# Crumb Rubber Modification of Binders: Interaction and Particle Effects

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ABSTRACT: *Crumb rubber has been used to enhance the performance of hot mix asphalt pavements since the 1960s by improving the rheological properties of the crumb rubber modified (CRM) binders. Several researchers have identified the CRM-binder interaction as diffusion of the lighter binder fractions into the CRM particles. This physical interaction is two-fold: (1) the rubber particles swell and (2) the viscosity of the binder matrix increases due to removal of a portion of the oily fraction. While this interaction has been the major consideration with CRM binders, the effect of the CRM particles acting as fillers has not received much attention. This investigation resulted in a method to quantify both the interaction effect (IE) and particle effect (PE) of CRM, which contribute to the increased rheological properties of CRM binders. These effects were determined using a rotational viscometer and a dynamic shear rheometer (DSR) to measure the rheological properties of CRM binders produced with three sizes of CRM, two crumb rubber processing methods (ambient and cryogenic grinding), two CRM contents, and three binder sources. It was concluded that binder source had a significant effect on the IE, followed by CRM content. The PE was most significantly affected by the CRM content, followed by the CRM particle size.*

KEYWORDS: *Crumb rubber, asphalt, binder, rheology, asphalt-rubber, scrap tires.*

## 1. Introduction

In 2003, approximately 290 million scrap tires were generated in the United States. This scrap tire problem has become a major issue in the past 15 years as the number of scrap tires has steadily increased since 1990 when 233 million scrap tires were generated. While the number of scrap tires has increased, available disposal space has declined. In 2003, approximately 80% of the scrap tires generated were utilized in some market such as tire derived fuel, civil engineering applications, and rubber modified asphalt. The remaining scrap tires were disposed of either in landfills, or some other way, legally or not. While there has been significant progress, there is still more that must be done to further lessen the burden on the environment as many states have established legislation imposing restrictions on the disposal of scrap tires (RMA, 2004).

One method to beneficially utilize scrap tires is to use crumb rubber to modify hot mix asphalt (HMA). Crumb rubber is produced by processing whole tires using some form of grinding method, at either ambient or cryogenic temperatures, to reduce the size of the rubber to a fine powder having particle sizes generally smaller than 2 mm (RMA, 2004). In the United States, the addition of crumb rubber, or crumb rubber modifier (CRM), is typically accomplished using the “wet” process in which the CRM is blended with the asphalt binder to produce a CRM binder that is then mixed with the aggregate.

This concept of utilizing scrap tire rubber in asphalt was initially developed in the mid-1960s for use in asphalt surface treatments. In the 1970s, the use of CRM expanded to HMA and has continued to evolve since the CRM binders provide enhanced performance of asphalt mixtures, including increased resistance to permanent deformation and thermal and fatigue cracking (Heitzman, 1992).

While the utilization of CRM in HMA has significantly evolved in the past three decades, there are still topics that have not been completely explained and several assumptions that have been accepted, but not completely validated. One such topic is the interaction that occurs between the CRM and the binder. It has been established that the interaction between CRM and asphalt binders is a physical one in which the CRM, through diffusion, absorbs a portion of the aromatic fraction of the asphalt binders resulting in swelling of the CRM particles. This particle swelling compounded with the reduction in the oily fraction of the binder results in an increase in the CRM binder viscosity. Such an increase in viscosity results in a thicker film coating on the aggregate particles in hot mix asphalt (HMA) mixtures. The increase in film thickness provides for a more durable HMA mixture showing increased resistance to oxidative aging and thermal and fatigue cracking (Heitzman, 1992).

There are several factors that play a role in the CRM-binder interaction. On the part of the binder, the interaction depends on the amount of the aromatic fraction, the temperature, and the viscosity. The properties of the CRM that can affect the interaction include production method (ambient or cryogenic grinding), particle size, specific surface area, and chemical composition (i.e., amount of natural rubber) (Heitzman, 1992). Throughout the years, it has been reported that the specific surface area of CRM is the most important physical property of the crumb rubber influencing the interaction (Heitzman, 1992; West *et al*., 1998; and LaGrone, 1980). This finding has been based on the viscosity of the CRM binders tested.

Since the interaction that occurs with CRM binders is dependent on the presence of aromatic oils in the asphalt binder, the source of the base asphalt binder has a significant effect on the performance of CRM binders. There are many different asphalt binder sources around the world, having different chemical compositions, so it is imperative to utilize binders that are compatible with crumb rubber when producing CRM binders.

The majority of the CRM binders produced in the United States use ambient ground CRM due to its increased surface area as compared to CRM produced by the cryogenic grinding method. The two methods produce CRM having different surface morphology. Grinding at ambient temperatures produces CRM having rough and irregular surfaces. In contrast, the cryogenic grinding method creates angular and relatively smooth surfaces as the result of fracturing rubber particles that have been frozen with liquid nitrogen. The irregular shape of the ambient ground CRM has higher surface area than that produced using the cryogenic grinding method (Blumenthal, 1994).

In addition, CRM size also influences the surface area of the CRM and, therefore, the interaction of CRM binders. Typically, engineers have preferred finer CRM particles (-40 mesh [0.425 mm]) over coarser material. However, in states such as Arizona and California, the preferred CRM size is in the -14 mesh (1.4 mm) range (Hicks *et al*., 1995). The CRM binders produced with these coarser CRMs have performed successfully for decades, indicating that CRM surface area may not be the most important factor influencing the interaction that occurs in CRM binders.

