HIGH TEMPERATURE PROPERTIES OF CRUMB RUBBER MODIFIED BINDERS

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ABSTRACT: Each year, in the U.S. approximately 290,000,000 scrap tires are generated. There are many issues associated with the disposal of these tires, so there have been efforts to use these tires in civil engineering applications such as crumb rubber modified (CRM) asphalt. This study evaluated the high temperature properties of CRM asphalt binders made with varying sizes, types, and percentages of crumb rubber. In addition, two binder grades from two different crude sources were also included. A total of 108 CRM binders were tested in their original and rolling thin-film oven aged conditions using a rotational viscometer and dynamic shear rheometer. Results of this study indicated that the crumb rubber content had the largest effect on the high temperature properties. The size and type of crumb rubber also had significant effects on the CRM binder properties. Finally, the crude source was found to have a significant effect on the performance of the CRM binders.

KEY WORDS: Rubber, crumb rubber modifier, asphalt, binder, rheology, viscosity

1. INTRODUCTION

Each year, in the United States approximately 290,000,000 scrap tires are produced, which translates to approximately 1 tire/person/year [1]. There are many problems associated with these tires including disposal issues such as the banning of tires from landfills in many states. In addition, tire piles create breeding grounds for disease vectors such as mosquitoes. One solution to alleviating the scrap tire problem is to use them as crumb rubber modifier (CRM) in asphalt binders [2]. The use of scrap tires as CRM in asphalt mixtures has been investigated since the early 1960s. Since that time, several studies have been undertaken across the U.S. to insure the most efficient use of crumb rubber in the hot mix asphalt (HMA) mixtures.

However, there has been some speculation between researchers and engineers as to the optimum physical characteristics that crumb rubber should exhibit for the best performance as an asphalt binder modifier. This has raised the need for more research in the specific area of CRM binder specifications. When selecting crumb rubber for the modification of asphalt, some of the factors that the researcher/engineer must first consider include the type of binder and crumb rubber to use in the modification and the percentage and size of rubber to be used in the mix. Finally, the method in which the crumb rubber is mixed into the HMA has to be evaluated (i.e., dry method vs. wet method). In addition, the reaction time is an important factor that could potentially affect the properties of the modified binder.

There are many factors that need to be considered when determining the optimum combination of materials for CRM binders. For example, each crude source is different in chemical composition; therefore, each source could exhibit different mechanical properties. In addition, crumb rubber can be produced in almost any size from large aggregate sized particles to fine powder by employing several different production methods (i.e., ambient shredding or cryogenic grinding). With all of these factors contributing to the performance of the CRM binder, there is a need for CRM binder guidelines. It was the focus of this particular research to examine the effects of these factors on the performance of CRM binders produced by the wet process.

The primary objective of this research was to determine the effects of crumb rubber percentage, size, type, reaction time, and binder source on the high temperature properties of crumb rubber modified asphalt binders. Two virgin binder sources (C and P) and two grades (PG 58-22 and PG 64-22) were used for this research. Preliminary testing was completed to determine the best practices for mixing the crumb rubber into the asphalt binder. Only the high temperature characteristics were examined in this study. The failure temperatures for 108 original and RTFO aged CRM binders were determined using the dynamic shear rheometer (DSR). The rotational viscometer was used to examine the effects of crumb rubber on the binders' viscosity. The DSR was used to determine the failure temperature of each aged and original sample, which can be related to the binder's stiffness at a given test temperature.

2. MATERIALS AND METHODS

The experimental design used for this study is illustrated in Figure 1. Two types of crumb rubber (CR) were included in this research: Ambient and cryogenic. The ambient crumb rubber was produced by first shredding tires into approximately 38 - 50 mm chips, which were then passed through cracker mills and shredded into smaller particles. The steel and fiber were separated from the crumb rubber using magnets and blowers, respectively. The crumb rubber was sized using screens. The cryogenic production of crumb rubber began in a similar manner as the ambient process, but then the tire chips were frozen with liquid nitrogen and ground to size in a hammer mill. As with the ambient process, the steel and fiber were removed and the crumb rubber was sized using screens.

