8-15-2019

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Repository Citation
Khalili, M., Jadidi, K., Amirkhanian, S. (2019). Rheological Properties of Modified Crumb Rubber Asphalt Binder and Selecting the Best Modified Binder Using AHP Method. *Case Studies in Construction Materials, 11* 1-20. Elsevier.
http://dx.doi.org//10.1016/j.cscm.2019.e00276

Case Studies in Construction Materials 11 (2019) e00276

Contents lists available at ScienceDirect

Case Studies in Construction Materials

journal homepage: www.elsevier.com/locate/cscm

Rheological properties of modified crumb rubber asphalt binder and selecting the best modified binder using AHP method

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ARTICLE INFO

Article history:
Received 20 February 2019
Received in revised form 9 August 2019
Accepted 15 August 2019

Keywords:
Crumb rubber modifier
Asphalt binder
Rhelogical properties
Analytical hiarchy process

ABSTRACT

Crumb rubber modifier (CRM) is one of the most popular asphalt binder modifiers due to the economic benefits and desired physical and rheological properties of asphalt binders and asphalt mixes. This research focuses on evaluating the properties of rubber-modified asphalt binders and selecting the best modified binder. The modified binders were produced by blending virgin binders with CRM at various contents of different gradations, and different methods of grinding. CRM made through ambient and cryogenic grinding methods with two gradation sizes were produced and tested. Three different virgin binders from two sources were obtained and used. The Analytic Hierarchy Process (AHP) method was used to determine the best combination of virgin binder and CRM, based on the rheological properties and their importance in Nevada's construction code. Based on AHP analysis, ambient CRM obtained the highest priority. CRM contents of 10% and 15% were ranked higher than 20% depending on the grade of the virgin binder. Both mesh 20 and 40 CRM sizes were favorable.

1. Introduction

With growing worldwide concerns regarding climate change, the tendency towards using 'green' products is increasing, and the abundance of waste created is of serious concern. Consequently, numerous agencies in various sectors are attempting to find and/or improve methods to reuse this waste as recycled material. Based on a report from the U.S. Environmental Protection Agency (EPA) [1], According to USTMA approximately 81%, of generated scrap tire were recycled in the U.S. in 2017, in which 25% out of it was recycled as ground rubber. In addition, based on EPA the number of tire stockpiles have declined to 60 million tires in 2017. It is important to mention that, while civil engineering uses 8 percent of scrap tire, rubber modified asphalt is among the environmentally-friendly methods recommended for recycling scrap tires. [2].

One application for recycled tires is in rubberized asphalt binder. Early attempts about using scrap tire with pavement dates back to 1990s. A study by Kansas State University in 1994 estimated that if only 10% of all asphalt pavements laid in the U.S. contained 3% rubber by weight of binder, all scrap tires generated for that year would be utilized [3]. Due to their anti-oxidant contents, tires can be used to improve durability of asphalt pavement. The method of modifying an asphalt binder

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https://doi.org/10.1016/j.cscm.2019.e00276

with ground scrap tire is done by adding a crumb rubber modifier (CRM). The rubber is used as a modifier to increase the asphalt's elasticity, flexibility and durability against aging [4].

Adding more CRM to a binder causes an increase in viscosity [5]; in fact, there is a direct correlation between rubber content and binder viscosity according to Kim et al. [6]. Rubber increases viscosity and decreases the creep stiffness of the modified binder based on a research carried out by Wang et al. [7]. Further, Cong et. Al [8] revealed that in a rubber-modified asphalt binder, the softening point, elastic recovery, viscosity, complex modulus (G^*), and rutting parameter increase, while the amount of ductility, penetration, and phase angle (δ) decreases. In addition, rubber increases the fatigue resistance of the binder significantly [9]. Elastic recovery and rutting factors also improve with an increase in the percent of rubber in a binder [10,11].

The grinding process has a significant influence on the shape, texture, and physical properties of rubber particles, as well as on rubberized binder properties [11]. Two main methods of producing CRM are ambient and cryogenic methods. In the ambient method, the particle sizes range from 75 μm to 5 mm. Due to a tearing process, ambient processing results in a rough texture with a higher surface area. In the cryogenic method, liquid nitrogen is used to freeze scrap tires and then hammer them in order to crush the cooled tires into particles between 0.25 in. and mesh #30. The rubber particles produced using the cryogenic procedure usually have sharp edges or cubic shapes [12,13].

The results of testing indicated that binders modified with ambient ground rubber had greater viscosity than binders modified by cryogenic ground rubber. Ambient CRM particles had significantly more surface area compared to cryogenically ground rubber; consequently, binders modified with ambient rubber demonstrated higher phase angles. In addition, binders modified with larger rubber particles showed a larger complex modulus, which is a benefit for rutting resistance [14,15]. Adding 10% of rubber to a binder resulted in high temperature that was one degree higher than the original binder PG grade; mixing the binder with 15% of rubber increased the virgin binder PG grade at least two degrees higher in high temperature. This increase in temperature occurred regardless of the method used for the grinding process [16].

In addition to the benefits of rubber modified asphalt, investigators are interested to discover optimum rubber content. In this regard a study on samples having 4%, 8%, 12%, 16%, and 20% crumb rubber indicated that higher rubber content resulted in greater elastic recovery [17]. Results of rheological tests on rubber-modified samples that had rubber content between 3% and 24% revealed that 18% was the optimal rubber content. Some researchers have suggested that 5%–12% was the optimum rubber content for modifying a binder for dense-graded and open-graded mixtures respectively [18,19]. Celauro et al. proposed for producing rubber modified asphalt and used low shear blending protocol to estimate the optimum rubber content and discovered that 21% is the highest rubber content in terms of improving stiffness, elastic behavior and rutting resistance of binder [20].

There is considerable investigation around rubber modified asphalt binder. Pretsi published a literature review and presented the results of common experiments on rubber modified binder [21]. Yet there are concerns about the influence of the local materials on the properties of rubber modified binder as well as the best rubber content. In this study the authors performed comprehensive tests on binders provided from local suppliers in Nevada and modified with rubber. At the end, the investigators recommended a new approach based on Analytic Hierarchy Process (AHP) method to determine optimum rubber content.

AHP is among the most common methods which is used widely for selecting building materials, patching process and maintenance strategies [22–25]. It is also a common method to evaluate the asphalt pavement performance [26]. Jahanian et. Al used this method to determine the optimum percentage of Gilsonite in Gilsonite modified hot mix asphalt [27]. AHP combined with other decision making methods were used to evaluate the heavy duty asphalt and road with high traffic as well as recommending the most appropriate asphalt type for Europe [28,29]. Kou et. Al used AHP method to evaluate the aging grades of reclaimed binder [30]. Zang et. Al applied AHP theory to evaluate weight distribution of effective factors on pavement performance for modeling of the asphalt mixture performance [31].

Table 1
rubber size distribution.

Sieve Size	Percent Passing (% by weight)			
	Ambient		Cryogenic	
	Mesh 20	Mesh 40	Mesh 20	Mesh 40
No. 20 (850 μm)	100	100	100	100
No. 30 (850 μm)	100	100	95 - 100	95 - 100
No. 40 (600 μm)	60 – 65	85 – 90	30 - 35	90 - 95
No. 50 (425 μm)	15 - 20	55 - 60	2 - 5	45 - 50
No. 80 (300 μm)	10 - 15	20 – 25	2 - 5	10 - 15
No. 100 (150 μm)	8.0 - 12.0	17 - 20	2 - 5	5 - 10

2. Methodology

Asphalt binder was obtained from local manufacturers and mixed with CRM at high temperatures to produce a rubberized asphalt binder. Two different types of performance-grade binders, PG 64-16 and PG 58-28, and one viscosity-grade binder, AC20, were used. These binders came from two sources. Based on requirements of the Strategic Highway Research (SHRP) program of the National Research Council, the experiments were carried out on samples in order to determine the properties of the rubber-modified binders. For this reason, tests were performed for Viscosity, Bending Beam Rheometer, Dynamic Shear Rheometer, Ductility, and Flash point. In order to evaluate the effects of aging, samples were aged with both rolling thin-film oven (RTFO) and pressure-aging vessel (PAV). From each sample, three specimens were tested, and the average values were used in the analysis.

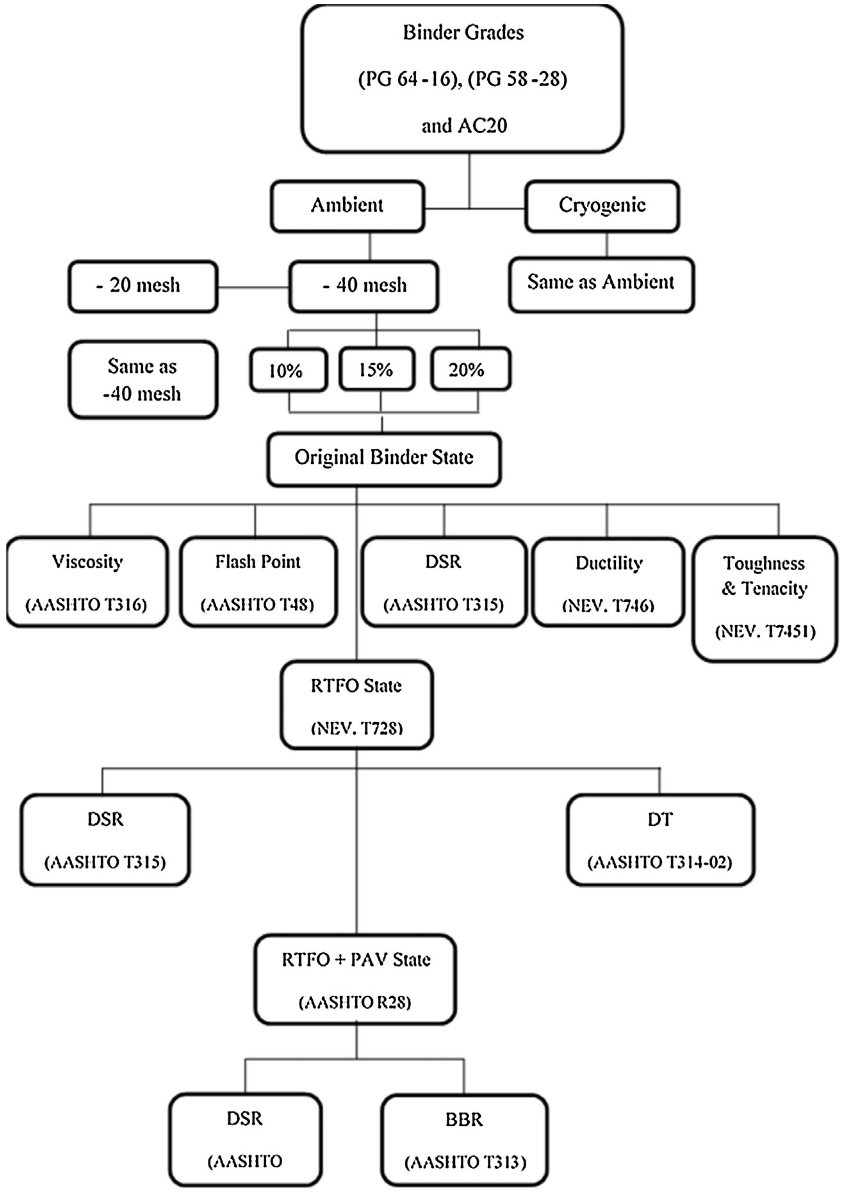

Fig. 1. Methodology of evaluating the properties of rubber-modified binders.