Another factor that differs from state to state regarding CRM binders is the amount of CRM that should be used. While some states, such as Arizona and California, require CRM contents of at least 15% by weight of binder, other states such as Florida and South Carolina utilize CRM in the 10% range depending on the application (Hicks *et al*., 1995). As the CRM binder properties depend on the particle size of the CRM, they are also influenced by the CRM content—as the content increases, the properties (e.g., rut resistance, crack resistance, and fatigue resistance) are enhanced (Chehovits, 1989).

Most studies that have examined the interaction of CRM binders have used viscosity to measure the interaction. While this property is important for the pumpability of binder and workability of the HMA, it does not directly relate to the in-service performance of the binder within an HMA mix. Additionally, due to the non-Newtonian behavior of most particulate filled liquids, such as CRM binder, viscosity measurements alone lack sufficient precision to adequately describe the complex properties of such systems (Wypych, 2000). In the Performance Grading system for asphalt binders developed by the Strategic Highway Research Program (SHRP), the high temperature performance of binders is determined using a dynamic shear rheometer (DSR). Data of importance from this test include the complex shear modulus (G*) and the phase angle (δ) of the binder (The Asphalt Institute, 2003). Few researchers have utilized a DSR to measure the interaction of CRM binders.

In CRM binders, there are essentially two effects of the CRM that were identified in this research: interaction effect (IE) and particle effect (PE). The IE is the effect of the CRM absorbing the aromatic oils from the binder. The PE is the effect of the CRM as a filler in the binder (Putman, 2005). As with any filler, the addition of CRM affects the rheology of the binder by increasing the viscosity and reinforcing the binder to some extent (Wypych, 2000). These two effects were determined by separating the CRM from the binder and comparing the CRM binder to the binder recovered after separation.

The primary objective of this study was to develop a method to quantify the interaction effect (IE) and particle effect (PE) of crumb rubber in CRM binders. This was accomplished using a rotational viscometer and dynamic shear rheometer (DSR) to measure the rheological properties of 18 CRM binders and three control binders.

## 2. Experimental Materials and Methods

A flowchart illustrating the experimental design for this study is included in Figure 1. A total of 21 binders (18 CRM and three base, or control) were tested to measure the specific effects of crumb rubber modification. Three base binders, each being a PG 64-22, were evaluated in the research. Each binder was from a different source: Venezuelan, Middle Eastern, and an unidentified blend. Because each of the binders was from a different crude source they exhibited different compositions.

Three different sizes of crumb rubber were used to produce the CRM binders in the laboratory. A single source of ambient ground crumb rubber was obtained and separated into individual size fractions. The sizes included in this study included the material passing the No. 16 (1.18 mm) sieve and retained on the No. 20 (0.850 mm), passing the No. 30 (0.600 mm) sieve and retained on the No. 40 (0.425 mm), and that passing the No. 50 (0.300 mm) sieve and retained on the No. 80 (0.180

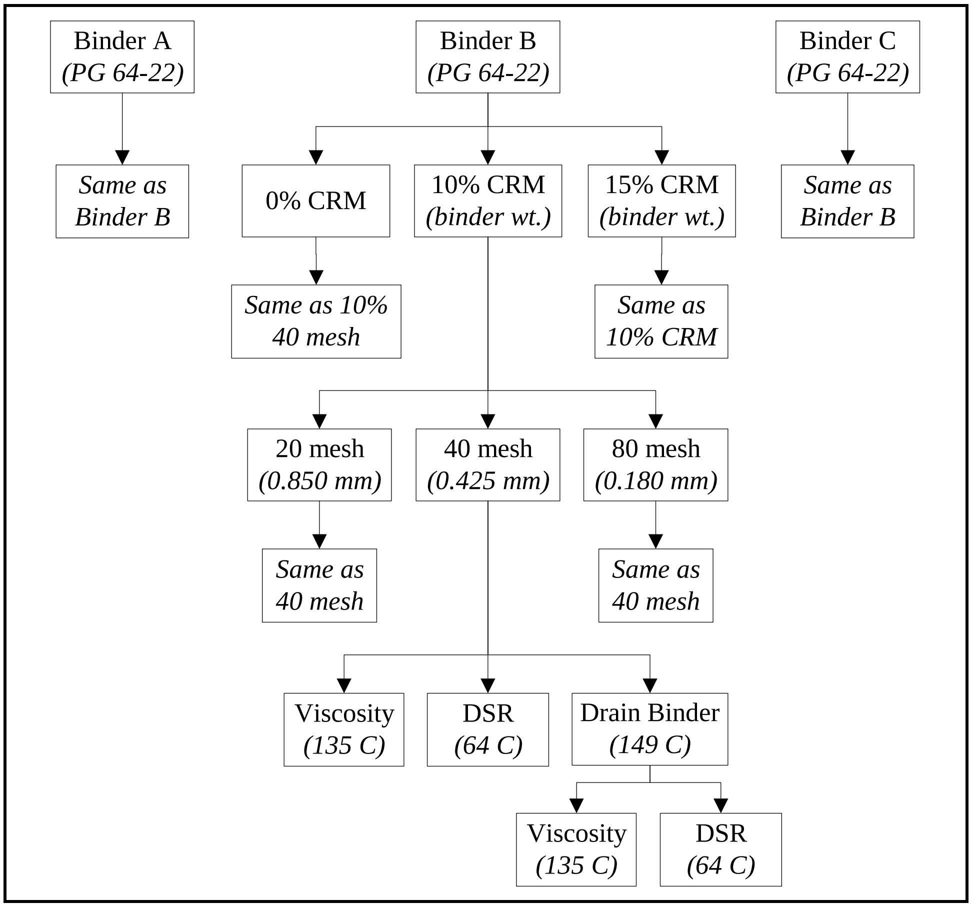

**Figure 1** *Flowchart of the experimental design.*

mm) sieve. Individual sizes were selected to minimize the effects of particle size gradation on the rheological properties of the CRM binders. Additionally, these particular sizes were selected to represent the range of crumb rubber used to modify asphalt binders across the United States.

