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Reacted and Activated Rubber effect on Stiffness Modulus and Cracking Resistance of Bituminous Mixtures

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Abstract

Traditionally, asphalt rubber (AR) mixtures have been difficult to produce. Their production requires specialized plants and equipment, which has resulted in their high cost to manufacture. In part this difficulty is due to the need to produce AR binder by blending it at high temperatures for a significant period of time (typically at about l90°C for 45 min to 1 h). A new technology that produces a reacted and activated rubber (RAR), which is an elastomeric asphalt extender, has been developed by hot blending and activation of a rubber granulate with a selected asphalt binder and activated mineral binder stabilizer. The objective of this study was to evaluate and characterize the performance of Reacted and Activated Rubber (RAR) modified dense graded asphalt mixtures in order to recommend a suitable RAR content to produce a mix that provides superior pavement performance characteristics. The research effort encompassed investigation of shear stiffness modulus and cracking resistance for performance evaluation of six dense graded asphalt mixtures, including one conventional and five modified mixes covering 48 samples. The stiffness modulus was increased as RAR increases, the cracking resistance results showed an increase of fracture energy as RAR increased. 15% RAR was found as the most appropriate content based on its performance characteristics.

Key words: RAR, bitumen, stiffness, cracking resistance, performance.

1. Introduction

The need for improved material performance has spurred the adoption of modified asphalt systems. Rubber has been used as a modifier on road projects in the United States since the late 1940s [1]. A few years after the first roads were repaved; the process to add crumb rubber from waste tires was developed in Phoenix, Arizona, in 1965. This process is a well-developed system of asphalt modification with nearly 50 years of development. Today, however, asphalt rubber (AR) mixtures are still difficult to produce and require specialized plant and equipment, which results in their high cost to manufacture. This difficulty is due in part to the need to produce AR binder by blending it at high temperatures for a significant period of time (typically at about 190°C for 45 min to 1 h) [1]. The complexities in the process have caused AR mixes to be significantly more expensive to produce than conventional paving mixtures.

According to Sousa et al. (2013), RAR was produced by mixing in heat and activated for a short period of time, then specially designed to form dry rubber granulated active rubber. RAR can be added to any type of Hot Mix Asphalt (HMA) to replace the asphalt part of the binder with different proportions. In Asphalt Mixing Plant RAR mixing was added directly to the pug mill or drum dryer. According to Medina and Underwood (2017), the soft asphalt used in RAR aims to reduce some of the increase in hardening caused by rubber, consequently enabling the production of asphalt with RAR at the same mixing and compaction temperatures. Crumb rubber used comes from the truck and car tires, which are processed and milled with ambient or cryogenic processes. RAR has a particle size distribution ranging from 0.595 mm to 0.075 mm sub [2].

Previous research by the authors investigated the effects of the addition of RAR with two different base binders at various dosages from 5 to 25% by utilizing a series of advanced arheological testing processes [4]. An overall reduction in the viscosity-temperature susceptibility property was found with increasing RAR content irrespective of the base asphalt binder. Additionally, an improvement in the complex shear moduli indicated higher rut resistance with RAR as well as higher recovery of these modified asphalts with lower strains accumulated for higher RAR based asphalts.

As part of this research [5], there was also a need for a detailed study on the performance evaluation of RAR modified asphalt mixtures using advanced materials characterization tests currently being used by the pavement community. Furthermore, the response of the RAR modification to the various environmental and loading conditions was essential to understand the suitability of RAR materials in conventional dense graded mixtures most commonly used worldwide. Thus, the objective of this study was to evaluate and characterize the performance of RAR modified dense graded asphalt mixtures in order to recommend a suitable RAR content to produce a mix that provides superior pavement performance characteristics [3].

However, the cracking resistance of a mixture, as most mechanical properties, is not only influenced by the binder type and content, but also by a wide range of factors such as the type andcontent of filler that constitutes the mastic or the amount and nature of the fines.

Recently, numerous researchers have investigated the influence of asphalt binders on the cracking resistance of mixtures by establishing a correlation between the rheological propertiesof the binders using conventional tests, e.g. elastic recovery test, bending beam rheometer or dynamic shear rheometer, and the cracking performance of asphalt mixtures at a defined temperature, e.g. overlay tester or indirect tension test [24,25].

