Contents lists available at http://qu.edu.iq

Al-Qadisiyah Journal for Engineering Sciences

Journal homepage: https://qjes.qu.edu.iq

Experimental study of the behavior of crumb rubber-modified asphalt under the influence of steam aging

Rana A. Yousif , Sady A. Taya , Abbas F. Jasim* , and Sarah F. Khalaf

Highway and Transportation Engineering Department, College of Engineering, Mustansiriyah University, Baghdad 10045, Iraq.

ARTICLE INFO

Article history:
Received 00 December 0000
Received in revised form 00 January 0000
Accepted 00 February 0000

Keywords:
Crumb rubber
Physical and rheological properties
Steam aging
Rolling thin film 0ven
Aged asphalt

ABSTRACT

Incorporating crumbed rubber into asphalt binder or asphalt concrete mixes has become increasingly common in recent years. Researchers have looked into how well this additive can improve both the modified bitumen and the modified asphalt mix. With the growing usage of rubber crumb modifiers in asphalt mixtures, the significance of certain asphalt qualities has been recognized. This has opened up more opportunities for a thorough examination of their rheological and physical properties. The asphalt-rubber binder's performance was often impacted by the amount of crumb rubber and the blending circumstances. In this study, a new method, the Steam Aging Technique (SAT), was utilized to study the attributes of the rubber-enhanced bitumen, which was aged throughout Bitumen's service. The primary goal of this research was to investigate the influence of traditional aging methods compared to the steam aging method, and the possibility of using the latter as an alternative test to traditional methods. Overall, physical test results showed notable increases in softening point and rotational viscosity and a decrease in penetration value for vapor-aged bitumen contrasted to non-aged bitumen. This research used a dynamic shear rheometer (DSR) and a temperature sweep test (TS) method to study rutting under control strain mode. The effectiveness of the use of steam aging has been observed and the possibility of using it as an alternative to the conventional aging methods available was investigated. It was found that there was a great convergence in the results extracted from the steam aging device with an addition rate of 5, 10, and 15% and an aging time of 45 minutes with the results extracted from the rotary kiln device, except for the 20% addition rate, which gave a difference in values.

© 2024 University of Al-Qadisiyah. All rights reserved.

1. Introduction

Transportation is the main artery for the economic development of countries and territories, such as the transportation of citizens, goods, and others. To ensure good economic growth, this is done through transportation networks whose platforms must ensure good ride quality, thus increasing the demand for transportation infrastructure. Pavement deterioration is exacerbated by the rising number of heavy vehicles on the road, so improved materials must be developed to meet the increasing challenges [1-3]. These circumstances have contributed to the development

* *Corresponding author.*
E-mail address: abbas.jasim@uomustansiriyah.edu.iq (Abbas Jasim)

https://doi.org/10.30772/qjes.2024.145870.1087
2411-7773/© 2024 University of Al-Qadisiyah. All rights reserved. This work is licensed under a Creative Commons Attribution 4.0 International License.

Accepted Manuscript

Nomenclature:

SAT	Steam aging technique	*PAV*	Pressure aging vessel
CB	Carbon black	PG	Performance Grade
CR	Crumb rubber	PTFO	Rolling thin film oven
DSR	Dynamic shear rheometer	TCR	Tire crumb rubber
*G**	Complex modulus	TS	Temperature sweep test

of various asphalt coating technologies over the past 50-60 years [4]. The use of additives to improve asphalt mixture properties is one area of study [5]. Crumb rubber (CR) made from used car and truck tires is a raw material in asphalt and other paving materials. Since CR helped lessen the improper disposal of used tires in nature, it gained more and more attention from the pavement industry and the academic research community. Despite years of research and development, crumb asphalt rubber pavements still have a hard time gaining widespread acceptance. Lo Presti [6] explains that this is due to the exceptional lack of support for local policy and because the experts involved lack the necessary information and training.

The performance attributes of the neat asphalt binder, such as resistance against rupture and stress cracking [7-8], need to be enhanced to prevent structural damage to the asphalt pavement and enhance the resilience of the pavement. Despite the urgent need to enhance the attribute of the bitumen, the cost of the additive must be taken into consideration, in addition to its impact on the environment, where countries are striving to get rid of waste rubber, which takes a very long time to decompose and return to its basic components [9]. The availability of landfill space has decreased even as the number of waste tires has grown. The steady increase in the amount of waste tires over the past few years has made this an increasingly pressing issue. One useful way to use scrap tires is by using asphalt binders modified with rubber powder in the construction of pavement. In this way, we can gain enhanced tensile strength and fatigue endurance, and reduced temperature susceptibility, and thus, the overall properties of the mix could be improved. It has been shown that using scrap tire rubber powder in modified asphalt binders can have positive effects on the environment and the economy [9-12].

The compatibility between asphalt and rubber must be enhanced if reliable, high-performance rubber asphalt is to be produced. Cross-linked rubber, carbon black (CB), silica, and other additives make up the bulk of tire rubber [13]. Since the asphalt binder and all its additives play an important role as a basic construction material of hot asphalt pavement, the study of its rheological and mechanical attributes is a very important section for every researcher. The fact that the binder is exposed to different aging environments related to temperature changes and access to oxygen, the aging factor had to be one of the important issues of the study, where aging changes the physical and rheological properties of asphalt binder alike.