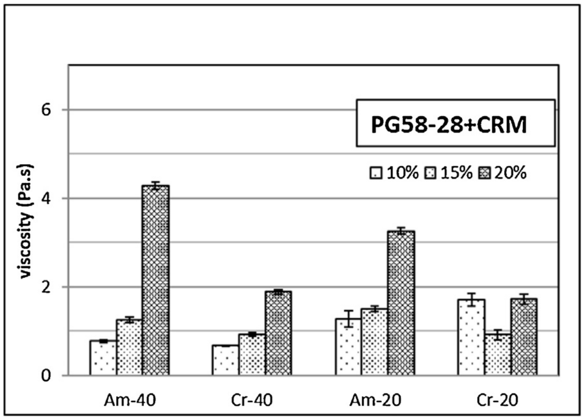

Fig. 2. Viscosity of CRM modified binder PG (58-28).

2.1. Sample preparation and experimental program

For practicality, each virgin binder was mixed at three CRM contents: 10%, 15%, and 20%. The two maximum sizes selected for CRM particles were #20 and #40, in order to take into consideration, the influence of rubber particle size in the modified binders. Both ambient and cryogenic CRMs were used. Table 1 demonstrates the rubber size distribution.

In order to produce the rubber modified samples, first, the required amount of virgin binder (e.g., PG 64-16) was heated to 177 ∘C. Usually, a container of approximately 600 g of binder was used. Then the required amount of CRM (e.g., 10% by total weight of the binder) was added to the hot binder as the matrix was blended (700 rpm). This blending continued for 30 min or longer ensuring that a homogenous matrix was obtained. Immediately, after the mixing was completed, the binder was tested (e.g., DSR). If the binder had to be stored and tested at a later date, the binder was heated and stirred vigorously before testing was initiated.

Performance tests were carried out on rubber-modified asphalt binder, polymer modified asphalt binders and the original asphalt binder and the results were compared. The flowchart in Fig. 1 shows the methodology and experiments carried out on each sample.

2.2. Aging process

In order to investigate the short term properties of the rubber modified asphalt, virgin, polymer modified as well as base binders mixed with CRM were conditioned in a Rolling Thin Film Oven (RTFO) in accordance to Nev. T728. DSR and Ductility tests were performed on RTFO-aged specimens. In addition, the RTFO-aged samples were conditioned with Pressure-Aging Vessel (PAV) in accordance with AASHTO R28 to determine the long term aging of the rubber modified binder.

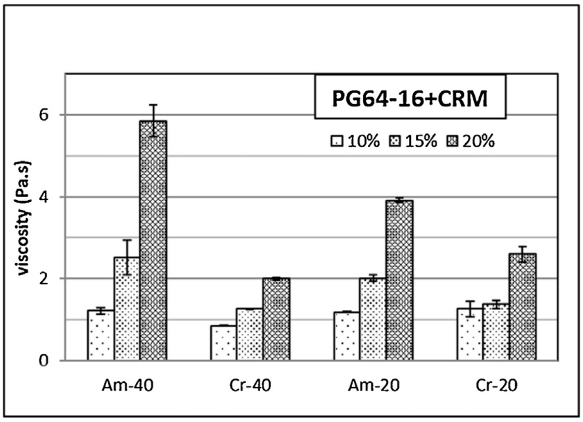

Fig. 3. Viscosity of CRM modified binder PG (64-16).

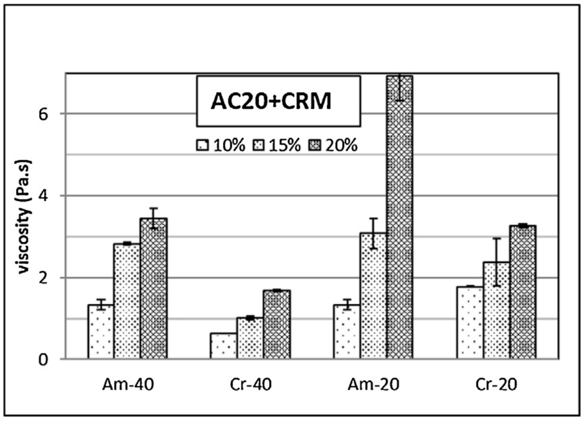

Fig. 4. Viscosity of CRM modified binder AC–20.

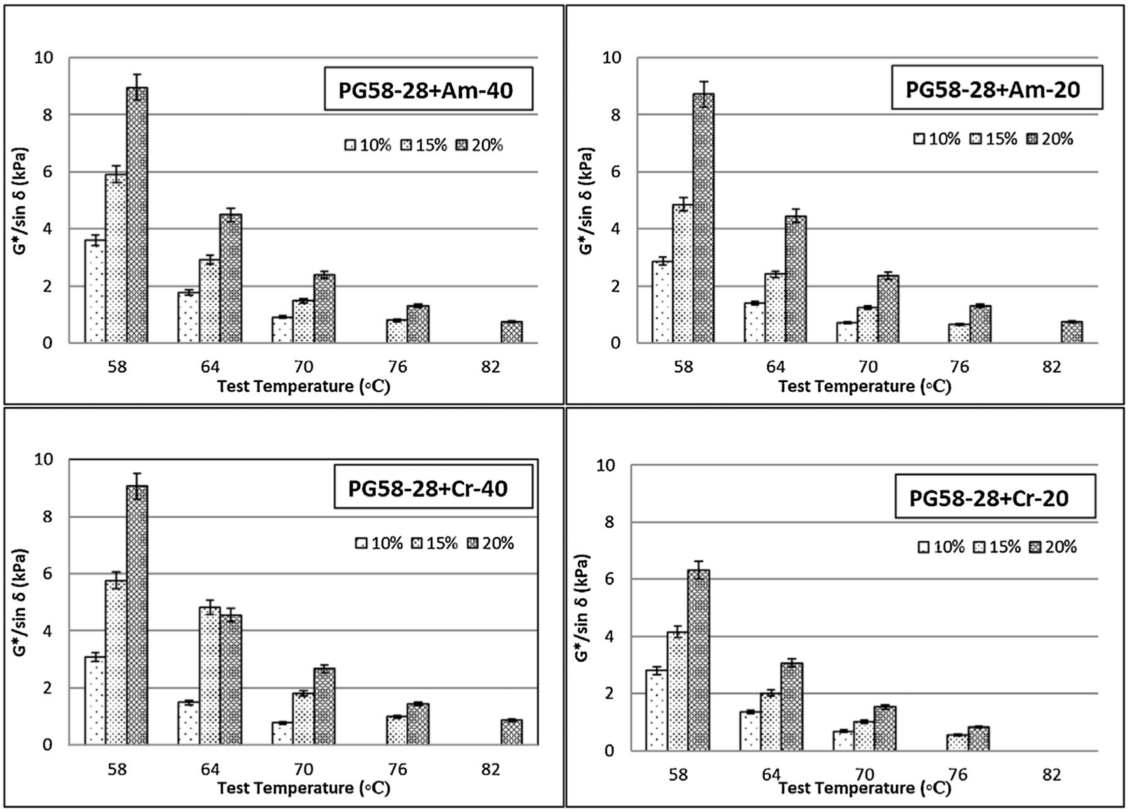

Fig. 5. G*/sin δ for samples of rubber-modified binder PG (58-28).

2.3. AHP method

Finally, the rubber size and content that led to the best rubber-modified binder performance was selected using the AHP method. Both rubber size and content were prominent factors in evaluating the properties of the rubber-modified binders. Finding the best rubber size and content was the main objective of this case study. This was due to the fact that there are not significant studies correlating rheological properties to rubber size and type and recommendations for best rubber type and size in regard to these properties. Considering the fact that this study was performed originally to investigate the suitability of rubber modified binder for Nevada, it was necessary to recommend the best rubber size and content. However, the results of experiments demonstrated that while adding rubber improves some properties of base binder, it has negative influence on some other properties. After discussing with local experts, the authors concluded that using AHP method is an appropriate to rank and select the optimum rubber in this case.

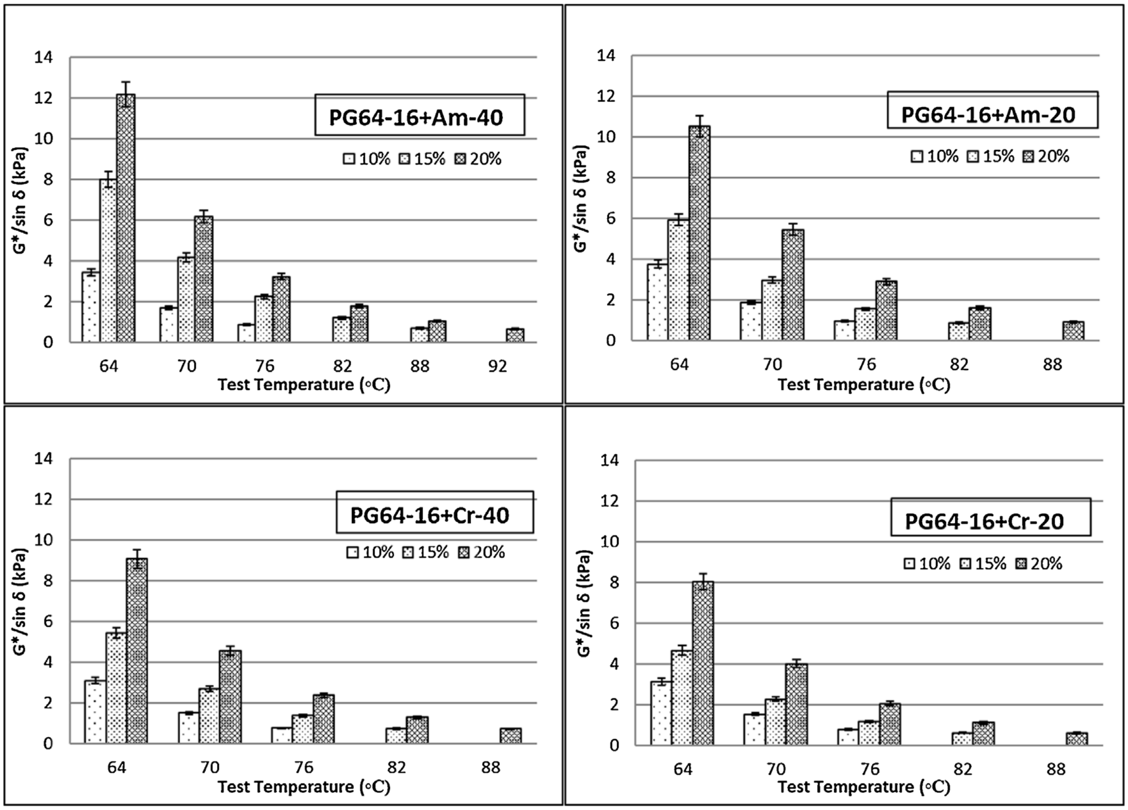

Fig. 6. G*/sin δ for samples of rubber-modified binder PG (64-16).