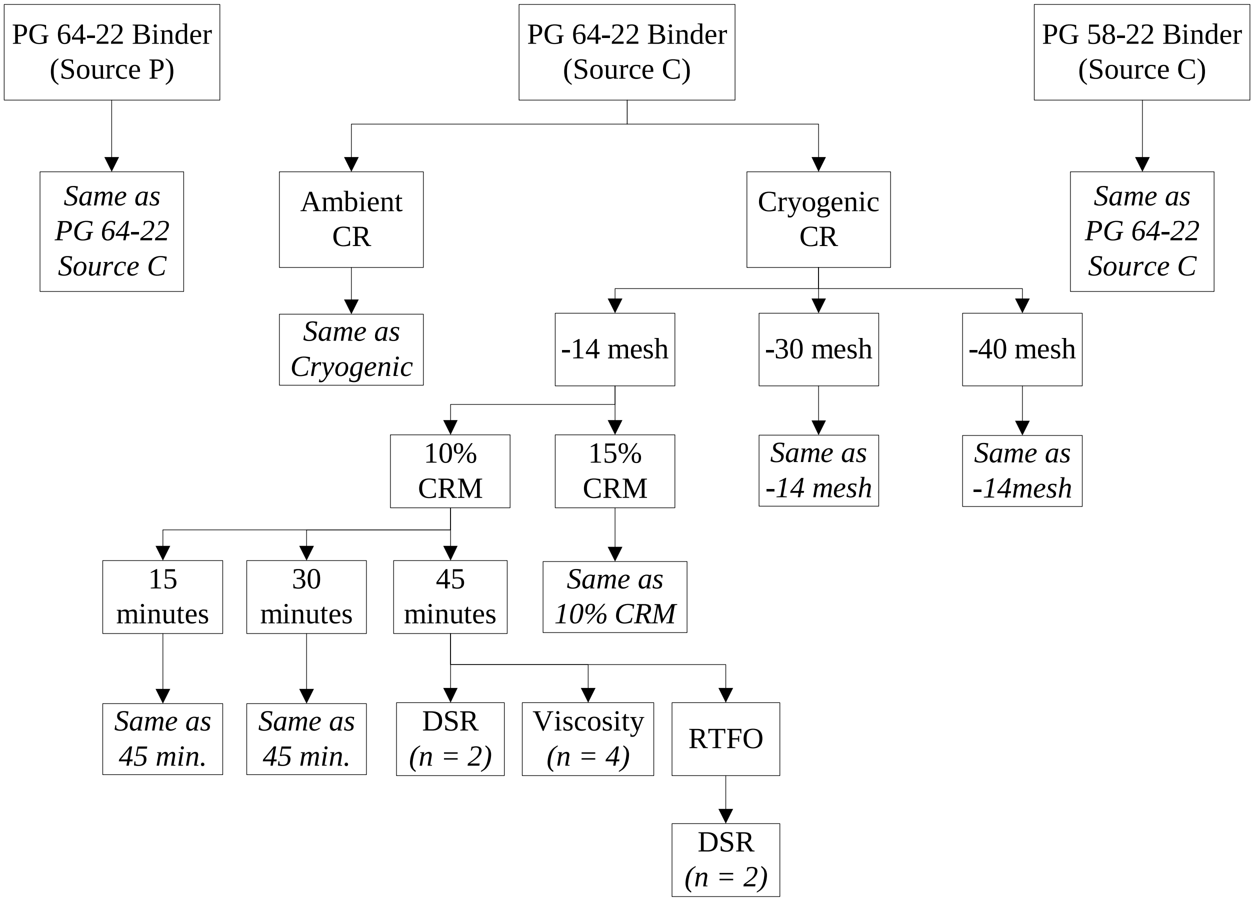

Figure 1. Experimental design *(CR – crumb rubber)*

Three sizes of crumb rubber were evaluated for each type of rubber (minus 14, minus 30, and minus 40 mesh). The gradation of each crumb rubber is included in Table 1. It is important to note that the only requirements regarding crumb rubber sizing set by ASTM D5603 is that no more than 10% can be retained on the designating sieve for crumb rubber designated as 30 mesh and smaller. For example, a minus 40 mesh rubber shall have no more than 10% material retained on the #40 (0.425 mm) sieve. For sizes larger than 30 mesh the requirement is no more than 5% can be retained on the designating sieve.

Table 1. Gradation of crumb rubber included in study

	Percent Passing *(% by weight)*					
	Ambient			**Cryogenic**		
Seive Size	**-14 mesh**	**-30 mesh**	**-40 mesh**	**-14 mesh**	**-30 mesh**	**-40 mesh**
No.16 (1.18mm)	97.1	100.0	100.0	100.0	100.0	100.0
No. 20 (850µm)	70.3	100.0	100.0	63.8	100.0	100.0
No. 30 (600µm)	44.1	100.0	100.0	26.9	99.5	99.3
No. 40 (425µm)	27.0	60.8	91.0	4.0	34.2	91.7
No. 50 (300µm)	16.7	19.3	59.1	3.3	3.6	45.9
No. 80 (180µm)	9.0	13.1	26.2	3.3	3.6	11.5
No. 100 (150µm)	7.6	11.1	18.6	3.3	3.6	7.4

Three different asphalt binders were used in this study. A PG 64-22 binder was obtained from source C and P each and a PG 58-22 binder was obtained from source C. Both of the PG 64-22 binder sources are commonly used in South Carolina and neighboring states. The PG 58-22 was included as it is another common grade of binder used in CRM binders across the U.S.