CRM binders were produced with two rubber contents: 10 and 15% by weight of binder. These CRM contents were selected to examine how the binder is affected by different quantities of rubber. These percentages also represent typical ranges of CRM utilized in asphalt applications.

Each CRM binder was produced in the laboratory using a mechanical mixer to blend the crumb rubber with the binder. A can containing 600 g of binder was heated to 182°C and placed on a sand bath over a hot plate. A high-shear radial flow impeller attached to the mixer was then placed in the binder and stirred the binder at a speed of 700 rpm. The appropriate quantity of room temperature crumb rubber was then continuously, but gradually added to the binder. All of the rubber was added within the first two minutes of mixing and mixing continued for 30 minutes while the temperature of the binder was maintained at 177°C for the duration (Putman *et al.*, 2005). After mixing, each can of binder was allowed to cool to room temperature for 24 hours before being reheated for testing.

A rotational viscometer was utilized to measure the viscosity of each binder at 135°C per AASHTO T316 (AASHTO, 2002). For CRM binders, a 10.5 g binder sample was tested with a number 27 spindle. The control binders were tested in accordance with the same procedure except an 8.5 g sample was tested with a number 21 spindle. A different test configuration was used for the CRM binders to allow additional space for rubber particles between the wall of the sample tube and the smaller diameter number 27 spindle. This configuration, however, does not provide the precision needed to test the control binders having significantly lower viscosities than the CRM binders.

Three viscosity measurements were recorded for each of three replicates for each binder. For all binders, each specimen was poured just prior to testing. Prior to pouring each sample, the can of binder was thoroughly stirred to insure homogeneous dispersion of the CRM throughout the binder.

The high temperature rheological properties of each binder were measured using a dynamic shear rheometer (DSR) per AASHTO T315 (47). The complex shear modulus (G*) and phase angle ($\delta$) of each binder was measured at 64°C. Each binder was tested in its unaged condition using a 25 mm parallel plate set up at a frequency of 10 Hz.

The CRM binders were tested using a 2 mm gap between the plates, while a 1 mm gap was used for the control binders. Since all of the binders were tested in the linear visco-elastic region, the different gap sizes did not affect the comparison of the CRM binders with the control binders. This has also been observed by other researchers (Tayebali *et al*., 1997).

Previous research conducted by several researchers used a 2 mm gap to test CRM binders using a DSR (Bahia and Davies, 1994 and 1995 and Tayebali *et al*., 1997). In each of these studies, the CRM binders tested with the 2 mm gap were tested in the linear visco-elastic region and the data had less variability than with the 1 mm gap. This decreased variability was attributed to less contact of the CRM particles with both of the parallel plates. If a 1 mm gap was used to test a CRM binder containing CRM that measured 1 mm or greater, the CRM particles would contact the plates and the resulting measurement would be a reading of the rheology of the CRM particles instead of the binder, therefore providing inaccurate results.

After testing of the binders, each binder was separated from the CRM to test the rheological and chemical properties of the drained binders. This separation was accomplished by first heating the can of binder in a 163$^{o}$C oven for approximately 60 minutes after which the binder was thoroughly stirred to homogeneously disperse the CRM throughout the binder. After stirring, 100 g of binder were poured into a 76.2 mm diameter 80 mesh (0.18 mm) sieve nested in a custom made retaining ring that rested on a metal sample container (Figure 2). The draining setup was placed in a 149$^{o}$C oven for 30 minutes. This temperature was selected as the binder was fluid enough to flow through the sieve. This caused the binder to separate from the CRM and accumulate in the sample container; while the CRM and any associated binder remained in the sieve. The absence of CRM particles in the drained binder was verified visually in each case. This process was conducted on all of the CRM binders as well as the control binders to ensure that all of the binders underwent identical conditioning.

