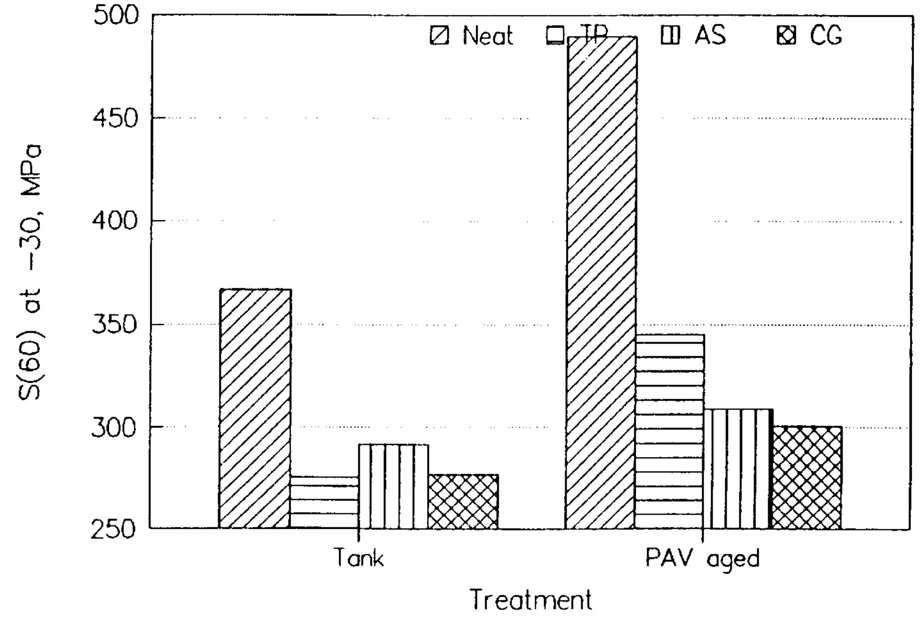
Figures 10 and 11 show the ratio of G" after to before mixing with the rubbers for one hour mixing, for asphalts A and B, respectively. The results shown are for the tank material tested within the range of 5 to 35C. The ratios and their variations with the different factors show some similarities and some distinctions when compared to the ratios of 1/J" discussed earlier. The ratios range from a low of 0.5 to a high of 5.8 depending on temperature, asphalt source, and rubber type. The effects can be summarized as follows:

- Similar to 1/J", the higher the temperature, the higher the ratios. The change can also be described as change in the G" temperature profile in the favorable direction. It is favorable because the values of G" at the lower end of the temperature range (higher values of G") are more critical with respect to fatigue cracking.
- The ratios are much smaller than the ratios of 1/J". This indicates that the effect of the rubber modifiers on G" is smaller than that on 1/J". This can be simply explained by examining Figures 6 and 7, which show that at lower temperatures the increase in G^* values is less and that the decrease in sinδ is greater.
- Asphalt B exhibits ratios less than one for several combinations of temperature and rubber type. At all temperatures and for all rubber types, the ratios for asphalt A are higher than the ratios for asphalt B.
- The 23-h storage shows no effect on the ratios, which confirms the finding that the swelling/interaction phenomenon observed at high temperatures does not have any influence on the properties at pavement temperatures.

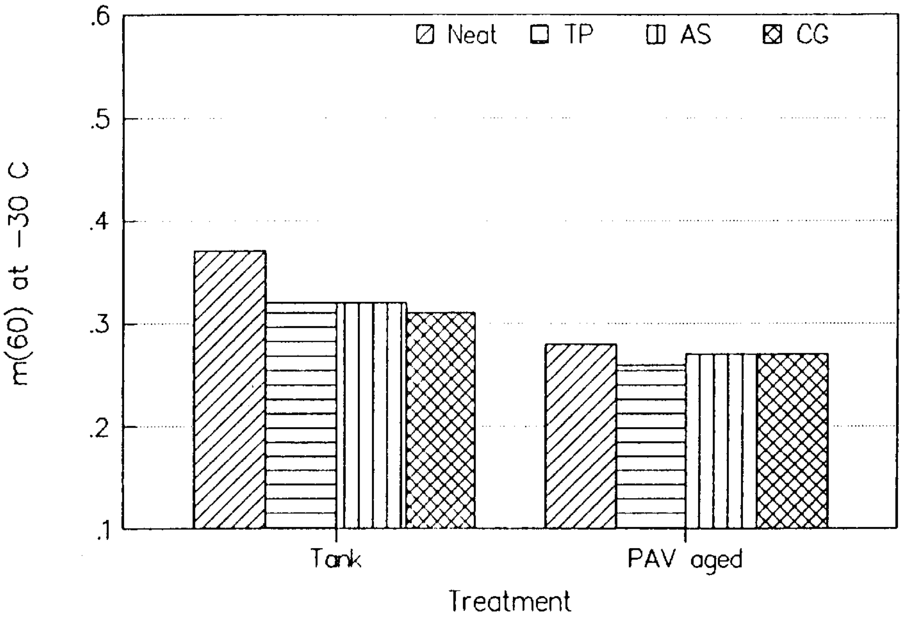
The above findings indicate that the addition of the rubber modifiers is highly asphalt-specific. The data indicate that the asphalt type is more important than the rubber type and that for certain asphalts the modifiers may result in a lower value of the loss modulus (G"). The numbers on the bar charts of Figures 10 and 11 are the values for G" at 10 rad/s, which is the parameter used in the SHRP specification to reflect contribution of binder to fatigue of pavement. As shown in Figure 10, even though there is a relative increase with respect to the base asphalt, the asphalt rubbers can meet the criterion of 5000 kPa at temperatures close to the lowest intermediate temperatures included in the SHRP specifications.

