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Article

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Laboratory Investigation on the Performance of Asphalt Bitumen Using Recycled Tyre Rubber Produced in Iraq

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Abstract

The bitumen properties directly correlate to great resistance to temperature and traffic load, which represent the main criteria for prolonging the life of a pavement. Waste materials are taken into consideration as possible candidates for expanding pavement lifespan in order to comply with those performance standards. Consequently, to meet the prerequisite for sustainable building methods, this research focused on using crumb rubber (250 microns or less) of waste scrap tires as a modifier to the bitumen asphalt. This crumb rubber is added with a percentage of 15% of bitumen pen 40/50 and mixed mechanically with the shear mixture for 0.5 hour at 180 °C to produce rubberized asphalt. To investigate the physical, rheological, and mechanical properties of modified bitumen, penetration, softening point, ductility, and viscosity experiments were conducted in addition to empirically determining temperature susceptibility and bitumen stiffness. Results showed that crumb rubber lowered the penetration by 15% in comparison to the reference asphalt bitumen while softening point increased by 10%. Furthermore, ductility decreased by 26%. Moreover, rotational viscosity increased by 72% and 155% at 135 °C and 165 °C, respectively. Modified asphalt shows less temperature susceptibility, where the penetration index changes from -0.91 to -0.07 and penetration viscosity number changes from -0.33 to 0.22, and stiffness improves by 60% for rubberized bitumen compared to the control asphalt bitumen.

Keywords: Crumb Rubber; Rubberized Asphalt; Stiffness Modulus; Wet Method.

1. Introduction

A high level of structural integrity is necessary for a high-quality pavement, which offers road users a strong (stable), smooth, and safe riding surface. However, asphalt pavements frequently deteriorate because of several causes, primarily traffic and temperature, which reduce their serviceability, efficiency, and safety [1-3]. In Iraq, rutting and fatigue cracking are the most frequent forms of asphalt pavement damage. Weak bitumen characteristics are one of the contributing elements to pavement distress. Bitumen is a viscoelastic substance that is sensitive to temperature changes. Factors contributing to this issue are insufficient physical properties, such as stiffness, temperature sensitivity, and rheological characteristics (resistance to fatigue cracking and rutting). To increase the pavement's service life, a considerable study is necessary on asphalt modification to ensure compliance with the current traffic loads and high temperatures [1-4].

Numerous waste rubber tires have piled up due to the fast growth of the automotive and rubber industries [5, 6]. The accumulation of used tires poses a serious environmental risk in addition to being a waste of rubber resources. In Iraq, the amount of rubber that is produced by one factory has reached 16 tons daily in 2022, according to a specified factory report rubber of different sizes, therefore using the recycling of waste tires has both significant social and economic benefits.

The use of modifier crumb rubber (CR) has gained popularity globally and has become a crucial material used in pavement and concrete. Its effectiveness as an environmentally-friendly building material has been proven. When compared to regular concrete, virgin asphalt is viewed as more long-lasting, eco-friendly, socially and economically feasible. [7-9].

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There is evidence that adding CR that is manufactured from the vehicles' waste tires by mechanical grinding technology in waste recycling plants as a modifier to asphalt will greatly enhance the technical properties of bitumen, enabling the modified asphalt mixture's road performance and service quality to satisfy the needs of road traffic activities [10-13]. Researchers have found that modified CR asphalt mixture has fantastic high and low temperature effectiveness (more production of rutting, fatigue, and thermal cracking), durability, elasticity, anti-aging properties, minimizes traffic noise, successfully avoids freezing in colder situations, and reduces the pavement thickness and possibility of reflective cracking [14-16]. Due to its excellent resistance to aging and fatigue and effectiveness in low temperatures, CR is a widely used modifier that is also cost-effective. [17].