Others have tried to establish a correlation between the critical cracking temperature for both asphalt binders and mixtures at low temperatures [26,27]. However, relationships between binder tests and mixtures tests have not been fully established due to significant differences in the test temperature. Based on the encountered discrepancies, this study aims to directly characterize the cracking resistance that different asphalt binders withstand by applying a direct tensile stress under different test temperatures.

Understanding the ability of an asphalt pavement to resist fractures from repeated loading condition is essential for developing superior HMA pavement designs. Previous studies have been conducted to understand the occurrence of fatigue and how to extend pavement life under repetitive traffic loading [28,29]. The use of CRM, expanded to HMA, continues to evolve since the CRM binders enhance the performance of asphalt mixtures by increasing the resistance of the pavements to permanent deformation and thermal and fatigue cracking. Many researchers have found that utilizing crumb rubber in pavement construction is both effective and economical [30].

Therefore, this paper evaluates the stiffness modulus using ITSM, ductility and tenacity that different types of asphalt binders provide to a mixture under one fixed environmental condition by applying the Fénix test [21,22]. This test, developed by the Road Research Laboratory of the Technical University of Catalonia, evaluates the crack resistance of asphalt mixtures by calculating the dissipated energy during mixture cracking [22].

2. Background

The components of RAR are asphalt, crumb rubber, and an activated mineral binder stabilizer. Conceptually, asphalt cements (or bitumen in Europe and elsewhere) can be any straight-run, plain, soft bitumen. The use of soft asphalt grades enables production of HMA at conventional mixing and laying temperatures without the loss of the proper workability, despite the addition of crumb rubber. Usually, the crumb rubber consists of scrap tires that are processed and finely ground by any proven industrial method. The scrap tires consist of a combination of automobile tires and truck tires, and should be free of steel, fabric, or fibers before they are ground. To produce RAR, the crumb rubber particles should be finer than 1.0 mm. A 30-40 mesh maximum particle size is preferred. AMBS is a new binder stabilizer that was developed to prevent excessive drainage of the bitumen in SMA mixes during mix haulage, storage, and laydown. This stabilizer (industrially known as "iBind") is an activated, micro ground, raw silica mineral (40 μm and finer), which is a waste by product of phosphate industries' mining. Activation, by nano monomolecular particle coating, is intended to obtain thixotropic and shear-thinning properties for the asphalt.

The binder film and mastic in the mix should possess high viscosity at rest (haulage, storage, after lay) to reduce drain down, and low viscosity in motion (mixing and laying) is needed to maintain the proper workability (2). During research and development, RAR was produced and tested at different formulations, dictated by the type and relative proportions of its three components [1]. On average, a typical RAR blend contains about 62% crumb rubber, 22% soft bitumen, and 16% AMBS. After the material has reacted in the blending equipment, another 10% AMBS is added in a coating mixer unit to prevent re-coagulation of the product. RAR has been found to enhance the properties of the plain bitumen to levels higher than polymer modified asphalt, and to levels even higher than conventional AR blends [1]. A hypothesized basic model for the mechanism of RAR as a bitumen enhancer is illustrated in Figure I.

