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ORIGINAL RESEARCH PAPER

Investigation of the Rheological and Bonding Characteristics of Crumb Rubber-Modified Asphalt Binders Mixed with Warm Mix Asphalt Additive and Antistrip Agent

Taha A. Ahmed[1] · Elie Y. Hajj[2] · Dawoud S. Bahzad[3] · Murugaiyah Piratheepan[2] · Ahmed Warrag[2]

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Abstract

This research study evaluated the influence of crumb rubber modification and the addition of warm mix additive and liquid antistrip agent on asphalt binder properties. The experimental plan consisted of evaluating the virgin asphalt binder and crumb rubber-modified asphalt binders (CRMABs) at different doses of crumb rubber (CR). The test results were used to select an optimum content of CR that would lead to a CRMAB that meets the local specifications for polymer-modified asphalt binders. The CRMAB at optimum dose was further evaluated to assess the influence of warm mix additive and liquid antistrip agent on the asphalt binder's resistance to moisture damage and fatigue cracking. The laboratory evaluation included the binder bond strength (BBS) test in accordance with AASHTO TP 91 and the estimation of damage tolerance of asphalt binders using the linear amplitude sweep (LAS) test following AASHTO TP101. The laboratory evaluation showed that the CRMAB with 8% CR met the local specifications for polymer-modified asphalt binders. The test results also showed while the increase in CR can have a positive effect on the rutting resistance of an asphalt binder, it may jeopardize its resistance to moisture damage and fatigue cracking. Further evaluation showed that the addition of a warm mix additive along with an antistrip agent can minimize the detrimental effects of CR on asphalt binder. In summary, this study demonstrates that a CRMAB can be engineered to meet asphalt binder specifications and result in an acceptable performance and durability. The findings from this study are highly beneficial for agencies with limited access to asphalt binder sources or performance grades but are interested in using recycled tire rubber from waste tire in their asphalt mixtures.

Keywords Crumb rubber · Asphalt · Rheology · Warm mix · Antistrip · Bond strength · Fatigue

1 Introduction

The increasing number of vehicles on the road results in a vast number of scrap tires [1]. The disposal of these waste tires has been one of the big environmental problems in modern society. Scrap tires are an example of products that are being disposed of by automotive repair centers in landfills or monofills. The ever-increasing volume of scrap tires poses challenges to the landfill owners and they explored burning the scrap tires because of the large space they consume. However, burning scrap tires is not an economical and environmentally friendly solution as it requires a high-temperature and controlled environment to burn the rubber present in scrap tires. Besides, burning rubber may discharge toxic pollutants into the air and cause environmental problems.

The number of used tires around the world is very significant, reaching 1.4 billion tires every year [2, 3]. Later, most

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✉ Taha A. Ahmed
t.ahmed@ack.edu.kw; Alhekhmdar@gmail.com

Elie Y. Hajj
elieh@unr.edu

Dawoud S. Bahzad
dbahzad@kisr.edu.kw

Murugaiyah Piratheepan
mpiratheepan@unr.edu

Ahmed Warrag
ahmedwarrag@nevada.unr.edu

[1] Department of Civil Engineering, Australian College of Kuwait, P.O. Box 1411, 13015 Safat, Kuwait

[2] Department of Civil & Environmental Engineering, University of Nevada, Reno, 1664 N. Virginia Street, MS0258, Reno, NV 89557, USA

[3] Petroleum Research Center, Kuwait Institute for Scientific Research, P.O. Box 24885, 13109 Safat, Kuwait

of these tires reach the state where they cannot be used anymore and classified as end-of-life tires (ELT). ELT comes in different volumes and durability and thus makes the recycling process complicated. According to the Asphalt Rubber Standard Practice Guide, published in 2011, the challenging part to recycle tires is that rubber, which takes a large portion of the tire (can reach up to 70%), is composed of 27% Synthetic Rubber, 15% Natural Rubber, 27% Carbon Black, 15% Steel, and 16% Fabric [2, 3].

Currently, there are several industrial applications that incorporate the recycling of waste tires in their processes. Some of these applications include new tires manufacturing, tire derived fuel production, civil engineering applications and products, molded rubber products, agricultural uses, recreational and sports applications, and crumb rubber-modified asphalt binder (CRMAB) applications [4–6].

In 2017, scrap tire market consumed just over 3.4 million tons, or 81.4%, of the estimated 4.2 million tons of scrap tires generated annually. The three largest scrap tire markets in 2017 are shown in Fig. 1 [7, 8].

To produce crumb rubber (CR), scrap tires are processed using either ambient grinding or cryogenic grinding process. During the ambient grinding process, the rubber size is reduced using a granulator by means of cutting and shearing action. However, in cryogenic grinding process, liquid nitrogen is used to bring tire temperature down to approximately – 120 °C before grinding. Below this glass transition temperature, rubber becomes nearly as brittle as glass and size reduction can be done by crushing and breaking [6, 8–11].

Adding CR to the asphalt binder can then be done through two main methods: wet and dry processes. The wet process covers all methods of blending the specified percentage of CR with the asphalt binder before mixing it with aggregate. This method requires mixing the CR in hot asphalt binder and holding the blend at a temperature of 190–230 °C (375–450 °F) for a sufficient period of time, typically 45 min, to allow a chemical interaction between the CR and the asphalt binder [7]. This method is known as the McDonald's wet process [1].

In the dry process, CR is mixed with the aggregate prior to adding the asphalt binder. The added CR can substitute 1.0–3.0% of aggregate weight. The CR acts as a rubber aggregate in the mixture and is added to the plant before the hot asphalt binder is introduced. This method only applies to hot mix asphalt production. The asphalt binder is not considered to be modified in this process because of the limited interaction between the CR and the asphalt binder.

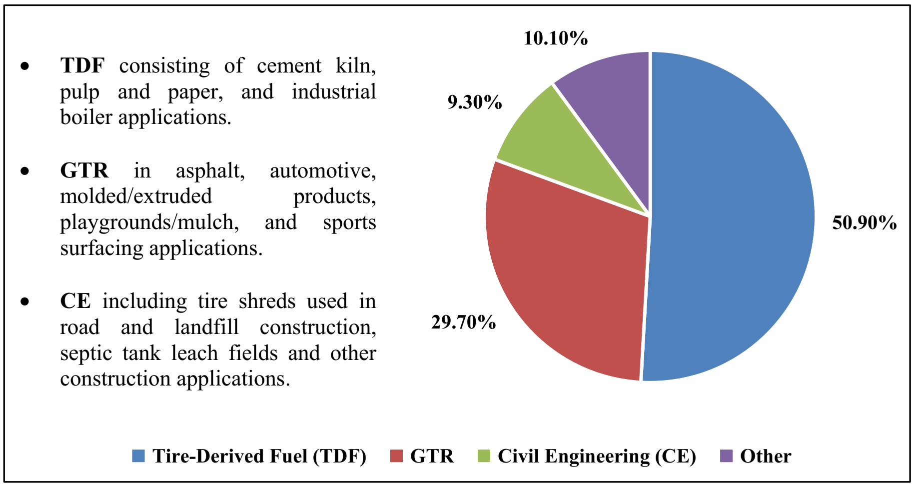
1.1 Crumb Rubber-Modified Asphalt Binder Design

According to the Rubber Pavement Association (RPA), mass production of CRMAB requires a laboratory approved asphalt binder design profile before the production starts. Initially, the appropriate asphalt binder should be selected to give the performance grade (PG) of the CRMAB that is applicable for the climatic region. Similar to the selection of asphalt binder grade, an appropriate CR gradation must be chosen to be used with the mix design. Afterwards, four tests are conducted on the CRMAB to insure the compatibility and interaction between the used materials and to check the CRMAB compliance with the representative agency requirements. The four tests are the following [2]:

1- Rotational Viscosity at 177 °C (350 °F) according to ASTM D2196.
2- Penetration at 25 °C (77 °F) according to ASTM D5.
3- Softening Point according to AASHTO T53 or ASTM D36.
4- Resilience at 25 °C (77 °F) according to ASTM D5329.