Many researchers have used the rolling thin-film oven (RTFO) and pressure-aging vessel (PAV) test to examine the effects of artificial aging on the rheology of binders [14]. More effective and speedier aging procedures for both neat and modified bitumen binders have been developed, including the stirred air-flow test [15] and microwave technology. Compared with laboratory aging, the aging test using the steam cocker device is a new method of aging that is less harmful to the environment and in a relatively short period compared to the rolling thin film device [16]. Historically, researchers have paid less attention to how asphalt binders age in the field [17].

2. Research objectives

This study has two main goals. As a first step, it utilizes a steam device to assess the aging process with the hope of one day deploying this technology in place of the conventional short-term aging device. The second objective of this study is to employ the Steam Age Apparatus to determine the sensitivity of rubber-modified asphalt binder to heat. If these goals are met, it will be possible to learn more about how asphalt binders age and how the steam device can be used in asphalt aging research.

3. Materials and methods

3.1. Asphalt binder

An asphalt binder with a penetration rate of 40/50 as a control bitumen was used in this study. The physical characteristics of this primary binder are listed in Table 1.

Table 1. Features of the neat bitumen used

Test Name	Slandered Used	Test Result
Penetration @ 25 °C	ASTM D5	47
The softening point, °C	ASTM D36	50
Flashpoint, °C	ASTM D92	330
Fire point, °C	ASTM D92	120
Specific Gravity	ASTM D70	1.034
Viscosity @ 135 °C (cpoise)	ASTM D4402	0.431
Viscosity @ 165 °C (cpoise)	ASTM D4402	0.136

3.2. Crumb rubber modifier

Crumb rubber is recycled rubber produced from scrap tires of cars and trucks. During the recycling process, the steel wire and tire (fluff) are removed, leaving rubber tires with a granular texture. Continuous processing with a granulator or crushing mill, possibly with the help of coolers or by mechanical means, reduces particle size even further. Figure 1 demonstrates the process used to create premium grade, ultra-fine (40 mesh) tire crumb rubber. This material meets all ROHS standards. T-MESH 40 has a high pass rate and is clean from foreign pollutants because of its novel production method and rigorous quality control. Table 2 lists the chemical components of the tire crumb rubber (T-MESH 40) and Table 3 lists its physical attributes.

Accepted Manuscript

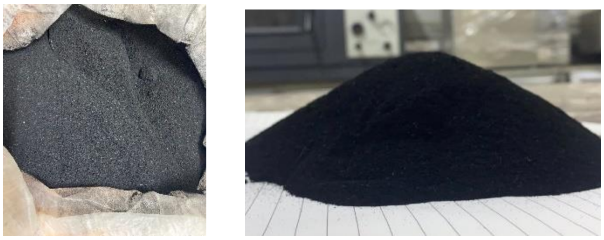

Figure 1. The used tire crumb rubber

Table 2. Chemical constituents of the used tire crumb rubber [18]

Attributes	Standards	Results
Acetone Extract%	JIS K 6350	10±5
Ash Content %	TGA	5±3
Carbon Black %	TGA	32±5
Rubber Hydrocarbon %	TGA	52±8

Table 3. Physical attributes of the used tire crumb rubber [18]

Attributes	Standard used	Results
Passing (%)	ASTM D 5644	> 90
Loss on Heat (%)	ASTM D 1509	< 1
Metal Content (%)	ASTM D 5603	≤ 0.1
Fiber Content (%)	ASTM D 5603	≤ 0.3

4. Rubber-modified binder production

The asphalt binder was mixed with recycled rubber crumb using a wet method. The rubber-modified asphalt binder was produced by mixing finely ground rubber crumbs with the bitumen at a high temperature to ensure the homogeneity of the mixture and then it can be used with aggregates to produce modified concrete mixes. As the asphalt binder's lighter fractions (essential oils) absorb the recycled rubber microparticles, the former may swell and, as a result, the latter may harden, creating a viscous gel with a fairly high viscosity [19]. Blending the bitumen with the rubber crumb modifiers involved slowly adding the modifiers while the mixture was heated to between 160 and 170 degrees Celsius and mixed at a shearing rate of 1000 RPM for one hour using a high-shear mixer.. Next, the mixtures are placed in metal canisters covered with foil before being used in relevant laboratory tests.

Figure 2. Tire crumb rubber modified preparation

5. New conditioning criterion for moisture susceptibility

By using a steam cooker apparatus for sample conditioning, a new approach moisture susceptibility criterion was developed by steam produced by a food steamer.

5.1 Preparation of Steam Aged Asphalt Binders

For the preparation of the asphalt sample, PAV vats were used. The aging procedure is as follows: Stir the sample and pour 50g into the container of the preheated aging measuring vessel as shown in Figure 3. Pour out two pans and place them in the food steamer, as shown in Figure 4. Next, take the sample out of the machine and put the aged asphalt samples in small cans to be used for further testing.

