Research Article

Sarah Safaaldeen Musa, Noorance Al-Mukaram* and Ihsan Habib Dakhil

Asphalt binder modified with recycled tyre rubber

https://doi.org/10.1515/eng-2022-0495
received June 06, 2023; accepted July 17, 2023

Abstract: In the last few decades, tyre rubber waste has been considered a risky issue to the ecosystem. A huge amount of used and deformed tyres is disposed of in landfill or recycled into other products. The main goal is to modify 60/70 bitumen grade to achieve 40/50 bitumen results. In this work, tyre rubber waste was added at different weights from 5 to 20% after cutting into small particles to use in the modification process of 60/70 asphalt binder. The modified asphalt was tested to meet the Iraqi standard specifications of roads and bridges. In the experimental work, Central Composite Design was applied to attain mathematical models that describes binder consistency by relating three operating parameters: tyre rubber ratio, mixing temperature and time. The predicted models relate to the penetration and softening point of the modified binder achieved R^2 of 97 and 99%, respectively. The obtained results indicated that the penetration and softening point improved after adding 20% recycled tyre rubber at 170°C and 20 min of mixing time.

Keywords: tyre waste, crumb rubber, modified bitumen, design of experiments

1 Introduction

Over few decades, poor road pavement performance has become a widespread issue due to a dramatic increase in the traffic volume and poor maintenance services. In addition, increasing temperatures and axle loadings result in many road surfacedistresses particularly fatigue, rutting and bleeding problems. Therefore, appropriate solutions have been suggested to reduce the structural damages. Different modifiers are added by weight to the bitumen binder before mixing with aggregates. For example, adding styrenebutadiene rubber and styrene butadiene styrene as powders may improve asphalt thermal and mechanical properties. However, adding aforementioned polymers are not always the best choice due to their expensive cost. Therefore, providing other alternatives encouraged researchers as well as industrial companies to find out environmental aspects toward sustainability such as using recycled tyre rubber (RTR).

Annually, over 1 billion scrap tyres are generated worldwide in addition to 4 billion tyres that are accumulated in landfills as well as stockpiles based on a report by the World Business Council for Sustainable Development [1]. To reduce the impact of tyre waste disposal environmentally, crumb rubber (CR) is used as a modifier to produce a homogenous asphalt binder through the common method called "wet process" established by Charles McDonald in 1960s [2]. In this method, CR is added into the bitumen binder before mixing with aggregate composition. Under controlled temperature and mixing time (i.e., 170°C for 45–60 min), the CR melts and the characteristics of asphalt will get improved significantly [3].

A number of investigations and efforts have been conducted on the utilization of the CR in asphalt mixes to examine its effect on asphalt engineering performance. Chemical interaction of the CR and asphalt is affected by their properties in terms of CR size, concentration, source and asphalt characteristics such as penetration, viscosity, source, etc. A high rate of interaction is a result of high CR-specific surface area. In addition, the fast-swelling rate of CR particles is obtained when mixed with low viscous asphalt because there is a significant increase in the asphaltene amount of the residual binder [4]. High compatibility between CR and asphalt was achieved by using CR from scrap truck tyre because of the higher natural content of rubber [5].

Other important factors were taken into consideration when adding CR, such as mixing temperature and speed. The results of previous studies showed that the physical characteristics of modified asphalt enhance at lower interaction

* **Corresponding author: Noorance Al-Mukaram,** Civil Engineering Department, Al-Muthanna University, Samawah, Iraq, e-mail: noorance@mu.edu.iq
Sarah Safaaldeen Musa: Civil Engineering Department, Al-Muthanna University, Samawah, Iraq, e-mail: almusawysarah@mu.edu.iq
Ihsan Habib Dakhil: Chemical Engineering Department, Al-Muthanna University, Samawah, Iraq, e-mail: em2ihsan@mu.edu.iq

circumstances (i.e., 160°C and 10 Hz) which is commonly known as swelling extent. However, the asphalt properties declined after increasing the mixing temperature and time to higher levels [6–8]. This is mostly true due to the fact that polymer swelling is caused by diffusing small molecules of solvent through its structure. As a result, a cleavage of polymeric chains may occur which indicated a reduction in the asphalt molecular weight.