Two crumb rubber contents were evaluated for each type and size of crumb rubber (10% and 15% by weight of binder). This was an important factor to investigate as the addition of crumb rubber has limits. For the crumb rubber to be effective in the binder, there is a minimum amount of crumb rubber that must be added. On the other hand, there is a maximum amount of crumb rubber that can be added before the CRM binder becomes too viscous to apply and use in the field.

Preliminary testing indicated that the most effective method of mixing the crumb rubber with the asphalt binder was to use a high-shear radial flow impeller at a speed of 700 rpm and a temperature of 177^{o}C. Each 600 gram container of binder was placed on a hot plate and heated to 185^{o}C. The binder was heated above blending temperature of 177^{o}C to compensate for the heat loss that resulted when adding the crumb rubber to the binder. After the crumb rubber was added, the temperature was stabilized at 177^{o}C for the mixing duration. Three mixing durations were evaluated in this study (15, 30, and 45 minutes).

Each CRM binder was tested using a rotational viscometer and dynamic shear rheometer (DSR) to evaluate its high temperature properties. A Brookfield rotational viscometer was used to test the viscosity of the CRM binders at 135^{o}C in accordance with AASHTO T316. A number 27 spindle and a specimen size of 10.5 grams were used for this study. There was one modification made to this procedure, however. Instead of pouring all four viscosity samples at the same time, one sample was poured at a time to eliminate settlement of the crumb rubber in the specimen that would produce inaccurate results. Prior to pouring each sample, the container of CRM binder was gently stirred for one minute to disperse the crumb rubber throughout the binder.

The DSR testing was conducted per AASHTO T315 with the exception of the gap size. In order to accommodate the larger rubber particles present in the minus 14 mesh, the gap in the parallel plate set up was increased from 1 mm to 2 mm. Preliminary testing was conducted to ensure that the binders were still being tested in the linear viscoelastic region and previous testing on CRM binders has employed the same modification [3]. Prior to molding each specimen in a silicone mold, the can of CRM binder was gently stirred for one minute to disperse the crumb rubber throughout the binder.

The grade determination feature of the DSR was used to determine the failure temperature for each CRM binder in both the original state (unaged) and after short-term aging in the rolling thin film oven (RTFO). This procedure tests the sample at a starting temperature (i.e., 64°C for PG 64-22 base binder and 58°C for PG 58-22 base binder) and increases the temperature to the next PG grade (e.g., 70°C) if the G*/sinδ value is greater than the value required by AASHTO M320 (1.000 kPa for original binder and 2.200 kPa for RTFO aged binder). After recording all of the data, the failure temperature is determined through interpolation as the temperature at which the G*/sinδ value is less than the required value. Two replicates were tested for each aging condition of each CRM binder.

3. RESULTS AND DISCUSSION

Following a statistical analysis of the effects of mixing duration on the performance of the CRM binders, it was concluded that mixing duration did not have a significant impact on the results. Due to the lack of statistical significance of the mixing duration, only the results of the 30 minute mixing durations are included in this report. The properties of the CRM binders prepared using the other mixing durations (15 and 45 minutes) followed similar trends as the 30 minute durations.

3.1. Viscosity

The results of the viscosity testing are summarized in Table 2 and illustrated in Figures 2 through 4. It is evident from these results that the addition of crumb rubber to an asphalt binder has a significant impact on the binder's viscosity. In general, each of the variables (i.e., crumb rubber content, type, size, and binder source) had an effect on the viscosity of the CRM binders. Crumb rubber content was deemed as having the most influence on the viscosity. For each binder source, the CRM binders containing 15% crumb rubber had significantly higher viscosities than those modified with 10% crumb rubber.