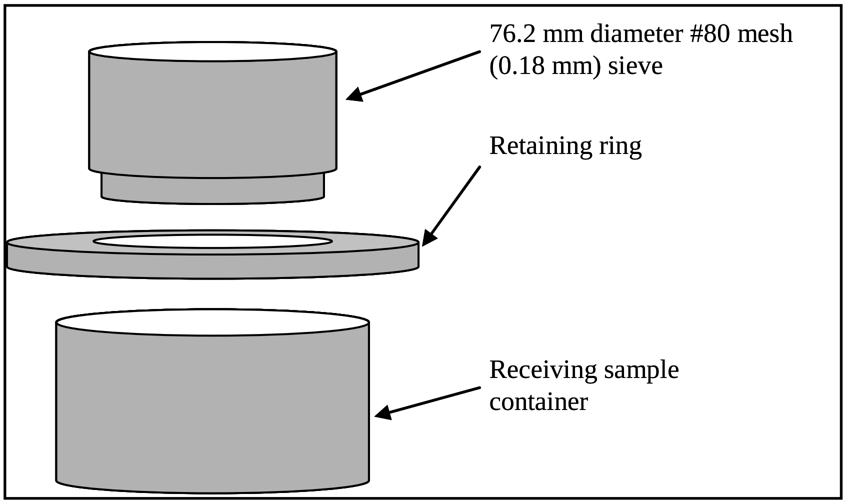

**Figure 2** *Schematic of CRM binder draining setup.*

After draining, each recovered binder was tested using the rotational viscometer and DSR. The viscosity was tested in the same manner as the undrained control binders (i.e., 8.5 g specimen and number 21 spindle). The G* and δ were also measured with the DSR in the same manner as the undrained control binders (i.e., 1 mm gap). A 1 mm gap was utilized due to the fact that the CRM was removed, eliminating the necessity to use a larger gap. Additionally, preliminary testing on control binders indicated no statistically significant differences between the binders tested with 1 and 2 mm gaps.

## 3. Experimental Results

The results of this study are presented in the following section. The results of analysis of variance (ANOVA) tests followed by Fisher's test for least significant difference are presented in the figures through the use of letters. Binders having at least one letter in common, produced statistically similar results at the 95% confidence level ($\alpha = 0.05$).

### *3.1. CRM Binder Viscosity*

The viscosity results of the base and CRM binders are included in Table 1 and Figure 3. It can be seen that the addition of crumb rubber to the binder significantly increases the viscosity of the binder. Additionally, the viscosity of the CRM binders significantly increased with increasing CRM content. This finding was expected as the additional filler material will naturally increase the viscosity of the binder.

**Table 1** *Viscosity results of CRM binders tested at 135°C.*

| Binder Source | Viscosity, *Pa-s* | | | | | | |
|---|---|---|---|---|---|---|---|
| | | 10% CRM | | | 15% CRM | | |
| | Base | 20 mesh | 40 mesh | 80 mesh | 20 mesh | 40 mesh | 80 mesh |
| **A** | 0.703 | 2.332 | 2.560 | 2.709 | 4.796 | 5.471 | 5.974 |
| **B** | 0.472 | 1.553 | 1.409 | 1.447 | 2.832 | 3.524 | 3.892 |
| **C** | 0.430 | 1.467 | 1.363 | 1.455 | 3.047 | 3.512 | 3.803 |

Based on the results of the viscosity testing, it is evident that the binder source has the largest effect on the viscosity of the CRM binders. The base binder from source A had the greatest viscosity of the three binders and it produced the CRM binders having the highest viscosities. Base binders B and C had similar viscosity and as such produced CRM binders of generally similar viscosity with a given crumb rubber size and content.

The size of the crumb rubber particles also influenced the viscosity of the CRM binders. Generally, the finer CRM produced binders with greater viscosity. This trend is clearly shown for binder A, while the CRM binders made with binder source B and C followed this trend at the 15% CRM content.

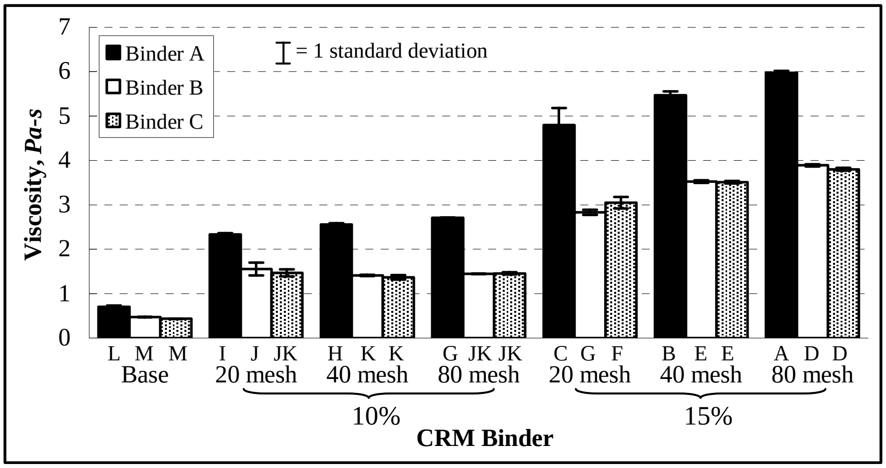

**Figure 3** *Viscosity results of CRM binders tested at 135$^o$C.*

### *3.2. CRM Binder Complex Shear Modulus (G*)*

The complex shear modulus, G*, results from testing the base and CRM binders with the dynamic shear rheometer (DSR) at 64$^o$C are included in Table 2 and Figure 4. As with the viscosity, the addition of crumb rubber to asphalt binder increases the high temperature stiffness (G*) of the binders. Also, the G* increases with the amount of CRM added to the binders.

The size of the CRM did not show the same trend with the binder G* as with the viscosity as seen when comparing the G* results with the viscosity results in Figure 3. The complex shear modulus generally decreases with CRM size at both 10 and 15% CRM and for all three binders. Similar findings have been previously reported with the explanation that coarser materials are more resistant to flow than finer particles (Abdelrahman and Carpenter, 1999).