Changes S(t) and m(t) at Minimum Pavement Temperatures

Figures 12 and 13 depict the bar charts for the values of creep stiffness S(t) and the logarithmic creep rate, m(t), measured with the bending beam rheometer at 60-s loading time for asphalts A and B, respectively. Each figure includes the S(60) and m(60) values for the base asphalt and after modification with the different rubbers. The figures depict binders in the unaged condition and after aging with the TFOT followed by the PAV. Each figure represents the data for a single temperature. The temperature was selected to be that at which the value of the stiffness is in the range of 300 MPa, which is the limit selected by SHRP for the binder specification. The following observations about the effect of rubbers on the low-temperature stiffness can be stated:

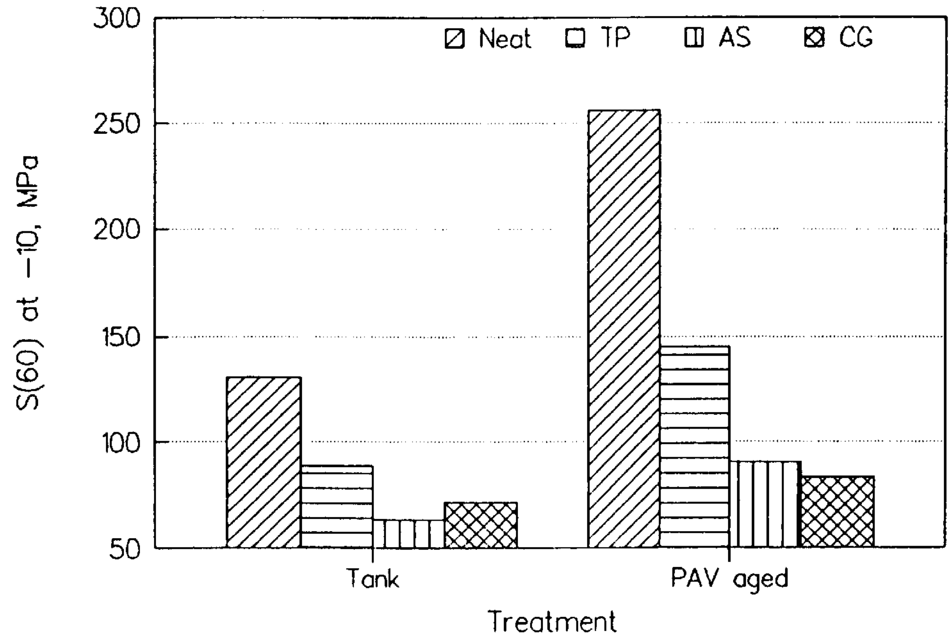


(a) Effect on Stiffness Vlaues



(b) Effect on Logarithmic Creep Rate "m"

Figure 12. Effect of Different Rubbers on Creep Response of Asphalt A at -30C



(a) Effect on Stiffness Vlaues

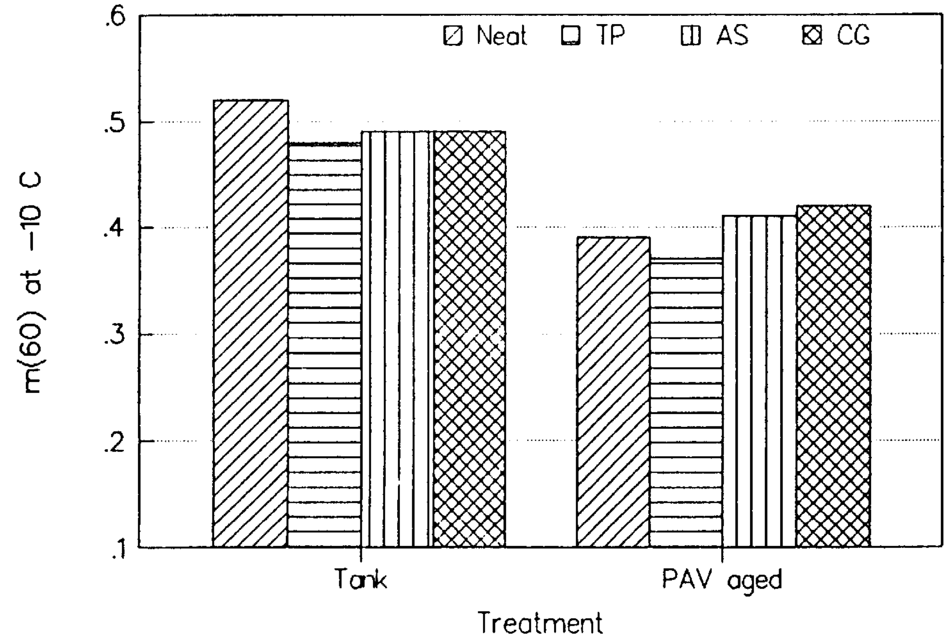


Figure 13. Effect of Different Rubbers on Creep Response of Asphalt B at -10C

- For both asphalts, the addition of the rubber results in reduction of the stiffness before and after the PAV aging. The reduction ranges between 40 and 140 MPa.
- The reduction is more pronounced for the PAV-aged material for both asphalts. Since the properties after aging are more critical, this trend is favorable with respect to the predicted influence of binder on pavement cracking.
- The reduction in stiffness is within 25 MPa for the unaged condition for the three rubbers. This indicates that the rubber type is not that important with respect to the reduction. After PAV aging, however, the difference between the effects of the rubbers is slightly greater. Rubber type TP is approximately 30 to 50 MPa higher than the other two rubbers, which give very similar stiffness values.
- Except for asphalt B with AS and CG rubbers after PAV aging, all other asphalt rubbers show a reduction in the m(60) value when compared to the base asphalt. The changes, however, are not that significant. The reduction ranges between 0.01 and 0.03 while the increase is approximately 0.02. Obviously the reduction in m(60) is not favorable; m(60) is an indicator of the rate at which the binder can relax thermal stresses when it is cooled at a certain rate. A lower value is a indication of a slower relaxing binder.
- The rather limited data indicate that rubber source is not that important a factor in the changes. The data also indicate that the changes are slightly different before and after aging and that after aging the trend is toward less reduction, or even an increase in the m(60) value.