Table 2. Viscosity results for different crumb rubber types, contents, sizes, and binders

Crumb Rubber Content	**Crumb Rubber Size**	**Viscosity *(Pa-s)***					
		PG 64-22 Source P		**PG 64-22 Source C**		**PG 58-22 Source C**	
		Ambient	**Cryogenic**	**Ambient**	**Cryogenic**	**Ambient**	**Cryogenic**
0%	Control	0.423		0.594		0.353	
10%	-14 mesh	1.534	1.193	2.495	1.826	1.632	1.451
	-30 mesh	1.272	1.085	2.121	1.644	1.308	1.059
	-40 mesh	1.923	1.140	2.560	1.661	1.800	0.990
15%	-14 mesh	3.510	1.771	6.539	3.003	3.974	2.774
	-30 mesh	2.678	1.827	4.428	3.846	3.670	2.218
	-40 mesh	4.266	1.912	8.165	2.717	4.509	2.443

The type of crumb rubber also had a significant effect on the viscosity of the CRM binders. In all cases, the ambient crumb rubber produced higher viscosities than the cryogenic crumb rubber of the same size and content. This has been attributed to the increased surface area of crumb rubber produced by the ambient method as compared to the cryogenic method.

Crumb rubber size had an effect on the viscosity, but the trends were not as expected. It was expected that the finer crumb rubber would produce higher viscosities due to the increased surface area. This was not necessarily the case, however. For the ambient crumb rubber, the minus 40 mesh crumb rubber resulted in the highest viscosity for all of the binders. The minus 14 mesh produced the next highest viscosities and the minus 30 mesh crumb rubber resulted in the lowest viscosities for the ambient crumb rubber. At the 10% crumb rubber content, there was no significant difference between the minus 30 and minus 40 mesh ambient crumb rubber and the minus 14 mesh CRM binders had higher viscosities for each binder. There was not a repeating trend at the 15% crumb rubber content.

The source of the asphalt binder also had an effect on the CRM binder. This is evident as the CRM binder made with the PG 64-22 binder from Source C showed a higher increase in viscosity over the control than the CRM binder made with the PG 64-22 binder from Source P. In addition, in some cases, the PG 58-22 from Source C produced CRM binders with viscosities higher than the CRM binders made with the PG 64-22 binder from Source P. This demonstrates that the crude source does affect the performance of CRM binders.

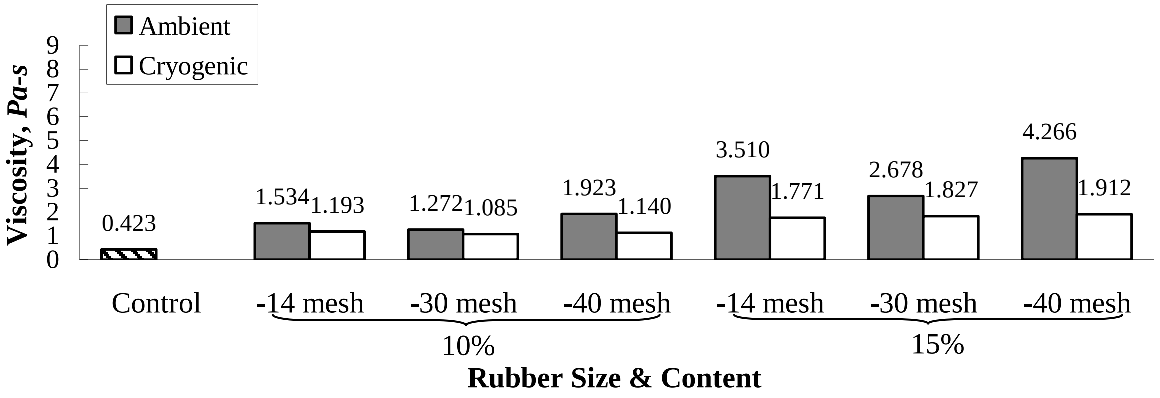

Figure 2. Viscosity results of PG 64-22 binder from Source P *(control does not contain crumb rubber)*

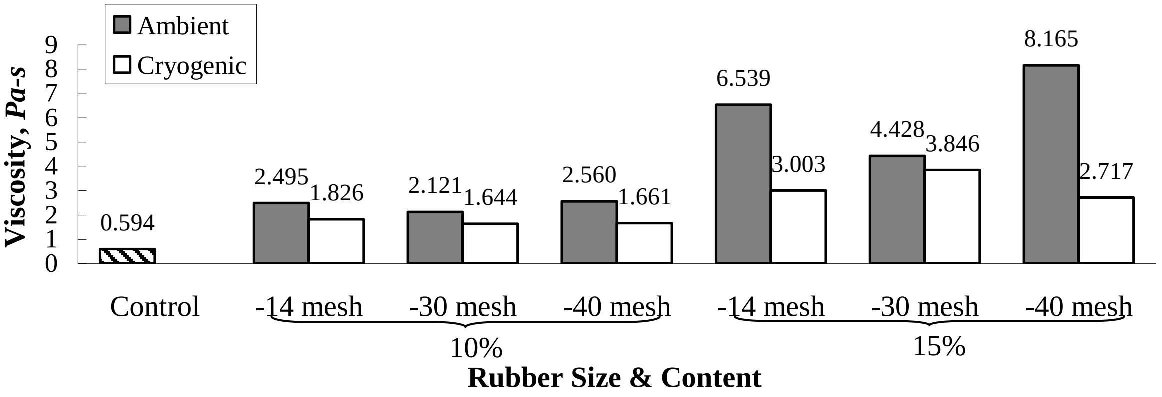

Figure 3. Viscosity results of PG 64-22 binder from Source C *(control does not contain crumb rubber)*