**Table 2** *G* results of CRM binders tested at 64$^o$C.*

| Binder Source | G*, *kPa* | | | | | | |
|---|---|---|---|---|---|---|---|
| | | 10% CRM | | | 15% CRM | | |
| | Base | 20 mesh | 40 mesh | 80 mesh | 20 mesh | 40 mesh | 80 mesh |
| **A** | 1.995 | 6.864 | 6.928 | 6.034 | 10.179 | 10.116 | 9.578 |
| **B** | 1.537 | 3.662 | 3.265 | 3.312 | 5.451 | 5.606 | 5.070 |
| **C** | 1.361 | [$] | 3.908 | 3.875 | 6.119 | 5.727 | 5.074 |

[$] *Sufficient material was not available to complete this test*

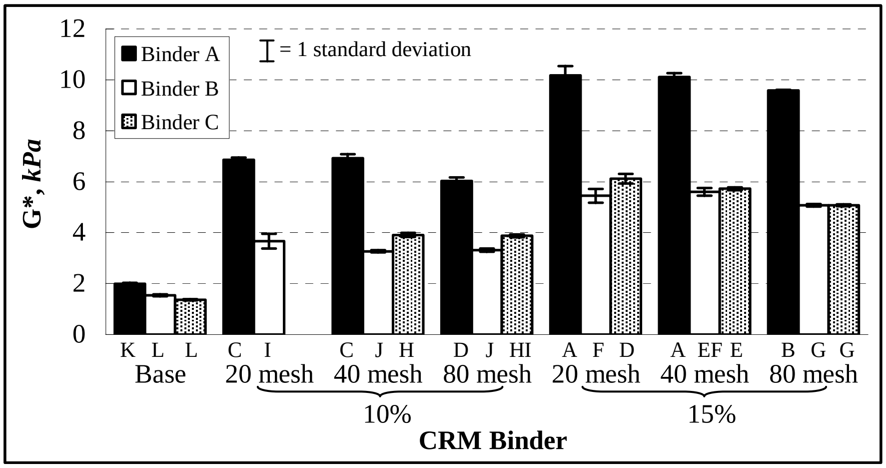

**Figure 4** *G* results of CRM binders tested at 64$^o$C.*

### *3.3. Drained CRM Binder Rheological Properties*

After the crumb rubber was removed from the CRM binders via a draining procedure, the viscosity and G* were measured on the remaining binder residue. The viscosity results are included in Table 3 and Figure 5 and the G* results are presented in Table 4 and Figure 6. After examination of the results it is evident that the viscosity and G* of the drained binders are greater than those of the base binders. This indicates that the crumb rubber particles do, in fact, absorb some of the lighter fractions of the binders as a result of the CRM-binder interaction. The rheological properties of the drained binders also increase with the crumb rubber content indicating that when more rubber is present, it will absorb more of the lighter binder fractions.

**Table 3** *Viscosity results of drained CRM binders tested at 135$^{o}$C.*

| | **Viscosity, *Pa-s*** | | | | | | |
|---|---|---|---|---|---|---|---|
| | | **10% CRM** | | | **15% CRM** | | |
| **Binder Source** | **Base** | **20 mesh** | **40 mesh** | **80 mesh** | **20 mesh** | **40 mesh** | **80 mesh** |
| **A** | 0.628 | 0.913 | 0.934 | 0.951 | 1.105 | 1.164 | 1.149 |
| **B** | 0.476 | 0.546 | 0.545 | 0.554 | 0.599 | 0.623 | 0.626 |
| **C** | 0.430 | $ | 0.558 | 0.572 | 0.593 | 0.606 | 0.614 |

$ *Sufficient material was not available to complete this test*

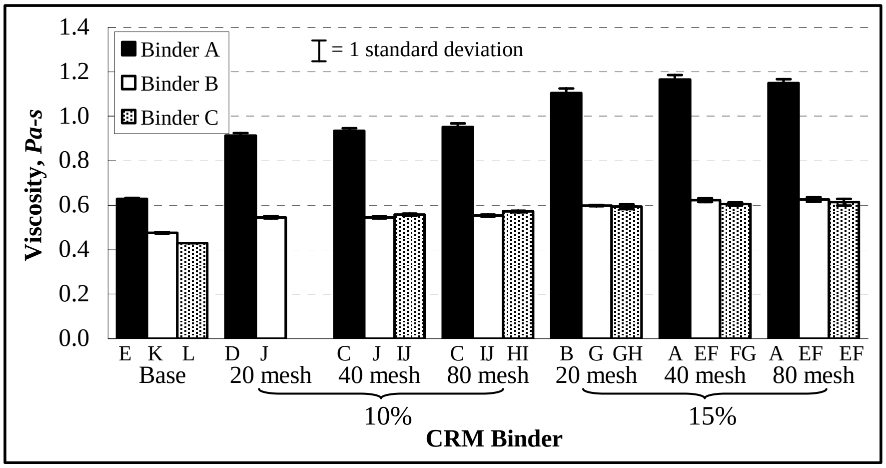

**Figure 5** *Viscosity results of drained CRM binders tested at 135$^{o}$C.*

**Table 4** *G* results of drained CRM binders tested at 64$^{o}$C.*

| **Binder Source** | **G*, *kPa*** | | | | | | |
|---|---|---|---|---|---|---|---|
| | | **10% CRM** | | | **15% CRM** | | |
| | **Base** | **20 mesh** | **40 mesh** | **80 mesh** | **20 mesh** | **40 mesh** | **80 mesh** |
| **A** | 2.038 | 3.716 | 3.978 | 3.760 | 4.990 | 5.179 | 4.803 |
| **B** | 1.565 | 1.899 | 1.834 | 1.850 | 2.140 | 2.387 | 2.375 |
| **C** | 1.341 | [$] | 2.024 | 2.263 | 2.287 | 2.405 | 2.290 |