3. Results and discussion

3.1. Original (un-aged) asphalt binders

In order to analyze the original (un-aged) asphalt binder a set of tests were performed on each original asphalt binder samples. These tests include viscosity, flash point, dynamic shear test, ductility and toughness and tenacity. The results of these tests and the analysis of the results are presented in the following sections.

3.1.1. Viscosity

The results of a viscosity test, which was performed with a rotational viscometer at 135 °C are presented in Figs. 2–4. As expected, based on the literature review, viscosity increases with the increase of rubber content. The rubber content had a greater influence on the properties of the ambient samples in comparison to cryogenic ones. Moreover, there was a distinct relationship between the rubber grinding process and viscosity. With the same rubber content and size samples made with cryogenic CRM had lower viscosity compared to ambient CRM. The average viscosity of ambient samples was almost twice the average viscosity of cryogenic samples. This trend, which was also observed in the work of other researchers, is a result of higher surface area of ambient CRM, hence thicker gel around crumb rubber particles.

For ambient samples, there was a sharp increase in the viscosity relevant to the rubber content. The samples made with 20% rubber content on average exhibited 52% and 37% more viscosity compared to the ones with 15% and 10% rubber, respectively. This trend was lower for cryogenic samples. In contrast, rubber size had a relatively lower effect on viscosity in 58% of samples. Binders mixed with rubber having a small particle size showed slightly lower viscosity. It can be seen that there is a slight increase from cryogenic #40 to cryogenic #20. This growth was relatively higher from ambient #40 and ambient #20. As Figs. 8–10 indicate, the viscosity of all ambient samples with 20% CRM were higher than 3 Pa.s, which is the maximum allowed for pumping purposes at asphalt plants.

3.1.2. Dynamic shear rheometer

Dynamic Shear tests were carried out on modified binder samples at various temperatures. The results are presented in Figs. 5–7, which is G*/sin δ for various binder samples at temperatures ranging from 58 °C to 88 °C. It should be noted that binder grade, type of CRM and particle size were abbreviated in figures' legend. For example, modified asphalt binder made

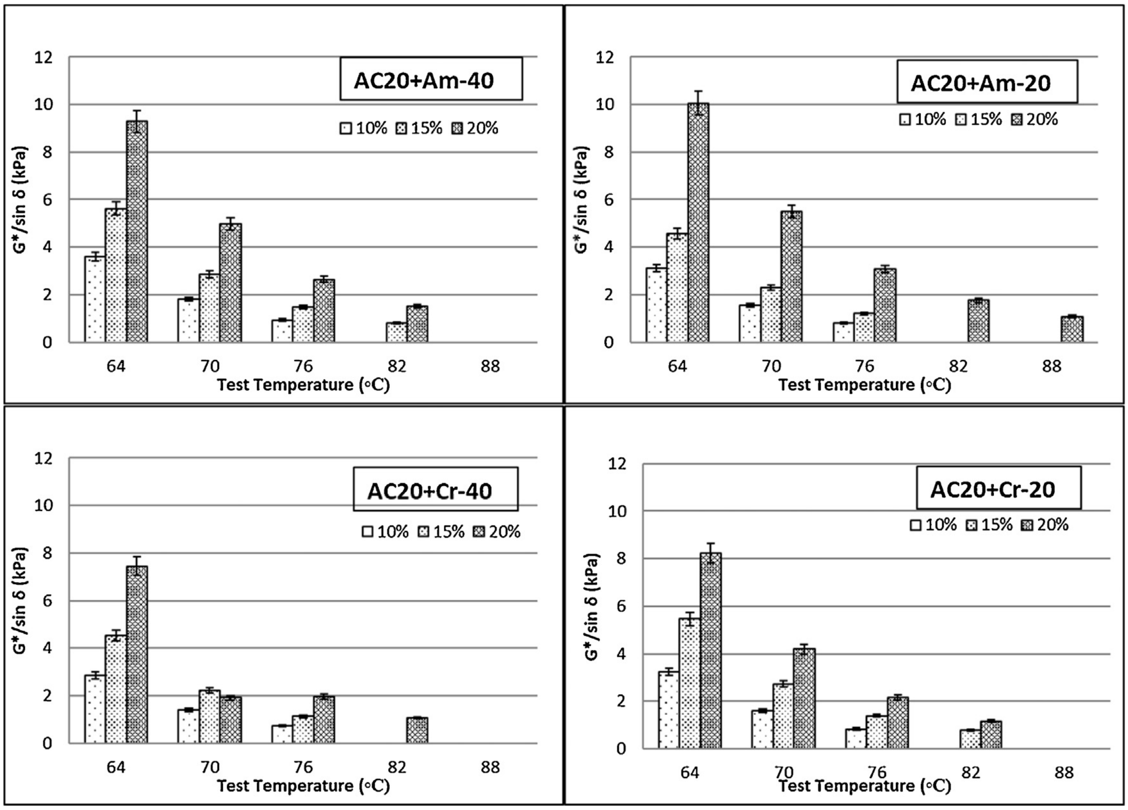

Fig. 7. G*/sin δ for samples of rubber-modified binder AC-20.

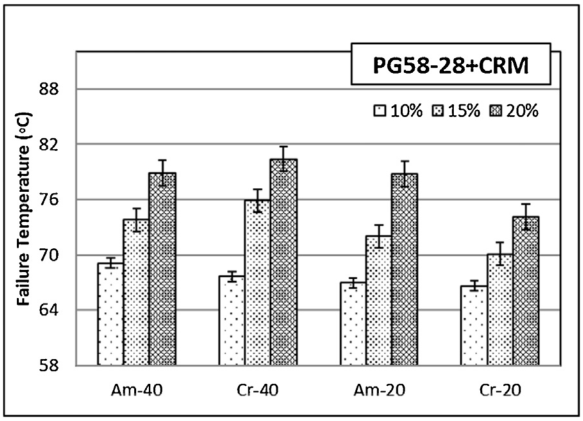

Fig. 8. Failure Temperature of CRM modified binder from PG58-28.

with PG58-28 with Ambient, Mesh 40 CRM was abbreviated to 5828-Am-40. As can be seen, the binder made with ambient rubber demonstrated higher G*/sin δ compared to cryogenic samples.

There is a direct relation between rubber content and G*/sin δ, and this parameter increases significantly with the addition of rubber. The highest G*/sin δ was observed for samples made with 20% of rubber ambient #40, while the lowest magnitude belonged to binders modified with 10% rubber. Considering the fact that G*/sin δ is an indicator for elastic component of complex shear modulus, any increment in this parameter would lead to improving the rutting resistance properties of asphalt pavement. Binder samples with 20% rubber content may have a G*/sin δ approximately three times higher compared to samples having 10% rubber.

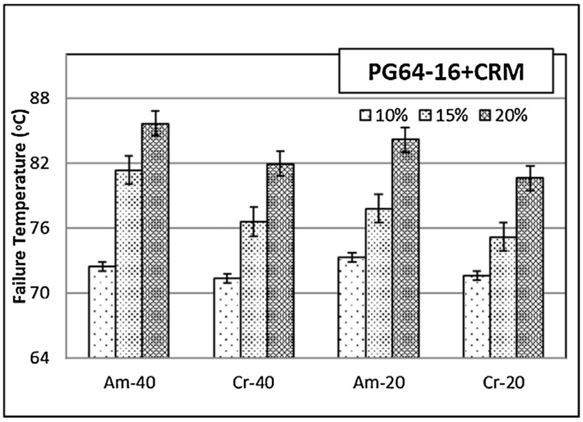

Fig. 9. Failure Temperature of CRM modified binder from PG64-16.

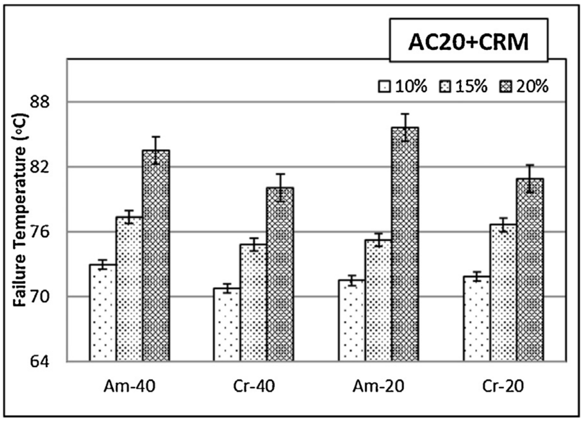

Fig. 10. Failure Temperature of CRM modified binder from AC20.

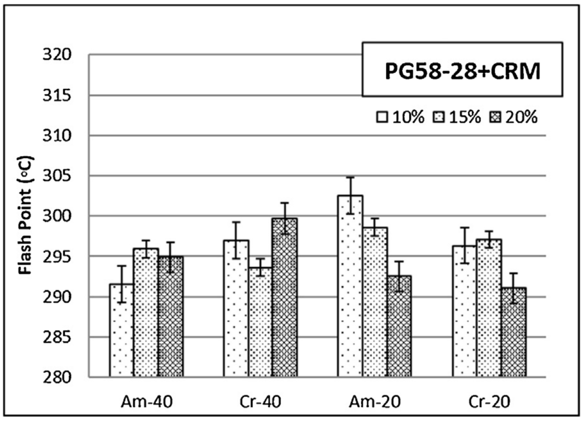

Fig. 11. Flash point of rubber-modified binder PG (58-28).

