A study on the significance of the crumb rubber classification on the ductility test for rubberized asphalt binder

Forat Yasir AlJaberi¹

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Abstract

Several types of modifiers have been used as additives into asphalt cement in order to enhance the performance of the Hot Mix Asphalt for road pavements such as PVA, SBS and crumb rubber. The aim of the present work is to study the effect of the crumb rubber classification according to the size of scrap tires, i.e., car and truck tires, on the behavior of the modified asphalt ductility test and Marshall mechanical properties of the asphalt concrete specimens. Samples of asphalt cement had been modified by using two types of crumb rubber: car crumb rubber (CCR) and truck crumb rubber (TCR). Mixing temperature (150–180 °C), contact time (20–60 min), CCR (10–20 wt%) and TCR (0–4 wt%) were tested to establish the mathematical correlations of the ductility response using a central composite design rotatable and uniform. Minitab-17 was performed for the regression and the graphical analysis of the obtained results. The optimum values of the operating variables that give (24 cm) of ductility response were (180 °C) of mixing temperature, (21 min) of contact time, (18 wt%) of CCR and (3.5 wt%) of TCR. The results showed an obvious enhancement of Marshall stability and flow according to these optimum values, 13 kN and 4 mm, respectively, in comparison with the unmodified binder in spite of minimizing the ductility value.

Keywords Asphalt cement · Car crumb rubber · Truck crumb rubber · Preparation · Ductility · Marshall properties

List of symbols

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
AC	Asphalt cement (g)
CRM	Crumb rubber modifier (g)
MB	Modified bitumen (g)
CCR	Car crumb rubber (wt%)
TCR	Truck crumb rubber (wt%)
Y_{Coded}	Coded value of ductility response (cm)
Y_{Real}	Real value of ductility response (cm)
$Y_{\text{ductility}}$	Real value of ductility response (cm)
PVA	Polyvinyl acetate
SBS	Styrene–butadiene–styrene

1 Introduction

Asphalt cement is one of the main materials that must be used to produce Hot Mix Asphalt (HMA) for road pavements according to the general standards of American Society for Testing and Materials (ASTM) and/or American Association of State Highway and Transportation Officials (AASHTO) [1, 2].

In general, these pavements over time are damaged and can cause failure such as rutting (wheel track groove) because of the continuous passing of traffic loads and the climate conditions, especially in the higher temperature zones; therefore, this failure is extremely affecting the performance of the conventional pavement and costly as millions of dollars are spent every year to overcome this crisis. Asphalt binders used to protect the sub-layers

✉ Forat Yasir AlJaberi, Furat_yasir@yahoo.com | ¹Chemical Engineering Department, College of Engineering, Al-Muthanna University, Al-Muthanna, Iraq.

from the influence of water should be modified to resist the impacts of dynamic load and the ecological factors. Therefore, researchers are trying to solve these problems by performing numerous types of additives, such as styrene–butadiene–styrene (SBS) [3–7], polyvinyl acetate (PVA) [8] and tire crumb rubber to enhance the durability of asphalt cement and the performance of the HMA as a consequence.

Billions of tires are produced and sold every year in the world due to the rapidly growing number of transportation vehicles and other usages of tires [8, 9]; as a result, millions of tires are consumed and wasted (Fig. 1a) according to the rule of End of Life Tires [10]. About 35% of waste tires are reused, but the rest is disposal and has caused environmental problems for soil and humanity [11] because of the durability, i.e., un-degradable, properties of tires.

Figure 1b and Table 1 show the typical composition of tires according to their uses and sizes, i.e., cars and trucks. As noted clearly, car tires contain synthetic rubber more than natural rubber in contrast to that of the truck tire. But some kinds of tires are consisting of a full percentage of natural rubber such as agricultural, aircraft and industrial tires [12].

In order to solve the problems of pollution and roads failure, many researches had utilized crumb rubber that was derived from waste tires as an additive to enhance the asphalt pavement performance [3, 13–28]. Crumb rubber is the only modifier derived from waste materials by recycling of waste tires [6, 15, 17, 29].

Several tests should be performed in order to investigate the performance of the modified bitumen (MB) such as the penetration test (ASTM-D5 and AASHTO-T49), the softening point test (ASTM-D36 and AASHTO-T53) and ductility test [1, 2].