A number of conventional and microscopic tests including dynamic shear, penetration, softening point, tensile strength, Fourier transform infrared spectroscopy and scanning electron microscopy have been carried out to simulate asphalt resistance to permanent deformation and cracking following the modification process. Previous studies revealed that penetration decreases as the CR content increases up to 20% at 190°C mixing temperature, while the softening point increases to 72°C at the same percentage and mixing condition [9]. Accordingly, the modified asphalt showed good performance in cracking within its service life. Thereby, modifying asphalt with CR shows an advantageous impact in term of water resistance by developing the elasticity of asphalt mixtures as well as decreasing maintenance costs and road noise [10–13].

The current work aims to investigate adding RTR as a modifier to enhance 40/50 bitumen properties since the last is widely used in airports and road constructions. Penetration and softening point tests are usually measures of binder consistency under different temperatures. The key of this research is to find the optimal temperature and mixing time after adding a certain amount of RTR to 60/70 bitumen that achieve 40/50 bitumen penetration and softening point. By applying different contents of RTR (5–20% with an increment of 5%) of asphalt weight and different ranges of mixing time (20–60 min) and temperatures (130–180°C), binder consistency was modelled mathematically using Central Composite Design (CCD). Details of the experimental work and methodology are described in the next section.

2 Methodology

2.1 Materials

Two materials were prepared for achieving the goals of this experimental work. They are locally produced in Iraq as follows.

2.1.1 Asphalt binder

A bitumen of 60/70 penetration grade was used in the current work. This type of bitumen is produced in the Samawah oil refinery in Iraq for use in paving roads and building construction. As mentioned previously, the objective of this study is to modify 60/70 bitumen to reach 40/50 penetration grade. The obtained data of physical properties of these bitumens are presented in Table 1 after conducting the required tests in the Samawah oil refinery [14].

2.1.2 RTR

It is also known as CR and is obtained by cutting scrap tyres into shreds and then ground into small particle sizes (about 10 mm) after removing reinforcing cords as illustrated in Figure 1. These particles were collected from Diwaniya rubber factory. For this study, the RTR was prepared as 5, 10, 15 and 20% of asphalt binder weight.

2.2 Laboratory tests

Samples of the modified binder were prepared in the laboratory using a mechanical mixer for mixing the RTR particles with 60/70 bitumen. First, about 600 g of binder was heated and then placed on a sand bath above a hot

Table 1: Physical properties of 60/70 versus 40/50 asphalt binders [14]

Tests	Units	Asphalt grade (60/70)	Asphalt grade (40/50)	ASTM
Penetration 100 g at 25°C and 5 s	1/10 mm	64	43	D5
Absolute viscosity at 60°C	Poise	3,380	3,268	D88
Kinematic viscosity at 135°C	C st	406	403	D88
Ductility at 25°C and 5 cm/min	cm	153	130	D113
Softening point (ring & ball)	°C	57.6	53.7	D36
Specific gravity at 25°C	g/cm^3	1.02	1.04	D70
Flash point (Cleveland Open Cup)	°C	227	235	D92

Figure 1: RTR particles produced by Diwaniya rubber factory.

plate. A high-shear radial flow impeller attached to the mixer was placed in the binder for stirring at a speed of 700 rpm. Then, a certain amount of RTR particles (i.e., 5–20% in weight) was added gradually to the binder. The continued mixing time was also varied (i.e., 20–60 min) at each specific quantity of RTR. The temperature of the binder was controlled for a specific range (i.e., 130–180°C). After mixing, each can of modified binder was allowed to cool at room temperature for 24 h before being reheated for testing. The total number of prepared modified asphaltic samples was 15 in the current work. Table 2 shows the range of the operating parameters.

Next, empirical tests of penetration and softening point are used to determine the asphalt consistency in terms of temperature susceptibility after adding the RTR modifier in different contents. Based on ASTM D5, the penetration test of bitumen took place at 25°C. A 100 g prescribed needle is placed on the surface of the asphalt cement for 5 s to measure the penetration depth. The softening point was also tested according to ASTM D36. The test is executed by confining asphalt samples in brass rings and loading the samples with steel balls. The samples are placed in a water bath at a certain height above a metal plate for heating at a specific rate. Following that, the heated steel ball will pull the sample down toward the metal plate. Then, the water temperature is measured and designated as the softening point of the modified asphalt.