Other tests can also be used to evaluate the rheological characteristics of the CRMAB. These tests measure the CRMAB susceptibility to the main failure modes in asphalt

Fig. 1 Scrap tire markets in 2017 [7, 8]



- **TDF** consisting of cement kiln, pulp and paper, and industrial boiler applications.
- **GTR** in asphalt, automotive, molded/extruded products, playgrounds/mulch, and sports surfacing applications.
- **CE** including tire shreds used in road and landfill construction, septic tank leach fields and other construction applications.

mixtures, which include permanent deformation-related distresses such as rutting or shoving, fatigue and thermal cracking, and disintegration-related problems such as raveling and stripping.

1.2 Advantages and Disadvantages of CRMABs

Since CR is one of the important products that are produced from the process of recycling scrap tires, CRMAB can be the key to recycle the large numbers of scrap tires that are taking place in landfills. The CR is used as a modifier to improve the rheological properties of the asphalt pavement at high- and low-temperature conditions, which can extend the life of the asphalt pavement. Using CRMABs also can minimize asphalt pavement cracking, rutting, potholes, and permanent deformation, thus reducing pavement maintenance costs. Despite these benefits, the process of preparing CRMAB can be hard and require a two-stage process due to the fact that the interaction between the asphalt and the CR particles surface is weak. The added cost of liquid nitrogen, which is used to produce the CR and the process of making CRMAB may increase the initial cost of an asphalt pavement [2, 3, 8].

Many studies show that additives and modifiers are added to the asphalt binder to enhance the mechanical properties of the asphalt pavement and minimize the permanent damages such as cracking and rutting. A recent study conducted by Irfan et al. [12] evaluated Marshall and Superpave Gyratory-compacted CR-modified asphalt mixtures (CRMAM). In this study, several tests have been done to evaluate the CRMAM including indirect tensile strength, resilient modulus, and permanent deformation. The CRMAB increased resilient modulus and Marshall stability by 43% and 30% in comparison to the controlled mixtures. Moreover, the CRMAM proved that permanent deformation has been improved by 12% in comparison with the controlled mixtures. The CRMAM showed significant improvements in their international roughness index (IRI) results compared to the controlled mixtures. Hence, using the CRMAB for paving roads can improve the performance criteria specified [12].

Improving the long-term performance of hot mix asphalt (HMA) mixtures means reducing the leading modes of distress to pavement failure. These modes include permanent deformation-related distresses such as rutting or shoving, fatigue and thermal cracking, and disintegration-related problems such as raveling and stripping. Several studies showed that CRMAB can improve asphalt pavement performance by reducing/delaying the propagation of those distresses [4, 5, 11]. The added CR can increase the elasticity of the asphalt binder and reduce the mix sensitivity to temperature changes. Increasing asphalt binder elasticity improves its fatigue characteristics while reducing binder sensitivity to temperature changes reduces its rutting potential by increasing its stiffness. In addition, several studies showed that the added CR can improve the adhesion between the binder and aggregate which reduces the raveling and stripping problems [7, 13]. Several states in the USA such as, California, Arizona, Florida, and Washington are using CRMAB in their mix designs specifications.

2 Motivation

Currently, majority of the Gulf Countries have been using one asphalt binder grade for all of their asphalt mix designs. Whenever grade modification is needed, a suitable amount of polymer modifier is added to obtain the desired modification. So far, using CR for asphalt modification is not specified in many of those countries. This can be attributed to the lack of diversity in asphalt binder grades in the Gulf region in addition to the limited usage of CR in asphalt pavement applications.

The state of Kuwait has been using asphalt binder with 60/70 penetration (pen) grade for all HMA mixtures with occasional addition of polymer modifiers (if needed). In 2018, Kuwait constructed its first rubberized-asphalt road trial using 15% and 18% CR to evaluate the performance of asphalt mixtures prepared using CRMABs [14, 15]. The overall results of this project showed that the volumetric properties of all the asphalt mixtures used in this study were satisfactory except the Marshall stability values being below the target and insufficient to deliver the expected performance. The study recommended that more detailed testing is required to better characterize the CRMAB rheological response including creep and fatigue properties.

Therefore, the findings from the CRMAB research study presented in this paper will be highly beneficial to the state of Kuwait and for other countries with limited access to asphalt binder sources or performance grades but are interested in using recycled tire rubber from waste tire in their asphalt mixtures.

3 Research Objectives

The main objective of this research study was to evaluate the rheological and adhesive/cohesive characteristics of the CRMABs in comparison to the original asphalt binders used in asphalt mixtures in Kuwait. Several percentages of CR material were added and investigated to determine the optimum CR content that improves the performance of the asphalt binder. The effect of adding warm mix asphalt (WMA) additive and antistrip agent on the CRMAB characteristics was also evaluated.

4 Research Methodology

Several tests were used in this study to evaluate the characteristics of the laboratory-produced CRMAB. These tests measure the CRMAB susceptibility to the main failure modes in asphalt mixtures, which include permanent deformation-related distresses such as rutting or shoving, fatigue and thermal cracking, and disintegration-related problems such as raveling and stripping. Accordingly, the overall research plan shown in Fig. 2 was conducted to evaluate the rheological and bond strength characteristics of the laboratory-produced CRMAB.

4.1 Material Collection and Preparation

Materials needed to complete this research study included: Virgin (Original) asphalt binder, warm mix asphalt (WMA) additive, crumb rubber (CR) and liquid antistrip agent “AD-HERE LOF 65-00”.

Asphalt binder was collected from local asphalt plant in Kuwait [16]. It should be noted that the Ministry of Public Works (MPW) in Kuwait specifies asphalt binder of 60/70 pen grade as the only asphalt binder type that can be used for all HMA mixtures in Kuwait. An organic-based additive warm mix asphalt named SonneWarmix was used for this research study. The SonneWarmix additive was added directly to the liquid asphalt at a dose of 1.0% by mass of the asphalt binder. The antistrip agent AD-HERE LOF 65-00 was added to asphalt binder blends at a rate of 0.5% by mass of the asphalt binder based on manufacturer’s recommendation.

Crumb rubber (CR) material was collected locally from a certified local producer of CR material in Kuwait [17]. The gradation was chosen according to the Rubber Pavements Association (RPA) specification [2].

Recently, the Ministry of Public Works (MPW) in Kuwait started to implement the Superpave mix design system for all of their new pavement projects in Kuwait and it is planning on replacing the current Marshall mix design practice, with the Superpave mix design system within the next few years. The newly implemented Superpave mix design procedure was adopted from part 5 “Asphalt Works” in Section 6 “Road Works” of Qatar Construction Specification (QCS) [18, 19]. Therefore, the properties of all collected materials were checked against the Kuwaiti, Qatari and international specifications [18–20].

4.2 Laboratory Testing for the Asphalt Binder Blends

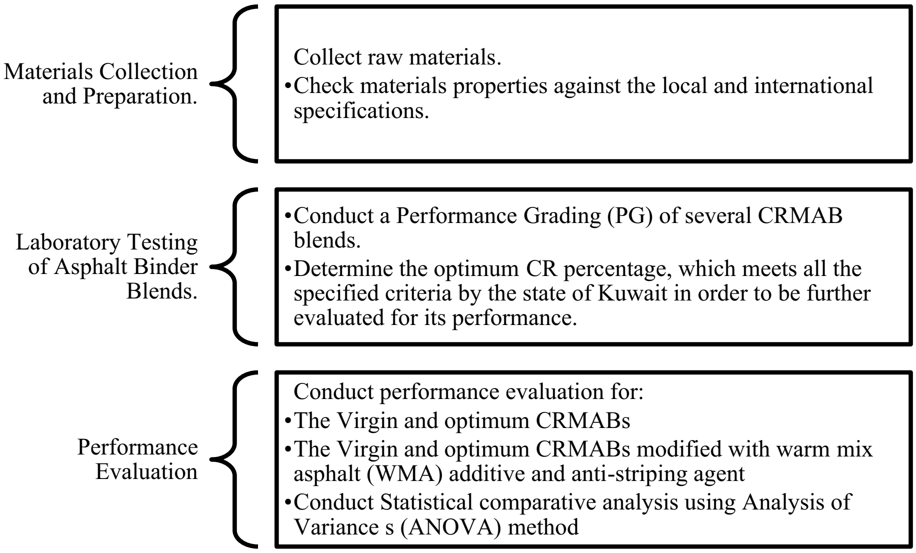
The laboratory program shown in Fig. 3 was executed for six different percentages of CR in addition to the Virgin asphalt binder. The CR percentages were 4, 6, 8, 10, and 15% by weight of asphalt binder. This step is essential to determine the optimum CR percentage that meets the required specifications and provides better performance.