The above observations, when looked at collectively, naturally lead to the conclusion that incorporation of the rubbers may result in better performing binders with respect to potential for thermal cracking. The observations, however, indicate that the changes are smaller by far than the changes observed for the properties at high and intermediate temperatures.

Changes in Failure Properties at Lowest Pavement Temperatures

Strain at failure measured using a deformation rate of 1 mm/min is the criterion used in the SHRP specifications to reflect the propensity of binders to brittle failure. A minimum limit of 1 percent is recommended in the specification. Figures 14a and 14b depict the strain-at-failure values for asphalts A and B, respectively, before and after aging with the PAV. Each figure is at a selected temperature at which the strain to failure of the base asphalt is close to the 1 percent limit.

The following trends can be observed from the bar charts.

- The strain to failure is significantly increasing as a result of the addition of the rubbers, particularly for the unaged binders.
- Although tests were done at different temperatures, it appears that rubbers are more effective in increasing strain of asphalt A than asphalt B.
- Except for asphalt B in the unaged condition, the rubber type does not appear to play a major role in the changes caused by the rubber.
- The increase in strain at failure is larger in the unaged condition than after PAV aging.

The above observations about failure performance of asphalt rubbers are admittedly limited in scope. They are, however, quite expected when the nature of crack propagation mechanisms is considered. For any particulate composite, a stronger dispersed face can significantly improve failure behavior by altering crack growth paths or crack arrest mechanisms. In the case of rubber particles in asphalt, at low temperatures such as the temperatures used in this study, the rubbers are much more flexible (strain tolerant) than the asphalt. It is, therefore, reasonable to expect an increase in strain tolerance as is observed in this study. A word of caution may be prudent here; the improvements should not be exaggerated: the strain to failure of asphalts is extremely sensitive to temperatures, as indicated by previous studies.

Changes in Aging Characteristics in the TFOT and in the PAV

Two aging characteristics are important for paving binders: the aging that takes place during the mixing-construction stage of the hot-mix asphalt, and the long-term field aging that takes place during the service life of the pavement. The TFOT procedure is expected to simulate the former while the PAV is expected to simulate the latter.

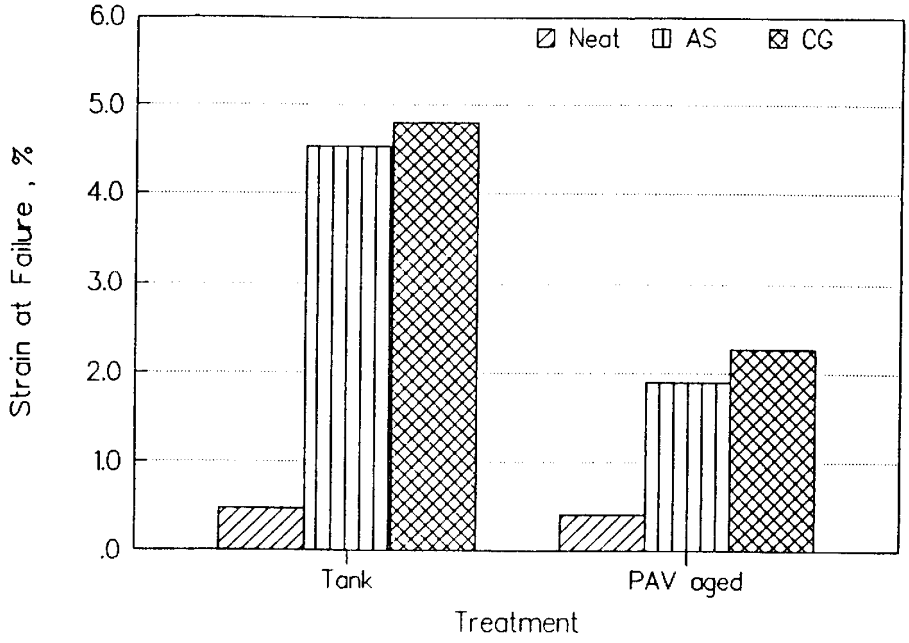
Figure 15 depicts the relative change in the value of the rutting parameter $G^*/\sin \delta$ before and after the TFOT procedure. It also shows the mass loss for the base asphalt before and after the addition of the rubbers. Figure 16 depicts the relative change in the G" values before and after the TFOT and PAV aging collectively. With regard to aging, the SHRP specification places limits on the mass loss and is the basis for the criteria for intermediate and low temperature properties on PAV-aged material. This evaluation takes into consideration oxidative aging that takes place in the field. Upon examination of the bar charts in Figures 15 and 16, the following trends can be observed:

- The effect of rubber addition appears to result in greater mass loss. The increase in mass loss is asphalt-dependent. For asphalt A, which shows a higher mass loss than asphalt B, the increase is very marginal while for asphalt B, the addition of the rubber more