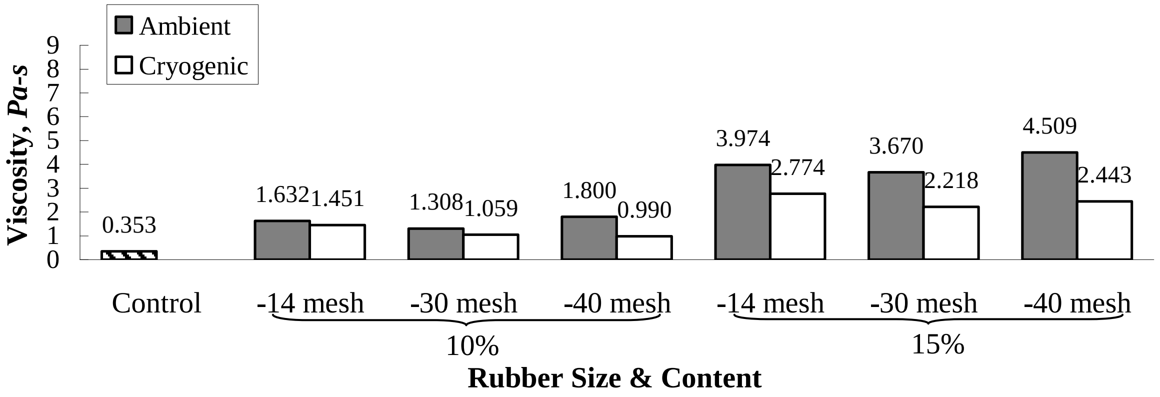

Figure 4. Viscosity results of PG 58-22 binder from Source C *(control does not contain crumb rubber)*

3.2. DSR Failure Temperature

The results of the DSR testing for the original and the RTFO aged binders are summarized in Tables 3 and 4 and illustrated in Figures 5 through 10. It is evident from these results that the addition of crumb rubber to an asphalt binder has a significant impact on the binder's high temperature performance as indicated by its upper performance grade (PG) temperature. In general, each of the variables (i.e., crumb rubber content, type, size, and binder source) had an effect on the failure temperature of the CRM binders. Crumb rubber content was deemed as having the most influence on the failure temperature. For each binder source, the CRM binders containing 15% crumb rubber resulted in significantly higher failure temperatures in both the original and RTFO aged condition than those modified with 10% crumb rubber.

Table 3. Failure temperatures of original (unaged) CRM binders

Crumb Rubber Content	**Crumb Rubber Size**	***Original Failure Temperature (^oC)***					
		PG 64-22 Source P		**PG 64-22 Source C**		**PG 58-22 Source C**	
		Ambient	**Cryogenic**	**Ambient**	**Cryogenic**	**Ambient**	**Cryogenic**
0%	Control	66.2		69.7		62.1	
10%	-14 mesh	75.5	73.5	83.8	81.6	76.4	73.1
	-30 mesh	74.6	75.1	82.1	82.1	72.7	73.4
	-40 mesh	76.3	74.1	82.5	79.5	74.5	72.2
15%	-14 mesh	82.8	78.1	92.0	85.5	85.7	81.5
	-30 mesh	81.1	80.1	88.9	89.8	79.7	77.0
	-40 mesh	85.1	78.4	91.0	84.7	84.3	79.3

Table 4. Failure temperatures of RTFO aged CRM binders

Crumb Rubber Content	**Crumb Rubber Size**	***RTFO Failure Temperature (^oC)***					
		PG 64-22 Source P		**PG 64-22 Source C**		**PG 58-22 Source C**	
		Ambient	**Cryogenic**	**Ambient**	**Cryogenic**	**Ambient**	**Cryogenic**
0%	Control	n/a		74.5		n/a	
10%	-14 mesh	77.0	74.4	85.1	86.3	77.5	77.9
	-30 mesh	75.2	75.8	82.5	82.1	76.8	75.5
	-40 mesh	74.2	74.7	83.8	82.9	75.7	77.4
15%	-14 mesh	80.1	80.9	93.5	92.2	82.6	82.4
	-30 mesh	80.0	75.8	87.8	90.4	79.9	79.1
	-40 mesh	79.0	78.7	90.9	85.4	80.7	80.1

Crumb rubber type, while affecting the failure temperature in most cases, was not as large a factor as it was with viscosity. As shown in Figures 5 through 10, the failure temperatures for the ambient CRM binders were not always higher than the cryogenic CRM binders of the same size with the same binder for either the original or unaged conditions. In most cases, the minus 30 mesh crumb rubber produced CRM binders with statistically similar failure temperatures for both ambient and cryogenic crumb rubber.