Results of the test for various temperatures showed similar behavior. It was observed that $G^*/\sin\delta$ declined as the temperature increased. The only exceptions to this were binders made with cryogenic #40 CRM at 64 °C and 70 °C of PG58-28 and AC-20, respectively. In these instances, binders with 20% CRM showed lower $G^*/\sin\delta$ than binders made with 15% CRM. The grade of virgin binder also affected this property of asphalt binder. Samples made with binder PG 64-16 and AC20

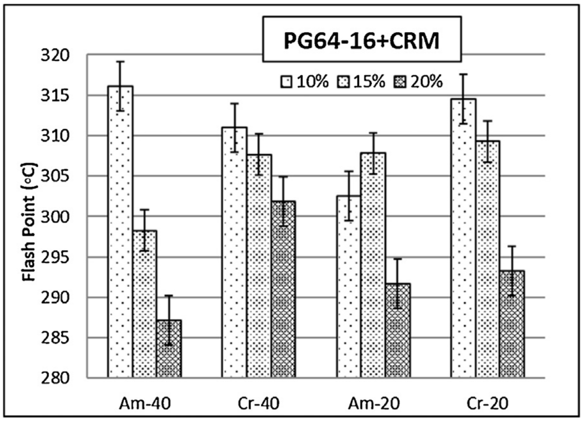

Fig. 12. Flash point of rubber-modified binder PG (64-16).

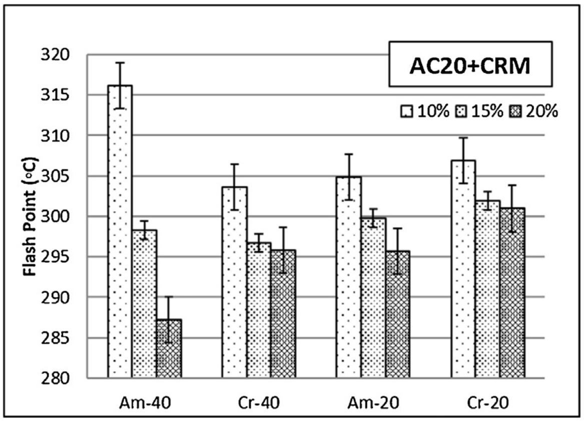

Fig. 13. Flash point of rubber-modified binder AC-20.

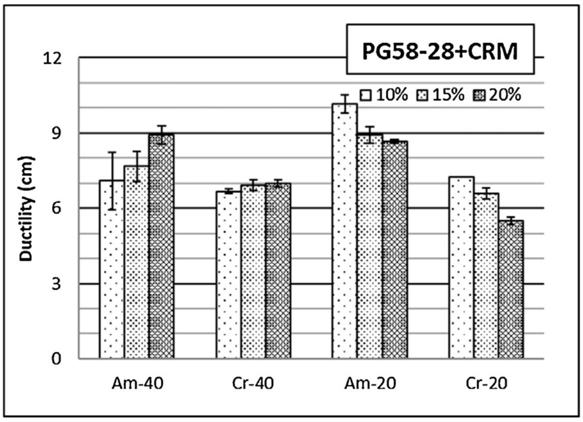

Fig. 14. Ductility of rubber-modified binder PG (58-28).

demonstrated higher G*/sin δ compared to PG 58-28 source binder at a given temperature. For some modified binders G*/sin δ at some high temperatures dropped significantly below 1 kPa that the equipment fails to complete the test.

The phase angle, which is another parameter evaluated based on the DSR test, decreased as the rubber content increased. In other words, a modified binder mixed with 20% rubber inevitably had a lower phase angle compared to samples that had 10% rubber. No significant differences were observed between the various grinding processes and rubber sizes.

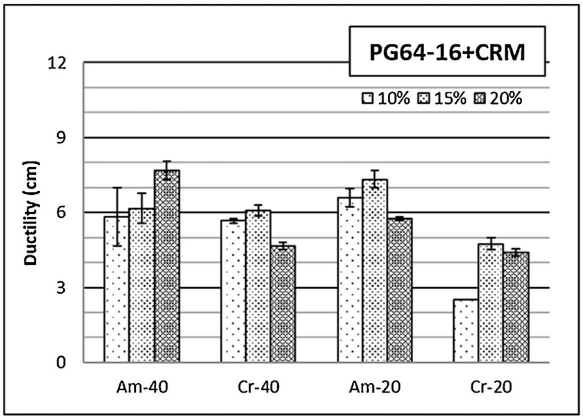

Fig. 15. Ductility of rubber-modified binder PG (64-16).

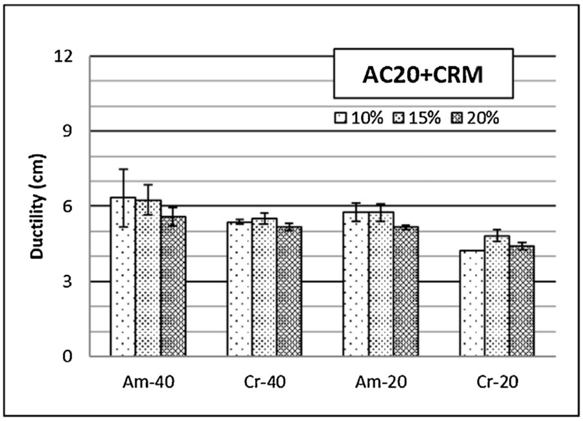

Fig. 16. Ductility of rubber-modified binder AC-20.

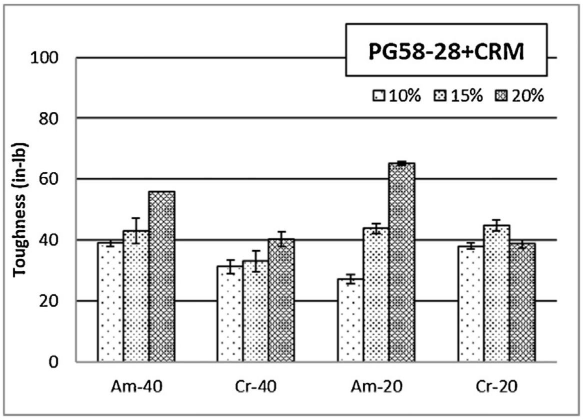

Fig. 17. Toughness of CRM binder PG (58-28).

Failure temperature for an original (un-aged) binder is defined as the temperature at which $G^*/\sin\delta$ is equal to 1 kPa. This temperature is calculated by logarithmic interpolation. The test results and calculations, which are demonstrated in Figs. 8–10, revealed that the failure temperature increased with the increase of rubber content, and the rate of change in failure temperature was similar for various samples. Modified samples made with virgin binder PG58-28 resulted in slightly lower failure temperatures. In addition, in comparison between two rubber sizes #40 showed higher failure temperature than #20, with the exception of modified binders made of AC-20 with cryogenic CRM. The trend comparison between two grinding process has

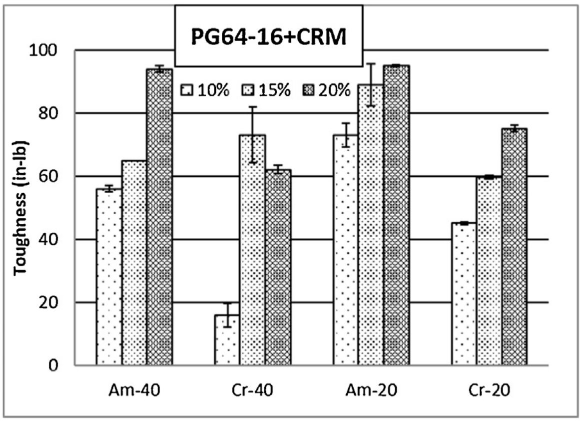

Fig. 18. Toughness of CRM binder PG (64-16).

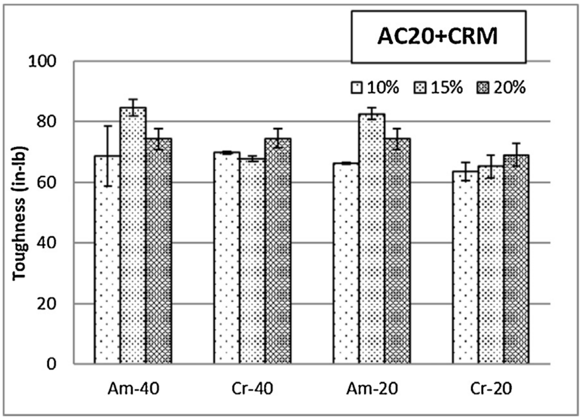

Fig. 19. Toughness of CRM binder AC-20.

more exceptions. Modified binders made with ambient samples had higher failure temperature than cryogenic samples regardless of CRM size. However, there were four exceptions to this trend which were 10 and 15% #20 of AC-20: and 15 and 20% #40 of PG58-28.

3.1.3. Flash point

The flash point tests results are presented in Figs. 11–13. For samples made from PG64-16 and AC-20, the flash point temperature decreased as the rubber content increased. This was probably because rubber ignites at lower temperatures compared to asphalt binder. This decrease was relatively low, and all of the samples displayed flash points higher than the minimum required by local specifications. No distinguishable correlation was found between rubber size and type, and flash point properties.

3.1.4. Ductility

It was necessary to analyze the results of the ductility, toughness & tenacity tests on the samples in order to reveal the elastic properties of modified asphalt binder, as well as their tensile behaviors. Figs. 14–16 show the ductility tests conducted on modified samples, in order of type and size of the rubber, as well as for the binder source. On average, binder grade PG 58-28 showed higher results, which meant modified asphalt binder had a higher elasticity than other types. For samples made with rubber ambient #40, ductility improved with the addition of rubber; in general, however, adding more rubber led to a decline in the ductility properties of AC-20 rubber-modified asphalt. It must be mentioned that, on average, the rate of ductility for CRM modified samples were significantly lower than virgin binders, which was almost 40 cm. Introducing the foreign material of crumb rubber depreciates the uniformity and homogeneity of virgin asphalt binder which results in early failure under tension stress of ductility test. Additionally, it was important to mix the rubber-modified asphalt well, before carrying out the tests on the samples, to make sure there was adequate coherence and uniformity in the modified binder. All ductility tests were performed at 4 °C.