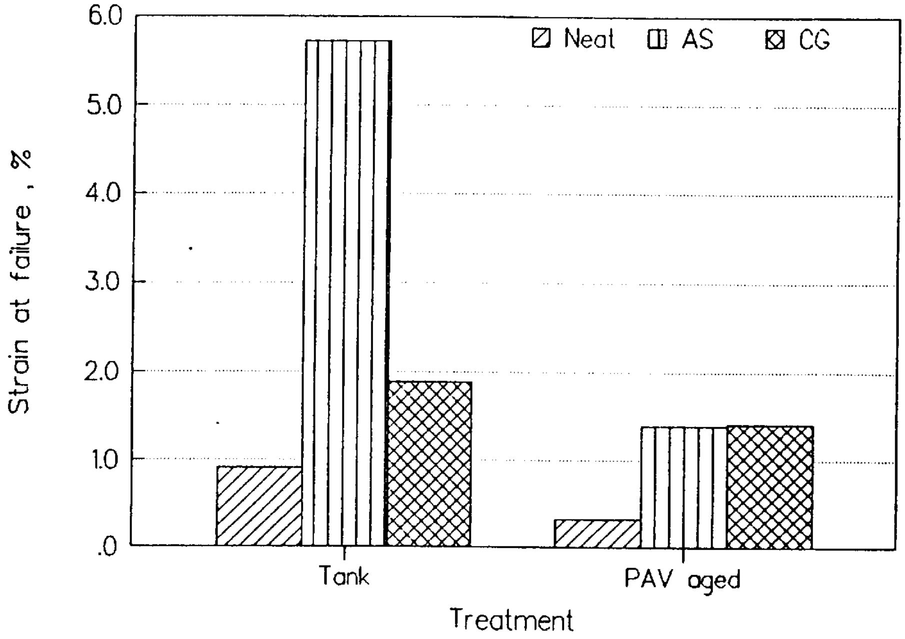
than doubles the mass loss. The rubber type does not apear to be an important factor.

- The relative change in 1/J" is similar for base and rubberized asphalts. This indicates again that the interaction of rubber with asphalt is not significantly altering the volatilization mechanism of the asphalts.
- With regard to the relative change in G" values shown in Figure 16, it is clear that all asphalt rubbers at all temperatures are exhibiting less change upon aging in the TFOT and PAV.
- The effect of rubber on aging, as reflected in the G" measurements, does not appear to be highly rubber-specific nor asphalt-specific. There are probably some variations, but they can safely be considered marginal.
- The effect of rubber on aging, as reflected in the creep and failure properties at low temperatures, has been addressed in the previous two sections. The effect shows the same trend but at a lesser magnitude than the effect reflected in the values of G".

The observation that mass loss is increasing was not expected. The swelling/interaction phenomenon is hypothesized to be the result of migration of the softer components to swell the rubber. If this hypothesis is valid, a decrease in mass loss is expected. The limited data collected in this study do not support this hypothesis.



(a) Asphalt A at -20 °C



(b) Asphalt B at -10 °C

Figure 14. Effect of Different Rubbers on Failure Properties of Two Asphalts.

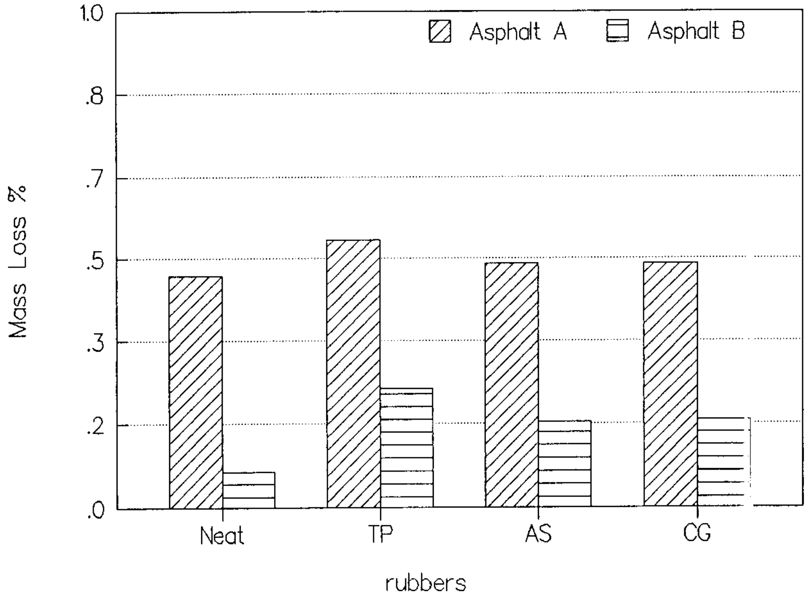
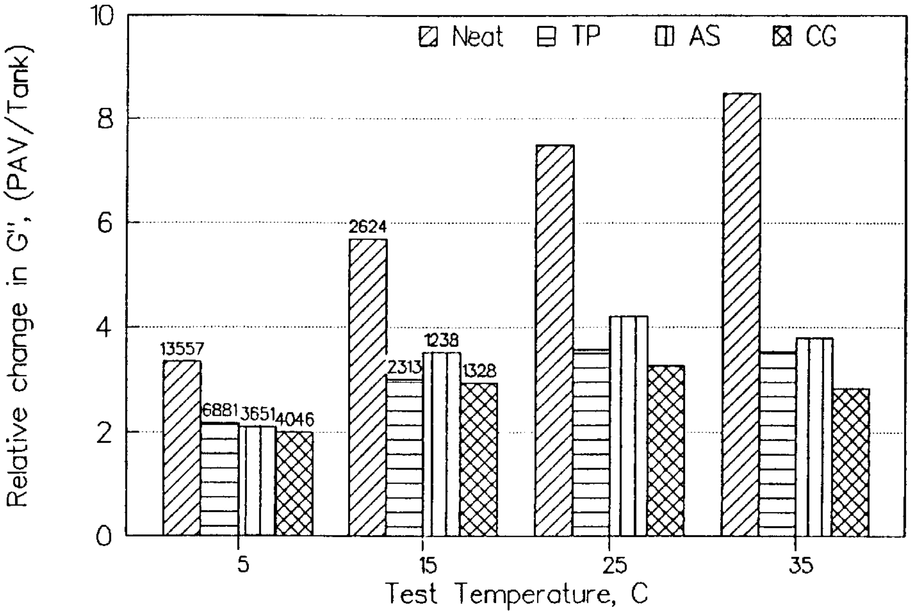
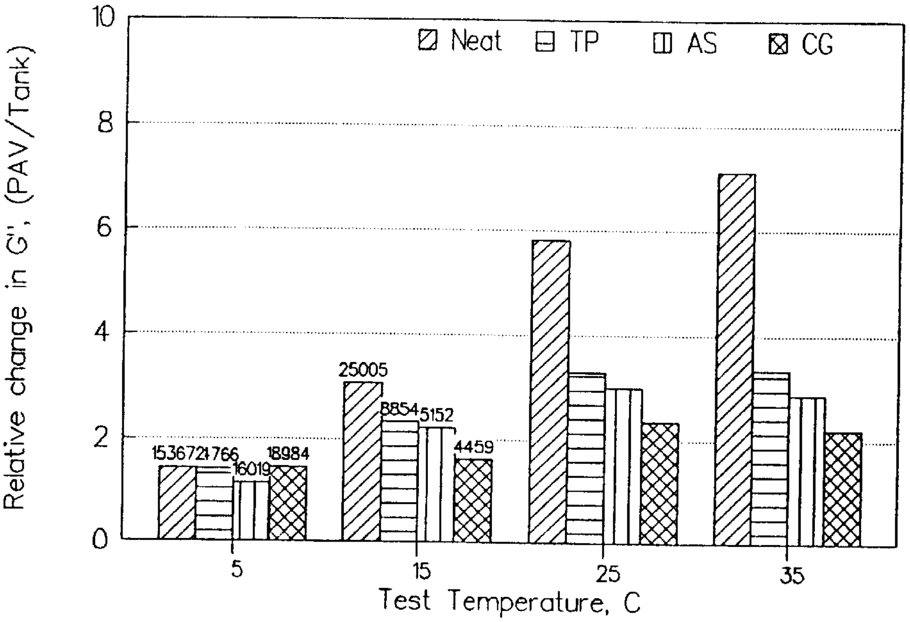