Table 2: Operating parameters range

Parameter	Symbol	Minimum value	Maximum value
Tyre rubber ratio (wt%)	X_1	5	20
Temperature (°C)	X_2	130	180
Mixing time (min)	X_3	20	60

2.3 Design of experiments

CCD according to response surface methodology through the Box-Wilson method [15] was used to achieve a mathematical model describing binder consistency by relating three operating parameters. The effect of adding RTR ratio (wt%), temperature (°C) and mixing time (min) on the penetration and softening point of the binder was evaluated in the current study. The number of experiments (N) required to predict these models depends on the number of operating factors (f = 3) tested according to the following equation:

$$N = 2^f + 2f + 1. \tag{1}$$

Thus, the required number of experiments for three factors is 15 experiments and the operating parameters in the mathematical model will be represented by a quadratic polynomial second-order equation which has an independent variable of each factor as (X). As shown in Table 2, the symbols X_1, X_2, X_3 denote the amount of tyre rubber ratio, temperature and mixing time, respectively. The predicted responses as a dependent variable of Y which is used to represent the penetration and softening point of the binder are as shown in the following equation:

$$\begin{aligned} Y = A_0 &+ A_1X_1 + A_2X_2 + A_3X_3 + A_4X_1^2 + A_5X_2^2 + A_6X_3^2 \\ &+ A_7X_1X_2 + A_8X_1X_3 + A_9X_2X_3, \end{aligned} \tag{2}$$

where A_0 to A_9 represent the constants of the mathematical model that can be estimated by regression analysis. To optimize the operating parameters for getting the best

Table 3: Coding and range of investigated parameters

Parameter	Symbol	Level and range		
		−1	0	1
Tyre rubber ratio (wt%)	X_1	5	12.5	20
Temperature (°C)	X_2	130	155	180
Mixing time (min)	X_3	20	40	60

operating values on bitumen consistency, the statistical software program (Minitab version-19) will be used.

Table 3 shows the ranges of three investigated variables by coding based on the experimental design concept.

3 Results and discussion

As shown in Table 4, the experimental design of the full factorial design with three levels of coded parameters (X_1, X_2 and X_3) was used to predict approximate values of penetration and softening point of the binder.

The experimental results were analysed statistically to conduct the mathematical models that describe the penetration and softening point of the binder with obtained correlation coefficient R^2 and variance explained S as demonstrated in the following equations:

1. Penetration

$$\text{Penetration} = -57 + 2.69X_1 + 1.21X_2 + 0.344X_3 - 0.0563X_1^2 - 0.0034X_2^2 - 0.00956X_1X_2 + 0.00028X_1X_3 - 0.00158X_2X_3, \quad (3)$$

achieved (R^2) = 0.9734 and (S) = 96.74%

2. Softening point

$$\text{Softening point} = -37.93 + 0.7403X_1 + 1.0467X_2 + 0.1095X_3 - 0.036X_1^2 - 0.0033X_2^2 + 0.001267X_1X_2 + 0.00083X_1X_3 - 0.000475X_2X_3, \quad (4)$$

achieved (R^2) = 0.9965 and (S) = 98.18%

3.1 Effect of temperature and mixing time on bitumen penetration

Figures 2 and 3 illustrate the specific effect of adding 5, 10, 15 and 20% of RTR on bitumen performance in terms of penetration under various mixing times and temperatures. It can be summarized that at lower RTR content and as the temperature increased to 155°C, high penetration was reported particularly when the mixing time is set at 40 min. Next, a gradual increase of RTR% was tested in consistent with raising temperature from 130 to 180°C. As a result, the performance of modified bitumen shows low penetration. It is also worth mentioning that the homogeneity of bitumen becomes better and results in the reduction of penetration less than 50 when the added RTR particles started to melt as

Table 4: Design experiments of coded and real operating variables

Run	Coded parameters			Real variables			Response 1/ Penetration	Response 2/ Softening point
	X_1	X_2	X_3	RTR%	Temperature	Mixing time		
1	−1	−1	−1	5	130	20	52.333	47.0
2	1	−1	−1	20	130	20	49.667	47.0
3	−1	1	−1	5	180	20	52.333	48.0
4	1	1	−1	20	180	20	49.667	49.0
5	-1	−1	1	5	130	60	54.333	48.9
6	1	−1	1	20	130	60	59.000	49.0
7	−1	1	1	5	180	60	58.333	49.0
8	1	1	1	20	180	60	48.667	50.0
9	−1	0	0	5	155	40	57.000	50.1
10	1	0	0	20	155	40	53.333	51.0
11	0	−1	0	12.5	130	40	57.000	50.0
12	0	1	0	12.5	180	40	56.482	51.04
13	0	0	−1	12.5	155	20	57.220	51.8
14	0	0	1	12.5	155	60	61.326	53.3
15	0	0	0	12.5	155	40	59.275	52.6