After selecting the optimum CR percentage, a performance evaluation, in addition to the full PG grading, were conducted for the following asphalt binder blends:

- The Virgin and optimum CRMABs.
- The Virgin and optimum CRMABs modified with warm mix asphalt (WMA) additive and antistrip agent.

The performance evaluation included the bond strength of asphalt binders, including their susceptibility to moisture damage, and the resistance to damage caused by

Fig. 2 Overall research plan



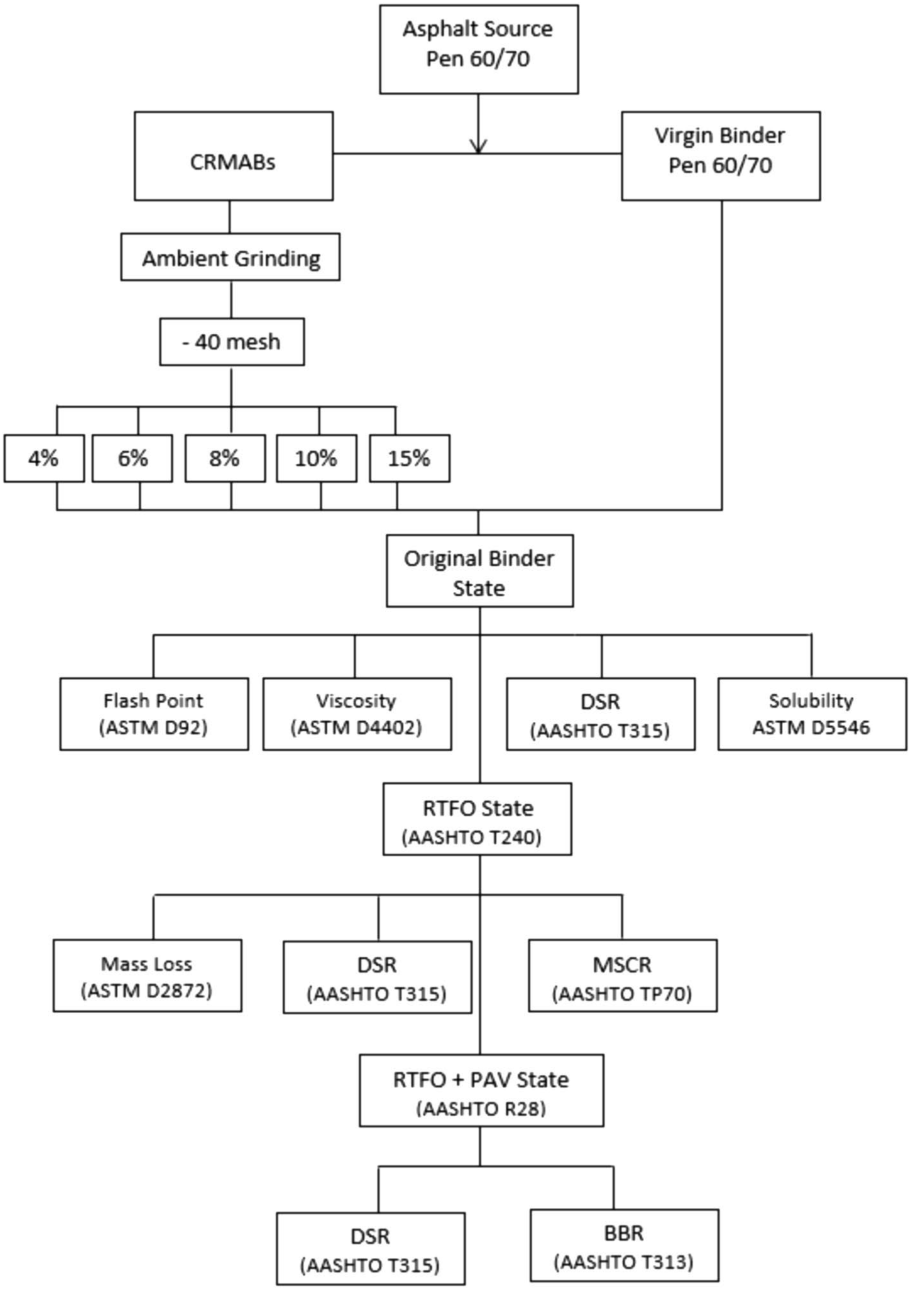


Fig. 3 Experimental design for lab testing of asphalt binder blends

fatigue and rutting. The tests conducted in the performance evaluation task are shown in Fig. 4.

In addition, a comparative statistical analysis using Analysis of Variance (ANOVA) procedure was conducted using the Statistical Analysis Software (SAS) to examine the significance of the percentage of CR modification, WMA additive, antistripping agent and their interactions on the performance evaluation test results [21].

5 Results and Analysis

5.1 Material Properties

The properties of the virgin asphalt binder 60/70 pen grade along with specifications are shown in Table 1. The test results show that the asphalt binder meets the QCS criteria.

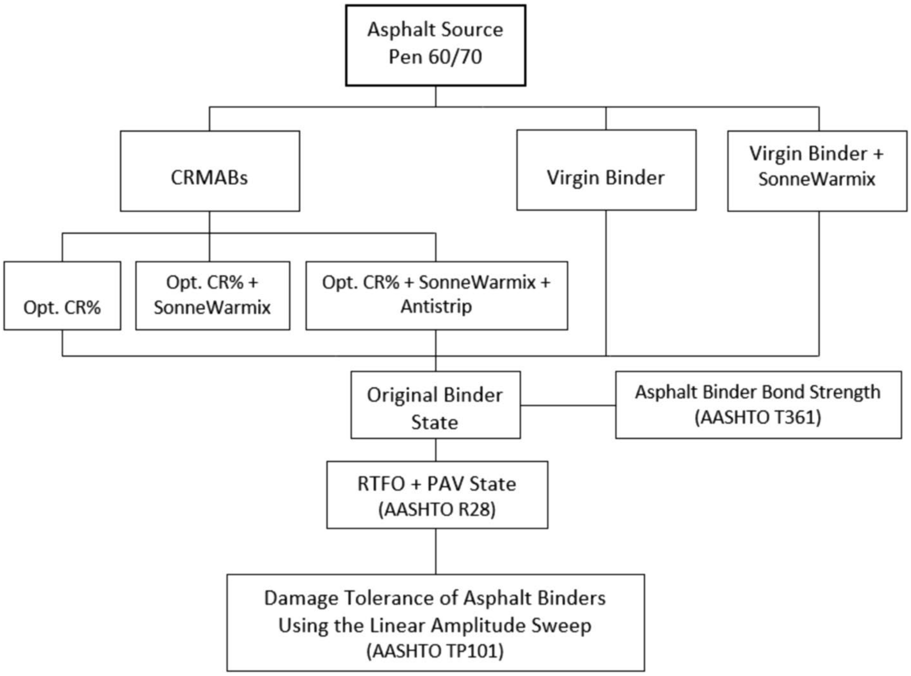


Fig. 4 Performance evaluation experimental plan

Table 1 Properties of virgin asphalt binder 60/70 pen grade

Parameter	Test method	Test results	QCS criteria 60/70 pen grade [19]	
			Min	Max
Relative density of semi-solid bituminous materials	ASTM D70	1033	–	–
Penetration (0.1 mm) at 25 ℃-100 g, 5 s	ASTM D5M	70	60	70
Softening point ring and ball apparatus, ℃	ASTM D36	50	46	–
Flash Point Cleveland Open Cup, ℃	ASTM D92	311	230	–
Ductility at 25 ℃, cm	ASTM D113	150+	100	–
Solubility trichloroethylene, %	ASTM D2042	99.4	99	–
Loss on heating, %	ASTM D6	0.09	–	0.2
Penetration of residue of original after TFOT, %	ASTM D5	96	52	–
Ductility of residue after TFOT at 25℃, 5 cm/min, cm	ASTM 150+	150+	50	–