[$] *Sufficient material was not available to complete this test*

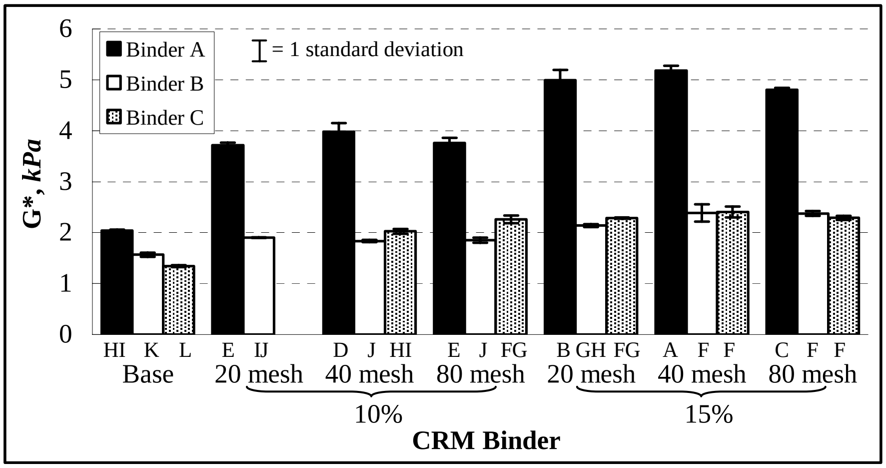

**Figure 6** *G* results of drained CRM binders tested at 64$^o$C.*

### *3.4. Determination of Interaction and Particle Effects*

As a result of the analysis of the rheological properties of the CRM binders and the drained binders, it was clear that the absorption of the light binder fraction by the crumb rubber (interaction) was not the sole cause of the increases in viscosity and G*. There was another factor, which was the result of the rubber particles acting as a filler within the binder. To quantify these effects, the terms interaction effect (IE) and particle effect (PE) were developed. The IE is the effect of the crumb rubber absorbing the light binder fractions and the PE is the effect of the rubber particles as fillers in the binder. These terms are defined by equations 1 and 2 and graphically by Figure 7. The IE and PE can be applied to both viscosity and G*.

$$IE = \frac{Drained - Base}{Base} \qquad [1]$$

$$PE = \frac{CRM - Drained}{Base} \qquad [2]$$

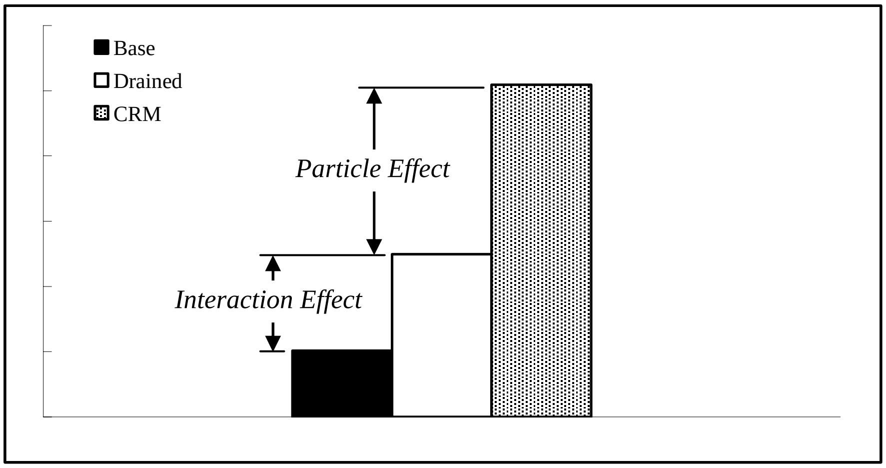

**Figure 7** *Definition of interaction effect (IE) and particle effect (PE).*

### *3.5. Interaction and Particle Effects on CRM Binder Viscosity*

The interaction effects of crumb rubber modification (IE) on the viscosity of CRM binders produced with binder sources A, B, and C are presented in Table 5 and Figure 8. The IE of the CRM binders is not greatly affected by the particle size of the crumb rubber. The largest influence on the IE is the binder source. Binder source A shows statistically significantly higher IE values than binder C, which has higher values than binder B. This indicates that although base binder B had a similar viscosity to binder C, it is not as compatible with the crumb rubber. Evidence of this is seen with the increased IE values of all of the CRM binders produced with binder C over those made with binder B. Binder A appears to be the most compatible of all with respect to viscosity. Additionally, the IE is magnified by the amount of crumb rubber present in the CRM binder.