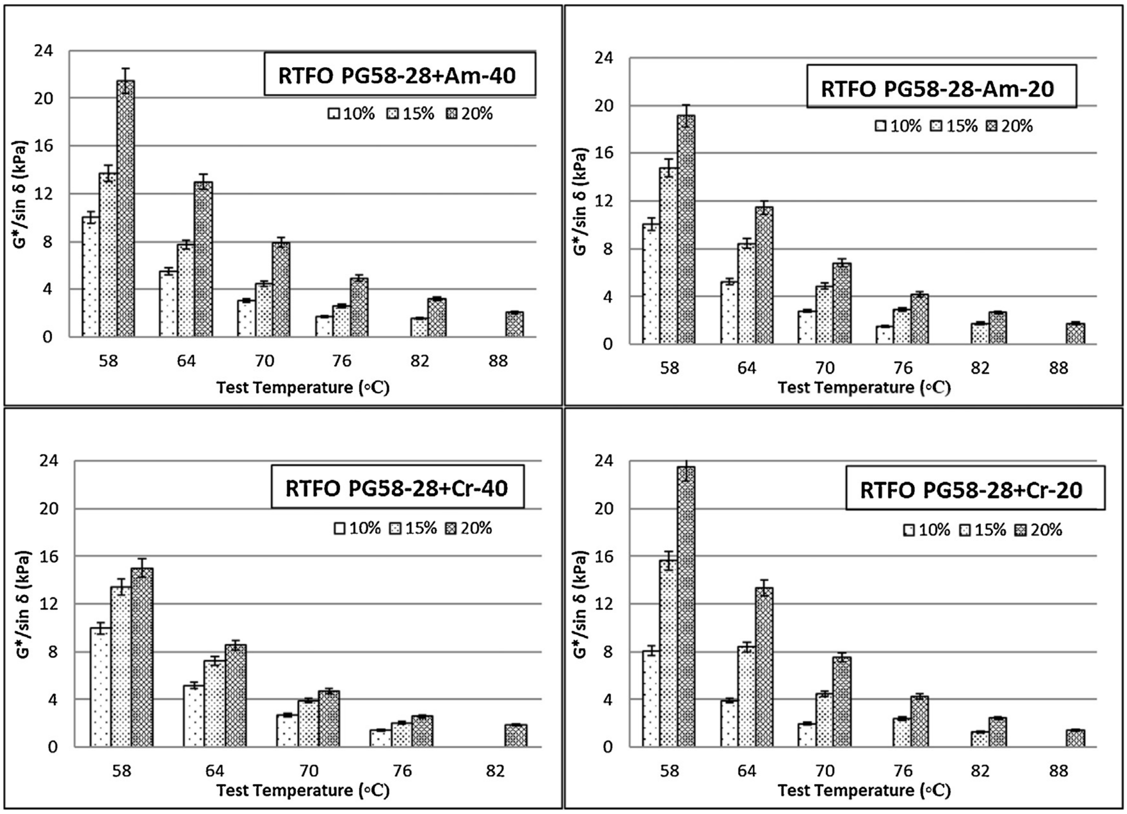

Fig. 20. G*/sin δ for RTFO aged samples of rubber-modified binder PG (58-28).

In some cases, binder samples with 15% rubber demonstrated slightly higher ductility. This was true for samples made with binders AC20 and PG 64-16; meanwhile, for modified binder PG 58-28, ductility results was absolutely relevant to the grinding process. On the other hand, ductility of the cryogenic samples increased with rubber content for ambient samples; however, there was an obvious decline in ductility with the increase of the percent of rubber.

As it is illustrated in Figs. 14–16, it was found that samples made with binder PG 64-16 lost ductility properties more than other binder sources compared to virgin binder. For this binder source, rubber size and grinding type did not significantly effect on binder behavior. Binder AC20 modified with smaller rubber particles exhibited rather higher ductility, on average, than other samples.

3.1.5. Toughness and tenacity

The results of toughness and tenacity tests illustrate the elastic properties of binders. The results of toughness are presented in Figs. 17–19; however, results for tenacity are not presented because no obvious trend was observed. Unlike ductility, modified binders made of AC20 and PG64-16 display greater toughness compared to PG58-28. For PG grade samples, the amount of toughness improved with the increase of rubber content; except for some cryogenic samples. All toughness-tenacity tests were performed at 25 °C.

3.2. RTFO-aged asphalt binders

The results of the DSR tests on RTFO-aged samples exhibited similar behaviors as the samples that were not aged. However, the rate of change between samples made using the cryogenic and ambient methods was different. For RTFO-aged samples (Figs. 20–22), cryogenic #20 resulted in a higher G*/sin δ compared to other rubber types. Similar to un-aged samples, the modified binder source PG 58-28 demonstrated a lower G*/sin δ compared to the other sources. In general, G*/sin δ increased with rubber content, while the phase angle diminished. A direct relation was also observed between the failure temperature and the rubber content.

When comparing the ductility of the un-aged binders (Figs. 14–17) with the RTFO-aged binders (Figs. 26–28), it can be seen that except for virgin binder PG 64-16, the other two grades did not show significant declines in ductility properties after aging. This means that short-term aging did not lead to any reduction in ductility, which is a positive point.

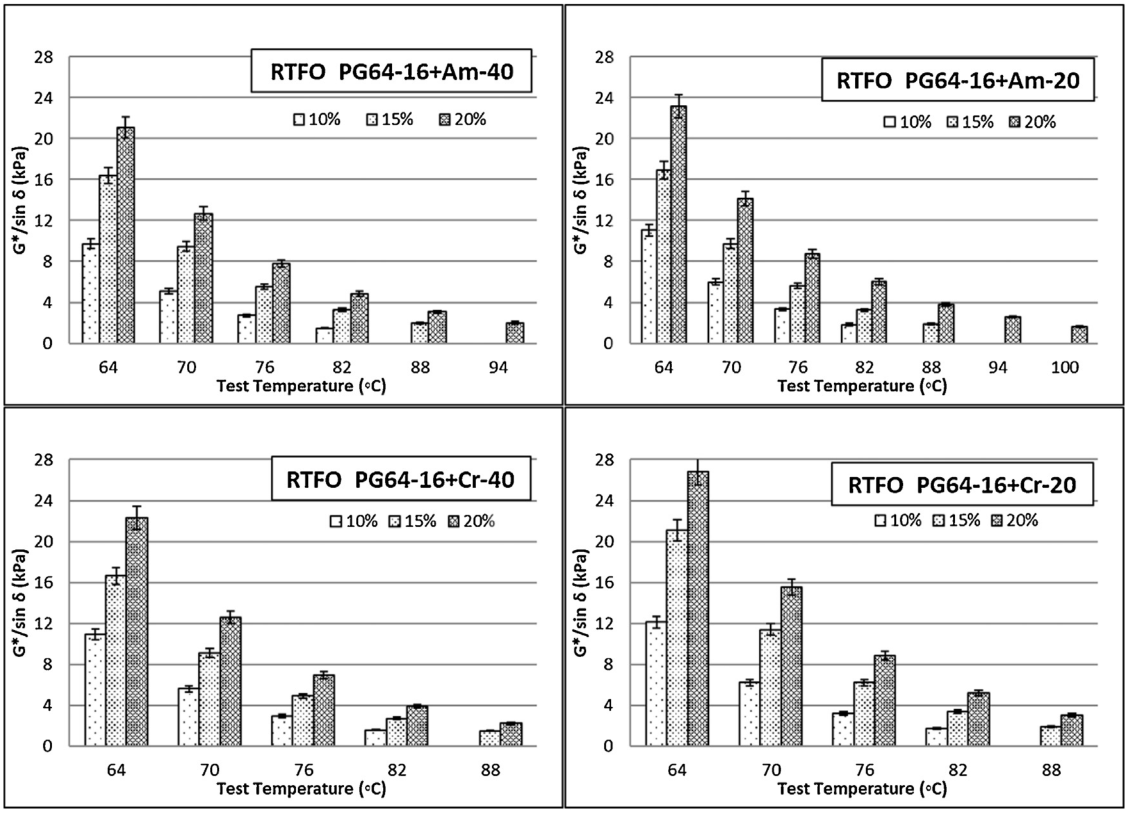

Fig. 21. G*/sin δ for RTFO aged samples of rubber-modified binder PG (64-16).

Failure temperature for RTFO-aged binder is defined as the temperature at which G*/sin δ is equal to 2.2 kPa. This temperature is calculated by logarithmic interpolation (Figs. 23–25). Failure temperature of RTFO-aged samples were higher than un-aged ones. The average increase in failure temperature due to aging was approximately 6 °C.

Figs. 26–28 illustrates that RTFO-aged samples showed lower ductility with no exception. In the process of aging oxidation and oil evaporation make the modified binders more brittle which failed earlier in tension compared to un-aged samples.

3.3. Low-temperature properties of modified binders

Low-temperature properties of modified binders were evaluated based on testing PAV-aged samples. Asphalt binder stiffness and m-value, presented in Figs. 29–31, is the result of a Bending Beam Rheometer (BBR) test. In all tests the stiffness and m-value were measured at 60 s after loading applied. It was evident, except for modified PG64-16, that stiffness decreased with the increase in rubber content. Modified samples made with binder PG64-16 demonstrated lower stiffness compared to the other two virgin binders. The average stiffness of PG58-28 and AC-20 for 10, 15 and 20% CRM are 166, 130, 107, 132, 105 and 91 MPa, respectively. While these numbers for PG64-16 are 61, 52 and 45 MPa. It should be noted that BBR test was conducted at −12 °C on samples made with PG61-16 and AC-20 and at −18 °C for samples made with PG58-28. The m-values did not show significant differences for various rubber percentages as well as for rubber types and sizes. However, the average m-value of modified binders made with PG64-16 were 0.356 and was significantly higher than the ones from AC-20 and PG58-28 which were 0.292 and 0.295, respectively.

3.4. Recommended crumb rubber content/type based on AHP method

It was important to determine an optimum content of rubber to be mixed with a binder as a modifier. This optimum rubber content should satisfy the requirements of each test presented earlier in this paper. Considering the fact that the behavior of a modified binder varies with rubber size, type, and percentage, finding an appropriate regression model among all the parameters was necessary.