Figure 15. Effect of Different Rubbers on Mass Loss in the TFOT for Two Asphalts.



(a) For Asphalt A



(b) For Asphalt B

Figure 16. Relative Change in G* sinδ After PAV Aging for Two Asphalts.

Summary of Findings

Three types of Crumb Rubber Modifiers were mixed with asphalts with different compositions to study the effect of the modifiers on rheological, failure, and aging properties of the asphalts. Based on the analysis of collected measurements, the following conclusions can be drawn.

- SHRP testing procedures can be used to characterize asphalt rubbers, with minor modifications, without major problems. Caution should be used, however, in sample preparation due to the increased stickiness and granulated nature of the binders. More research is also needed to evaluate the linearity (geometric and material) that asphalt rubber might exhibit with different particle sizes and compositions.
- The effect of rubbers on performance-related properties of asphalt cements may be summarized as follows:
- CRM's result in increased viscosity at pumping and mixing temperatures. This effect is not favorable, since it makes pumping of binders, mixing, and compacting of HMA produced with these modified binders more difficult.
- CRM's result in increased values of $G^*/\sin\delta$ (1/J"), particularly at high pavement temperatures. The main effect is caused by an increase in G^* values while the decrease in $\sin\delta$ is only secondary. Increases in 1/J" are significant and are considered very favorable with respect to increasing the contribution of binders to rutting resistance.
- The effect of crumb rubbers on $G^* \sin\delta$ (G") values depends on testing temperature. At low temperatures, where the G" values are relatively high, a reduction in G" values could be observed for the asphalt rubbers when compared to the base asphalt. This, however, was not true for all asphalts. Some asphalts showed a marginal increase in values. In both cases the changes are very small and much smaller than the changes observed in 1/J" measured at high temperatures. As the test temperature increases (25 to 35C) G" after rubber addition becomes larger than the values for the base asphalt. The general conclusion that may be drawn is that at G" values within the range of 3 to 6 MPa, the effect of rubbers can be assumed marginal.
- The effect of CRM on S(t) and m(t) at lowest pavement temperatures may also be considered marginal. Some reduction in S(t) values is observed for all rubbers used, which is favorable, but minor reductions in m(t) are also observed, which is not favorable. The changes are all of a much smaller order of magnitude when compared to changes at high temperatures. The collective effects may be characterized as marginal.
- The effect of CRM on strain at failure ϵ_f appears to be favorable. An increase in strain at failure was observed for all asphalts. The magnitude of change is, however, small. Considering the variable nature of the test results, the effect of the rubbers can be described as marginally favorable.
- The factors that play an important role in the effects of CRM's on properties of asphalt cements are different at different temperature ranges:
  - At high temperatures, the effects are highly asphalt- and rubber-specific. Different rubbers were also shown to change the 1/J" temperature profiles in a different manner.
  - At intermediate temperatures, the source of the asphalt was found to be more important than the rubber type. Temperature is still a factor for some asphalts that show different G" temperature profiles after mixing with rubbers.
  - At low temperatures, the changes in rheological and failure properties for the tested binders are relatively small. Although some effects of asphalt source were apparent, each asphalt maintained its pre-rubber mixing characteristics.
- Storage Stability (swelling/interaction) was found to be very important at high temperatures (135 to 185C). The effect is observed to reflect a continuous increase in rotational viscosity. The increase is, however, observed to be a function of asphalt source, rubber type, and test temperature. For one of the rubbers the effect was negligible, while for the other two it was very significant. The ambient shredded rubber and the cryogenically ground behaved very similarly after storage at high temperatures.