The size of the crumb rubber, again, was not as large a factor as it was with viscosity. While size influenced the failure temperature, there was not a specific trend that could lead to the conclusion that, for example, a finer crumb rubber would produce a higher failure temperature. There were some sizes that produced similar failure temperatures with all three binders in the unaged condition. The cryogenic minus 14 mesh and the ambient minus 30 mesh produced similar failure temperatures for each binder at the 10% crumb rubber content. Also, the cryogenic minus 30 mesh and the ambient minus 40 mesh resulted in similar failure temperatures at the 10% crumb rubber content. There were other similarities, but none that were consistent for each binder.

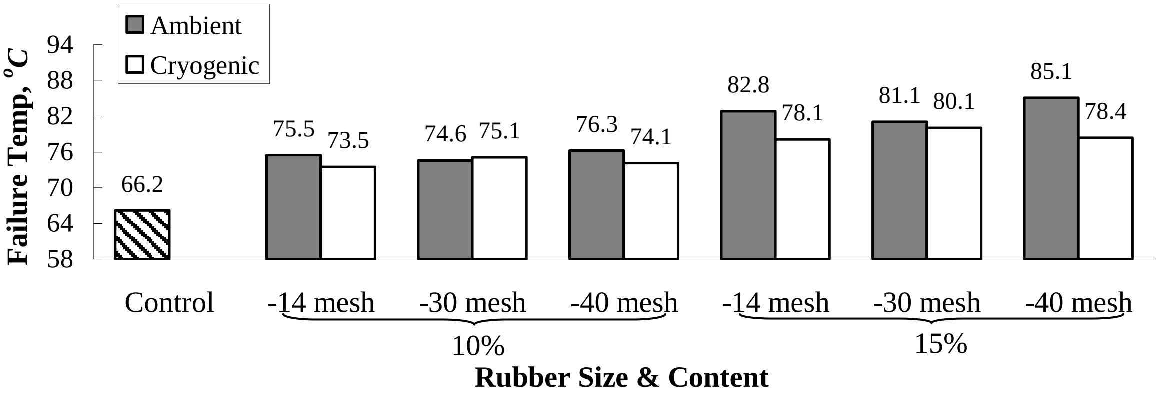

Figure 5. Failure temperatures for unaged CRM binders made with PG 64-22 binder from Source P

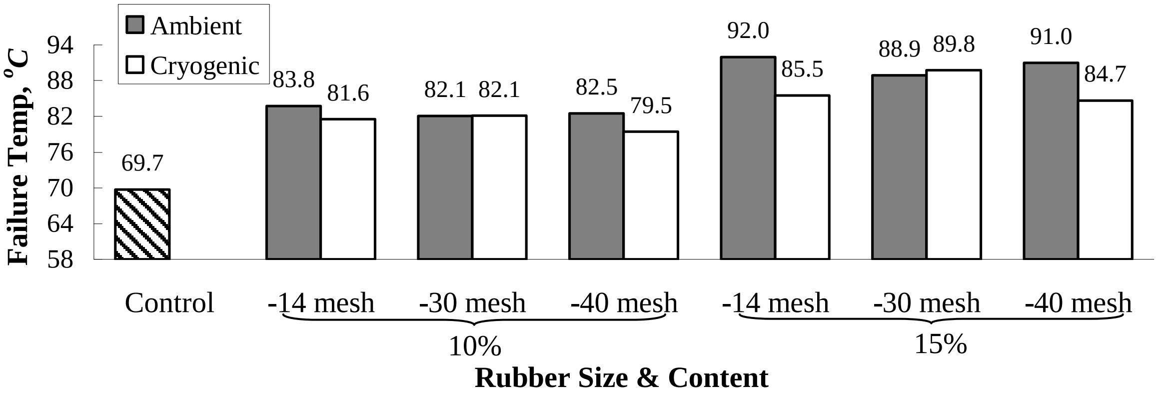

Figure 6. Failure temperatures for unaged CRM binders made with PG 64-22 binder from Source C