Three processes, the wet method, dry method, and terminal blend method, are acknowledged globally for incorporating CR into asphalt binder or asphalt mixture: The wet method (ARwet) involves mixing fine CR made from recycled waste tires with the virgin bitumen (asphalt rubber-AR) In order to provide a better binder for asphalt mixes, The dry method (ARdry) includes mixing the CR initially with the hot aggregate in a batch factory mixer at a surrounding temperature in order to enable the CR to heat up by conduction for a predetermined amount of time and afterwards a neat bitumen is added to create the dry, and terminal blend asphalt rubber method (ARtb) that consider as a particular form of ARwet sometimes referred to as a semi-wet process is a binder made up of CR particles that have been wholly digested in the asphalt bitumen after that blending at the asphalt refinery [18]. The most desired method is the wet process due to the fact that it transfers the polymer's CR-modified properties better to the asphalt binder than an indirect connection, which subsequently leads to good performance [19].

Two types of pathways are evident whenever bitumen and rubber interact: swelling and chemical degradation [20]. Ordinarily, when crumb rubber particles sink into the asphalt matrix, saturates and aromatics (maltenes) spread into the rubber networks and are absorbed by them, resulting in rubber swelling. The swelling of CR particles continues with interaction time increasing, and after several times rising in volume, it will reach an equilibrium stage. Extending the bitumen rubber interaction time at high temperatures after the equilibrium stage has been reached leads to rubber disintegration (split CR particles for smaller individuals due to rubber network collapse). During increasing interaction temperature is high enough, this last phenomenon is further subdivided into two chemical reactions: depolymerization and devulcanization, which destroy chain bonds or crosslink bonds of polymer, leading to a decrease in the average molecular weight of rubber. Rubber particle degradation into the liquid phase of bitumen is considered damage to the development of mechanical properties of crumb rubber modified binder (CRMB), however helpful for the storage stability of CRMB mixture [21]. Nevertheless, at the typical mixing temperature of wet method rubberized asphalt (about 180 ^{o}C) incomplete degradation (fractional) takes place, and finally, binder characteristics are dominated by the CR swelling method [20, 22].

The literature demonstrates that bitumen and rubber interaction using the wet approach are influenced by several variables, such as CR percentage, CR particle size, time mixing, and temperature [23, 24]. Bressi et al. [25] displayed that the most-used quantity of rubber within the range of 5 for 20 % and the maximum particle size of CR particles used in ARwet is between 0.25 to 1 mm (0.56 mm is the mean particle size of rubber), a number of agencies have specified different CR gradations (0.075 mm to 1.2 mm) [26]. while for time mixing was 30, 45 - 60 min at temperatures ranging from 180 to 218 ^{o}C [25, 27], the most typical shear mix used to manufacture modified binders Between 1000 and 2000 rpm and 4000 and 5000 rpm [25]. The investigations conducted by Poovaneshvaran et al. (2020) revealed that the addition of CR resulted in significant improvements in all conventional properties of asphalt. Additionally, the higher the CR content, the greater the tensile and shear strength of the modified CR asphalt [28]. Razmi and Mirsayar (2018) discovered that the optimal CR content for modified CR asphalt was 15% and that this content had the highest crack resistance, which significantly depended on the load mode. Moreover, based on various tests [29].Sutanto et al. (2018) concluded that the conventional properties, viscoelastic properties, and anti-permanent deformation properties of modified CR asphalt were exceptional, which makes them more suitable for use in road pavement applications [30]. Consequently, the aim of this research is to boost previous studies that have investigated the advantages of CR bitumen by doing several laboratory experiments that will explain and discuss. From this point of view, it is necessary to explain affected of the properties of the basic experimental tests of asphalt (penetration, softening point, viscosity, ductility, etc.) and determined some parameters that give an indication of the effect on the modified performance and possibly used in hot climatic and increased traffic volume in Iraq.

2. Material*Bitumen*

The asphalt utilized in this research was from the Al-Shueayba refinery in Basrah south Iraq with a (40-50) penetration grade. Various conventional physical tests, like softening point, penetration, specific gravity, ductility, and others, that meet the requirements of the State Corporation for Roads and Bridges in Iraq, were performed to describe the asphalt's characteristics. The reported properties of the conventional bitumen used are listed in Table 1.