  The effects of storage, however, were found to have no effect on the rheological and failure properties at temperatures in the range to which pavements commonly are exposed (-30 to 75C). There were no effects on either the G^* values or the $\sin\delta$ values at any of the measurement temperatures even for the most interactive systems indicated by the rotational viscometry data.

- Relative change in properties measured before and after the PAV aging indicates that the introduction of rubbers may result in reduction in hardening due to oxidative aging. The TFOT data indicate that the loss mass increases as a result of addition of the rubbers. Both the PAV data and the TFOT data indicate that the changes in aging characteristics are not rubber type-specific.
- The final finding of this study is that additional research is needed to reveal the nature of interaction between asphalt cements and rubbers. It is clear from this study and many previous studies that the research community does not fully understand the mechanism by which the interaction between these two materials takes place.

References

1. C. Clark, K. Meadron, and D. Russell, "Tire Technology and Markets," U. S. Enviromental Protection Agency, Noyes Data Corporation, NJ, U.S.A., 1993.
2. Arizona Department of Transporation (ADOT) Report, "The History, Development, and Performance of Asphalt Rubber at ADOT, AZ-SP-8902, December, 1989.
3. M.A. Heitzman, "State of the Practice- Design and Construction of Asphalt Paving Materials with Crumb Rubber Modifier," U.S. Department of Transporation, Federal Highway Administration, FHWA-SA-92-022, Washington, D.C., May 1992.
4. M.R. Piggot, and R.T. Woodhams, "Recycling of Rubber Tires in Asphalt Paving Materials," Department of Chemical Engineering and Applied Chemistry, University of Toronto, Toronto, Ontario, March 1979.
5. S. Lalwani, A. Abushihada, and A. Halasa, "Rubber-Asphalt Blends Measurements of Rheological Properties to Assess Toughness, Resiliency, and Temperature Sensitivity," Proceedings of the Association of Asphalt Paving Technologies, Vol. 51, 1982, pp. 562-579.
6. J.W.H. Oliver, "Optimizing the Improvements Obtained by The Digestion of Comminuted Scrap Rubbers in Paving Asphalts," Proceedings of the Association of Asphalt Paving Technologies, Vol. 51, 1982, pp. 169-188.
7. J.G. Chehoveits, R.L. Dunning, and G.R. Morris, " Characteristics of Asphalt-Rubber by the Sliding Plate Microviscometer," Proceedings of the Association of Asphalt Paving Technologies, Vol. 51, 1982, pp. 240-261.
8. J.G. Chehoveits, " Crumb Rubber Modifier Workshop Notes, Session 9: Binder Design Procedures," Federal Highway Administration, Office of Technology Applications, 1993.

Discussions

MR. GOVINDA GOWDA: (Prepared Discussion) Thank you Dr. Bahia for an excellent paper, your paper has set high standards for us and we hope to catch up with you at least by next year. I do have a couple of questions on the use of Dynamic Shear Rheometer (DSR) and Brookfield Viscometer (BV) to evaluate the performance related properties of CRM modified asphalt-binders.

The DSR works just fine for conventional single phase or homogenous binders like, AC-30, AC-20, Polymer Modified AC, Ecoflex^{TM} Asphalt-Rubber. Whereas, the Asphalt-Rubber prepared by the McDonald Process with rubber particles having particle size of 2-mm size and in excess, has indicated very poor repeatability and reproducibility in the test results. The repeatability and reproducibility has been as low as 5 and 10 percent respectively.

One of the major causes seems to be the size of the test specimen and the methodology of preparing the test specimens for DSR Test. Segregation of the rubber particles, difficulty in preparing the test specimen with the same proportion and identical dispersion of the CRM are the typical problems experienced with the testing of coarse CRM modified binders.

With so much variability in the test results, my questions to you are:

- Are we really looking at the true results for the binders modified with coarse CRM?
- Are the results masked due to the "Cushioning Effects" contributed by the CRM particles when the specimen is sheared during testing?
- Should we, meaning the FHWA, The Asphalt Institute, University Researchers and Industries recommend the SHRP tests on CRM Modified Binders having particle size greater than the thickness of the sample?
- Do you recommend other alternative tests for these type of modified binders?

- You have concluded in your paper saying that caution must be exercised during the specimen preparation. Could you enlighten us what they are and how they are to be exercised?

DR. HUSSAIN BAHIA: Thank you for this presentation. This is a very well taken point. My intent in the project was not really to be so precise as the neat asphalts. The study was to address major effects of CRM. That is why I keep saying that we have relatively small variability. There is no way we are going to be able to get to the same repeatability with a non-homogeneous material as we see with a homogeneous material. I fully agree with you that something has to be done to address these issues. A guideline or some suggested procedure should be put in place so that we can all use it and reflect to it. The repeatability you reported is very similar to mine. It is, however, above the neat asphalts. For some people it is significantly above the neat asphalts. My interest was looking at major changes not small changes. Now, do we have a representative sample in the small sample? We tried to get one as much as we could. We used silicon rubber molds. You are probably familiar with it. It is a better way than pouring on the plate. We tried to make sure that every sample, before it was poured, was stirred properly.

MR. GOWDA: Now, the next part of my question is about the use of Brookfield Viscometer, the BV does not give repeatable and reproducible results for McDonald Asphalt rubber with particle greater than 2 mm. We have obtained Brookfield Viscosity as high as 11.9 Pa-S in comparison to the SHRP specified maximum value of 3 Pa-S.

What is the practical significance of this specification? The SHRP specification indicates a maximum value for the Brookfield Viscometer but one of the footnote says, "The Specifications can be waived at the Discretion of the specifying agency if the supplier warrants that the binder can be pumped and maintained at a temperature that meets all safety standards."