Several samples failed to satisfy the requirements for one or more tests based on local specifications. While adding more rubber improved several properties, it had a negative influence on some other parameters. The same was true about the type of process used in manufacturing the rubber. Additionally, while cryogenic samples exhibited better results for some tests,

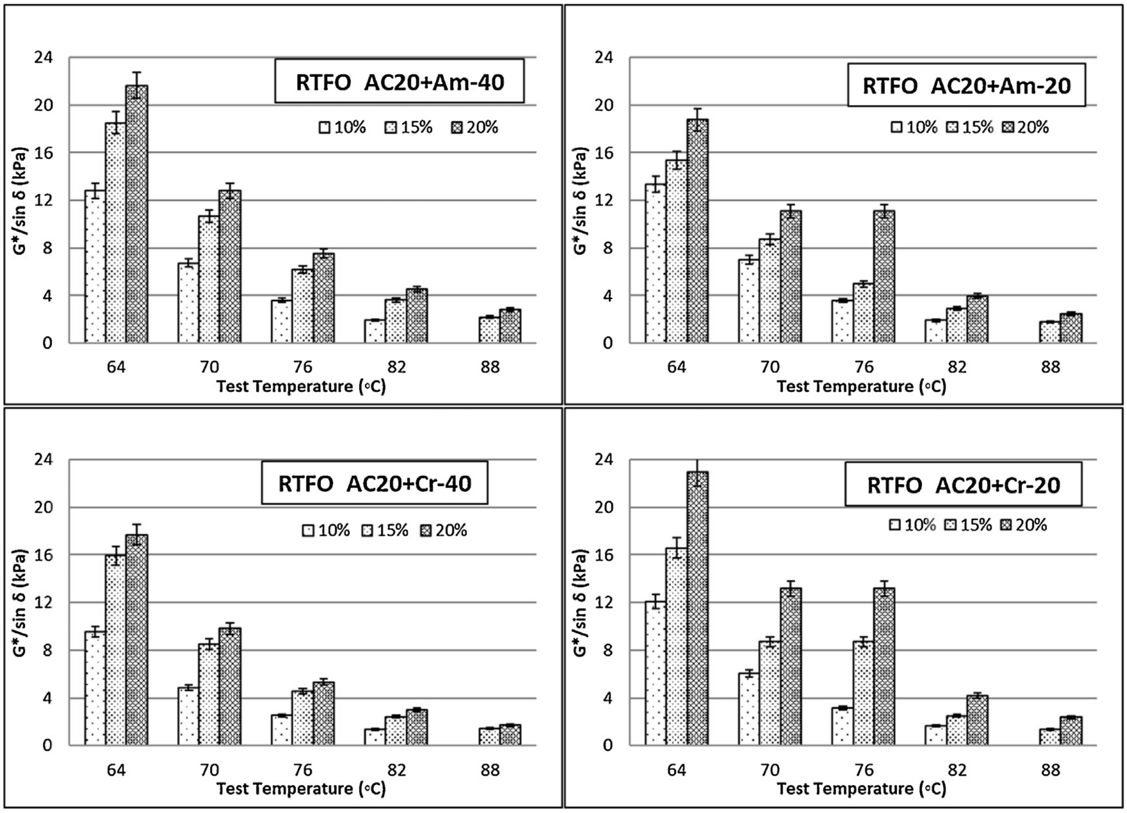

Fig. 22. G*/sin δ for RTFO aged samples of rubber-modified binder AC-20.

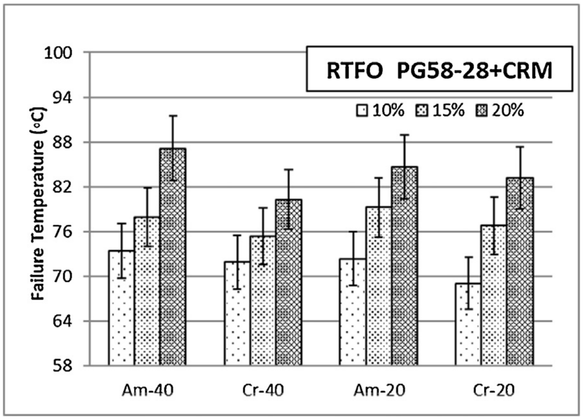

Fig. 23. RTFO-aged failure temperature of rubber-modified binder PG (58-28).

ambient types showed improved results for other tests. Rubber size also had an effect on several parameters. In some experiments, it was found better to use smaller particles, while other experiments demonstrated improvements when using larger particle sizes.

In order to find the best blend for each binder source, the Analytical Hierarchy Process (AHP) method was used. AHP is a multi-criteria decision-making approach and was introduced by Saaty [32]. It has particular applications in group decision making, and is used in a wide variety of decision situations. The selection of one alternative from a given set of alternatives, usually where there are multiple decision criteria involved, is one of the applications of AHP. AHP considers a set of evaluation criteria and a set of alternative options, among which the best decision is to be made.

For the purpose of this research, first in a pairwise comparison system, scores were allocated to the results of the tests performed on the CRM modified samples based on their importance in grade verification of asphalt binder and performance

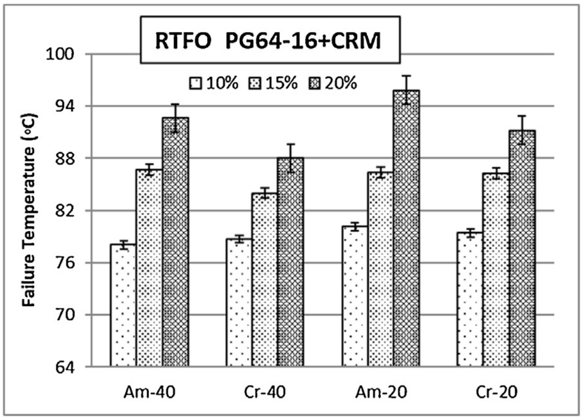

Fig. 24. RTFO-aged Failure Temperature of rubber-modified binder PG (64-16).

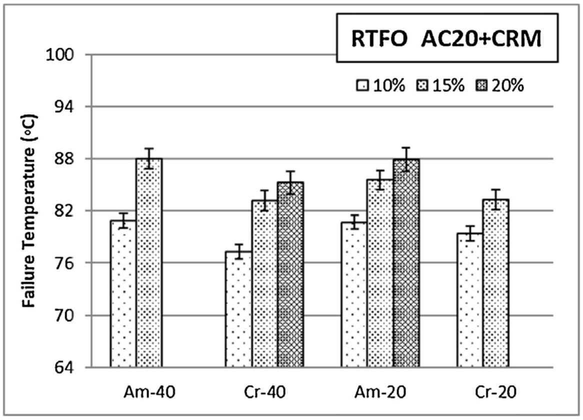

Fig. 25. RTFO-aged Failure Temperature of rubber-modified binder AC20.

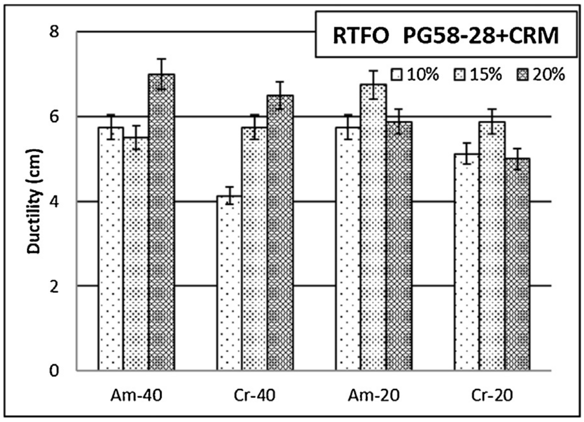

Fig. 26. RTFO-aged ductility of rubber-modified binder PG (58-28).

of asphalt mix. Opinions of several engineers and specialist individuals from local academic, governmental, and private entities were polled for that purpose. It should be noted that the allocated scores varied among different virgin binders. After establishing the pairwise comparison matrix, a standardized matrix was constructed and parameters such as maximum eigenvalue (λ_{max}), consistency index (CI), consistency ratio (CR) for the matrix, and final priority (weight) of each criterion (test result) were calculated. Table 2 presents the results of the AHP calculations.

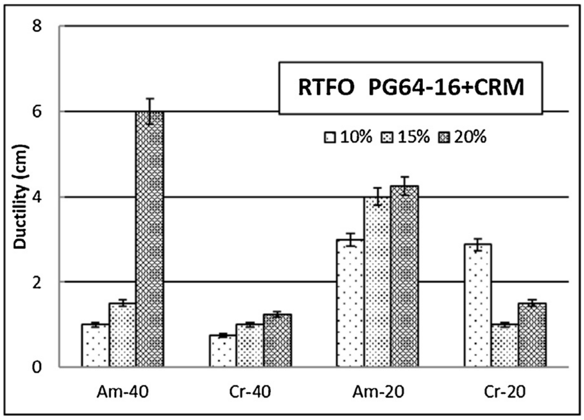

Fig. 27. RTFO-aged ductility of rubber-modified binder PG (64-16).

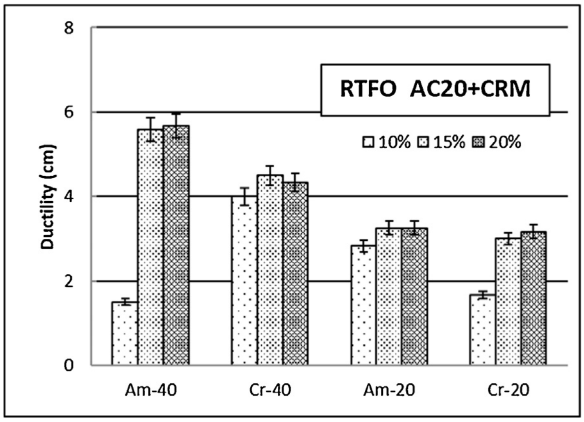

Fig. 28. RTFO-aged ductility of rubber-modified binder AC-20.

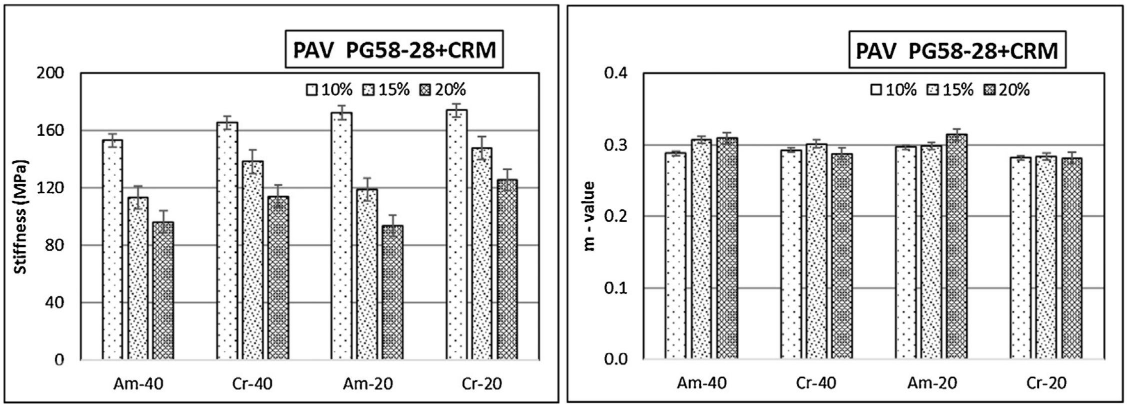

Fig. 29. Stiffness and m-value of PAV-aged rubber-modified binder PG (58-28).