Figure 3. Asphalt Binders Before and After Steam Aging

Figure 4. Steam Cooker Apparatus used in the aging process

5.2 Steam aging apparatus

The steam aging apparatus consists of the following elements:

1. Electricity can be used to heat the water bath to temperatures of up to 100 degrees Celsius.
2. A reliable balance that can measure down to 1g in precision is ideal.
3. As shown in Figures 3 and 4, the environmental chamber has three racks with enough space to test two cylindrical samples with two trays of PAV pans.

5.3 Test principle

To achieve the moisture saturation, nominally identical test specimens are heated in a steam cooker assembly with a partial water bath at 89.2 °C and a pressure of 0.8 mbar for the times (15, 30, 45, and 60 minutes) listed in Table 4.

Accepted Manuscript

Table 4. Steam Temperature and Pressure with One Opening Outlet [16]

Time minutes	Apparatus Temperature, °C	Core Temperature, °C	Skin Temperature, °C	Pressure Measured (mbar)
15	98.2	94.9	95.7	0.80
30	98.2	96.8	97.2	0.80
38	98.2	98.2	98.2	0.80
45	98.2	98.2	98.2	0.80
60	98.2	98.2	98.2	0.80

6. Results and discussion

Conventional tests such as softening point, penetration, and rotational viscosity assessments were carried out serially on the asphalt binder without and with the addition of rubber. Table 5 shows the results obtained from the tests of the crumb rubber-enhanced bitumen, as indicated in the following paragraphs.

Table 5. Steam Temperature and Pressure with One Opening Outlet [16]

Test	Unit	Mix coding				
		MB-40R0	MB-40R5	MB-40R10	MB-40R15	MB-40R20
Penetration	1/10mm	47	43	39	35	31
Brookfield Viscosity @ 135 °C	(Pa.s)	0.6538	0.8913	1.0981	1.3251	1.6187
Brookfield Viscosity @ 165 °C	(Pa.s)	0.2099	0.3124	0.3505	0.3713	0.3992
Softening Point	(°C)	50	54	60	65	69
Flash point	(°C)	331.5	361.0	387.5	399.5	410.5
*After Rolling Thin Film Oven Test						
Penetration	1/10mm	32.5	28.5	22.5	19.7	17.5
Loss on weight (163°C, 50gm, 5h), (%)		0.3	0.278	0.267	0.260	0.24
Softening Point	(°C)	54.5	57.6	63.1	67.2	69.8

6.1 Penetration test

The results showed a percentage of decrement in the penetration values for the percentages of crumb rubber utilized in this research. Through Figure 5, it is possible to notice the reduction in the liquefaction value with the continuous increase in the percentage of rubber. This is due to the general properties of rubber and its apparent ability to enhance the physical behavior of the modified bitumen, such as stiffness, tensile strength, and others .Lower penetration readings imply a more rigid and stable binder as the amount of tire rubber powder in the mix increases [18, 20]. Figure 5 displays the results of the thin-film oven test (RTFOT), and Figure 6 displays the results of the steam aging test (SAT), both of which show a decrease in the penetration values of the base and modified bituminous binders during aging.

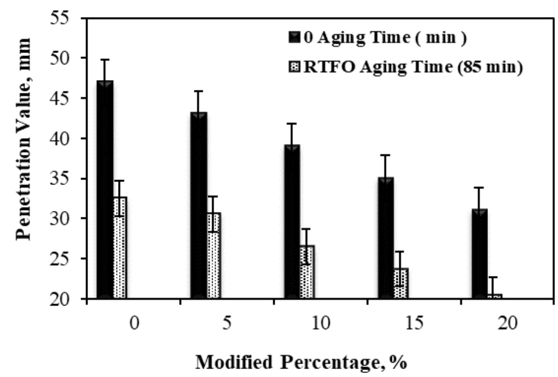

Figure 5. Penetration Value for CR Modified Asphalts before and after Rolling Thin Film Oven Test.

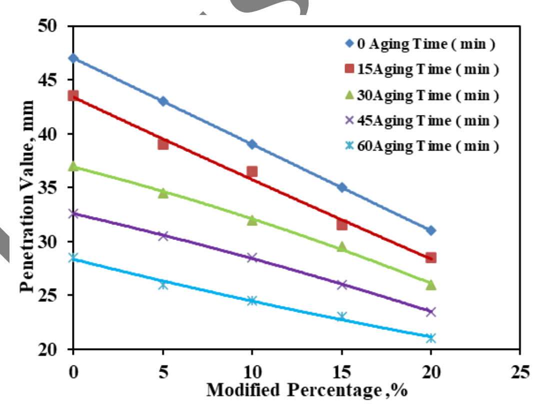

Figure 6. Penetration Value for CR Modified Asphalts for Steam Aging.

6.2 Softening point test

The outcomes showed that the softening point value of the enhanced binders was improved by increasing the CR particle content and aging time due to the asphalt binder hardening. As the rubber serves as reinforcement for the asphalt binders, asphalt binders with a higher softening point could be less prone to persistent deformation (rutting), hence an increase in this temperature is desirable.