DR. BAHIA: My point of view based on my understanding of the specification is that this is a workability parameter. If you are within that limit for the viscosity, your asphalt should be workable enough and pumpable. It is a measure of workability of the binder. The numbers of 9 and 11 that you show means that your binder is not workable enough to effectively build the pavement.

MR. GOWDA: What concerns me is that the SHRP specification indicates a maximum allowable value for the Brookfield Viscosity and dilutes it by waiving from safety considerations. What if the binder is overheated to achieve the viscosity?

DR. BAHIA: Tom Kennedy has a very good answer for that. He always says that if the contractor cannot pump his binder, why are we worried about it. He is not going to be able to build the pavement. I think that is a very reasonable statement. If you are a producer and you cannot deliver the material to its final position, you are not going to be in business any more.

MR. GOWDA: Thank you.

MR. JAMES SORENSON: I perhaps cannot give you any answers but I would like to address some of the questions that were raised on what we are going to do with some of these nonhomogeneous mixtures and how they react. We do not believe the SHRP tests were developed to test crumb rubber. And we do not think we understand the fundamental properties of crumb rubber and its reaction and interaction with a lot of our test procedures. To go beyond that, we don't believe that many waste materials or other products that are being considered as an additive in neat binders are fully understood. Be that as it is, perhaps some of our research people here can expand on it, if necessary. FHWA has a half million dollars in fundamental research on rubber asphalt underway at Western Research Institute, Laramie. This project is in its second year of research. We expect to get some fundamental characteristics out of that. We are just finalizing award of a joint pool fund research project which will look at rubber asphalt mixtures and their performance in the field. The target of that is to come up with some mixture design parameters as well as performance indicators. But I would not look for results from that until 1997 to 1999.

We are being pressed to look at a lot of things. I think many of the questions raised by Arkansas are valid but there are not defined answers. To try to take a look at some of the issues with long term performance, our research office has 20 states participating in a pooled fund accelerated load test which is planned to start next year. We do not anticipate results from that until 1996 or 1997. I brought it up last year. I brought it up earlier this week. We have a lot of basic fundamental questions with dealing with waste in asphalt pavements. I think we all need to keep raising the questions and raising the issues. Let's go out and do some of the research collectively to get some of the answers.

DR. BAHIA: Thank you. I think you are right. The SHRP test systems were not developed to address crumb rubber. However, we have the system which can be used effectively. I think we all have to try to use it for this modifier as well as other modifiers and come up with a final modified procedure. These instruments can measure fundamental properties. There is nothing, I think, that can stop us from incorporating any modifier and using it with these testing devices.

MR. ROBERT DUNNING: We have had experience on asphalt rubbers for over several decades. In fact, when they first started talking about the work in Washington, we did the mix design for the hot system. If you go out to ski in British Columbia you will go over roads for which we designed the mix for the British Columbia Ministry of Transportation. I will answer some of your questions. One, you asked about interaction. In the late 1970s we had some 'yearsly buttons'. Little rubber buttons we had manufactured and vulcanized to the point where all the sulfur was used up. Then we compared the swelling of those 'yearsly buttons' with the swelling of the same buttons in Toluene. Those in the rubber industry use swelling as a measure of cross-link density. So this is a well known system in another field. So we found two things: 1) the swelling was about a factor of 2 (two) so we anticipate that the rubber (SBR) should swell about a factor of 2 (two). Then we could use the swell of those buttons as a guide as to how much crumb rubber we should use to get the particular viscosity. Different asphalts have a different solubility parameter so they swell differently. 2) One has to be very careful on generalizing too much. If you have all truck tires, which is natural rubber, you will find that your storage stability will disappear because the isoprene molecule comes apart at high temperatures where the SBR does not. So I would be careful about being a little too general.

You asked about the mass loss. In 1978 we published a paper that showed that the RTFO test, for example, is essentially an air blowing process. In fact, in the laboratory at Douglas Oil we used the RTFO to mimic air blowing and were able to correlate the results with our air blowing stills at the plant. In air blowing there are really two separate oxidation mechanisms. One is a polymerization which increases the viscosity. The other is a chain sission which ends up in an air blowing still as extra oil coming which comes over the top. In some of the literature they talk about anti-oxidants for asphalt. If you look at the anti-oxidants they are using you will find that they are free radical accelerators. So I would suggest that the mass loss is caused by the free radical accelerators which are used for vulcanization acceleration of rubber that accelerates the chain sission, which is the second mechanism in air blowing, and just causes a higher loss of these chains. I would suspect that is probably the most logical explanation for that.

With respect to the high mixing temperatures, contractors involved in it don't have any trouble making the mix. We have been involved in quite a few different jobs. In reality contractors usually know what they are doing and they will find a way to do it.

DR. BAHIA: Thank you, Bob, for those comments. I want to emphasize the point that crumb rubbers derived from truck tires are not similar to what I have used here. There was a good reason why we selected only passenger tires. If you read the FHWA documents and other research on crumb rubber, truck tires are re-used right now. They are being recycled cost effectively. It is my understanding from the literature that the problem is with the passenger tires because they cannot be effectively recycled.

DR. MARK BOULDIN: Thanks a lot, Hussain, for a very good paper. One thing I wanted to ask you after doing all the SHRP testing on these ground tire rubber modified asphalts. We know the next binder specification is going to effectively exclude ground tire rubber from meeting the PG grades because of the solubility test that we are incorporating to get around the dangers that we see with mineral fillers, etc. Do you feel similarly to Ron Reese that we should come up with a specification specifically written around SHRP specifications for ground tire rubbers that would be another PG grade? For example, we would have PG homogenous and a PGGTR or something like that. Is that your recommendation?