Table 1 Typical composition of passenger and truck tires [12]

Composition	Car tire	Truck tire
Natural rubber	14%	27%
Synthetic rubber	27%	14%
Carbon black	28%	28%
Steel	14–15%	14–15%
Fiber, fillers, accelerators, etc.	16–17%	16–17%
Average weight	New 11 kg, scrap 9 kg	New 54 kg, scrap 45 kg

In spite of the employment of several advanced rheology characterization methods, the ductility test is still in use as an indicator for asphalt performance [30] according to the specifications of ASTM-D113 and AASHTO-T51. The ductility test measures the tensile stress required to break the bond between molecules of the asphalt cement itself. It involves the elongation of a sample by ductilometer with the force measured at very elongation intervals with speed equal to 5 cm/min [1, 2].

Bakheit and Xiaoming [31] proved that the mechanical properties of the modified binder were clearly enhanced when CRM was mixed with asphalt and aggregate based on the design of the binder mix. They found that the Marshall stability decreases from 7.6 to 6.32 kN as the CRM content increases from 6 to 24%. The improvement of rutting resistance and stability of the rubberized binders were also conducted by Franesqui et al. [32] when 10 wt% of CRM was performed with contents of asphalt cement and blended for 60 min. While Varun et al. [11] observed that any increase in fine CRM added to the HMA will increase the viscosity and decrease the resilience of the modified binder, and the authors found that the extender oil presented in the asphalt cement was

Fig. 1 a Landfills for accumulation of waste tires. b Typical composition of tires

inversely related to the CRM content and directly related to the ductility response. Meanwhile, as the CRM content increases, the extender oil and the ductility decreased consequently.

Al-Azawee and Qasim [10] studied the effect of using CRM on the basic properties of HAM with different percentages (0, 5, 10 and 15%), and they proved that the use of 10% content of CRM produced a significant impact on Marshall stability. Moreover, they found that the ductility response had been decreased as the CRM content increased. Tabatabaee et al. [30] mentioned that the ductility test is required in spite of other advanced rheology characterization tests and the ductility test should be employed in case of a stable geometry of the studied sample for the lower temperature zones.

In another study, Shafabakhsh et al. [33] studied the impact of adding 10 wt% of crumb rubber on the rutting performance of HMA by using wheel track test apparatus. They revealed that the use of this additive caused a significant decrease in the depth of rutting of the rubberized binder compared to the conventional binders. Moreover, Mashaan et al. [34] proved that the addition of CRM has a notable impact on the physical properties of the modified binders by decreasing the ductility response from 90 cm for the unmodified binder to 30 cm when 20 wt% of CRM was utilized.

Abass [13] used coarse crumb rubber as a bitumen modifier and designed the experiment by using a central composite rotatable design and a statistical program. This study found that 20 wt% CRM, 3 cm particle size, and 6.482 wt% of asphalt cement had been given effective performance properties. However, Liu et al. [35] studied the interaction mechanism between CRM and asphalt cement by employing 18 wt% of CRM derived from three different sources of waste tires. They conclude that the natural rubber with a chemical structure (2-methyl-1, 3-butadiene) can reserve more flexibility and the rubberized mix has a notable performance of low-temperature creep property because the viscosity and the ductility decrease as the mixing temperature raised.

While Bahia [15] concluded that all kinds of CRMs produced by different processes, i.e., ambient, cryogenic, and other types produced by special process, affect the basic rheological, failure and aging properties of different types of asphalt cement. Moreover, Battey [3] made a comparison among different types of additives containing styrene–butadiene–styrene (SBS) or styrene–butadiene rubber (SBR), polyethylene and ambient CRM as modifiers for hot mix and then compared them with the conventional mixture. The study proved that all of these modifiers had a significant applicability of enhancing the performance of the conventional mixture by reducing the rutting failure of the rubberized binder.

Girimath et al. [36] investigated the effect of adding reclaimed asphalt pavement (RAP) (0, 15, 25 and 40%) on basic properties (penetration, softening, ductility) of CRM binder. They found that the addition of RAP contributes to the stiffening nature of CRM binder. Msallam and Asi [37] proved that the use of crumb rubber as an additive to asphalt cement was clearly effective in enhancing the performance of modified HMA mixes.