The softening point values increase with the proportion of tire rubber powder in the mixture, which indicates that the binder becomes more rigid and stable [19]. Results of softening point values ranked and adjusted asphalt binder increased after each of the aging conditions for the test Thin Film Oven (RTFOT), as shown in Figure 7, and the steam aging test (SAT), as shown in Figure 8.

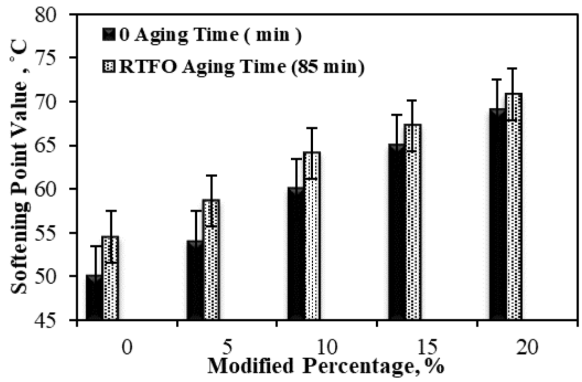

Figure 7. Softening Point Value for CR Modified Asphalts before and after Rolling Thin Film Oven Test

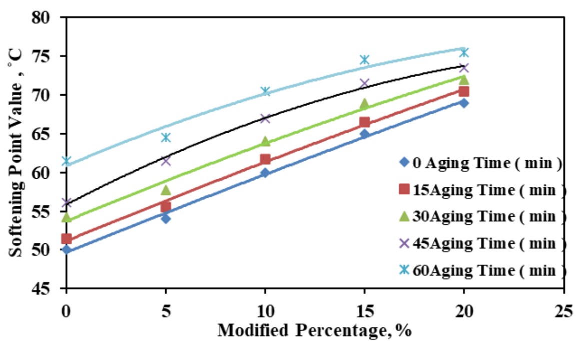

Figure 8. Softening Point Value for CR Modified Asphalts for Steam Aging

6.3 Viscosity tests

One of the most significant characteristics that play an important role during the manufacturing period from the manufacture of hot asphalt mixture to the mechanism of laying and compacting it to form a new pavement is viscosity [22]. It was observed from the extracted results, a significant improvement in the value of viscosity with the increase of the percentage of rubber, where the increase in the proportion of CR powder leads to a significant improvement in the viscosity of the aged rubberized asphalt contrasted to the aged unmodified binder. Viscosity is an ever-increasing nonlinear function of the CR ratio and the relative increase is an issue related to the application of temperature [19].

Figure 9 compares the viscosity values of the base and the modified bitumen, where the viscosity behavior was observed by increasing the proportion of the modified rubber additive. The modified rubber bitumen has significantly higher values for all measures of viscosity compared to the bitumen used as a control. According to the Superpave specification standard, all changed asphalt binder viscosity data fell below the maximum permitted value of (3 Pa.s). Excessive value of viscosity is not beneficial for workability amid transportation and mixing processes.

To verify that an asphalt binder can be cured and pumped in a hot mixing plant, its viscosity is measured. Figures 9-12 display the results of viscosity measurements taken at medium and high temperatures of 135°C and 165°C, respectively, for uncoated binders and RTFO with or without rubber crumb. Regardless of the aging condition, it is clear that the addition of crumb rubber enhanced the viscosity of the binders at both temperatures. Another difference is that the viscosity of the unmodified binder is lower than that of the old modified RTFO. Moreover, adhesives with a higher percentage of crumb rubber have a much higher viscosity value.

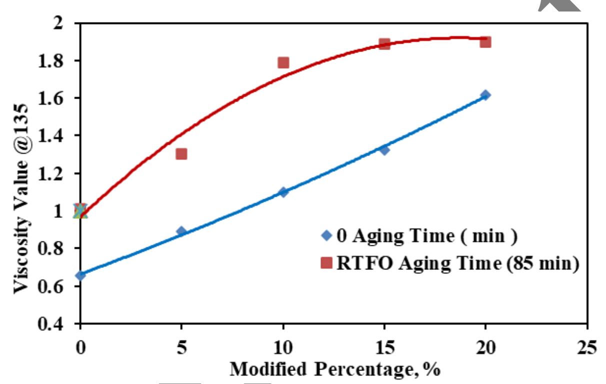

Figure 9. Viscosity at 135°C for CR modified (Un-Aged and RTFO Aged)Binder in Different Percent

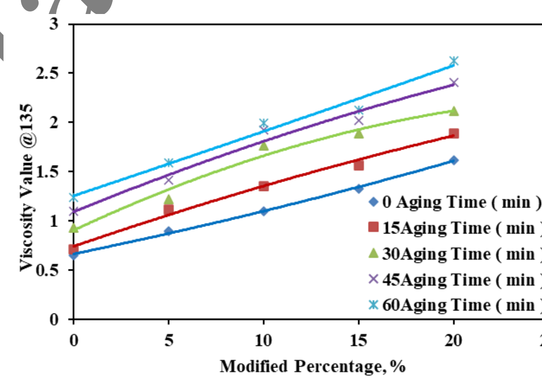

Figure 10. Viscosity at 165°C for CR modified (Un-Aged and RTFO Aged) Binder in Different Percent