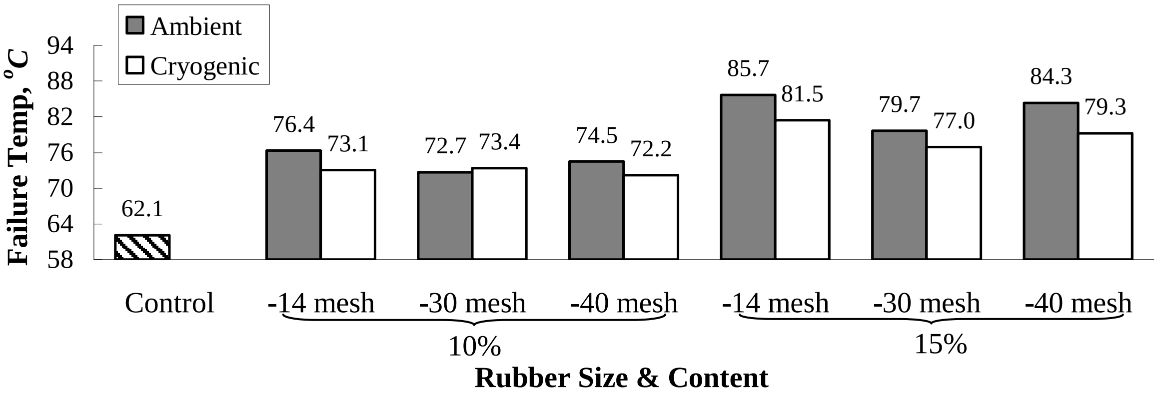

Figure 7. Failure temperatures for unaged CRM binders made with PG 58-22 binder from Source C

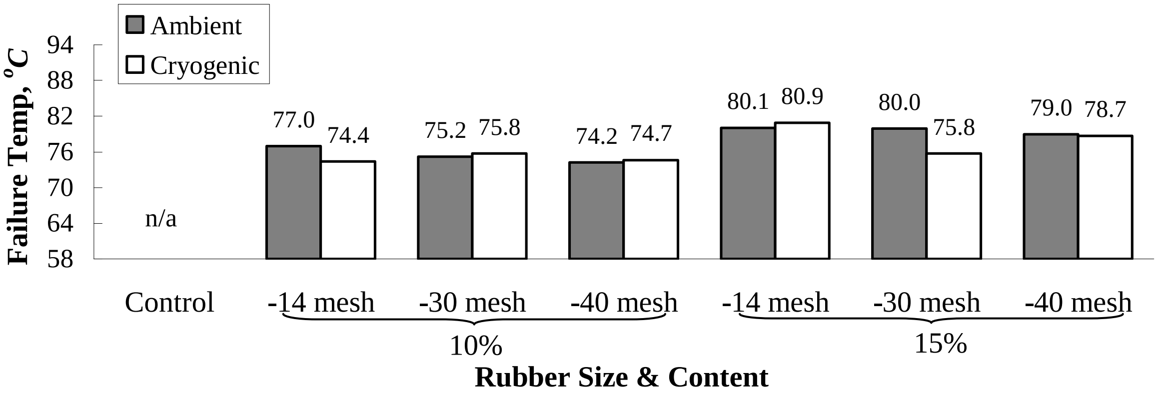

Figure 8. Failure temperatures for RTFO aged CRM binders made with PG 64-22 binder from Source P

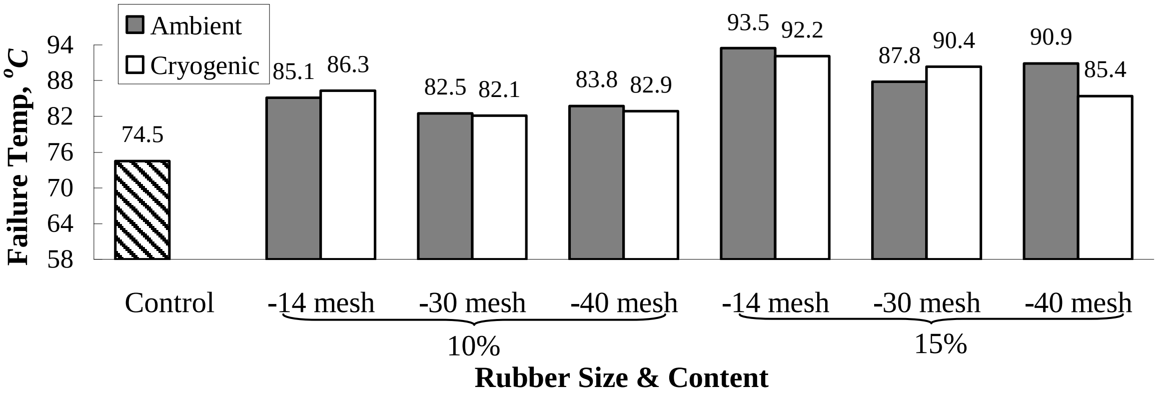

Figure 9. Failure temperatures for RTFO aged CRM binders made with PG 64-22 binder from Source C