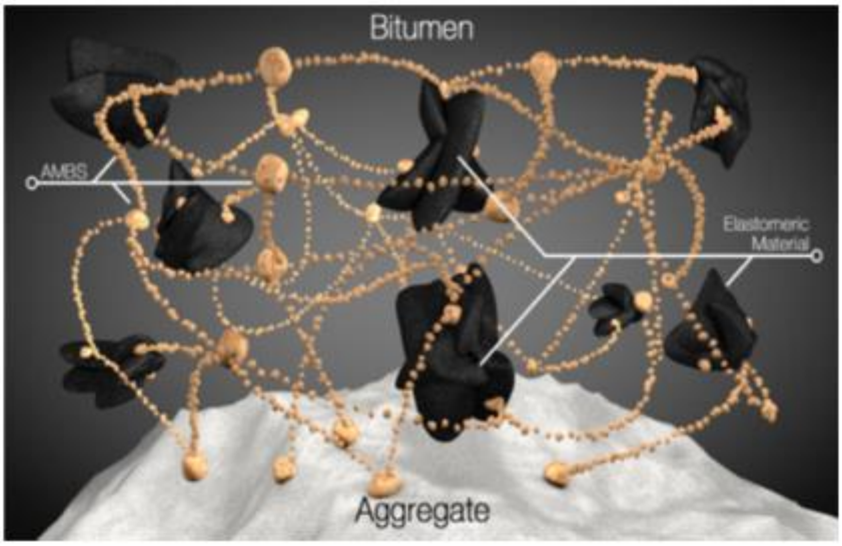

Figure 1: Suggested model for mechanism of RAR as asphalt extender [1].

2. Objective

The main objective of this study is to evaluate and examine the effect of reacted and activated Rubber on the laboratory performance of bituminous mixtures.

3. Materials

3.1 Reacted and activated rubber (RAR)

RAR is composed of soft asphalt (bitumen), finely ground scrap tire rubber and fillers reacted at optimal proportions and temperatures as reported in [6]. **Fig. 2** represents a the gradation of reacted and activated rubber (RAR) [3]. Generally, RAR consists of about 62–65% crumb rubber, 20–25% soft asphalt, and 15–20% filler. During the production of the RAR material, the asphalt used will be a softer kind to enable an improvement in the viscosity, and also ensure the workability of the binders even at higher rubber contents. The rubber particles used in the composition of RAR are of the maximum size of 600 lm. The fillers used in the RAR conglomerate are microscale additives to reduce moisture sensitivity of the asphalt mixes [7]. The activation was achieved by nano monomolecular particle coating**.** The base binder was modified by different contents of RAR ranging from 5 to 25% by mass of bitumen.

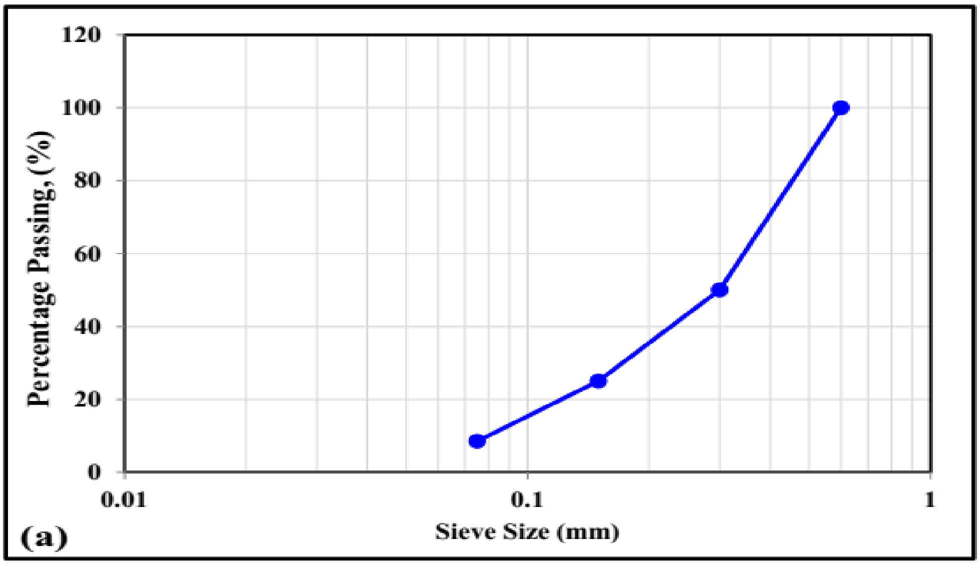

Figure 2: Gradation of reacted and activated rubber

3.2 Binders

The base binder that was used in this study was 35/50 penetration grade typically used for construction of pavements in Algeria; this binder was obtained from national bitumen Contractor. Different modified RAR binders were prepared, the first set of RAR binders were prepared by heating the base binder 180°C and adding the different percentages of RAR, 5, 10, 15, 20 and 25% by weight of the binder for testing, Since the blending process of the RAR modified binders does not have a standard procedure, the mixing time and temperature range for these binders, which were respectively, 5 min and 170–180°C were chosen to simulate the mixing process in the pugmill, transport, and laydown[4]. Also, the speed of the motor while blending was about 3000 rpm, A high laser thermometer was used to maintain the mixing temperature around 180°C. Physical tests were conducted on the un-modified and RAR modified binders, these tests are Penetration [8], softening Point [9], Ductility [10] and Elastic Recovery [11].