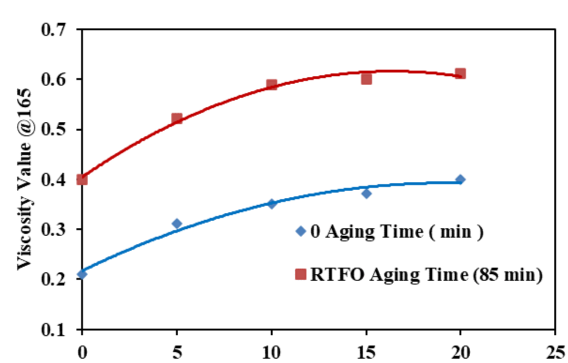

Figure 11. Viscosity at 135°C for CR-Modified Bitumen after Steam Aging

Accepted Manuscript

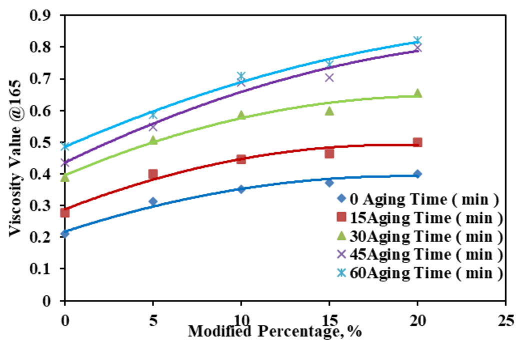

Figure 12. Viscosity at 165°C for CR Modified Bitumen after Steam Aging

The test results shown in Figures 13 to 16 revealed the percentage increase in the viscosity values of the bitumen modified with CR compared to the fine asphalt binder, as they indicate that by increasing the percentage of crumb rubber, the viscosity values increase. Where the increase in the percentage of the additive had a greater effect than the aging, and the outcomes showed that the increase in the hardness of the mixture was due to the increase in the percentage of CR, aging time, and temporal aging. The results also showed that the modification has a greater effect on the viscosity increase than the aging time.

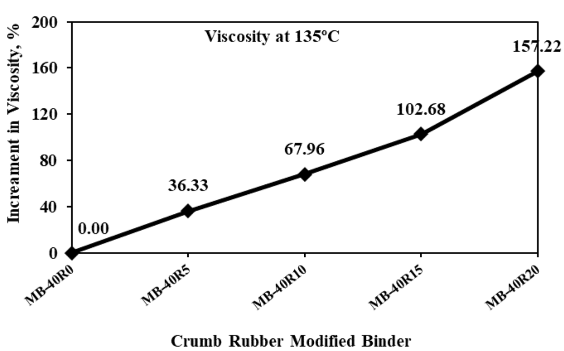

Figure 13: Increase Rate Viscosity for CR-Modified Binder at 135°C.

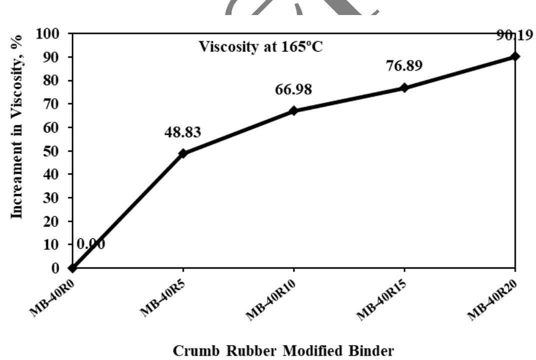

Figure 14. Increase Rate in Viscosity for CR-Modified Binder at 165°C

This phenomenon develops as a result of the relationship between the increase in modification ratio and the duration of aging. A considerable amount of asphalt goes through oxidation (liquefied asphalt) and is absorbed by the rubber crumb as the aging period and modification ratio rise. But the extent and intensity of these changes differ with the rate of modification and the length of time spent aging.

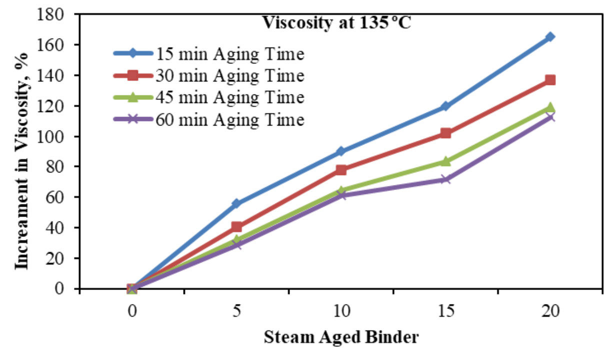

Figure 15. Increase Rate in Viscosity after Steam Aging at 135°C

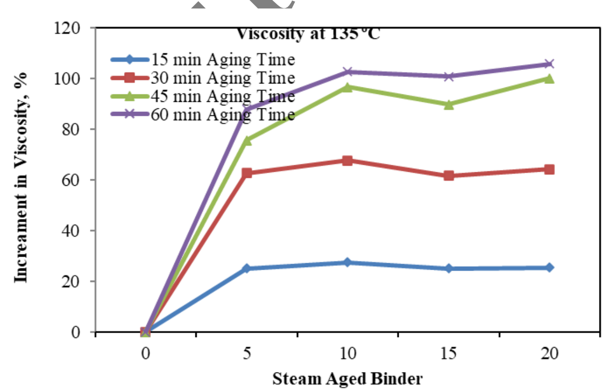

Figure 16. Increase Rate in Viscosity after Steam Aging at 165°C

6.4 The rheological performance

After reviewing the results obtained from conducting physical tests, which include both penetrations, softening point, and viscosity, it was noted that by increasing the tire crumb rubber (TCR) to the bitumen, the physical attributes of the enhanced bitumen were improved with different rubber percent that was previously proven. The decrease in the penetration value and the increase of both the degree of softening and viscosity led to enhancing the hardness of the binder and increasing its ability to resist permanent deformation.