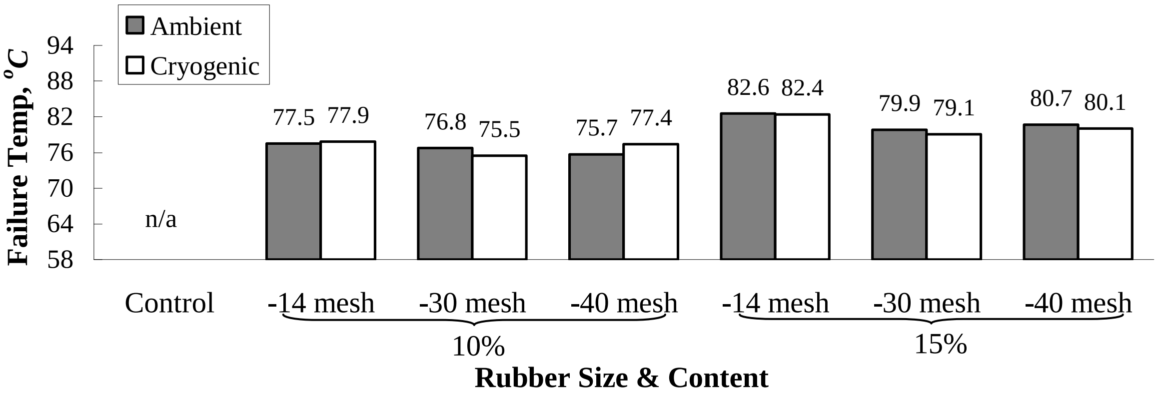

Figure 10. Failure temperatures for RTFO aged CRM binders made with PG 58-22 binder from Source C

As with the viscosity results, the binder source did affect the performance of the CRM binder with regard to failure temperature. The CRM binders made from binder Source C resulted in a larger average increase in failure temperature, relative to the control for the unaged condition. The CRM binders made with the PG 64-22 binder from Source C (failure temperature of 69.7 ^{o}C) averaged a 22.3% increase in failure temperature and the CRM binder made from with the PG 58-22 binder from Source C (failure temperature of 62.1^{o}C) averaged a 24.7% increase in failure temperature. The average increase for the CRM binders made with the PG 64-22 from Source P was 17.6% over the control (failure temperature of 66.2^{o}C). The failure temperature of all of the control binders was not tested for the RTFO aged condition.

4. CONCLUSIONS

Based on the results of this study of the high temperature rheological properties of crumb rubber modified asphalt binders produced in the laboratory with varying crumb rubber types, sizes, contents, and binders, the following general conclusions can be made:

- Crumb rubber content was determined to have the strongest effect on the viscosity and failure temperature of the CRM binders. Depending on the base binder, the addition of 10% crumb rubber, by weight of binder, can increase the PG grade of the binder by at least one grade (e.g., from PG 64-22 to PG 70-22). The addition of 15% crumb rubber can increase the PG grade of the binder by at least two grades (e.g., from PG 64-22 to PG 76-22).
- Crumb rubber size had a stronger effect on the viscosity of the CRM binders than the failure temperature. In general, for the ambient crumb rubber, the minus 40 mesh crumb rubber produced the highest viscosities, followed by the minus 14 mesh, and then the minus 30 mesh. For the cryogenic crumb rubber, the size did not have as significant an effect on the viscosity.
- Crumb rubber size had a slight influence on the failure temperature of the CRM binders. In all cases, for the ambient crumb rubber, the minus 14 and minus 40 mesh crumb rubber produced the highest failure temperatures. The minus 30 mesh crumb rubber generally produced the highest failure temperatures for the cryogenic crumb rubber.
- Crumb rubber type (ambient or cryogenic) had a significant effect on the viscosity of the CRM binders as the ambient crumb rubber always produced higher viscosities than the cryogenic crumb rubber.
- Crumb rubber type did not have as significant an affect on the failure temperature as it did on the viscosity. In general, the crumb rubber type did not have an effect on the overall PG grade of the CRM binders.
- Asphalt binder source did have a major impact on both the viscosity and the failure temperature of the CRM binders. For Source P, the PG grade increased one and two grades at the 10% and 15% crumb rubber contents, respectively. The PG grade increased two and three grades at 10% and 15% crumb rubber, respectively, for Source C.

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