Table 1. General Properties of Asphalt Bitumen 40/50 pen Used.

Property	Unit	Guideline	Outcome	SCRB specifications
Penetration (25 ºC, 5 s,100 g)	0.1 mm	ASTM-D5	43.5	40-50
Penetration index (PI)	-	[31]	-0.91	-
Softening point (TR&B)	ºC	ASTM-D36	52.5	-
Specific gravity at 25 ºC	g/cm^3	ASTM-D70	1.03	-
Ductility (25 ºC, 5 cm/min)	cm	ASTM-D113	120	>100
Brookfield viscosity @135 ºC	Pa.s	ASTM-D4402	0.7	-
Brookfield viscosity @165 ºC	Pa.s	ASTM-D4402	0.153	-
penetration viscosity number (PVN)	-	[32]	-0.33	-
Flash point (Cleveland open cup)	ºC	ASTM-D92	265	>232

2.2. Fine Rubber (CR)

CR used that was produced from a local tire recycling factory in Al-Diwaniya governorate, Iraq. The factory provides CR by recycling automobile and truck tires using mechanical grinding procedures at normal temperatures, as shown in Fig. 1. The rubber produces in three sizes: (0-1), (1-3), (2-4) mm. CR size used in this study was based on size (250 microns or less) from sieve analysis rubber on sieve #60 or less. Other properties provided by the manufacturing plant that are related to CR are listed in Table 2.

Table 2. Crumb Rubber Chemical and Physical Properties.

Property	Value and description
Ash content, %	6
Heating loss, %	0.5
Steel content, %	0.05
Fiber content, %	0.3
Specific gravity, gm/cm^3	1.13
Color and Form	black powder

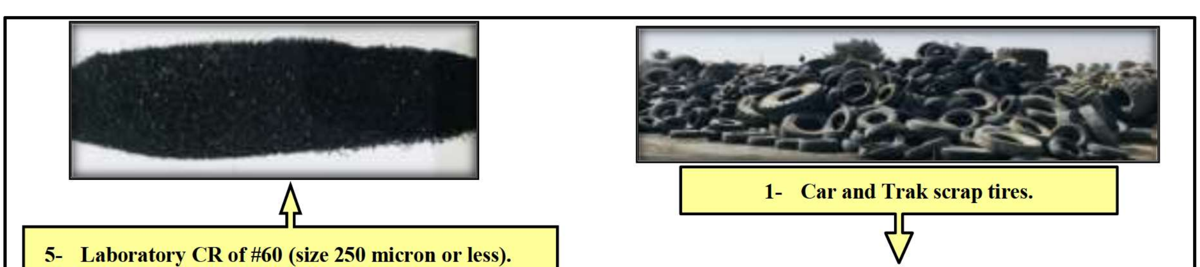

Fig. 1. Preparation Method CR in Plant and Laboratory.

2.3. Asphalt-Rubber Binder (Rubberized asphalt)

Asphalt rubber is produced by mixing and reacting hot asphalt with crumb rubber and, if requested, additional components or additives with specific conditions as shown in [33, 34]. The bitumen was heated to become fluid at a suitable temperature that was not due to asphalt degradation, and then this asphalt was applied in an iron container for a shear mixer with heating to 180 ºC. After that, 15 % CR was poured gradually because added CR caused absorption of asphalt heat, using the mechanical shearing mixture with a speed of 3500 rpm the time 30 minutes were required to pour CR to produce rubberized asphalt. The shear system for the mixer and the heating are shown in Fig. 2 according to [33].

Fig. 2. Manufacture Shear Mixer and Heating System at University of Kerbala.