Partl et al. [38] concluded that the addition of (15–20 wt%) of crumb rubber produced by different methods (mechanical shredding-based process; particles < 400 μm , cryogenically based process; particles < 400 μm , water jet-based process and de-vulcanized; particles < 400 μm and water jet-based process; particles < 1000 μm) to bitumen increases the complex modulus at high temperatures and reduces stiffness at low temperatures compared to neat and SBS modified bitumen. Moreover, they found that the bigger surface area of CRM (< 1000 μm) caused the smaller ductility of the bitumen, but the ductility had been increased at low temperature for the modified bitumen. Nguyen and Tran [39] studied the impact of using crumb rubber as a modifier on the mechanical properties of rubberized asphalt concrete under the variation of crumb content and curing time. They found that the optimum value of crumb rubber was 1.5–2% and the curing time ranging 0–5 h that had enhanced the performance.

AlJaberi 2013 only studied the effect of crumb rubber classification, according to the size of waste tire sources, whether it is car tire or truck tire, on the penetration and softening point responses of the modified asphalt cement, but the ductility response was not evaluated [29].

According to my survey and knowledge, there is no previous study that had concerned about investigating the impact of classifying crumb rubbers based on their source of scrap tires on the conventional test of ductility for a modified asphalt cement. Therefore, the aim of the present work is to investigate the impact of performing two types of crumb rubber modifiers produced from different waste tires that had been obtained and classified according to the size of waste tires on the ductility response of asphalt cement and Marshall properties of rubberized asphalt binder.

2 Experimental design

2.1 Materials

In the present study, asphalt cement was supplied from Basra refinery located in the south of Iraq as shown its physical properties in Table 2.

Table 2 Physical properties of Basra asphalt cement

The property	Unit	Test	Value
Specific gravity at 25 °C	g/cm ³	ASTM-D-70; AASHTO-T-228	1.03
Flash point	°C	ASTM-D-92; AASHTO-T-73	275
Penetration at 25 °C (100 g, 5 s, 0.1 mm)	1/10 mm	ASTM-D-5; AASHTO-T-49	46
Softening point (ring and ball)	°C	ASTM-D-36; AASHTO-T-53	48
Ductility at 25 °C, 5 cm per min.	cm	ASTM-D113; AASHTO T51	34
Solubility in CCl ₄ wt% min	%	AASHTO-T-44	99

Table 3 Operational parameters

Parameters	Ranges
Mixing temperature (°C)	150–180
Contact time (min)	20–60
CCR (wt%)	10–20
TCR (wt%)	0–4

Two types of crumb rubber produced from waste tires were performed in this study as additives to the bitumen: car crumb rubber CCR and truck crumb rubber TCR. The size of both types of crumb rubber equals 0.6 mm (sieve No. 30).

Samples of modified asphalt cement were prepared according to the experimental design by adding the required amount of crumb rubber to bitumen. In this study, the aggregates and mineral filler were employed according to the specification of (ASTM-C127 and C128) and (ASTM-D242/2003 or AASHTO-M17/2010), respectively.

2.2 Instruments

The required amounts of CCR and TCR had been weighed using a digital balance manufactured by ADEM company (USA). Asphalt cement was heated to the designed

temperature using oil bath provided by LABTECH (Malaysia), and a mechanical stirrer-type ANALIS (Belgium) was employed to agitate the mixture. A ductility apparatus manufactured by Yoshida company (Japan) was performed to estimate the ductility value of the modified asphalt cement samples. Marshall properties had been estimated by using Marshall instrument manufactured by ELE international company (England).

2.3 Sample preparation of modified asphalt cement

Table 3 lists the ranges of the operational variables that influence the studied responses where their limits had been chosen according to the survey of the literature.

When the sample containing asphalt cement was heated until it reached the designed temperature, the required amounts of CCR and TCR were then added and the mixture was agitated along the designed period of each experiment. After the experiment was finished, the copper mold (Fig. 2a) was filled by the modified bitumen (MB) sample and cooled for 30 min at room temperature and then the sample was tested by the ductilometer apparatus (Fig. 2b) with the speed of pulling equaling 5 cm/min. Replicate samples were tested for each observation three times.

Fig. 2 **a** Copper mold filled by bitumen and the pulling process. **b** Ductilometer apparatus

2.4 Statistical analysis

The value of ductility response was estimated using experimental analysis via response surface methodology (RSM) as well as the statistical program Minitab-17 software to obtain the graphical analysis and the mathematical correlation that relates the ductility of the modified asphalt cement to the operating parameters using Eq. (1) according to the details listed in Table 3.

$$Y = B_0 + \sum_{i=1}^q B_i X_i + \sum_{i=1}^q B_{ii} X_i^2 + \sum_i \sum_j B_{ij} X_i X_j + \varepsilon \quad (1)$$

where Y is the studied responses; $X_1, X_2, \dots, X_q$ are the operational parameters; B_0 is a constant regression constant, B_i is the linear regression coefficient, B_{ii} is the squared regression coefficient and B_{ij} is the cross-product regression coefficient; ε is a random error.