3.3 Mixtures

To select the aggregate gradation of the mixture to be evaluated in this study, the gradations of aggregates of dense graded and RAR modified mixtures used in paving projects in Algeria were examined. Based on that, the selected asphalt mixture had a 14 mm nominal maximum aggregate size (NMAS) and was designed to meet the European Standards specifications for EN 13108-1 for high traffic surface mixtures (class 3). **Fig 3** showed gradation limits and target mixture specifications for the dense graded mixture, this later is named BBSG 0/14 (bétons bitumineux semi-grenus -half granulated bituminous concrete-) in the standard. It is noted that designed mixture included: 31% crushed aggregates 8/14mm, 24 % crushed aggregates 3/8mm and 45% manufactured sand 0/3mm. The mechanical characteristics of aggregates are summarized in the **Table1**, it is noted that the mix design was targeted to construct a new bituminous pavements.

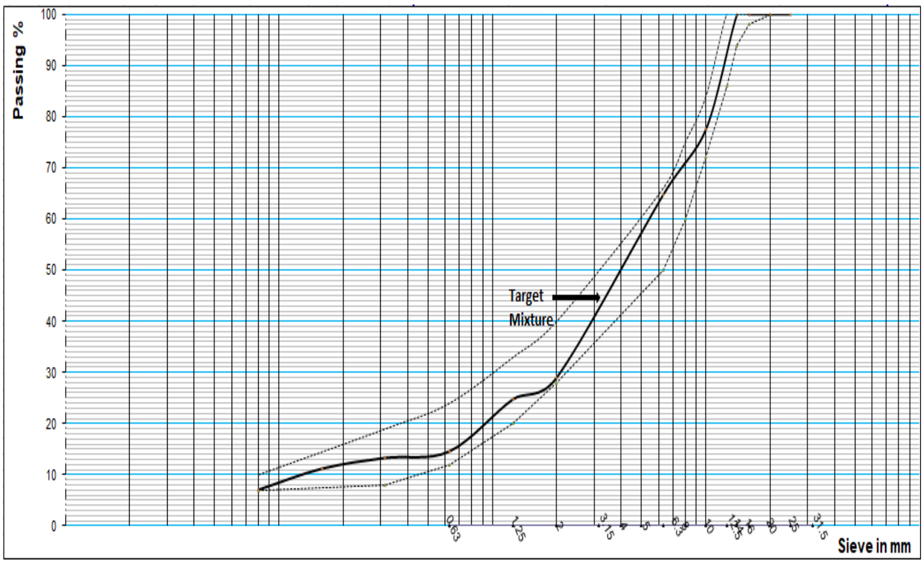

Figure 3: Gradation of target mixture BBSG 0/14 according to EN13108-1

Aggregates were heated for 4 hours at 180°C in the oven. Then the bitumen, aggregates and reacted and activated rubber were mixed at 180°C for 4 minutes to ensure homogenous mixing, the mixture was kept in the oven for 1h 30min to simulate the short term aging. **Table 2** illustrates the binder content for each of the seven mixtures. Same base binder content was kept constant for all mixtures to isolate the effect of RAR content.

Table 1: Mechanical characteristics of aggregates

Aggregates	Standard Test	0/3	3/8	8/15
Specific Density (t/m^3)	ASTM C127-15 C128-15	2.71	2.71	2.71
Absorption (%)	ASTM C127-15 C128-15	0.6	0.5	0.5
Finesse Modulus %	EN 933-1:2012	2.56	-	-
Sand Equivalent (%)	EN 933-8	60	-	-
Methylene Blue Test (%)	EN 933-9	0.03	-	-
Los Angeles (%)	EN 1097-2:2010	-	18	17
Micro Deval (%)	EN 1097-1:2010	-	16	14

Table 2: Different bitumen contents for different RAR content

RAR Content (%)	Bitumen Content (%)
0	5.60
5	5.88
10	6.16
15	6.44
20	6.72
25	7.00

4. Mixtures Testing

A laboratory testing program was performed to evaluate the performance of the control and the RAR modified mixtures with respect to Indirect Tensile Stiffness Modulus and Cracking Resistance. The following sections provide details about tests conducted on mixtures considered in this study. The Air voids were kept between 5 and 9% returning to EN13108-1.