3. Tests Program

The results of laboratory tests often match the performance of asphalt mixes on real pavements. Bitumen has different complex properties, and in order to explain these characteristics accurately, it is necessary to conduct several experiments that accurately simulate a wide variety of operating conditions, including temperature, loading rate, strain, and stress. Some of these parameters are empirically determined, as described briefly below:

3.1. Penetration Experiment

The penetration test was conducted using the simplest approach, following the guidelines laid out in ASTM-D5 [35]. The penetration test measures consistency by the distance, in millimeters, of a standard needle that is perpendicularly diffused in the bitumen sample under specific conditions: time 5 s, temperature 25 °C, and loading 100 g. This test's primary objective is to establish the hardness (stability) of asphalt binder; a small penetration value shows the bitumen hardness and vice versa, hence evaluating its resistance to rutting failure and cracking deformation.

3.2. Softening Point Experiment

The softening point experiment was performed following the specification ASTM-D36 [36]. The softening temperature of bitumen is determined using two rings and two balls of through placed bitumen in the rings until cool, then a 3.5g ball is placed on the sample in a water bath and began heating. The temperature at which two balls touch the base plate is recorded and taking the average, this is the softening point (the degree at which asphalt begins to flow). The softening point test is very important because it establishes the temperature resistance of bitumen and how the binder behaves at an elevated temperature. The goal of this test is to determine the asphalt's flexibility by finding its softening point.

3.3. Ductility Experiment

The Ductility test was conducted following the ASTM-D113 [37]. The ductility of bitumen is measured in centimeters of elongated bitumen put into a brass mold and then horizontally dragged at a predetermined pace using a specialized device. This examination is interesting due to its ability to explain asphalt expansion before cracking when exposed to tension. To prevent fatigue-induced cracking and failure of bituminous materials, the material must possess a certain degree of ductility.

3.4. Rotational Viscosity Experiment (RV)

The viscosity at temperatures of 135 °C and 165 °C was measured using a Brookfield Thermosel viscometer and reported in Pascal.Second (Pa.s) according to ASTM-D4402 [38]. Bitumen's resistance to flow and internal friction are assessed by measuring its viscosity. The rotating viscosity (RV) test is used to determine the asphalt's viscosity at high temperatures, either during production or construction. The RV indicates the performance of the bitumen; at high temperatures, the asphalt binder's low viscosity will cause rutting or flushing. Moreover, at low temperatures, excessive viscosity will produce non-load cracking. To satisfy the climatic parameters, a sufficient viscosity grade must be determined.

3.5. Temperature Susceptibility (TS)

A temperature-dependent change in stiffness, consistency, and viscosity is called temperature susceptibility. Penetration index (PI) and penetration viscosity number (PVN) refer to quantitative measures for the response of asphalt binder to temperature variation [1, 2]. For road construction, asphalt's recommended limit of PI is -1 to +1, where the lower the PI of the binder, the higher the temperature susceptibility, and vice versa. Meanwhile, the suggested range for the PVN index is -2.0 to +0.5, with the same principle as the PI index. When asphalt is classified as having a high susceptibility to temperature change, this is unfavourable because, during low service temperatures, the viscosity of the binder will increase gradually, which will result in low temperature cracking. PI and PVN terms may be a result of the relationship between the penetration–softening point value and penetration viscosity value, as shown in Eqs. (1) and (2), respectively [1]. These parameter indicators were used to determine the bitumen's temperature susceptibility.

$$\mathbf{PI} = \frac{(1951.4 - 500\ \mathrm{LogP} - 20\ \mathrm{SP})}{(50\ \mathrm{LogP} - \mathrm{SP} - 120.14)} \quad \ldots\ldots\ldots\ldots \quad (1)$$

$$\mathbf{PVN} = \left[\frac{4.258 - 0.7967\ \text{LogP} - \text{LogV}}{0.795 - 0.1858\ \text{LogP}}\right] \times [-1.5] \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (2)$$

Where: P represents penetration value at 25 °C in (mm), SP denotes softening point value in (°C), and V represents viscosity at 135 °C in (mpa.s).