A total of thirty-one runs were employed as cube points: 16, center points in the cube: 7, axial points: 8, the center points in axial is none and the rotatability α is 2. Table 4 lists the actual and coded values of the operational parameters.

In general, the accuracy of the mathematical correlation coefficients was estimated by the application of Chi-square (χ^2) (Eq. 2). The higher value of the correlation coefficient (R^2), the lower value of (χ^2); it is a better indication of the applicability of the obtained model:

$$\chi^2 = (Y_{\text{Real}} - Y_{\text{Coded}})^2 / Y_{\text{Coded}} \quad (2)$$

where the real and coded responses are represented by Y_{Real} and Y_{Coded} , respectively.

3 Results and discussion

Table 5 explains the values of the operational parameters, the experimental response (Y_{iReal}) and calculated response (Y_{iCoded}) and Chi-square (χ^2) indicator.

The proportion of variance equals (0.96123), and the correlation coefficient (R) was (0.98042); therefore, the

number of iterations was terminated. Figure 3 explains the relation between the observed and predicted values of the ductility response.

The coefficients of the second-order polynomial correlation had been obtained by using Minitab program according to the regression analysis rule for the ductility response. To ensure the accuracy of this calculation, all the regression coefficients will be statistically significant and taken into consideration.

Equation (3) relates the ductility response to the operational variables in terms of the coded variables.

$$\begin{aligned} Y_{\text{Coded}} = & 16.900 + 1.042X_1 + 0.167X_2 \\ & - 0.792X_3 + 0.542X_4 + 0.618X_1^2 \\ & + 0.056X_2^2 + 0.119X_3^2 + 0.556X_4^2 \\ & + 0.188X_1X_2 - 0.188X_1X_3 + 0.375X_1X_4 \\ & + 0.563X_2X_3 - 1.000X_2X_4 - 0.125X_3X_4 \end{aligned} \quad (3)$$

In terms of actual variables, Eq. (4) reveals the relation between the ductility response and the operating variables as follows: the form of this correlation had been estimated by the use of the nonlinear estimation order.

$$\begin{aligned} Y_{\text{Real}} = & 316.109 - 3.541X_1 - 0.578X_2 - 0.037X_3 - 5.183X_4 + 0.011X_1^2 \\ & + 0.0006X_2^2 + 0.019X_3^2 + 0.556X_4^2 + 0.0025X_1X_2 - 0.010X_1X_3 \\ & + 0.050X_1X_4 + 0.023X_2X_3 - 0.100X_2X_4 - 0.050X_3X_4 \end{aligned} \quad (4)$$

3.1 Effects of the operational variables on the ductility response

Each of the studied operational variables has a notable effect on the value of the studied response as shown in the following explanation when other variables are taken at their mean values.

3.1.1 Effect of temperature

Figure 4a explains the effect of mixing temperature on the behavior of the modified bitumen (MB) ductility response when other values of the operational variables were taken at their mean values (40 min of mixing time, 15 g of CCR and 2 g of TCR). The result shows that the ductility response decreased as the temperature increased until reaching 160 °C; then, the ductility tended to raise its maximum value at 180 °C of the mixing temperature.

The interpretation of this behavior could be expressed as follows: As the mixing temperature raises, more of the aromatic oils had been evaporated along the duration of the experiment, and this led to cut the MB line earlier.