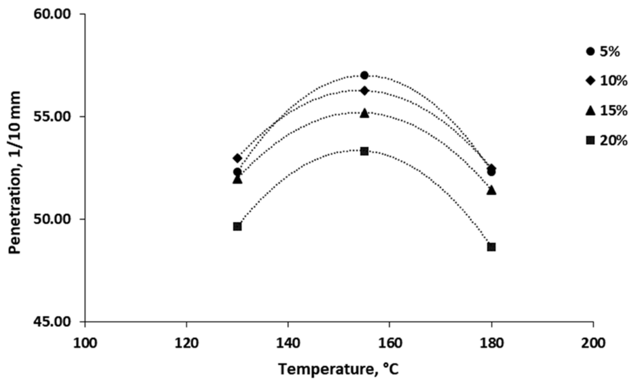

Figure 2: Penetration versus temperature at different RTR ratios.

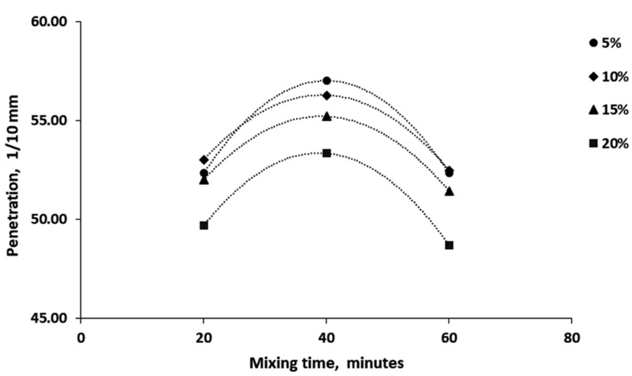

Figure 3: Penetration versus mixing time at different RTR ratios.

the mixing time increased up to 60 min. Similar outcomes were reported by previous works [6–9,16]. Finally, the modified bitumen 60/70 achieves the required penetration grade of bitumen 40/50 according to the Iraqi specifications SORB/R9 [17]. The lowest penetration was 47 which is closed to the obtained result of bitumen 40/50 shown in Table 1 after adding 20% RTR at 180°C and 60 min.

3.2 Effect of temperature and mixing time on bitumen softening point

The effect of modifying bitumen with 5–20% RTR on softening point is illustrated in Figures 4 and 5. The results were obtained and analysed at different mixing times and temperatures. It can be explained that various range of softening points (47–51) were obtained when the temperature increased up to 160°C. As a result, it was observed that increasing RTR content leads to increase softening point of the binder which may result in an increase in the viscosity property. It is also necessary to report that

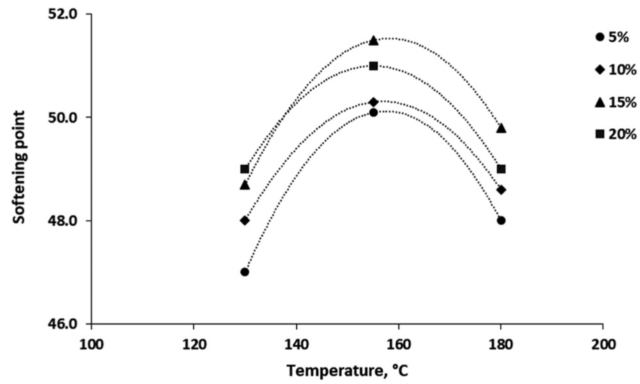

Figure 4: Softening point versus temperature at different RTR ratios.