In the second portion of the process, all blends of one virgin binder were ranked based on the test results. The blend samples that had results closer to those of the traditional polymer-modified were ranked higher. The test results on polymer modified asphalt binders are presented in Table 3. The priority vectors for each blend in each criterion was calculated according to Equation 1:

$$PV_{ij} = 1 - \frac{(AD_i - MinAD)}{(MaxAD - MinAD)} \times FP_j$$

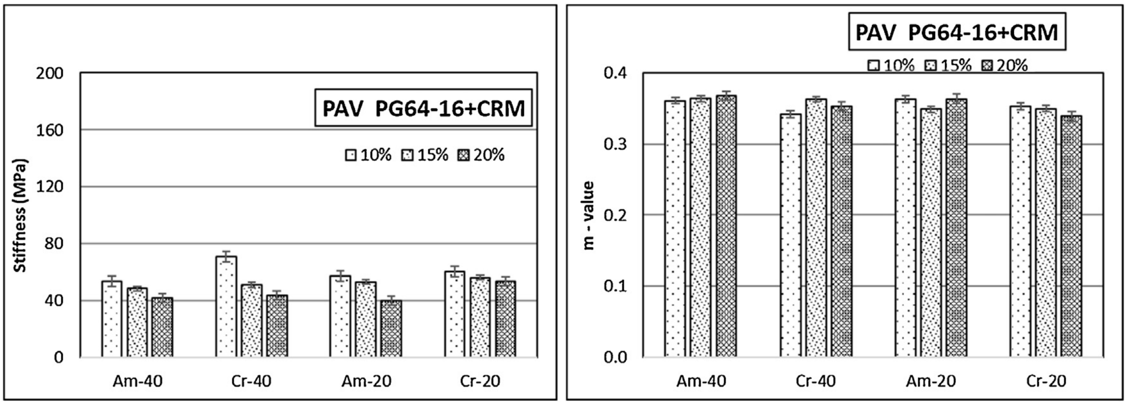

Fig. 30. Stiffness and m-value of PAV-aged rubber-modified binder PG (64-16).

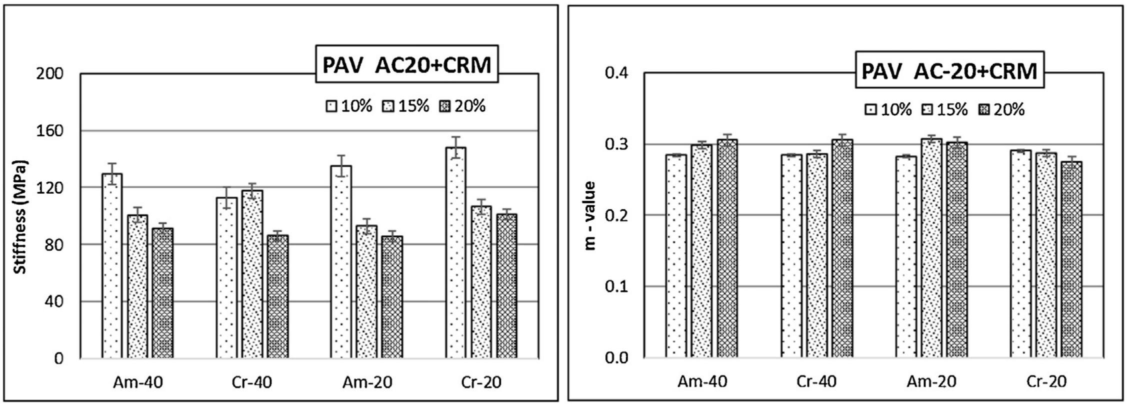

Fig. 31. Stiffness and m-value of PAV-aged rubber-modified binderAC-20.

Table 2
Results of AHP calculations.

	Weight		
Criteria/Virgin Binder	PG58-28	PG64-16	AC-20
Flash point	2.70	2.73	2.79
Tenacity	21.16	5.59	6.58
Toughness	7.55	8.10	7.99
Viscosity	16.16	14.95	15.59
Ductility-ORG	13.21	13.32	13.97
Ductility-RTFO	5.51	11.29	11.17
Failure Temp-ORG	23.43	23.59	22.35
Failure Temp-RTFO	10.28	20.44	19.55
λ_{max}	8.093	8.105	8.053
CI	0.013	0.015	0.008
CR	0.009	0.011	0.005

Table 3
Results of tests on polymer modified asphalt binders.

	PG64-28	PG76-22 (Source A)	PG76-22 (Source B)
Flash point (°C)	322	317	311
Viscosity (Pa.s)	0.84	2.85	1.66
Failure Temp-Org (°C)	68.4	76.4	75.7
Ductility (cm)	93	34	34
Toughness (in-lb)	510	128	111
Tenacity (in-lb)	458.0	93	80
Failure Temp-RTFO (°C)	65.9	76.4	75.7
Ductility-RTFO (cm)	25.6	17.6	20.8

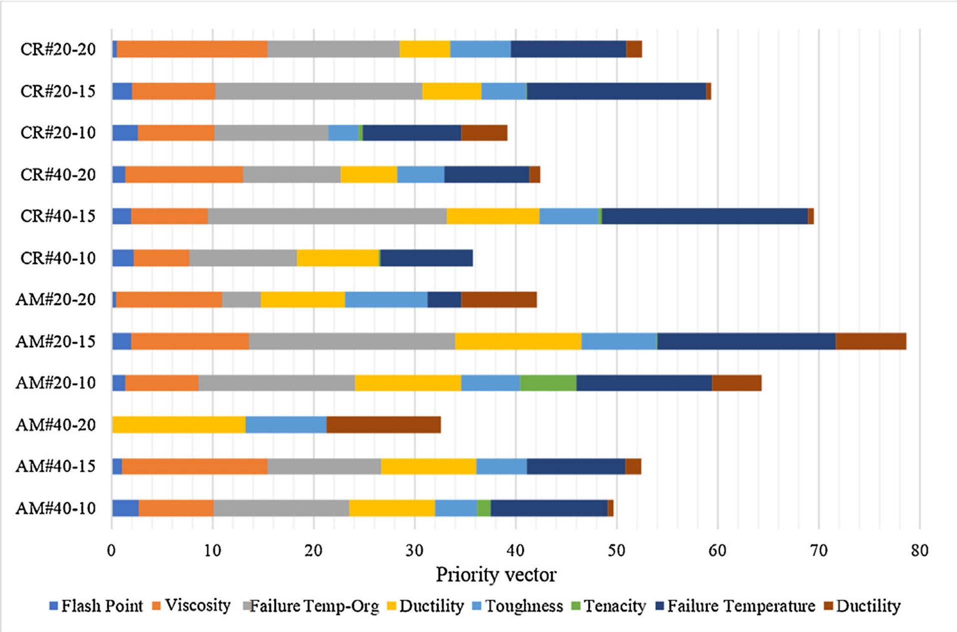

Fig. 32. Priority vector for rubber type and content for virgin binder PG64-16.

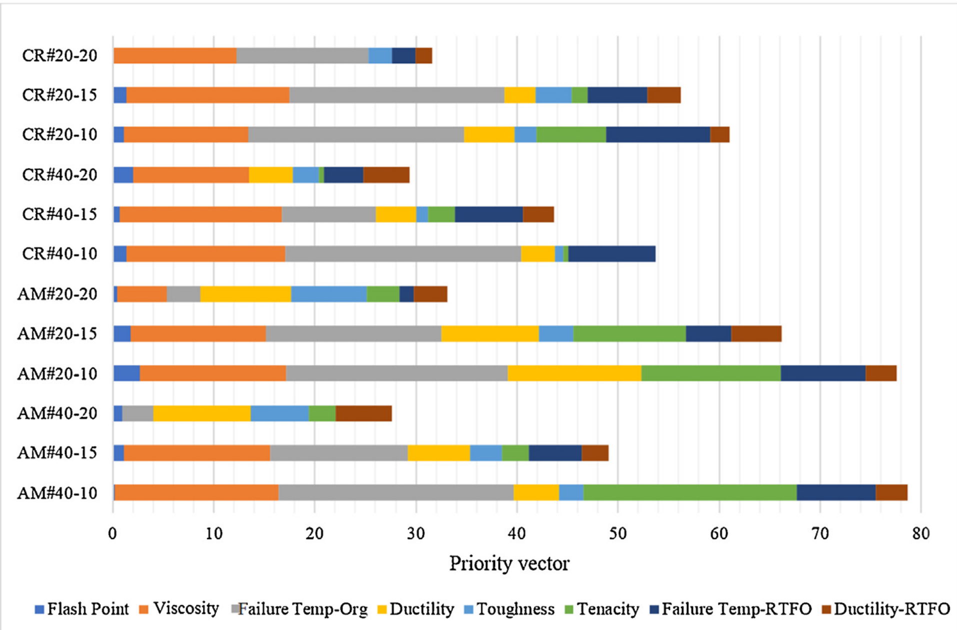

Fig. 33. Priority vector for rubber type and content for virgin binder PG58-28.

where:

PV_{ij} = priority vector of blend i in criterion j

AD_i = absolute difference between value of blend i in criterion j and value of polymer modified binder in criterion j

$MinAD$ = minimum of the absolute differences

$MaxAD$ = maximum of the absolute differences

FP_j = final priority (weight) of criterion j

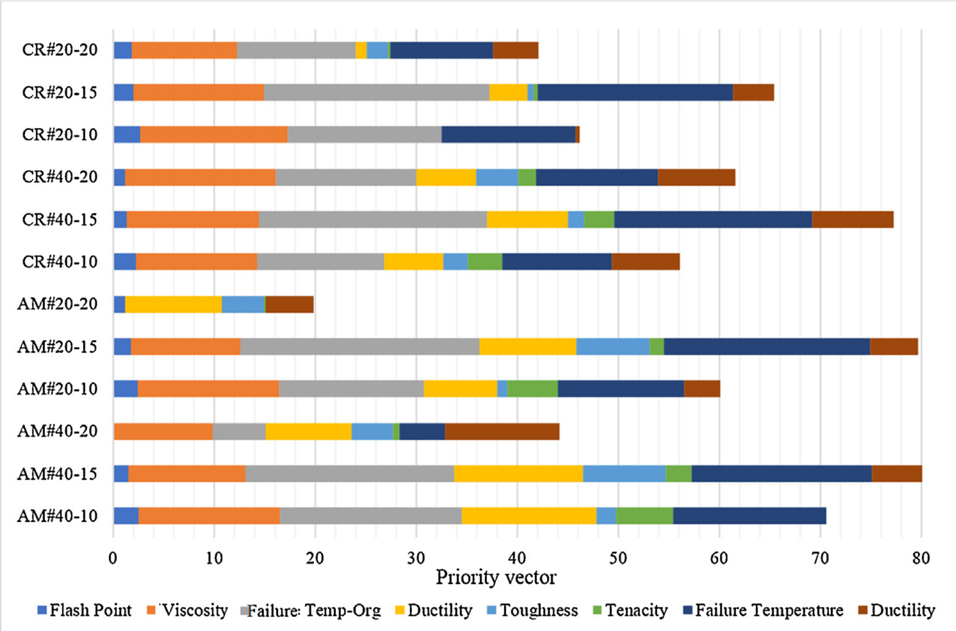

Fig. 34. Priority vector for rubber type and content for virgin binder *AC-20*.