But the swelled particles of crumb rubber will extend the length of asphalt line in the ductilometer apparatus due to the increase in elastomer status of the MB as a

Table 4 Actual and coded operational variables

Actual variable (X_i)	Coded variables				
	-2	-1	0	1	2
X_1 =mixing temperature (°C)	150	158	165	173	180
X_2 =contact time (min.)	20	30	40	50	60
X_3 =CCR (g)	10	12.5	15	17.5	20
X_4 =TCR (g)	0	1	2	3	4

Table 5 Experimental and calculated values of ductility and Chi-square values

Run	Real variable				Y_{Real} (cm)	Y_{Coded} (cm)	χ^2
	$X_1(^{\circ}\text{C})$	$X_2(\text{min})$	$X_3(\text{g})$	$X_4(\text{g})$			
1	173	50	17.5	3	19.00000	19.02084	0.000023
2	158	50	17.5	3	16.00000	16.18750	0.002172
3	173	30	17.5	3	19.00000	19.18750	0.001832
4	173	50	12.5	3	20.00000	20.10416	0.000540
5	173	50	17.5	1	19.50000	19.43750	0.000201
6	158	30	12.5	1	17.00000	17.10417	0.000634
7	173	30	12.5	1	18.50000	18.43750	0.000212
8	158	50	12.5	1	18.00000	17.93750	0.000218
9	158	30	17.5	1	15.00000	15.02083	0.000029
10	158	30	12.5	3	19.50000	19.68750	0.001786
11	173	50	12.5	1	20.00000	20.02083	0.000021
12	173	30	17.5	1	15.50000	15.60417	0.000695
13	173	30	12.5	3	22.50000	22.52083	0.000019
14	158	30	17.5	3	17.00000	17.10416	0.000634
15	158	50	12.5	3	16.50000	16.52084	0.000026
16	158	50	17.5	1	18.00000	18.10416	0.000599
17	180	40	15	2	21.50000	21.45833	0.000081
18	165	60	15	2	17.50000	17.45833	0.000100
19	165	40	20	2	16.00000	15.79167	0.002748
20	165	40	15	4	20.50000	20.20833	0.004210
21	150	40	15	2	17.50000	17.29167	0.002510
22	165	20	15	2	17.00000	16.79167	0.002585
23	165	40	10	2	19.00000	18.95834	0.000092
24	165	40	15	0	18.00000	18.04167	0.000096
25	165	40	15	2	16.00000	16.90000	0.047929
26	165	40	15	2	17.00000	16.90000	0.000592
27	165	40	15	2	17.50000	16.90000	0.021302
28	165	40	15	2	18.00000	16.90000	0.071598
29	165	40	15	2	16.00000	16.90000	0.047929
30	165	40	15	2	16.00000	16.90000	0.047929
31	165	40	15	2	17.00000	16.90000	0.000592

result of a higher content of natural rubber presented in both types of crumb rubber, especially the truck crumb rubber TCR. The ductility response relates to the value of mixing temperature according to Eq. (5) as follows when other variables were kept at their mean values:

$$Y_{\text{ductility}} = 245.6 - 2.902X_1 + 0.009216X_1^2 \quad (5)$$

In case of varying the agitation time and at mean values of both types of CRM, the mixing temperature obeys the same behavior observed in Fig. 4a, but the less the mixing time, the higher value of ductility response as shown in Fig. 4b because any increment of mixing time caused the extender oils to be more evaporated, and then, the ductility value decreases consequently.

But in case of higher temperature, the longer the mixing time, the higher the ductility response. Meanwhile, as the

CRM swelled, their latex will be saturated by the aromatic oils and the rest of these oils will increase the elasticity of modified bitumen (MB), and then, the ductility will be increased as a result.

Figure 5a and b explains the effect of varying temperature on the ductility response in case of using CRM-type CCR only or type TCR only at mean value of the mixing time. The irregular behavior of ductility response shown in Fig. 5 may have occurred due to the difference of the absorption capacity of the extender oils by the synthesis and natural rubber presented in both types of waste CRM, but in case of the absence of CCR, the higher the TCR content in BM, the higher the value of ductility response due to the elasticity influence of the natural rubber presented in the TCR that extends the elongation of the BM sample in the ductilometer.

Fig. 3 Observed versus predicted ductility response values

Fig. 4 Ductility versus mixing temperature: **a** other variables at mean values and **b** for several values of mixing time and mean values of CCR and TCR

3.1.2 Effect of mixing time

As shown in Fig. 6 and in case of mean values of mixing temperature (165 °C), CCR (15 wt%) and TCR (2 wt%), the ductility value had been increased as the contact time increased due to the absorption operation of the aromatic oils content presented in the MB by CRM particles which gives an elastomer effect for the modified bitumen; then, the ductility value will increase as a consequence.

However, the continuous increment of the mixing time under the same conditions of other operational variables will minimize this response due to the continuous

evaporation of the aromatic content. Moreover, the saturated CRM will not swell more to give the studied sample more elasticity and elongation in the ductility test apparatus.