To analyze the effect of reacted and activated rubber on the cohesion and bearing capacity of the bituminous mixes, the six mixes were designed with an identical mineral skeleton. The mixes were short term aged in the over for 1h30min at 160C for conventional and 180C for RAR modified mixes. The manufacturing temperature for the conventional 35⁄50 reference mix was 160–165°C. The RAR mixes were elaborated at a slightly higher temperature because the addition of reacted and activated rubber increased mix viscosity. The higher temperature thus guaranteed the workability of the mix.

The mixtures were designed, based on the results of the SGC test (EN 12697 – 31). In the gyratory compaction test, three sets of specimens were evaluated for each of the mix formulas. Each specimen had a diameter of 100 mm was compacted by the application of a vertical stress (normally 600KPa) via end platens to a known mass of asphaltic mixture within a 100 or 150mm internal Ø mould. The longitudinal axis of the mould is rotated (gyrated) at a fixed angle to the vertical whilst the platens are kept parallel and horizontal. (The size specified in each formula). During compaction the height of the sample is automatically measured and both the mixture density and void content calculated. Once the optimal bitumen content was determined for each mix,

4.1 Indirect Tensile Strength Modulus according to EN 12697-26

Stiffness modulus is an important mechanical characteristic of the road base and surface layers. This test describes a material stiffness that most closely simulates the behavior of material under a moving wheel [21]. Basically, the term stiffness refers to stress divided by corresponding strain [22]. The stiffness can be easily measured by Indirect Tensile Stiffness Modulus Test. by using ITSM Testing Machine. The test conducted was in accordance to EN 12697-26 Method for the determination of the indirect tensile stiffness modulus of bituminous mixtures which is a non-destructive test [23]. The test was conducted by applying five pulse loads with a suitable waveform (**fig 5**). This repeated load generates movement (strain) along the vertical plane of cylindrical specimen. The load was applied for a period of 0.1 seconds and rest period (load is released) of 0.9 seconds. Therefore, the stiffness modulus, S_m can be determined using the equation 1 below:

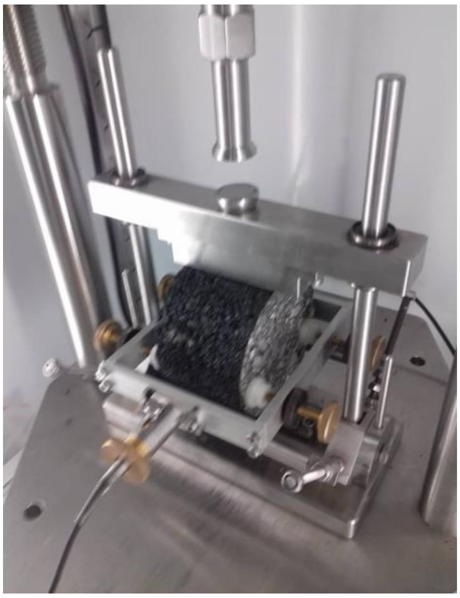

Figure 5: Indirect Tensile Stiffness Modulus Machine

$$Sm = F \times (m + 0.27) \div (z \times h) \quad (1)$$

S_m: indirect tensile stiffness modulus (MPa),
F: applied load (N),

z: mean amplitude of horizontal deformation obtained from 5 applied of the load pulse (mm),
h mean thickness of the test specimen (mm);
m: Poisson's ratio - 0.35 for temperature 15°C.