CRMABs with varying crumb rubber contents were produced in the laboratory. The performance of the CRMAB blends were evaluated in accordance with AASHTO M320 & M332 Superpave PG system. Challenges were faced during the preparation of CRMABs. The original effort consisted of heating the asphalt binder and the crumb rubber to 200 °C (392 °F) before blending the materials together using a regular mixer at 2500 rpm for 45 min. It was observed that the process for blending crumb rubber with asphalt binder did not produce a homogenous material. Few more trial blends were completed with varying mixer speeds, temperature, and mixing durations. None of those attempts resulted in an acceptable asphalt binder blend. A high shear mixer with intermediate screen size (Fig. 5) was then utilized, which resulted in a homogenous CRMAB. The mixing temperature of 200 °C (392 °F) and duration of 45 min were selected. However, the mixer speed was adjusted to 3500 rpm to ensure full blending.

The sieve analysis was conducted in accordance with the American Association of State Highway and Transportation Officials (AASHTO) T27 standard to examine the particle size distribution of the CR [22]. The test results are summarized in Table 2. Several CRMAB blends were prepared using different size of CR particles. Based on the homogeneity of the blends, it was decided to use only the CR passing 0.42 mm sieve (No. 40) in the further evaluation of CRMABs.

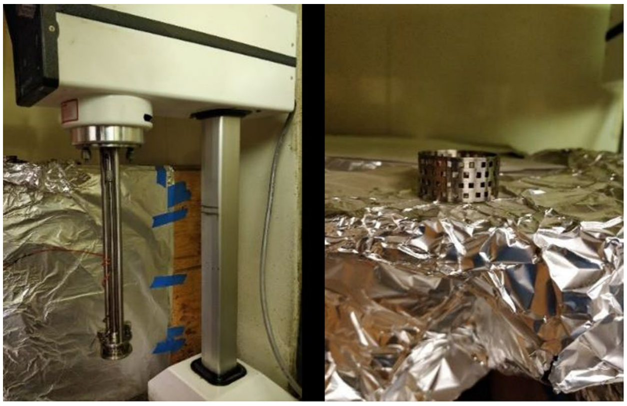


Fig. 5 Photographs for: **a** high shear mixer and **b** medium size work head

Table 2 Crumb rubber gradation

Sieve size	Percent retained	Percent passing
2.36 mm (No. 8)	0.0	100.0
2.0 mm (No. 10)	0.0	100.0
1.18 mm (No. 16)	0.0	100.0
0.600 mm (No. 30)	30.6	69.4
0.425 mm (No. 40)	65.0	35.0
0.300 mm (No. 50)	82.2	17.8
0.150 mm (No. 100)	95.6	4.4

5.2 Laboratory Testing for the Asphalt Binder Blends

The virgin binder and the CRMABs with different CR contents (4, 6, 8, 10, and 15%) were graded in accordance with AASHTO M320 Standard Specification for Performance-Graded Asphalt Binder. The asphalt binders were subjected to short- and long-term aging using a Rolling Thin Film Oven (RTFO) and a Pressure Aging Vessel (PAV), respectively. The original, RTFO-aged, and PAV-aged asphalt binders were tested for shear modulus and phase angle using Dynamic Shear Rheometer (DSR). The high-temperature grade of the asphalt binder was determined as the minimum of the pass/fail temperature of the original and RTFO-aged binders. After the RTFO and PAV aging, the asphalt binders were tested again on the DSR and Bending Beam Rheometer (BBR) to determine the intermediate and lower temperature grades of asphalt binders, respectively. In addition, the Rotational Viscosity (RV) of the asphalt binders was measured on the original asphalt binders using Brookfield rotational viscometer. Moreover, the Multiple Stress Creep Recovery (MSCR) test was conducted using the DSR on all the asphalt binders following AASHTO T 350–14 at the high PG temperature of each respective asphalt binder. The asphalt binders were then graded using MSCR test results in accordance with AASHTO M 332–14. The performance grading results are summarized in Table 3 along with the Qatari and Kuwaiti Specifications for asphalt binders [18–20].

Based on the PG grading test results, the 10% and 15% CRMABs were graded as PG82H-10 and PG82S-10, respectively, thus indicating stiffer binders. Both grades cannot be used to produce asphalt mixtures in the state of Kuwait because of their high stiffness, which may lead to a premature cracking problems. Furthermore, the test data shown in Table 6 suggest that a dosage of less than 10% CR should be used with this asphalt binder to obtain a CRMAB with acceptable characteristics. After testing CRMABs at different CR contents, an optimum of 8% CR was selected to fulfill the high-temperature requirements of PG76-xx for modified asphalt binders specified by the Qatari and Kuwaiti Specifications.

The optimum CRMAB was further evaluated by adding a warm mix additive (SonneWarmix) at a dosage of 1% by mass of the asphalt binder. The SonneWarmix additive was also added to the virgin asphalt binder at the same dose; thus, allowing for the examination of the impact of the additive alone on asphalt binder. The optimum CRMAB was further evaluated with both SonneWarmix and a liquid antistrip agent “AD-HERE LOF 65-00” added at a dose of 1.0% and 0.5% by mass of the asphalt binder, respectively. The performance evaluation of the new blends was conducted using PG system, and all combinations were subjected to a similar testing sequence as before. The performance grading results of the new combinations were compared against those of the Virgin asphalt binder, 4%, 6%, and 8% CRMABs.

Table 4 summarizes the high, intermediate, and low critical temperatures and ΔTc for the Virgin and new CRMAB blends. The ΔTc for the evaluated asphalt binder blends is calculated by subtracting the lower temperature continuous grade when the m-value is equal to 0.3 from the lower temperature continuous grade when the stiffness is equal to 300 MPa. The ΔTc is a parameter proposed by Asphalt Institute for measuring the loss of relaxation properties of aged asphalt binders [23]. Negative ΔTc indicates an m-controlled asphalt binder. Studies have shown that as the ΔTc becomes more negative, the asphalt binder tends to lose its relaxation property and becomes more susceptible to early cracking.

Figs. 6 and 7 show the continuous/critical grading temperatures and ΔTc measured for the evaluated virgin and CRMAB blends. Fig. 8 shows the measured rotational viscosity (RV) values for virgin and CRMAB blends with the error bars representing the 95% confidence interval. Overlapping of the confidence intervals generally implies the similarity in the measured RV values between the various asphalt binder blends.