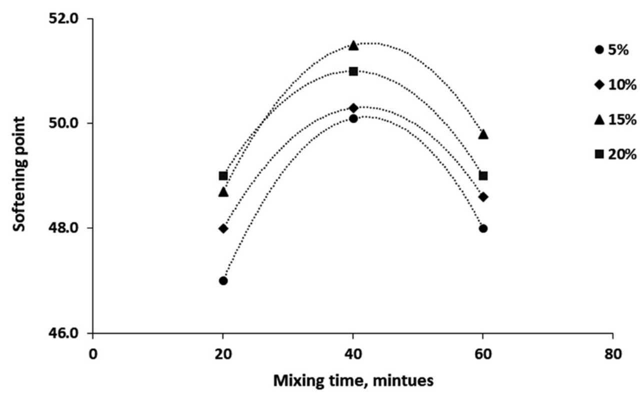

Figure 5: Softening point versus mixing time at different RTR ratios.

the softening point of bitumen shows a significant reduction when the mixing time varied from 40 to 60 min particularly after adding 20% RTR content at 180°C. The obtained softening point of modified bitumen was close to that shown in Table 1 related to 40/50 asphalt. Similar results were stated in previous works [10,16,18,19].

3.3 Optimization

Figure 6 shows the optimization of operating variables. It can be concluded that the best result obtained was shown at approximately 20% RTR to achieve approximately 50 mm penetration grade when the mixing time was set at 20 min and the optimal mixing temperature was 170°C. After this point, the RTR swollen and produced gel-like materials that increased the viscosity of bitumen [3]. Finally, the obtained softening point was reported as 50.24 which is close to the obtained value of bitumen 40/50 shown in Table 1.

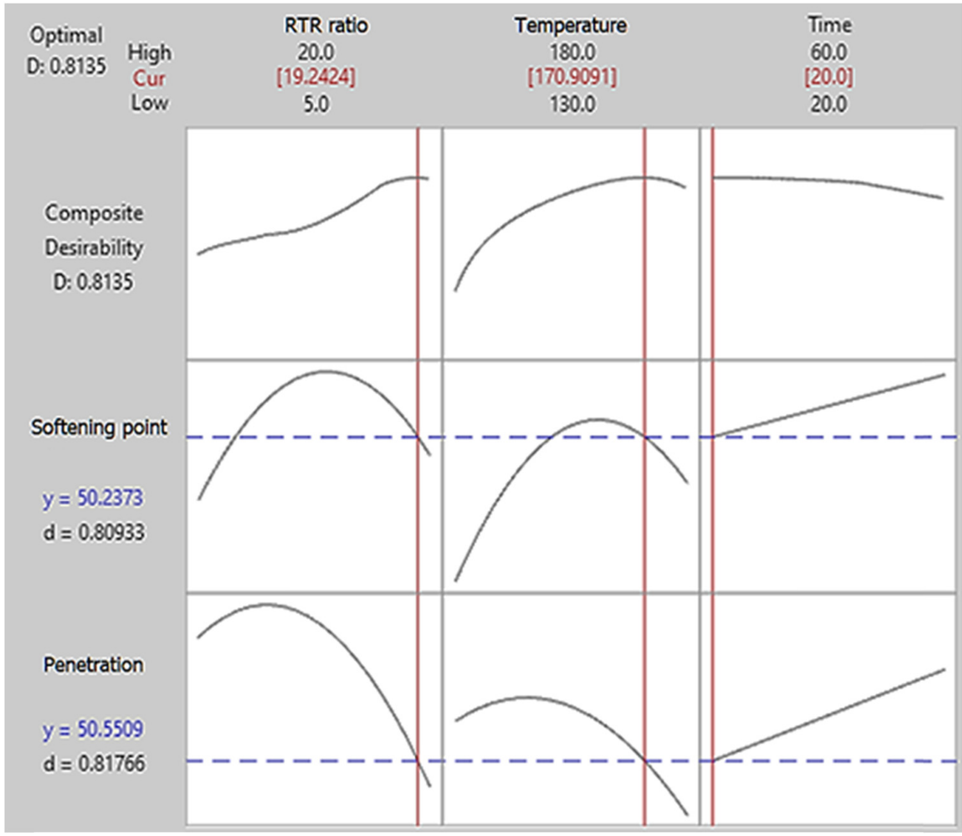

Figure 6: Optimization of operating variables.