4.2 Fénix Test

A new experimental test has been developed by the Road Research Laboratory of the Technical University of Catalonia, Barcelona, Spain, to evaluate cracking resistance of asphalt concrete mixtures by calculation of the dissipated energy during the cracking process [21]. The Fénix test is used to calculate the dissipated energy during the cracking process, which is a combination of all energies released during material deformation and cracking [22]. The testing device can be seen in Figure 6 [21]. The evaluation of this energy is an effective way of measuring cracking resistance of asphalt concrete mixtures. In addition, the Fénix test generates tensile stresses around the cracking area, using the work done to propagate the crack across the induced plane **Figure 6**.

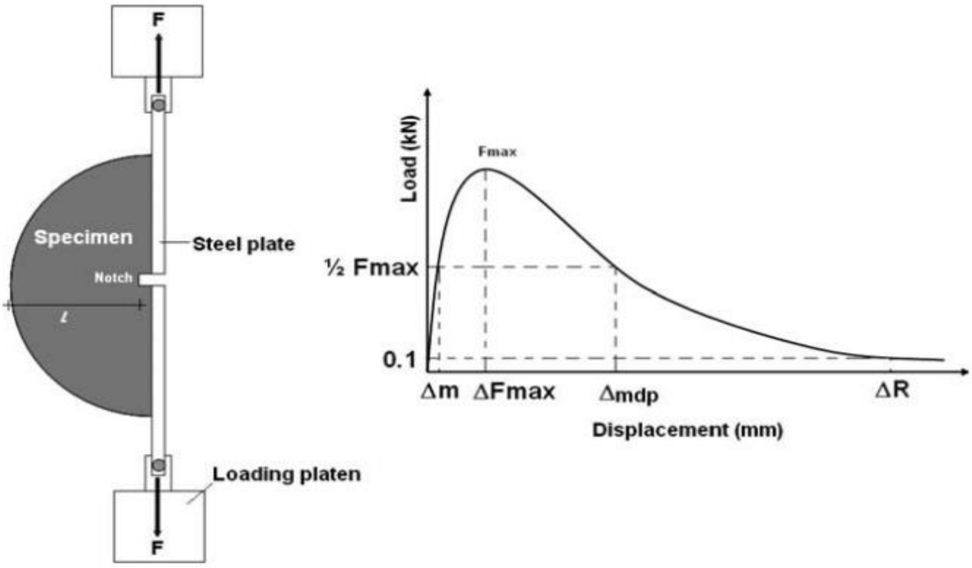

Figure 6: Fénix Test Setup and load-displacement output Curve [21].

The test procedure consists of subjecting one-half of a 63.5-mm thick cylindrical specimen with a diameter of 101.6 mm prepared by Marshall or gyratory compaction to a tensile stress at a constant displacement velocity (1 mm/min) and specific temperature [21]. A 6-mm deep notch is made in the middle of its flat side where two steel plates are fixed. The specimen is glued to the steel plates with a thixotropic adhesive mortar containing epoxy resins. Each plate is attached to a loading platen so that they can rotate about fixing points.

Load and displacement data are recorded throughout the test to calculate the parameters involved in the cracking process. The fracture energy during cracking, G_F, is calculated by Equations 1 [22]:

$$G_F = \frac{\int_0^{df} F(u)\,.\,du}{S} \tag{1}$$

where

GF: fracture energy (J/m^2)

F: load (kN)

u: displacement (mm)

S: specimen fracture surface (m^2)

df: displacement at the end of the test (mm). It is considered that the test ends at 4. 10^{-2} m of displacement.

The Tensile Stiffness Index (IRT) represents the slope of the stress-displacement curve between 25% and 50% of the peak load [22], and it is related to the mixture modulus. It is obtained using Equation 2:

$$\mathrm{IRT} = \frac{0.5Fmax - 0.25Fmax}{d0.5Fmax - d0.25Fmax} \quad (2)$$

Where
IRT = tensile stiffness index) (kN/mm),
*F*max = peak load (kN), and
$d_{0.25Fmax}$ and $d_{0.5Fmax}$: displacement before peak load at 25 and 50% of the peak load (mm), respectively