3.6. Stiffness Modulus (St)

The stiffness modules, a fundamental feature used to describe the mechanical properties (viscoelastic properties) of asphalt binder by similarity to the elastic modulus of solids, were evolved by Van der Poel [39]. St is the ratio between applied stress and obtained strain during loading time t. As a result of the special nature of bitumen, the stiffness modulus value is dependent on temperature and loading duration. If the direct measurement of stiffness modulus is impossible, it may be estimated empirically using the Van der Poel nomograph (Shell Nomo graph). Using this nomography, the bitumen's stiffness modulus at any circumstances of temperature and loading time is determined just by the penetration and softening points. This study will investigate St at a temperature of 25 °C and a loading duration of 0.02 s (equivalent to a vehicle speed of 50 km/h) [31].

4. Results & discussion

4.1. Penetration Experiment

Fig.3 portrays the results of the penetration test for unmodified and modified bitumen specimens. Rubberized bitumen showed reduced penetration at 37 mm compared with conventional asphalt at 43.5 mm. Penetration was lowed approximately by 15%. A lower penetration number implies that the bitumen is stiff and hard. Under this research, CR increased the stiffness of the bitumen during the mixing process through the CR absorption of some oils (low molecular weight) in the asphalt that affords viscosity and fluidity, add on that small size helps to speed this process, which uses small size particles CR that led to a high CR surface area per unit of mass of bitumen, resulting in fast dissolution. The bitumen's stiffness was increased by 15 % CR. Low susceptibility to high temperatures is a result of high stiffness.

4.2. Softening Point Experiment

Softening point results of asphalt binder for the unmodified and modified specimens are illustrated in Fig. 4. For the modified sample, the softening point value increased with a 15 % CR content addition. The increased ratio to approximately 11%. A higher softening point means that bitumen can endure a certain level of temperature until the phase transition from solid to liquid. Results obtained indicate that the temperature at which the bitumen softened was high owing to strong particle forces between the CR and the bitumen and increased bonding between the particles because of increased asphaltenes' high molecular weight, responsible for strength and stiffness, in addition to the strong chemical resemblance between asphalt binder and CR. This behaviour demonstrates that bitumen displays little temperature sensitivity.

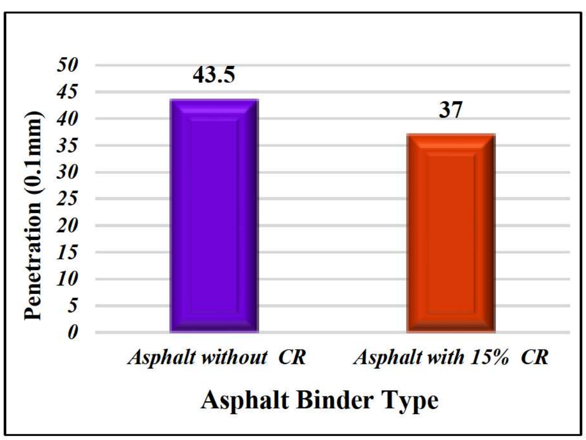

Fig. 4. Penetration Values for Unmodified and Modified Bitumen Samples.

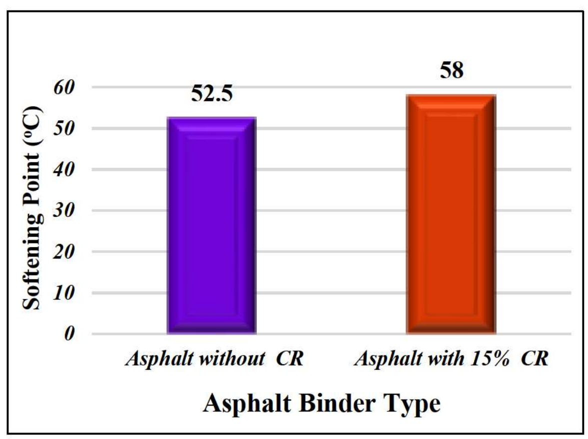

Fig. 3. Softening Points for Unmodified and Modified Bitumen Samples.