Table 3 Summary of the asphalt binders PG testing

Property	Virgin 60/70 pen	4% CR	6% CR	8% CR	10% CR	15% CR	Specifications	Test standards
PG high temp, ℃	64	70	76	76	82	82	**76** ℃ Qatari and Kuwaiti	AASHTO M320
Flash point, ℃ (min)	311	317	317	317	323	317	230	ASTM D92
Viscosity at 135 ℃, Pa.s, (max)	0.63	0.89	1.24	1.66	2.54	3.04	3	ASTM D4402
Dynamic shear G*/Sinδ and 10 rad/s, kPa (min)	2.01	1.89	1.32	1.66	1.66	1.91	1	ASTM D7175
Solubility, % (min)	99.4	99.25	99.2	99.2	99.14	99.05	99	ASTM D5546
Rolling thin film oven (RTFO) residue								
Mass change, % (max)	0.09	0.11	0.1	0.16	0.09	0.12	1	ASTM D2872
Temperature, ℃	64	70	76	76	82	82	PG High Temp	ASTM D7175
Dynamic shear G*/Sinδ and 10 rad/s, kPa (min)	2.32	2.58	3.16	2.34	9.16	3.09	2.2	
Multiple stress creep recovery (MSCR) test								
Temperature, ℃	64	70	76	76	82	82	PG High Temp	ASTM D7405
MSCR, $J_{nr\ 3.2}$, kPa^{-1}, (max)	1.7	1.9	2.3	3	1.99	2.78	E_0.6,V_1,H_2,S_4.5	
MSCR, $J_{nr\ diff}$, % (max)	19.4	35.1	51.2	53.7	73.3	87.2	**76** ℃ Qatari and Kuwaiti	
Traffic level	Heavy “H”	Heavy “H”	Standard “S”	Standard “S”	Heavy “H”	Standard “S”	Any	AASHTO M332
Pressurized aging vessel (PAV) residue								
Temperature, ℃	19	19	19	19	36	36	–	ASTM D7175
Dynamic shear G*Sinδ and 10 rad/s, kPa (max)	4550	4545	4200	3865	955	938	5000	
Bending beam rheometer								
Temperature, ℃	− 18	− 12	− 12	− 12	0	0	Any	ASTM D6648
Bending beam, S and 60 s, MPa (max)	227	91.2	92.9	82.2	24.8	23.84	300	
Bending beam, m-value and 60 s, MPa (min)	0.303	0.337	0.343	0.334	0.388	0.3	0.3	
Meet all local specifications	Yes/Virgin	No	Yes	Yes	No	No	Meet	Qatari and Kuwaiti
MSCR grade	64H-28	70H-22	76S-22	76S-22	82H-10	82S-10	76S-Any	AASHTO M332

J_{nr} non-recoverable creep compliance

The presented data suggest that increasing CR percentage increased the critical high temperature. Moreover, increasing the crumb rubber in the CRMABs resulted in colder critical low temperatures based on the stiffness criterion and warmer low temperatures based on the m-value criterion; thus, leading to more negative ΔTc values.

On the other hand, the use of SonneWarmix additive slightly decreased the critical high temperature when added to the virgin binder and the 8% CRMAB. It also reduced the absolute value of the ΔTc (less negative) as shown in Table 4 and Figs. 6 and 7. The addition of antistrip agent to the 8% CRMAB with SonneWarmix resulted in colder low temperatures based on both stiffness and m-value criteria. However, this also resulted in a more negative value for ΔTc.

Fig. 8 shows that adding CR to the virgin asphalt binder increased its viscosity, while adding SonneWarmix reduced its viscosity. Adding antistrip agent led to further reduction in the rotational viscosity. The 95% confidence intervals for the mean RV values are also shown in Fig. 8. A no overlap between the 95% confidence intervals for the means of two RV values indicates that there is a statistically significant difference between the two means (at the 0.05 level of significance). However, the opposite is not necessarily true, as confidence intervals may overlap, yet there may be a statistically significant difference between the mean of the RV values.

5.3 Performance Evaluation

5.3.1 Asphalt Binders' Susceptibility to Moisture Damage

The asphalt binder bond strength (BBS) test was conducted in accordance to AASHTO T361-16 to assess the moisture damage susceptibility of the different asphalt binders [24]. A Pneumatic Adhesion Tensile Testing Instrument (PATTI) was used for the BBS test. Fig. 9 shows the experimental setup before and after the BBS test. Each asphalt binder was tested in a dry condition and after moisture conditioning for 24 h in a 40 °C water bath. Fig. 10 summarizes the test results for unconditioned and moisture-conditioned pull-off tensile strength as well as the retained bond strength after moisture conditioning. As shown in Fig. 10, adding 8% crumb rubber reduced the bond strength of the virgin asphalt binder by approximately 24% when tested at dry conditions,

Table 4 Continuous grading temperatures of evaluated asphalt binders

Asphalt binders	Critical high temperature (°C)	Critical low temperature based on stiffness criterion (°C)	Critical low temperature based on m-value criterion (°C)	Continuous intermediate grade (°C)	ΔTc (TS-Tm)
Virgin (60/70 pen)	69.9	− 31.3	− 28.3	19	− 3.0
Virgin + SonneWarmix	68.7	− 33.4	− 28.7	19	− 4.7
4% CRMAB	75.7	− 32.9	− 27.5	19	− 5.4
6% CRMAB	78.7	− 35.0	− 27.3	19	− 7.7
8% CRMAB	80.9	− 35.1	− 25.5	19	− 9.6
8% CRMAB + SonneWarmix	79.0	− 35.8	− 27.9	16	− 7.9
8% CRMAB + SonneWarmix + Antistrip	80.1	− 37.4	− 29.2	16	− 8.2

Fig. 6 Continuous grades of the evaluated asphalt binders

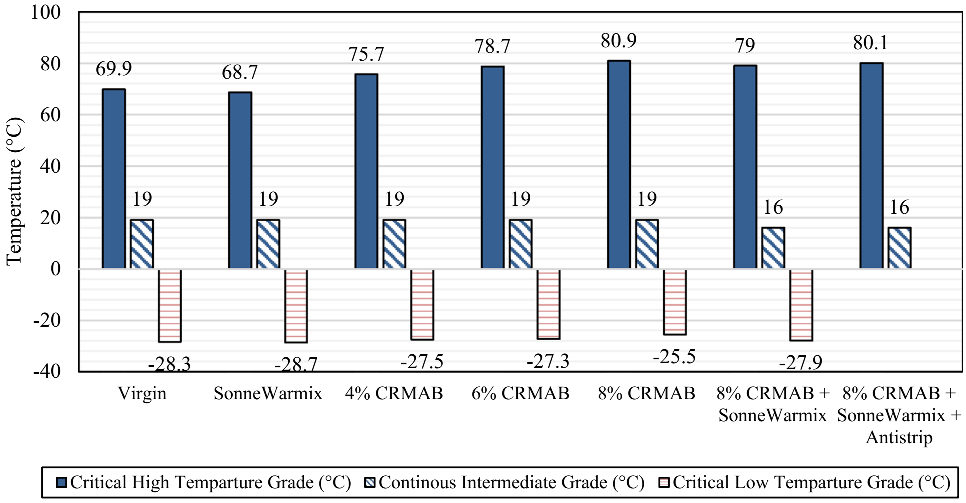


Fig. 7 Continuous low-temperature grade and Δ*T*c of the evaluated asphalt binders