Figures (17-19) show the outcomes of the DSR assessment at pre-determined temperatures and steps of 6 degrees Celsius. The results were presented to determine the change in consistency of the asphalt binder using the modified rubber as a function of temperature change with a frequency of 10 rad/sec. A minimum of 1.0 kPa is recommended for the rutting factor (G*/sinδ) for unaged bitumen to ensure that it is sufficiently resistant to rutting at relatively high service temperatures.

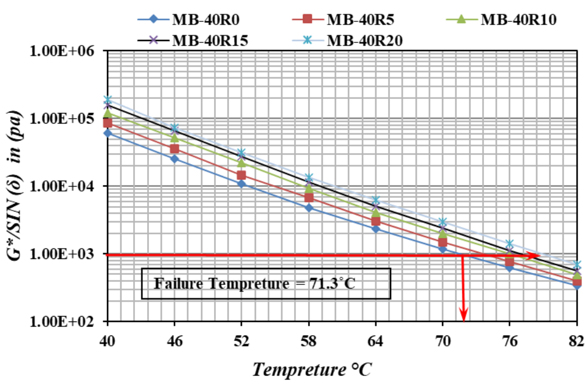

Figure 17. Temperature Sweep Test for CR-Modified Binder

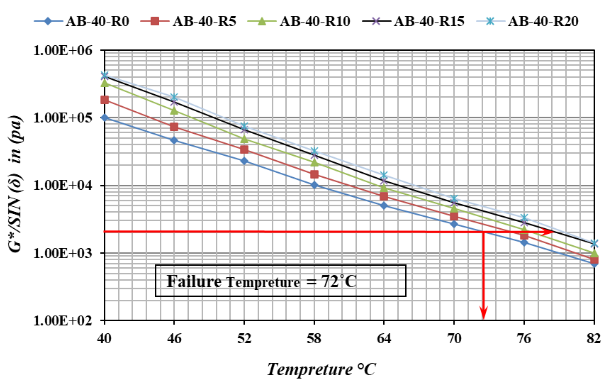

Figure 18. Temperature Sweep Test for Steam-Aged (45 minutes) for Crumb Rubber Modified Binder

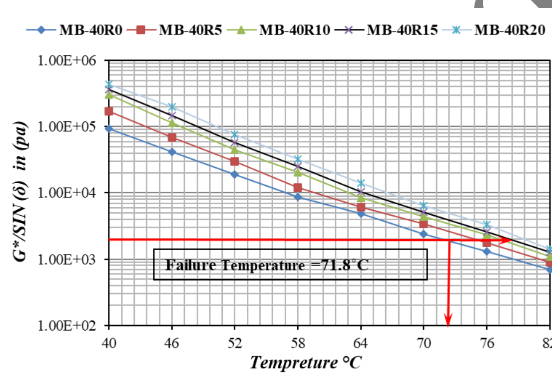

Figure 19. Temperature Sweep Test after RTFO Aged for Crumb Rubber Modified Binder

By following up the behavior of asphalt grade 40-50 used in the study and by using rubber as an improver of asphalt properties in different ratios, it was concluded that the rutting factors in the improved binders are much higher than that of the control binder. The same behavior was represented by aging asphalt in the steam kiln and Rolling Thin Film examination. Reducing sensitivity to the change in temperature and improving resistance to rutting (permanent deformation) at high temperatures was the behavior of the modified binders.

Moreover, the rubber-modified asphalt binder values had greater failure temperatures compared to the control binder, as shown in Figures (20-22). Consequently, the control binder's performance temperature (PG) was raised. The same behavior was associated with steam aging and the RTFO examination.

Figures 20 to 22 show that, regardless of aging condition, crumb rubber-modified asphalt has a higher complex modulus (G*) at the lower end of the temperature range and a higher complex modulus at higher temperatures compared to the neat asphalt binder regardless of the content of rubber crumbs. This indicates an improved sensitivity of the CR-modified asphalt to the change in temperature which leads to increased elasticity at low temperatures and increased stiffness at high temperatures. By following up the behavior of aging by steam compared to the traditional aging represented by the RTFO method, it was found that during the time of 45 minutes with steam it is very close to the traditional aging for all the ratios of the additive. This conclusion is very close to the results obtained from the traditional tests of asphalt and indicated previously.