The toughness index (TI) is defined as the fracture energy during the post-peak part of the curve, weighted by the displacement between the maximum load and 50% of maximum post-peak load, Eq. (3) [22]:

$$\mathrm{TI}=\mathrm{GF}.\Delta d = \frac{\int_{dfmax}^{df} F(u)\,.\,du}{S}\,.\,(d_{0.5PostFmax} - d_{Fmax}) \quad (3)$$

where
TI: toughness index ($J.mm/m^2$)
F: load (kN)
u: displacement (mm)
S: fracture surface (m^2)
dFmax and d0.5PostFmax: displacement at maximum load and displacement at 50% post-peak load (mm), respectively

Finally, the displacement at 50% post-peak load (d0.5PostFmax) has been considered as a parameter directly related to the ductility of the mixture, since it allows evaluating the type of fracture [22]

The experimental phase was made by preparing two Marshall Specimens for every mixture from control to modified mixtures. A sum of 12 Marshall Specimens were prepared to set the Fénix test on these mixtures. The test temperature was fixed at 25°C for all mixtures and the only factor that has been changed is the RAR content. A high accuracy laser thermometer was used to maintain the temperature at the value of 25°C. The Specimens were kept at the test temperature for 4 hours at least before testing.

5. Results and Discussion

5.1 Binders Testing Results

Table3 showed the results conducted on the un-modified and modified binders by physical testing to characterize the changes in their physical properties.

Table3: Conventional binder testing results for base and RAR binders.

RAR (%)	Penetration (1/10mm) -EN 1426-	Softening point (°C) -EN 1427-	Ductility (cm) -ASTM D113-07-	Elastic recovery (%) -EN 13398-
0	39,8	50,3	120	25,5
5	33	52,5	20,55	37,5
10	30,3	53	17,05	52,5
15	27,5	56	12,5	54,6
20	25,1	57,6	11,05	57,5
25	24,8	66,2	10,5	N/A

5.1.1 Standard penetration test (needle penetrometer) -EN 1426-

Needle penetrometer test is a method for measuring the consistency of bituminous binders, consistency in general is the way in which a substance holds together, the value of penetration is meant as indicator of how stiff the binder is at preselected temperature of 25°C, this penetration is measured in tenth of a millimeter.

Higher penetration values indicate softer binders while lower values indicate stiffer binders. Reacted and activated rubber (RAR) additive was used to modify the original bitumen 35/50 with different percentages 0, 5, 10, 15, 20 and 25% three replicates at 25°C of each sample were prepared and three readings of penetration values were taken for each replicate.

The results showed from **figure 7** that penetration values decreased with increase in RAR content. It indicates that penetration value at given temperature and for 35/50 binder was decreased with RAR content increased.

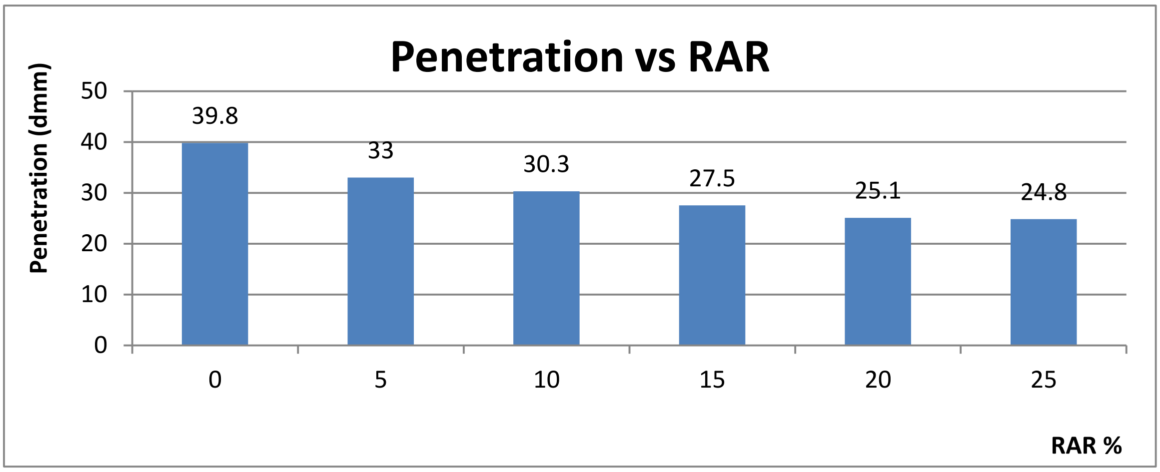

Figure 7: Penetration vs RAR %

Penetration Values obtained indicates that modified binder with RAR content will be performing better compared to neat bitumen to resist fatigue temperatures. The optimum value of RAR based upon the Standardized penetration test conducted would be 25%. Based upon the trend analyzed, even less penetration can be achieved with increasing RAR content.