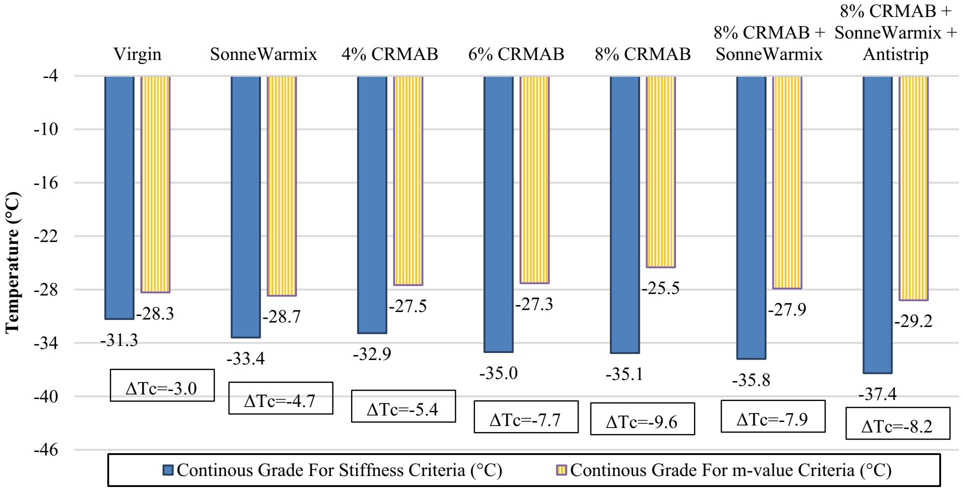
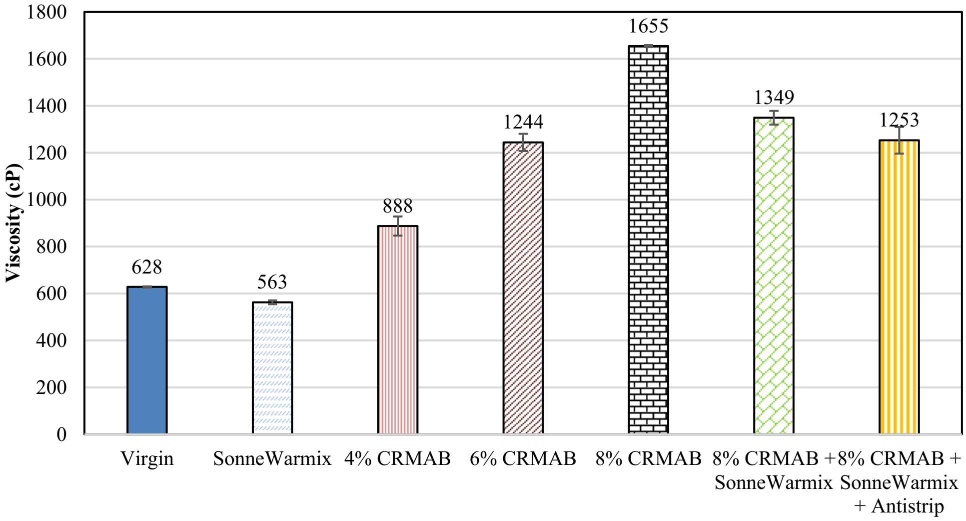


Fig. 8 RV results of asphalt binders (whiskers represent the 95% confidence interval of the mean strength values)



and by 44% when tested after 24 h of moisture conditioning. Adding SonneWarmix improved the bond strength of both the virgin asphalt binder and 8% CRMAB. Adding antistrip agent to the 8% CRMAB and SonneWarmix further improved the bond strength of the binder.

The 95% confidence intervals for the mean values of the unconditioned and moisture-conditioned pull-off tensile strengths are also shown in Fig. 6. Not overlapping error bars indicates that the 8% CRMAB has statistically significant lower unconditioned and moisture-conditioned pull-off tensile strengths when compared to the virgin asphalt binder with and without SonneWarmix. Even after adding SonneWarmix and antistrip agent to the 8% CRMAB, the moisture-conditioned tensile strength remained statistically significantly lower when compared to virgin asphalt binder. However, the percent retained bond strength increased from 69 to 85% when SonneWarmix was added to the 8%

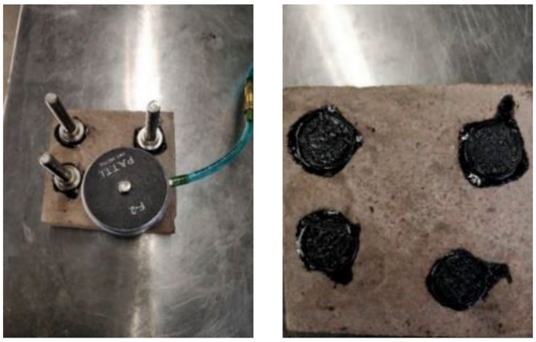

(a) (b)

Fig. 9 Photographs of the binder bond strength **a** before, and **b** after testing

CRMAB, and to 93% after adding the antistrip agent, indicating an overall better resistance to moisture damage.

One-way ANOVA analysis shown in Tables 5, 6, and 7 was conducted to evaluate the impact of WMA additive and antistrip agent on the virgin asphalt binder and CRMAB BBS (conditioned and unconditioned) values. The following can be observed from the one-way ANOVA analysis:

- In general, the addition of WMA additive (SonneWarmix) and antistrip agent (AD-HERE LOF 65–00) had a significantly low impact on the unconditioned BBS test values of the virgin asphalt binder and CRMAB. However, they had a significantly high impact on the conditioned BBS test values, which confirms with the test data analysis explained earlier.
- A paired mean comparison analysis at a significance level of 0.05 using *t* test procedure is shown in Tables 8. The paired mean analyses were conducted to determine the statistical significance of the BBS values of the different asphalt blends.
- Based on the pair comparisons shown in Tables 6 and 7, it can be concluded that the impact of WMA additive and antistrip agent varies from not significant to a highly significant depending on the asphalt blend type.

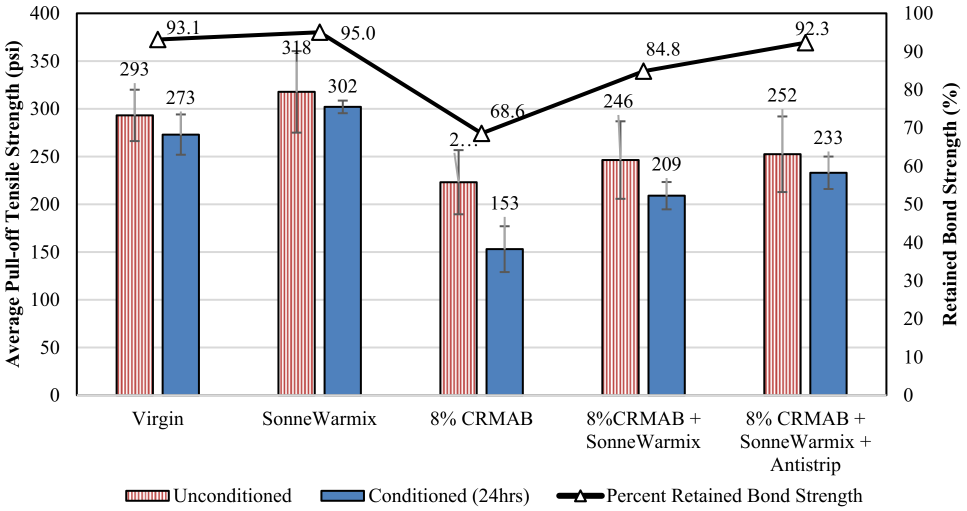


Fig. 10 Binder bond strength test results (whiskers represent the 95% confidence interval of the mean strength values)

Table 5 ANOVA table for the BBS values

Treatment	Source	Degrees of freedom	Type 1 SS	Mean square	*F* value	*P* value > *F*	Significance level
Unconditioned	Asphalt type	4	18,153.16	4538.29	4.54	0.028	Low significance
Moisture conditioned	Asphalt type	4	0430.20	10,107.55	26.12	< .0001	High significance

Table 6 Summary of *t* test analysis for unconditioned BBS test data

Parameter*	Estimate	Standard error	*t* value	Pr>|t|	Significance level
V vs VS	− 24.63	25.83	− 0.95	0.3651	Not significant
V vs 8%	73.30	25.83	2.84	0.0195	Low significance
V vs 8%S	46.77	25.83	1.81	0.1036	Not significant
V vs 8%SA	40.65	28.87	1.41	0.1928	Not significant
VS vs 8%	97.93	25.83	3.79	0.0043	High significance
VS vs 8%S	71.40	25.83	2.76	0.0219	Low significance
VS vs 8%SA	65.28	28.87	2.26	0.0501	Low significance
8% vs 8%S	− 26.53	25.83	− 1.03	0.3310	Not significant
8% vs 8%SA	− 32.65	28.87	− 1.13	0.2874	Not significant
8%S vs 8%SA	− 6.12	28.87	− 0.21	0.8369	Not significant

V = Virgin, VS = SonneWarmix, 8% = 8%CRMAB, 8%S = 8%CRMAB + SonneWarmix, 8%SA = 8%CRMAB + SonneWarmix + Antistrip Agent