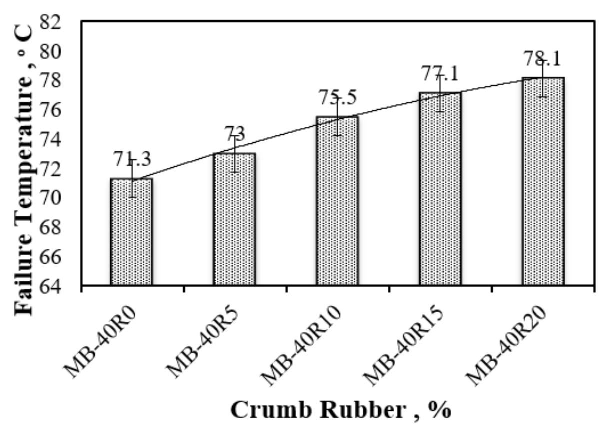

Figure 20. Failure Temperature for Crumb Rubber Modified Binder before RTFO

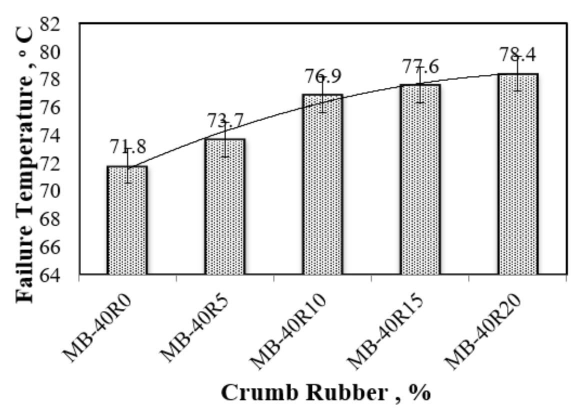

Figure 21. Failure Temperature for Steam Aged (45 minutes) for Crumb Rubber Modified Binder

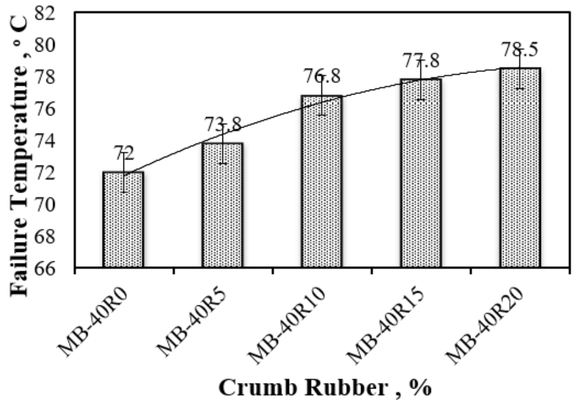

Figure 22. Failure Temperature for Crumb Rubber Modified Binder after RTFO

7. Conclusions

In this study, the effect of the use of rubber crumb as a modifier for asphalt binder with a penetration grade of 40-50 from the Iraqi Dora refinery was studied. Several conclusions are drawn from the findings:

1. The apparent enhancement in the physical attributes of the modified asphalt binder by adding CR, as shown in the decrease in the penetration values and the increase in both the degree of softening point and viscosity, which is attributed to the homogeneity obtained in the modified asphalt binder and its clear compatibility.
2. Using rubber as an improving agent for asphalt mixtures at high temperatures due to the increase in viscosity and failure temperature, which were noted to be within acceptable limits according to previous studies.
3. DSR tests indicated that bitumen-rubber mastics had better rutting coefficients (G*/sinδ) relative to the control asphalt binder.
4. Due to the long periods required for the rubber to decompose into its main components and for its clear improvement of the properties of the asphalt binder, it is recommended to use reclaimed tire rubber as a successful alternative to enhance the rheological behavior of the asphalt binder.
5. By following up the results of the traditional tests of the rubber-modified asphalt binder and comparing the results obtained from steam aging in addition to the traditional examination using the Rolling Thin Film Oven test, It was found that there was a great convergence in the results extracted from the steam aging device with an addition rate of 5, 10, 15% and an aging time of 45 minutes with the results extracted from the Rolling Thin Film Oven device, except for the 20% addition rate, which gave a difference in values.
6. The results obtained from the DSR test confirmed that the time of 45 minutes of steam aging for the four percentages is close to the results obtained by aging in a Rolling Thin Film, so we recommend using steam aging as an alternative to the rotary kiln because it gives very close results in addition to reducing pollution to the environment.

Authors' contribution

In writing this article, each author put in the same amount of time and effort.

Declaration of competing interest

No conflicts of interest have been disclosed by the writers.

Funding source

No particular funding was allocated for this project.

Data availability

The corresponding author can be contacted at any reasonable time for the data that back up the study's conclusions.

Acknowledgments

The writers are grateful to Mustansiriyah and Baghdad Universities for their ongoing encouragement of high-quality research.

References

[1] Ali, S. H., & Ismael, M. Q. (2021). Improving the Moisture Damage Resistance of HMA by Using Ceramic Fiber and Hydrated Lime. Al-Qadisiyah Journal for Engineering Sciences, 13(4), 274-283. https://doi.org/10.30772/qjes.v13i4.681

[2] Aboud, G. M., Jassem, N. H., Khaled, T. T., & Ali, A. (2020). Effect of Polymer's Type and Content on Tensile Strength of Polymers Modified Asphalt Mixes. Al-Qadisiyah Journal for Engineering Sciences, 13(1). https://doi.org/10.30772/qjes.v13i1.645

[3] Albayati, A. H., & Mohammed, H. K. (2011). Influence of styrene butadiene rubber on the mechanical properties of asphalt concrete mixtures. Al-Qadisiyah Journal for Engineering Sciences, 4(3), 258-274.