4 Conclusions

The re-use of RTR as a modifier of asphalt binder can contribute in reduction of waste tyre rubbers pollution as well as consider an economic solution in minimizing the costs of recycling and manufacture. This work aims to investigate the improvement of 60/70 bitumen to achieve 40/50 bitumen properties by adding RTR contents as a modifier under different ranges of mixing temperature and mixing times. According to the previously conducted studies, the penetration and softening point of modified asphalt binder were improved after adding certain contents of RTR. The optimization reveals that the maximum limit 50 mm penetration can be achieved after adding 20% RTR at 170°C and 20 min mixing time. In conclusion, the obtained results in the current work are in consistent with the requirements of the Iraqi specifications SORB/R9 related to the properties of 40/50 bitumen used in road paving. For future works, it is worth suggesting that the obtained modified asphalt should be tested in asphaltic mix design to investigate mixture performance against different types of cracks such as fatigue and rutting. Other polymers are recommended to mix with RTR in specific percentages to test the penetration and softening point of new binder properties.

Conflict of interest: The authors state no conflict of interest.

Data availability statement: Most datasets generated and analysed in this study are in this submitted manuscript. The other datasets are available on reasonable request from the corresponding author with the attached information.

References

[1] Development, W.B.C.f.S. Managing End-of-Life Tires. 2023. Cited 2023. https://www.wbcsd.org/Sector-Projects/Tire-Industry-Project/End-of-Life-Tires-ELTs.
[2] Heitzman MA. State of the practice: design and construction of asphalt paving materials with crumb-rubber modifier. Final report. Washington, DC (United States): Federal Highway Administration; 1992.
[3] Presti DL. Recycled tyre rubber modified bitumens for road asphalt mixtures: a literature review. Constr Build Mater. 2013;49:863–81.
[4] Airey GD, Rahman MM, Collop AC. Absorption of bitumen into crumb rubber using the basket drainage method. Int J Pavement Eng. 2003;4(2):105–19.

[5] Frantzis P. Crumb rubber–bitumen interactions: diffusion of bitumen into rubber. J Mater Civ Eng. 2004;16(4):387–90.

[6] Abdelrahman M. Controlling performance of crumb rubber-modified binders through addition of polymer modifiers. Transp Res Rec. 2006;1962(1):64–70.

[7] Abdelrahman M, Katti DR, Ghavibazoo A, Upadhyay HB, Katti KS. Engineering physical properties of asphalt binders through nanoclay–asphalt interactions. J Mater Civ Eng. 2014;26(12):04014099.

[8] Abdelrahman MA, Carpenter SH. Mechanism of interaction of asphalt cement with crumb rubber modifier. Transp Res Rec. 1999;1661(1):106–13.

[9] Dakhil IH. Improvement of asphalt binder by recycling of waste tyre rubber. Int J Adv Res. 2016;4(5):414–8.

[10] Lv Q, Huang W, Zheng M, Hu Y, Yan C, Wang J. Understanding the particle effects and interaction effects of crumb rubber modified asphalt regarding bonding properties. Constr Build Mater. 2022;348:128716.

[11] Manosalvas-Paredes M, Gallego J, Saiz L, Bermejo JM. Rubber modified binders as an alternative to cellulose fiber–SBS polymers in stone matrix asphalt. Constr Build Mater. 2016;121:727–32.

[12] Yaacob H, Ali Mughal M, Putra Jaya R, Hainin MR, Jayanti DS, Che Wan CN. Rheological properties of styrene butadiene rubber-modified bitumen binder. UTM Jurnal Teknologi; 2016;78(7–2):121–6.

[13] Tan Z, Wang J. Research of the rheological modification mechanism of crumb rubber-modified asphalt containing polyamide 6 additive. Adv Civ Eng. 2020;1–10.

[14] Refinery, S.O., Physical properties of 60/70 and 40/50 asphalt binders. 2023.

[15] Usman A, Sutanto MH, Napiah MB, Yaro NSA. Optimization in asphalt mixtures: a review. In Response surface methodology in engineering science. UK: IntechOpen; 2021.

[16] Zhu H, Zhang M, Li Y, Zou Y, Chen A, Wang F, et al. Swelled mechanism of crumb rubber and technical properties of crumb rubber modified bitumen. Materials. 2022;15(22):7987.

[17] Housing, M.o.C.a. Standard specifications for roads and bridges – section R9. Iraq. 2003.

[18] Abdelaziz M, Mohamed Rehan K. Rheological evaluation of bituminous binder modified with waste plastic material. In the 5th International Symposium on Hydrocarbons & Chemistry (ISHC5). Algiers; 2010.

[19] Hainin MR, Aziz MA, Aziz A, Adnan A, Hassan A, Putra Jaya R, et al. Performance of modified asphalt binder with tire rubber powder. J UTM Technol (Sci Eng). 2015;73(4):55–60.