Table 7 Summary of *t* test analysis for moisture-conditioned BBS test data

Parameter*	Estimate	Standard error	*t* value	Pr > |*t*|	Significance
V vs VS	− 29.20	16.06	− 1.82	0.0941	Not significant
V vs 8%	119.87	16.06	7.46	< .0001	High significance
V vs 8%S	63.06	15.03	4.20	0.0012	High significance
V vs 8%SA	39.36	15.03	2.62	0.0224	Low significance
VS vs 8%	149.07	16.06	9.28	< .0001	High significance
VS vs 8%S	92.26	15.03	6.14	< .0001	High significance
VS vs 8%SA	68.56	15.03	4.56	0.0007	High significance
8% vs 8%S	− 56.81	15.03	− 3.78	0.0026	High significance
8% vs 8%SA	− 80.51	15.03	− 5.36	0.0002	High significance
8S% vs 8%SA	− 23.70	13.91	− 1.70	0.1142	Not significant

V = Virgin, VS = SonneWarmix, 8% = 8%CRMAB, 8%S = 8%CRMAB + SonneWarmix, 8%SA = 8%CRMAB + SonneWarmix + Antistrip Agent

5.3.2 Asphalt Binders' Resistance to Fatigue Damage

The Linear Amplitude Sweep (LAS) test was conducted in accordance with the AASHTO provisional test method "AASHTO TP101-14" to evaluate the asphalt binder resistance to fatigue damage [25]. Frequency ranging from 0.2 to 30 Hz was used with a constant strain amplitude of 0.1% to assess the undamaged properties of the asphalt binders. Subsequently, amplitude sweep of ranging from 0.1% to 30% strain and constant frequency of 10 Hz was conducted to evaluate the damage characteristics of the asphalt binders. The number of loading cycles to failure (N_f) was estimated as 35% reduction in the initial modulus. The fatigue damage relationship in terms of N_f as a function of applied strain was developed using the following equation:

$$N_f = A(AppliedStrain)^B \tag{1}$$

where *A* and *B* are viscoelastic continuum damage (VECD) model coefficients. "A" parameter describes the material resistance to fatigue damage; higher A parameter indicates higher resistance to fatigue. "B" parameter describes the material sensitivity to strain level; lower absolute value for B indicates lower rate of decrease in fatigue life.

The test was carried out using the DSR on PAV-aged asphalt binders at 19 °C, which is the intermediate PG temperature of the virgin asphalt binder. Fig. 9 shows the calculated N_f as a function of applied strain (i.e., fatigue curve) of the different asphalt binders. Figs. 10 and 11 provide the VECD model coefficients A and B of the different tested asphalt binders. The 95% confidence intervals for the mean values of A and B parameters are also shown in the figures.

Fig. 12 shows that adding 8% CR improved the fatigue resistance of the virgin asphalt binder. However, Fig. 13 shows that the CR addition resulted in higher rate of decrease in fatigue life. Adding 1% SonneWarmix to the 8% CRMAB increased the fatigue cracking resistance and lowered the rate of decrease in fatigue life. Further decrease in the B parameter was achieved by adding antistrip agent. Overall, the 8% CRMAB with SonneWarmix and antistrip agent showed the best fatigue resistance among all the evaluated asphalt binders as demonstrated by a higher A parameter with a lower B parameter.

One-way ANOVA analysis shown in Table 8 was conducted to evaluate the impact of WMA additive and antistrip agent on the virgin asphalt binder and CRMAB LAS test parameters A and B. It can be seen from the one-way ANOVA analysis that the WMA additive and antistrip agent had a significant impact on the calculated A and B values of the virgin asphalt binder and the CRMABs.

Table 8 ANOVA table for the RV values

Parameter	Source	Degrees of freedom	Type 1 SS	Mean square	*F* value	*P* value > *F*	Significance level
A	Asphalt type	4	29,344,726,471	7,336,181,618	12.95	0.0075	High significance
B	Asphalt type	4	0.13903360	0.03475840	120.69	< 0.0001	High significance

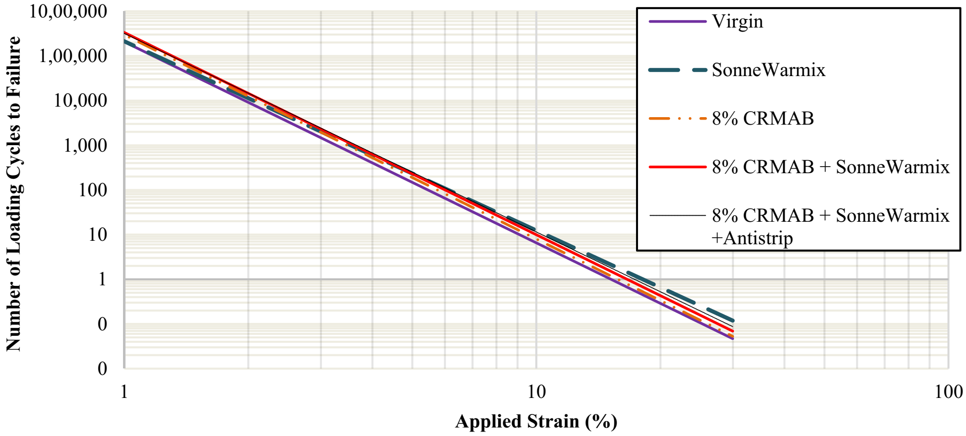


Fig. 11 Fatigue performance of asphalt binders in LAS test

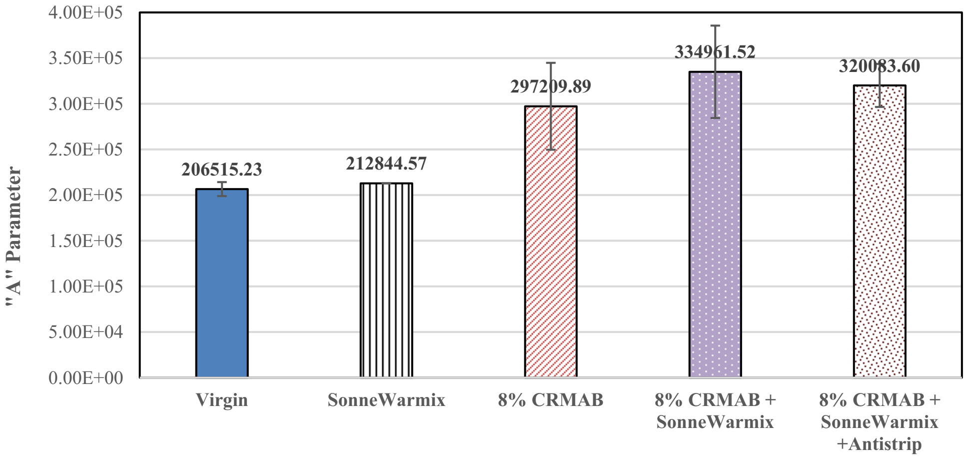


Fig. 12 LAS test results for “A” parameter of asphalt binders (whiskers represent the 95% confidence interval of the mean strength values)

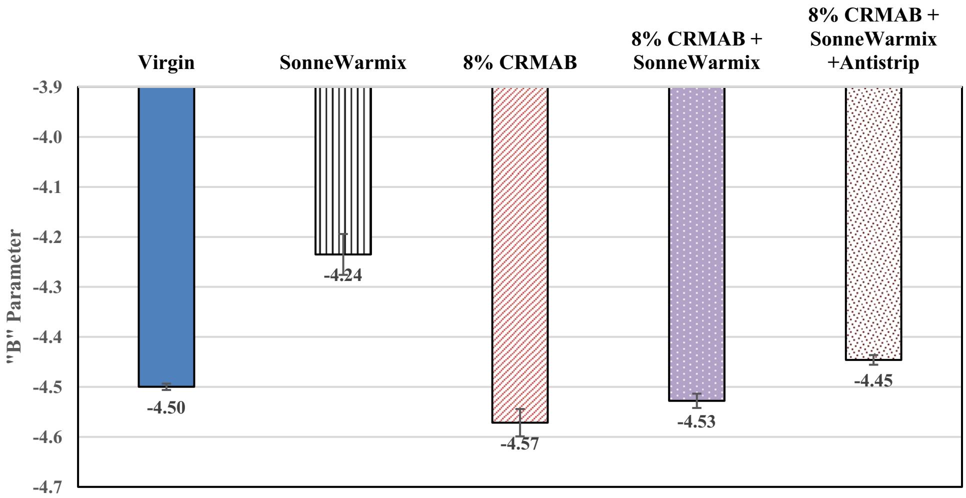


Fig. 13 LAS test results for “B” parameter of asphalt binders (whiskers represent the 95% confidence interval of the mean strength values)

6 Summary of the Findings

This study evaluated the effect of crumb rubber modification and addition of warm mix additive (SonneWarmix) and liquid antistrip agent (AD-HERE LOF 65-00) on an asphalt binder from Kuwait. The experimental plan consisted of evaluating the virgin asphalt binder 60/70 pen and CRMABs at different doses of CR. The test results were used to select an optimum content of CR that would result in a CRMAB that meets Kuwaiti and Qatari Specifications for polymer-modified asphalt binders.