**Table 5** *Interaction effects (IE) of CRM on the viscosity of CRM binders.*

| | Viscosity IE | | | | | |
|---|---|---|---|---|---|---|
| **Binder** | **10% CRM** | | | **15% CRM** | | |
| **Source** | **20 mesh** | **40 mesh** | **80 mesh** | **20 mesh** | **40 mesh** | **80 mesh** |
| **A** | 0.45 | 0.49 | 0.51 | 0.76 | 0.85 | 0.83 |
| **B** | 0.15 | 0.14 | 0.16 | 0.26 | 0.31 | 0.31 |
| **C** | [$] | 0.30 | 0.33 | 0.38 | 0.41 | 0.43 |

[$] *Sufficient material was not available to complete this test*

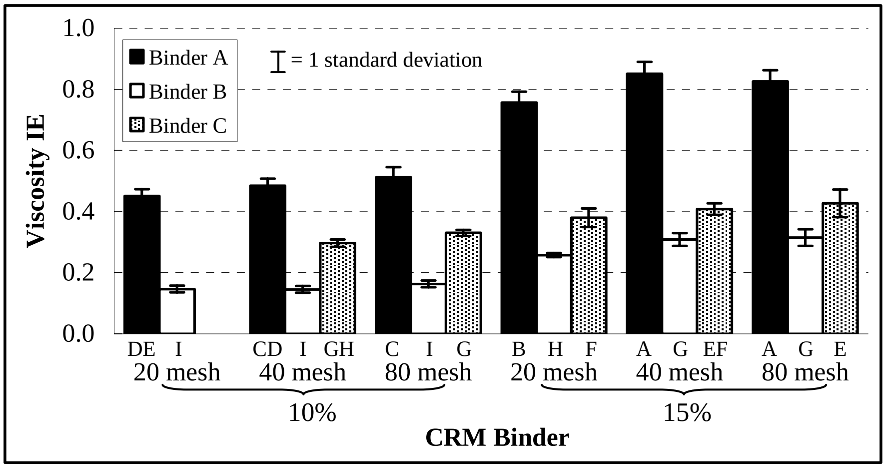

**Figure 8** *Interaction effects (IE) of CRM on the viscosity of CRM binders.*

The PE values for viscosity of the CRM binders are summarized in Table 6 and Figure 9. The PE has the most significant effect on the viscosity of the CRM binders as these values are much greater than the IE values. Additionally, at a CRM content of 15%, the PE is significantly influenced by the size of the rubber particles. Finer CRM resulted in greater PE values as was also seen in the viscosity results of the CRM binders.

**Table 6** *Particle effects (PE) of CRM on the viscosity of CRM binders.*

| **Binder Source** | **Viscosity PE** | | | | | |
|---|---|---|---|---|---|---|
| | **10% CRM** | | | **15% CRM** | | |
| | **20 mesh** | **40 mesh** | **80 mesh** | **20 mesh** | **40 mesh** | **80 mesh** |
| **A** | 2.26 | 2.58 | 2.80 | 5.87 | 6.85 | 7.65 |
| **B** | 2.12 | 1.81 | 1.88 | 4.69 | 6.09 | 6.86 |
| **C** | $ | 1.87 | 2.05 | 5.71 | 6.76 | 7.45 |

$ *Sufficient material was not available to complete this test*

### *3.6. Interaction and Particle Effects on CRM Binder G**

The IE values based on the G* results of the CRM binders are presented in Table 7 and Figure 10. As with the viscosity results, the binder source has the greatest influence on the IE. Binder A produced the greatest IE values, followed by binder C, and then binder B. While base binders B and C had similar G* values, the IE of the CRM binders produced with binder C were significantly greater than binder B. This indicates that binder C is more conducive to crumb rubber modification than binder B. There does not appear to be a consistent trend of IE with regard to particle size of the CRM, but the IE does increase with rubber content.

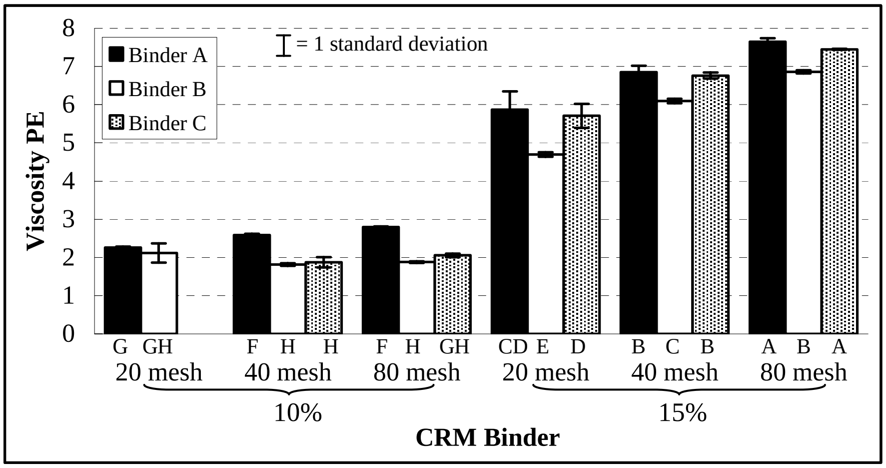

**Figure 9** *Particle effects (PE) of CRM on the viscosity of CRM binders.*

**Table 7** *Interaction effects (IE) of CRM on the G* of CRM binders.*

| **Binder Source** | **G* IE** | | | | | |
|---|---|---|---|---|---|---|
| | **10% CRM** | | | **15% CRM** | | |
| | **20 mesh** | **40 mesh** | **80 mesh** | **20 mesh** | **40 mesh** | **80 mesh** |
| **A** | 0.82 | 0.95 | 0.85 | 1.45 | 1.54 | 1.36 |
| **B** | 0.21 | 0.17 | 0.18 | 0.37 | 0.53 | 0.52 |
| **C** | [$] | 0.51 | 0.69 | 0.71 | 0.79 | 0.71 |