4.3. Ductility Experiment

Fig. 5 demonstrates the ductility experiment results of the unmodified and modified asphalt binder. A falling trend was observed with 15% CR content addition. The modified bitumen had 26% less ductility than the control bitumen. The results revealed that the modified bitumen tends to fracture as a consequence of the lower bitumen elongation caused by the 15% CR content. However, the cohesiveness of the bitumen was improved, thereby developing the rutting performance. The low ductility of the bitumen indicated stiffness and made it hard to stretch because of the high cohesion of the bitumen. Due to the large surface area of fine CR particles, strong particle bonding was created between the bitumen matrix and the CR. Thus, cohesion in the bitumen increases, leading to thicker bitumen being produced. Asphalt is more difficult to elongate and breaks faster than thinner bitumen, which elongates more.

4.4. Rotational Viscosity Experiment (RV)

RV values at 135 and 165 °C for unmodified and modified asphalt, respectively, are explained in Fig. 6. RV of the modified bitumen at 135 °C was higher than that of the control bitumen. RV of the control sample was 0.7 Pa.s and increased to 1.207 Pa.s for rubberized bitumen. When the test was conducted at 165 °C, the viscosity of the samples decreased for both types of asphalt. The viscosity of the control sample was 0.153 Pa.s, which increased to 0.390 Pa.s of the modified sample after adding 15% CR. From both analyses, you will notice increments in the viscosity of rubberized asphalt due to the increased absorption of materials with a small molecular weight, and which therefore will increase the density. The high viscosity of bitumen increased the mixing and compaction temperatures, as well as the construction costs. However, the high cohesion of the bitumen increased the adhesion between the bitumen and the aggregates, thereby enhancing the performance of the pavement.

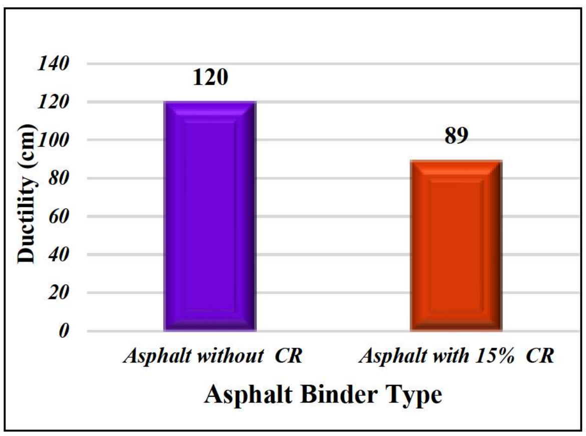

Fig. 6. Ductility Values for Virgin and Modified Bitumen Specimens.

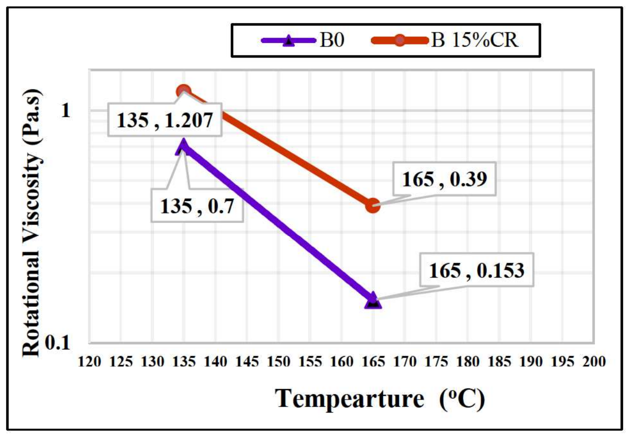

Fig. 5. RV Values for Unmodified and Modified Asphalt.

4.5. Response to Temperature (Temperature susceptibility)

Fig. 7 displays the PI and PVN values for the pure and enhanced bitumen with 15% CR. The PI for the modified samples was higher than that obtained for the control sample, and both and were located in the range of -1 to 1 that is a more suitable bitumen PI for road construction [1]. The PI was -0.9 to -0.07, respectively. That means modified bitumen would prove less sensitive toward temperature compared to virgin asphalt, as a result, the cracking process will be less in low temperatures and less rutting in high temperatures. On the other hand, the results of PVN give approximately the same indication as PI. Rubberized bitumen is higher than 0.22 compared to the conventional -0.33 and both types range from limited -2 to 0.5 as reported to be popular in road building [1]. The result shows that the PI and PVN values significantly increase with the addition of CR content due to the PI and PVN value attributed to the physical characteristics of the binder, which is hard and more viscous.