DR. BAHIA: No. I don't think so. I think we need to establish further relations between these binder properties we are measuring and mixture properties before we proceed. Again, you mentioned SHRP specifications, I made it a point that nothing on my slides showed an absolute value. I am talking about differences in fundamental engineering properties. I do not want to give the impression that if the G*/sinδ is increased from 1 to 10, you are getting 10-fold of better performance. We need to establish the relations between the binders and mixtures before we recommend any specifications for the crumb rubber. The main emphasis of this study was to find out whether these SHRP tools, not the specifications, the devices and the fundamental properties can really tell us anything about what is the value of the crumb rubber in the asphalt, if any.

DR. BOULDIN: Are you going to proceed into mix testing?

DR. BAHIA: That is right. This year we are doing the mixture testing and hopefully other people will do more. Then we can really establish a good relation between the crumb rubber modified binder properties and the mixture properties.

MR. GEOFF ROWE: I enjoyed your paper, Hussain, as usual, you do a very good job. I have a comment regarding, again, this effect of comparing like with like. To determine your compaction temperature you are measuring at a viscosity, but you have a solid componenet. This is a two-phase system. So what does the actual value of viscosity mean with relation to compaction? With compaction, perhaps we should be more interested in how the mix is behaving rather than the binder viscosity. Particularly since we have the solid rubber content. I think that this problem, and I would be interested if you would comment on it, not only extends to asphalt rubbers but other modifiers. Many producers of modifiers comment that the materials can be compacted yet they have higher viscosities and higher mixing temperatures. I think this is an issue that we need to look at because it not only affects the selection of the modifier but it has other compounding effects upon compaction temperature and how you actually do your mix designs.

DR. BAHIA: You know the rotational viscosity is certainly an indicator of resistance to flow. The contractor is interested in that. He wants to know how much flow resistance is there in this binder which is really the lubricant of the mix.

MR. ROWE: My feeling is that that viscosity requirement is based upon dense graded mixtures and conventional binders. With SHRP we are going to more open graded and coarser mixtures. In the UK we have different viscosity requirements for open graded materials versus dense graded materials because we see that these materials, the aggregate structure, affects the way the material compacts. I think there might be some problems when you are just going with a single viscosity and applying it to different mixtures with different aggregate structures.

DR. BAHIA: I agree with you. The viscosity is not going to tell you the whole story when you shift from one mix type to another. That is a very good point.

MR. RONALD REESE: I enjoyed your paper. The information is very timely. I'm glad to see that you provided us with a wealth of information and also your recognition that we need a lot more information. I hope others are also going to be adding to this discussion in the future. In the high temperature data that you showed, though you had so much information that you may have missed something I think is very important. You had a temperature range going from 5C up to 75C. Also the elastic contribution was watered down by using sinδ instead of looking at δ specifically. In either case, narrowing the temperature focus to between 60C and 70C it should be very disturbing that there are some rubber blends that show almost no elastic component. Almost identical to what just your base asphalt showed. That is alarming because the wet process material that we have all the good performance data on is distinctly different. We observe phase angles on the order of 60 to 70 degrees on those materials. The conclusion you drew I think could lead to problems if you were to take one of those without a large elastic component and use it in one of our asphalt rubber gap graded mixes for which we have extremely heavy loadings of binder. That might create some problems of binder migration.

DR. BAHIA: Thank you, Ron, for that comment. Let me answer first about the elasticity. First of all, you have to recognize this is a limited scope experiment. I included only four asphalts with only three rubbers. There is a good possibility if you use another rubber or another asphalt you will see enhancement in elasticity. What is of interest to me is looking at the whole spectrum of temperatures. Intermediate as well as moderately high temperatures. You mentioned about the $\sin\delta$ and the phase angle. You know very well my stand on this. I think $\sin\delta$ is more appropriate than the phase angle because $\sin\delta$ is related fundamentally to the energy dissipated. So we should use $\sin\delta$ rather than the phase angle. My conclusion is limited to the scope of the study. I think we need to do more work to investigate the issue of elasticity for CRM binders.

PROFESSOR IMAD AL-QADI: Hussain, a good job as usual. I have two questions. My first question is regarding the temperature. You mixed CRM at 160C. We had a job last year in Virginia in which we heated asphalt almost to 190C or 375F and when added 10 percent rubber, temperature dropped to about 320F. In your case, when you added the rubber did temperature drop to 140C? Did you consider in the one hour mixing time the drop in temperature period? Also, how long did it take to reach 160C again.

DR. BAHIA: We actually did a lot of work before we selected the 160C. I don't think it is appropriate to go to a higher temperature. You start destroying your base material.

PROF. AL-QADI: Right. I agree.

DR. BAHIA: You are trying to modify it. It really does not make sense to go to very high temperatures and damage the asphalt. About mixing, what we actually observed in all of our rubber mixing was a slight drop in the temperature when you add the rubber, but after about 30 minutes you see a very rapid extrothermic phenomenon. Temperatures start increasing to the level where we have to stop the heating and we have to control the rise in temperature. All these mixes were done at very well controlled temperatures 160C ± 5C. I have read in some of the literature that there is an endothermic reaction. We have not observed that with our systems. We had a surge of temperature and we had to control it by cooling the systems to keep temperature constant.

PROF. AL-QADI: Was the same pattern observed in the four different types of asphalt and three types of rubber?

DR. BAHIA: Yes.

PROF. AL-QADI: My second question is regarding the maximum size of rubber that was used; it is 1 mm. Do you think that would influence the results from the dynamic shear rheometer especially that we have a 2-mm gap? Is that what you used, 2 mm?

DR. BAHIA: Yes we used 2 mm. We did not really evaluate that. We evaluated the effect of the gap on the measurements. We observed that there is a very small effect. We did not have enough resources to try different sizes of the rubbers. The focus was on effects of different rubbers.