[$] *Sufficient material was not available to complete this test*

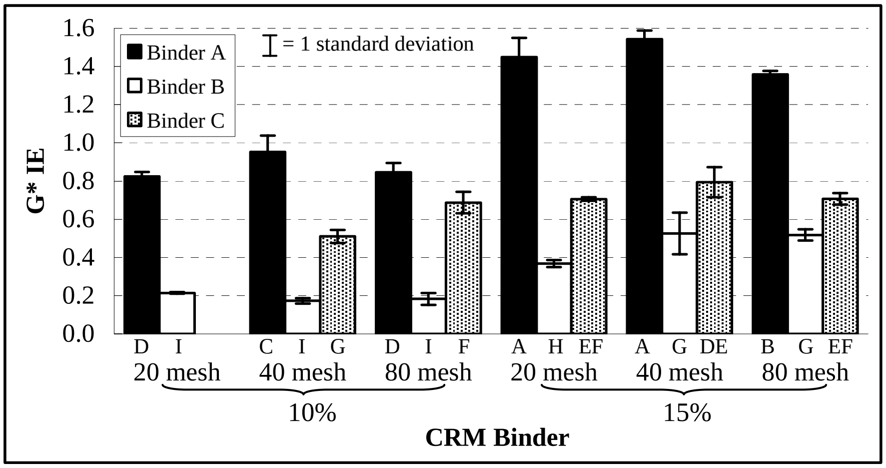

**Figure 10** *Interaction effects (IE) of CRM on the G* of CRM binders.*

Table 8 and Figure 11 summarize the PE of the crumb rubber on the G* values of the CRM binders. As with the viscosity PE, the G* PE is significantly influenced by the amount of CRM present in the binder. Also, the size of the rubber particles affected the PE on the binders. The trend was similar to that of the G* values of the CRM binders—the larger particles produced CRM binders having higher G* values than the finer rubber. Finally, the binder source showed significant influence on the PE values.

**Table 8** *Particle effects (PE) of CRM on the G* of CRM binders.*

| **Binder Source** | **G* PE** | | | | | |
|---|---|---|---|---|---|---|
| | **10% CRM** | | | **15% CRM** | | |
| | **20 mesh** | **40 mesh** | **80 mesh** | **20 mesh** | **40 mesh** | **80 mesh** |
| **A** | 1.55 | 1.45 | 1.12 | 2.55 | 2.42 | 2.35 |
| **B** | 1.13 | 0.91 | 0.93 | 2.12 | 2.06 | 1.72 |
| **C** | [$] | 1.40 | 1.20 | 2.86 | 2.48 | 2.08 |

[$] *Sufficient material was not available to complete this test*

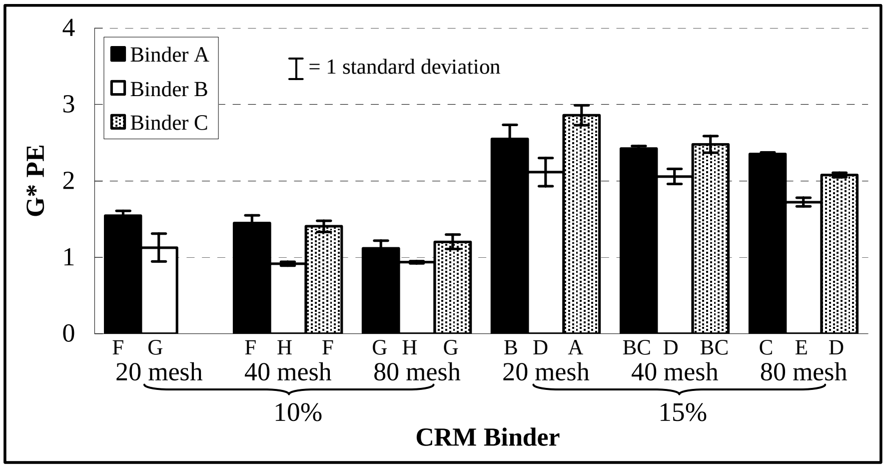

**Figure 11** *Particle effects (PE) of CRM on the G* of CRM binders.*

## 4. Conclusions

Based on the results of this study, the following conclusions were made:

- The addition of crumb rubber to asphalt binders increases the rheological properties of the binders.
- CRM binders containing 15% CRM, by weight of binder, had greater viscosity and G* values than those containing 10% CRM.
- The trend with CRM particle size was different for the viscosity and G* of the CRM binders. The viscosity increased with decreasing particle size, while the G* increased with particle size.
- The effects of CRM on asphalt binders can be separated into interaction effect (IE) and particle effect (PE). The IE is the effect of the lighter fractions of the binder diffusing into the CRM particles. The PE is the effect of the CRM particles acting as filler in the binder.
- The IE is greatly influenced by the crude source of the binder and could potentially be used as an indicator of a binder's compatibility with CRM. A higher IE value would indicate a more compatible binder.
- The IE is also significantly influenced by the amount of CRM present in the binder. Higher rubber contents yield greater IE values.
- The PE is most significantly affected by the CRM content of the binder. Higher CRM contents result in greater PE values.
- The effect of CRM size on the PE follows the same trends as either the viscosity or G* of the CRM binders.
- Binder source also influences the PE of a CRM binder, but not to the extent as the IE.

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