Equation (6) relates the ductility response to the mixing time as follows in the condition of mean values of other operational variables:

$$Y_{\text{ductility}} = 0.8961X_2 - 0.01063X_2^2 \quad (6)$$

The counter plot shown in Fig. 7a and b revealed the effect of CRM classification, i.e., CCR and TCR, on

Fig. 5 Ductility versus mixing temperature at mean value of mixing time (40 min): **a** CCR only **b** TCR only

Fig. 6 Ductility versus mixing time when other variables are kept at their mean values

the ductility response along the experiment in case of mean value of mixing temperature (165 °C). As observed in Fig. 7a, the lowest value of ductility was obtained at higher value of CCR and mixing time ranging between 35 and 45 min in case of mean values of mixing temperature and TCR crumb rubber. By contrast and for the same range observed of mixing time, Fig. 7b shows that the higher value of ductility was observed at the higher value of crumb rubber-type TCR in case of mean values of temperature and CCR. This behavior occurs depending on the content of the natural rubber (simple isoprene) and its applicability of oil content absorption and the elasticity status.

3.2 Optimization of operational variables

The optimum values of the operational variables, i.e., mixing temperature, mixing time, CCR and TCR crumb rubber and their validated value of the ductility response, were obtained by using a statistical software program (Minitab-17). Figure 8 and Table 6 show the results of the D-optimization measurement where the composite desirability (D) equals 1.

In practice, the optimum values should be taken into consideration in order to prevent the rigidity and the bleeding of pavement that may be caused by cracking, shoveling and rutting failures when the crumb rubber is employed more or less than the obtained optimum values.

Table 7 shows a simple comparison depending on the obtained mathematical model; the influence of crumb rubber classification into waste car crumb rubber CCR and waste truck crumb rubber TCR on the ductility response was extremely notable. As revealed, the percentages of voids in the total mix (VTM) and the voids in the mineral aggregate (VMA) had been increased, whereas the percentage of voids filled with modified bitumen (VFA) had been minimized due to the presence of crumb rubber throughout the asphalt cement.

In a previous study and for the same operational variables [28], the obtained values of the softening point and penetration tests at the optimum values were 81.471 °C and 25.933 mm, respectively [28].

Fig. 7 Ductility versus mixing time at mean value of mixing temperature (165 °C): **a** CCR only **b** TCR only

Fig. 8 The optimum values of the operational variables and the validated value of the ductility response for the modification of bitumen by using two types of CRM

Table 6 Optimum values of the operational variables and the corresponded ductility response

Variables	Temperature (°C)	Time (min.)	CCR (wt%)	TCR (wt%)	Ductility (cm)
Value	180	21	18	3.5	24

As observed in Table 7, the values of Marshall stability and flow had been obtained as 13kN and 3.6 mm, respectively, at the optimum values of the operational variables which were higher in comparison with that measured for the unmodified binder. In spite of minimizing the ductility value, Marshall properties were modified and the performance of the rubberized asphalt binder was enhanced consequently.

Table 7 Effect of using **AC** modifier on ductility test response

The variable	Unit	The value (without CRM)	The value (with CRM)	Specification limits
Temperature	°C	180	180	–
Time	min	60	21	–
CCR	g	0	18	–
TCR	g	0	3.5	–
Ductility	cm	34	24	–
VTM	%	3.1	5.2	–
VMA	%	14.1	16.7	–
VFA	%	78.2	68.0	–
Marshall stability	kN	9.6	13.0	8 (minimum)
Marshall flow	mm	4.5	3.6	2–4

4 Conclusion

The classification of crumb rubber according to the size of scrap tires, i.e., waste car crumb rubber CCR and waste truck crumb rubber TCR, affected the value of ductility response when they were used as additives to Basra asphalt cement due to the various contents of the natural rubber in both types of crumb rubber. Therefore, the present study proved that the addition of different types of CRM could enhance the Hot Mix Asphalt (HMA) according to the results obtained by Marshall stability and flow. The optimum values of the operational variables were (180 °C) of mixing temperature, (21 min) of mixing time, (18 wt%) of CCR, and (3.5 wt%) of TCR and the corresponding value of the ductility response was (24 cm) as well as 13 kN and 3.6 mm of Marshall stability and flow, respectively. The results show a significant impact of crumb rubber classification on the ductility and on Marshall properties.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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