Figs. 32–34 present the results of the calculations which led to selecting the best combination of rubber size, type, and content for modifying the asphalt binder.

The blend with the highest priority vector was selected as the 'best' blend. Based on the calculations, the asphalt binder having 15% ambient #20 rubber had the highest priority and was selected for modifying the asphalt binder with virgin binder of PG64-16. The winning blend for virgin binders of PG58-28 and AC-20 are ambient #40 with 10% and 15% CRM, respectively.

4. Summary and conclusion

Extensive testing and evaluations were carried out on various asphalt binder samples made with different amounts, types and sizes of crumb rubber in order to explore the rheological properties and characterizations, as well as to determine the optimum rubber content with regards to the binder source and type. The results of this investigation are summarized as follows:

- The particle size, shape, and content of CRM had significant effects on most of the rheological properties of a modified asphalt binder.
- Since rubber is a more viscous material compared to asphalt binder even at high temperature, viscosity of a modified binder increased with CRM content. Ambient CRM showed greater viscosity as well as greater effect of rubber content compared to cryogenic CRM. This behavior can be associated with higher surface area of ambient CRM, hence thicker gel around crumb rubber particles.
- Elastic component of dynamic shear modulus increased with rubber content for both un-aged and RTFO aged samples. This indicates that CRM may help significantly to improve the rutting resistance of asphalt pavement. Some studies have investigated and proved that claim by testing the asphalt mixes made with rubber modified binders.
- The failure temperature also increased with rubber content. This indicates that modifying asphalt binder with CRM increases the high-temperature grade. For example, high-temperature grade of PG58-22 binder may be increase to 76 °C by adding right amount CRM, while other properties remain within specifications. The rate of change in the failure temperature was similar for various samples.
- Elastic properties of CRM modified binders when stresses under direct tension at low to medium temperatures were tested through ductility and toughness-tenacity tests. The main conclusion was these properties decrease with increase in rubber content. However, shape and size of CRM did not show a meaningful effect on these properties. Adding irregular-shape and granular material of crumb rubber particles depreciates the uniformity and homogeneity of virgin asphalt binder which results in early failure under tension stress of ductility and toughness-tenacity test. Unlike ductility, modified binders made of AC20 and PG64-16 display greater toughness compared to PG58-28.
- Low-temperature properties of modified binders were evaluated based on testing PAV-aged samples with a BBR machine. Modified binder samples having higher rubber content had lower stiffness at low temperatures.

- In order to find the best blend of CRM for each binder source/grade, the Analytical Hierarchy Process (AHP) method was used. AHP is a multi-criteria decision-making approach which has particular applications in group decision making and is used in a wide variety of decision situations. The selection of one alternative from a given set of alternatives, usually where there are multiple decision criteria involved, is one of the applications of AHP. Based on AHP analysis, the recommended rubber content and type for virgin binder PG64-16 is 15% ambient # 20 and for binder PG58-28 and AC-20 are 10 and 15% ambient # 40, respectively.

Declaration of Competing Interest

The authors declare that there are no conflicts of interest.

Acknowledgements

This paper was based on a project with Nevada Department of Transportation (NDOT). UNLV libraries open article fund is supporting the fees for open access.

References

[1] Advancing Sustainable Materials Management, Fact Sheet, Reported to EPA (Environmental Protection Agency) November 2016 (Accessed November 20, 2018, (2014) . http://web.archive.org/web/20181120164554/https://www.epa.gov/sites/production/files/2016-11/documents/2014_smmfactsheet_508.pdf.
[2] Scrap Tire News, From Scrap Tires Recycling Blog/ Articles, (2019) . (Accessed May 15, 2019) https://scraptirenews.com/blog.php.
[3] R. Nelson, M. Hossain, A. Statewide, "Plan for Utilization of Scrap Tires in Kansas". Draft Final Report to Kansas Department of Transportation (KDOT) September, (1994) .
[4] R.G. Hicks, Asphalt Rubber Design and Construction Guidelines, Volume 1- Design Guidelines, Northern California Rubberized Asphalt Concrete Technology Center, 2002 January.
[5] S. Lee, C.K. Akisetty, S.N. Amikhanian, The effect of crumb rubber modifier (CRM) on the performance properties of the rubberized binders in HMA pavements, Constr. Build. Mater. 22 (2008) 1368–1376.
[6] H.H. Kim, S. Lee, Effect of crumb rubber on viscosity of rubberized asphalt binders containing wax additives, Constr. Build. Mater. 95 (2015) 65–73.
[7] H. Wang, Z. You, J. Mills-Beale, P. Hao, Laboratory evaluation on high temperature viscosity and low temperature stiffness of asphalt binder with high percent scrap tire rubber, Constr. Build. Mater. 26 (2011) 583–590.
[8] P. Cong, P. Xun, M. Xing, S. Chen, Investigation of asphalt binder containing various crumb rubber and asphalt, Constr. Build. Mater. 40 (2012) 632–641.
[9] L. Raad, S. Saboundjian, Fatigue behavior of rubber-modified pavements, Transp. Res. Rec. 1639 (1998) 98–1019.
[10] N.S. Mashan, A.H. Ali, A.M. Rehan, M. Abdelaziz, Effect of blending time and crumb rubber content on properties of crumb rubber modified asphalt binder, Int. J. Phys. Sci. 6 (9) (2011) 2189–2193.
[11] G.H. Shafabakhsh, M. Sadeghnejad, Yousef Sajed, Case study of rutting performance of HMA modified with waste rubber powder, Case Stud. Constr. Mater. 1 (2014) 69–76.
[12] R.C. West, G.C. Page, J.G. Veilleux, B. Choubane, Effect of tire rubber grinding method on asphalt-rubber binder characteristics, Transp. Res. Gate Rec. 1638 (1998) 98-0039.
[13] F.J. Navarro, P. Portal, F. Martinez-Boza, C. Valencia, C. Gallegos, Rheological characteristics of ground tire rubber-modified bitumen, Chem. Eng. J. 89 (2002) 53–61.
[14] C. Thodesen, K. Shatanawi, S.N. Amirkhanian, Effect of crumb rubber characteristics on crumb rubber modified (CRM) binder viscosity, Constr. Build. Mater. 23 (2008) 295–303.
[15] J. Shen, S.N. Amirkhanian, F. Xiao, B. Tang, Influence of surface area and size of crumb rubber on high temperature properties of crumb rubber modified binders, Constr. Build. Mater. 23 (2008) 304–310.
[16] J. Shen, S. Amirkhanian, The influence of crumb rubber modified (CRM) microstructures on the high temperature properties of CRM binders, Int. J. Pavement Eng. 6 (4) (2005) 265–271.
[17] D. Yousefi Kebria, S.R. Moafimadani, Y. Goli, Laboratory investigation of the effect of crumb rubber on the characteristics and rheological behavior of asphalt binder, Road Mater. Pavement Des. 6 (4) (2015) 946–956.
[18] C.K. Estakhri, J.W. Button, E.G. Fernando, Use, availability, and cost-effectiveness of asphalt rubber in Texas, Transp. Res. Rec. (1992) 1339.
[19] E.I. Szerb, I. Nicotera, B. Teltayev, R. Vaiana, C.O. Rossi, Highly stable surfactant-crumb rubber-modified bitumen: NMR and rheological investigation, Road Mater. Pavement Des. 19 (5) (2018) 1192–1202.
[20] B.C. Celauro, D.L. Presti, A. Bevilacqua, Definition of a laboratory optimization protocol for road bitumen improved with recycled tire rubber, Constr. Build. Mater. 37 (2012) 562–572.
[21] D.L. Presti, Recycled tyre rubber modified bitumens for road asphalt mixtures: a literature review, Constr. Build. Mater. 49 (2013) 863–881.
[22] S. Mahmoudkelaye, K.T. Azari, M. Pourvaziri, E. Asadian, Sustainable material selection for building enclosure through ANP method, Case Stud. Constr. Mater. 9 (2018)e00200.
[23] B. Kiani, R.Y. Liang, J. Gross, Material selection for repair of structural concrete using VIKOR method, Case Stud. Constr. Mater. 8 (2018) 489–497.
[24] J.Y. Do, D.K. Kim, AHP-based evaluation model for optimal selection process of patching materials for concrete repair: focused on quantitative requirements, Int. J. Concr. Struct. Mater. 6 (2) (2012) 87–100.
[25] M.M. Fouladgar, A. Yazdani-Chamzini, A. Lashgari, E.K. Zavadskas, Z. Turskis, Maintenance strategy selection using AHP and COPRAS under fuzzy environment, Int. J. Strateg. Prop. Manag. 16 (1) (2012) 85–104.
[26] W. Fan, L. Dai, Pavement evaluation with AHP based on expert's assessment June, 2015 23rd International Conference on Geoinformatics, IEEE, 2015, pp. 1–3.
[27] H.R. Jahanian, G.H. Shafabakhsh, H. Divandari, Performance evaluation of Hot Mix Asphalt (HMA) containing bitumen modified with Gilsonite, Constr. Build. Mater. 131 (2017) 156–164.
[28] L. Gáspár, D. Castro-Fresno, D. Jato-Espino, I. Indacoechea-Vega, I. Paeglite, P. Pascual-Muñoz, et al., Complex optimization of heavy duty asphalt pavement types in DURABROADS project, Transp. Res. Procedia 14 (2016) 3519–3526.
[29] D. Jato-Espino, I. Indacoechea-Vega, L. Gáspár, D. Castro-Fresno, Decision support model for the selection of asphalt wearing courses in highly trafficked roads, Soft comput. 22 (22) (2018) 7407–7421.
[30] C. Kou, P. Xiao, A. Kang, P. Mikhailenko, H. Baaj, Z. Wu, Methods to evaluate the aging grades of reclaimed asphalt binder, Appl. Sci. 7 (12) (2017) 1209.
[31] P. Zhang, Y.C. Cheng, J.L. Tao, Y.B. Jiao, Molding process design for asphalt mixture based on response surface methodology, J. Mater. Civ. Eng. 28 (11) (2016)04016120.
[32] T.L. Saaty, Homogeneity and clustering in AHP ensures the validity of the scale, Eur. J. Oper. Res. 72 (3) (1994) 598–601.