[4] Shanbara, H. K., Kifae, A. A., & Abass, R. A. (2013). IMPROVE PERFORMANCE OF ASPHALT CONCRETE OVERLAY BY USING SBR AS MODIFIED. Al-Qadisiyah Journal for Engineering Sciences, 6(3).

[5] Khudhair, H. S., & Kadhim, M. A. (2018). Evaluating the performance of asphalt rienforcement layer comprising polypropylene granules. Al-Qadisiyah Journal for Engineering Sciences, 11(2), 278-292.

[6] Presti, D. L., " Recycled tyre rubber modified bitumen for road asphalt mixtures: a literature review" Constr. Build. Mater. (2013). https://doi.org/10.1016/j.conbuildmat.2013.09.007

[7] Martin, J., L. A. Cooley Jr., Hainin, H. R. 2003. Production and Construction Issues for Moisture Sensitivity of Hot-Mix Asphalt Pavements. Proceeding in Transportation Research Board National Seminar. San Diego, California. http://onlinepubs.trb.org/onlinepubs/conf/reports/moisture_seminar.pdf

[8] Aziz, M.M.B. 2006. Preliminary Determination of Asphalt Properties Using Microwave Techniques. ARPN. Journal of Engineering and Applied Sciences, 2010. 5(11): 70–81.

[9] Shatnawi, S., Stroup-Gardiner, M., Stubstad, R. 2009. California's perspective on concrete pavement preservation. Proceeding of National Conference On Preservation, Repair, And Rehabilitation of Concrete Pavements, St. Louis, Missouri. http://sjnavarro.files.wordpress.com/2008/08/concrete-prr-scr.pdf

[10] García-Morales, M., Partal, P., Navarro, F. J., Gallegos, C. Effect of waste polymer addition on the rheology of modified bitumen. Fuel: 85(7): 936–943.

[11] Shatnawi, S., Stroup-Gardiner, M., Stubstad, R. 2009. California's perspective on concrete pavement preservation. Proceeding Of National Conference On Preservation, Repair, And Rehabilitation Of Concrete Pavements, St. Louis, Missouri. http://sjnavarro.files.wordpress.com/2008/08/concrete-prr-scr.pdf

[12] Adhikari, B., De, D., Maiti, S. 2000. Reclamation and recycling of waste rubber. Progress in Polymer Science. 25(7): 909–948. http://dx.doi.org/10.1016/S0079-6700(00)00020-4

[13] Rattanasom, N., Saowapark, T., Deeprasertkul, C. Reinforcement of natural rubber with silica/carbon black hybrid filler. Polym. Test. 2007, 26, 369–377. http://dx.doi.org/10.1016/j.polymertesting.2006.12.003

[14] Abbas, A., Choj, B. C., Masad, E., and Papagiannakis, T. (2002). "The influence of laboratory aging method on the rheological properties of asphalt binders." J. Test. Eval., 30(2), 171–176. http://dx.doi.org/10.1520/JTE12304J

Accepted Manuscript

[15] Vassiliev, N. Y., Davison, R. R., and Glover, C. J. (2002). "Development of a stirred air flow test procedure for short-term aging of asphaltic materials." Transp. Res. Rec., 1810, 25–32. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002354

[16] Yousif, R. A., Muniandy, R., Hassim, S., Jakarni, F. M. 2017. Effect of Steam Aging on Performance-Related Properties of Hot Asphalt Mixture. Journal of Materials in Civil Engineering. Vol.30, No.3. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002166

[17] Lu, X., Talon, Y., and Redelius, P. (2008). "Ageing of bituminous binders— Laboratory tests and field data." 4th Eurasphalt and Eurobitume Congress, Copenhagen, Denmark.

[18] Tayh, S. A., and Yousif, R. A. (2018). Effect of blending speed and blade level on the properties of reclaimed rubber modified bitumen ARPN J. Eng. Appl. Sci. 13 8386-92.

[19] Glover, I. C. 2007. Wet and Dry Aging of Polymer-Asphalt blends: Chemistry and Performance. Thesis, Louisiana State University

[20] Mashaan, N. S., Ali, A. H., Karim, M. R., Abdelaziz, M. 2011. Effect of blending time and crumb rubber content on properties of crumb rubber modified asphalt binder. International Journal of Physical Sciences. 6(9): 2189–2193.

[21] Yousif, R. A., Muniandy, R., Hassim, S., Jakarni, F. M., Aburkaba, E. (2015). An overview of quantification of fatigue resistance of asphalt mixture using pre-aged binder. WALIA journal. 31(S1): 125-132.

[22] Ali, A. H., Mashaan, N. S., Karim, M. R. 2013. Investigations of physical and rheological properties of aged rubberised bitumen. Advances in Materials Science and Engineering. 2013: 1–7.

Accepted Manuscript