4.6. Stiffness Modulus (St)

Fig. 8 presents the stiffness modulus of the bitumen under conditions pure and modified with 15% CR. The results were drawn based on the empirical Van der Poel nomograph [39]. The results showed that 15% modified CR bitumen has a better stiffness modulus than base bitumen. St for modified asphalt was 32 MPa and for control asphalt was 20 MPa. This increase in stiffness modulus of hardness (increased asphaltene) in modified asphalt binder is due to the high CR surface area that led to increased bonding between CR and the bitumen. Therefore, the CR effectively increased the stiffness of the bitumen.

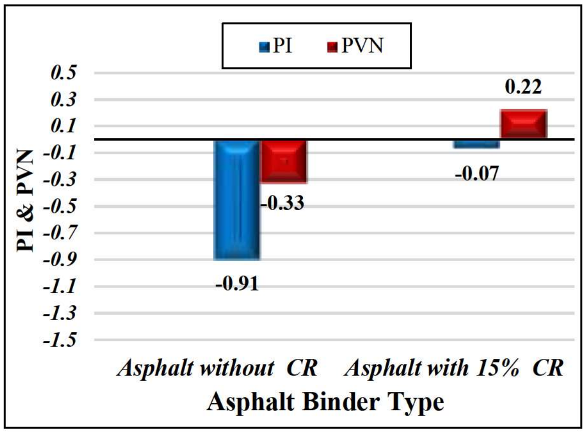

Fig. 8. PI and PVN of Pure and Enhanced Bitumen.

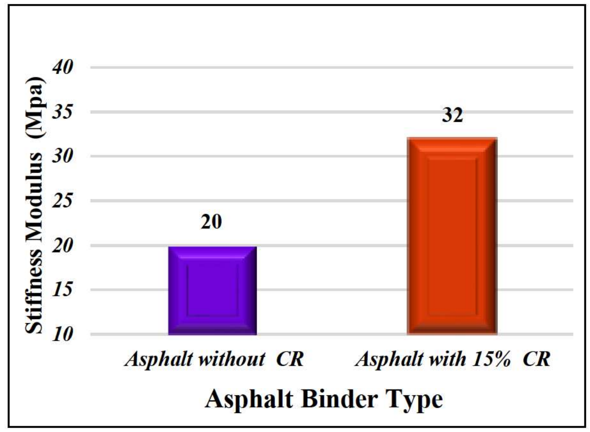

Fig. 7. St for Pure and Modified Bitumen.

5. Conclusions

The study's goal was to investigate the physical, rheological, and mechanical qualities of using a 15% crumb rubber powder as a modifier and to improve the use of crumb rubber in asphalt modification by the wet method. The results have confirmed the positive benefits of 15% CR in several bituminous tests. The following conclusions may be drawn from the obtained data:

- With the addition of this modifier, the resistance to deformation at moderate and high temperatures improved, as seen by the reduction in penetration CR, while the softening point raised when 15% was added to the physical characteristics' improver.
- The ductility of rubberized bitumen decreased significantly with the addition of 15% CR, which reflects the stiffness (hardness) of rubberized bitumen.
- Rubberized bitumen had the lowest viscosity than conventional, which led to more non-Newtonian behaviour.
- The rheological characteristics also show improvements in PI and PVN values where those findings revealed that the addition of 15% CR decreases the temperature sensitivity of asphalt.
- 15% CR modified asphalt has more stuffiness than pure bitumen and in turn, increases the stiffness of asphalt mixtures which reduces the cracking potential of pavements at intermediate temperatures and fatigue cracking that indicates enhanced mechanical properties.

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