The CRMAB at optimum dose was further evaluated to assess the effect of adding warm mix additive and liquid antistrip agent on the performance grade, moisture damage resistance, and fatigue cracking resistance. The following summarizes the findings from the laboratory evaluation:

- Homogeneous blends of CR and asphalt binder were achieved with crumb rubber passing 0.42 mm sieve (No. 40).
- The addition of 8% crumb rubber to the virgin asphalt binder resulted in a CRMAB that meets the Kuwait Specifications.
- The addition of 8% CR changed the virgin asphalt binder grade of PG64-28 to a PG76-22.
- The increase in CR content resulted in a more negative ΔTc value, indicating the presence of a higher percentage of aged hydrocarbons; however, it does not necessarily indicate the increased susceptibility to early cracking.
- The use of warm mix additive "SonneWarmix" with the 8% crumb rubber improved ΔTc value (less negative). It also restored the low-temperature grade of the virgin asphalt binder to –28 °C.
- Based on the BBS test results, a reduction in moisture damage resistance was observed with the addition of CR. Adding 8% CR to the virgin binder resulted in bond strength reduction of 24% when tested at the dry condition and 44% when tested after moisture conditioning. Moreover, the addition of 8% CR significantly reduced the percent retained binder bond strength after moisture conditioning.
- The addition of warm mix additive and antistrip agent improved the bond strength of the 8% CRMAB and showed less reduction in bond strength when tested after moisture conditioning. Furthermore, they reinstated the percent retained strength close to that of the virgin asphalt binder. Thus, indicating an improved resistance to moisture damage.
- The LAS test results showed that adding 8% CR improves the resistance to fatigue cracking, however, results in higher rate of decrease in fatigue life.
- The use of the warm mix additive and antistrip agent resulted in further improvement in the fatigue cracking resistance coupled with a lower rate of decrease in fatigue life.

In summary, this study showed that an optimum content of crumb rubber could be determined to produce a CRMAB that meets Kuwait Specifications for polymer-modified asphalt binders. However, while the increase in CR can have a positive effect on the rutting resistance of an asphalt binder, it can jeopardize the resistance to moisture damage and fatigue cracking. This can be overcome by the use of a warm mix additive along with an antistrip agent. Thus, this study demonstrates that a CRMAB can be engineered to result in an acceptable performance and durability. The findings from this study are highly beneficial to the state of Kuwait's ongoing and future CRMAB research and for other countries with limited access to asphalt binder sources or not yet developed a SuperPave performance grade paving map but are interested in using CR from waste tires in their asphalt mixtures.

For future work, a laboratory performance evaluation of asphalt mixtures prepared using the 8% CR, warm mix additives, and antistripping agents should be done. The performance evaluation should cover the key failure criteria of asphalt mixtures, which include mixture susceptibilities to rutting, moisture damage, and fatigue cracking. The results obtained from the recommended study along with the findings from this study can be used to develop the rutting and fatigue performance models, which can be used in a Mechanistic-Empirical analysis to estimate the performance of the CRM asphalt mixtures [26–29].

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Dr. Taha A. Ahmed is an Assistant Professor in the Civil Engineering Department at the Australian College of Kuwait (ACK), Kuwait. He has over 18 years of experience in academia and industry with an emphasis on performance characterization of asphalt materials and recycled construction materials. He has been a leader and a contributor to several research projects and published several peer-reviewed papers related to pavement materials/engineering, hot and warm mix asphalts, traffic engineering. His research interests include pavement design and analysis, pavement materials, transportation demand analysis, traffic engineering, and recycled construction materials. He won several grants in a highly competitive funding grant from Kuwait Foundation for the Advancement of Sciences (KFAS) in 2018 and 2019. These grants are in the fields of asphalt pavement in-service evaluation, crumb rubber modified asphalt binder. In addition, he won other research grants from the Australian College of Kuwait in 2017 and 2018 in the fields of pavement design and analysis and compressed earth blocks evaluation. He has reviewed many manuscripts submitted to leading journals in his field and has joined the organizing and scientific committees of major international conferences. He has also been appointed as the Vice-president for Middle-East region of the international Society for Maintenance And Rehabilitation of Transportation infrastructure (iSMARTi) since July 2016 until now.

Dr. Elie Y. Hajj is a professor in the Civil and Environmental Engineering Department and an associate director of the Western Regional Superpave Center (WRSC) at University of Nevada, Reno, USA. He has over 18 years of experience in academia and industry with an emphasis on sustainability of pavement systems, dynamic response of pavement structures, and full-scale testing of pavement systems. Dr. Hajj authored over 100 publications in journals, national and international conferences, and technical reports. He made more than 100 presentations in professional meetings, conferences, seminars, and workshops. He served as a principal investigator on multiple projects for FHWA, FAA, State DOTs, local governments, private industry, etc.

Dr. Hajj is currently chairing TRB AFK50 committee and a member of the ASCE, Association of Asphalt Paving Technologists, and the International Society for Asphalt Pavements. He is a founding member and an elected officer (since 2017) for the Academy of Pavement Science & Engineering (APSE). Dr. Hajj is also an associate editor for the International Journal of Pavement Engineering-IJPE.

Dr. Dawoud S. Bahzad has been assigned as Division Director—Science & Technology, for Petroleum Research Center, at the Kuwait Institute for Scientific Research (KISR), Kuwait. He obtained his Ph.D. in Chemistry and Catalysis from University of Wales, Swansea, in 1996. His previous experience was focused on catalyst preparation, deactivation, characterization, and obtaining testing of different catalyst systems using different type of feedstocks. His majority was focused on hydrotreating process (ARDS) and hydrocracking process (HC), which involves testing commercialized catalyst systems in the pilot plant units using actual feedstocks similar to the one used in the refinery. His present work is focused in different areas based on PRC strategic goal. He is involved in securing funds through joint work with local and international institutes, petroleum companies and universities in the area of upstream and downstream and in preparation of center strategy with particular regard to longer-term perspectives 2030 and to update the strategy every 5 years, in particular finalized 6th, 7th and 8th strategic plans for PRC center. He participated in reviewing and preparing KNPC, KOC and KPC strategy for 2040. He is in charge of initiations and execution of all contractual projects between PRC and clients specific all K-companies and institutes as well as universities.

Murugaiyah Piratheepan is a Research Scientist, University of Nevada Reno, USA. He has a masters degree in civil and environmental engineering from the University of Nevada Reno. He has more than 10 years of experience in academia and industry. His research interests include cold mix asphalt, cold-in-place recycling, chemically stabilized materials, warm-mix asphalt and performance characterization of asphalt materials.

Ahmed Warrag is a graduate research assistant at the University of Nevada Reno, USA. Ahmad has a masters degree in civil and environmental engineering from the University of Nevada Reno. His research interests include pavement management systems, pavement design and evaluation and performance-based asphalt mix designs.