5.1.2 Softening point (ring and ball) -EN 1427-

The softening point of bitumen is the temperature at which the substance attains certain degree of softening. So it the temperature in Celsius (°C) at which a standard ball passes through a sample of bitumen in mold and falls through a height of 2.5cm, when heated under water at specified conditions of test. The determination of softening point helps to know the temperature up at which a bituminous binder should be heated for various use applications. A binder should have sufficient fluidity before its application.

Two replicates of neat and other different modified bituminous binders were tested for their softening point. Temperature readings are collected when each of the steel ball touch the bottom plate. Two temperature readings were averaged for each replicate. The results of softening points are summarized in the **fig 8.**

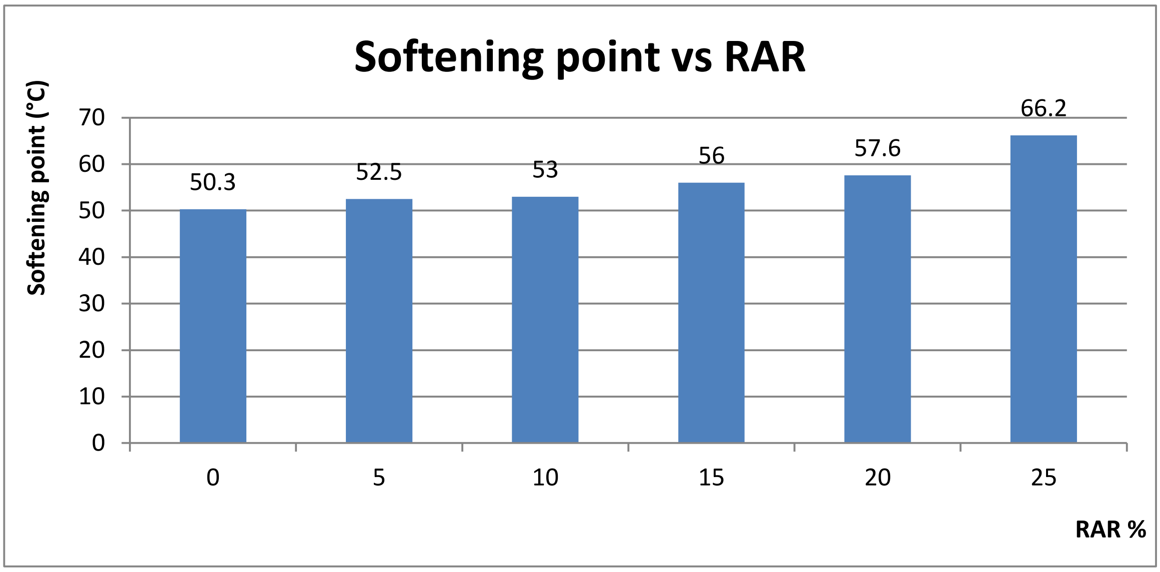

Figure 8: Softening point vs RAR %

The data of the fig supports that the greater the percentage of RAR, the greater the softening point. The more RAR, the stiffer the binder and the higher the temperature is needed to attain the softening point. Higher softening points indicate lower temperature susceptibility, and mitigation of rutting. Therefore, the optimum recommended value of RAR based upon the softening point test conducted would be 25 %, Higher values than 25% could be recommended to be studied further. Based upon the trend analyzed, the softening point can be increased.

5.1.3 Ductility -ASTM D113-07-

Ductility is the property of bitumen that permits it to undergo great deformation or elongation. Ductility is defined as the distance in cm, to which a standard sample or briquette of the material will be elongated without breaking. Dimension of the briquette thus formed is exactly 1 cm square. The bitumen sample is heated and poured in the mould assembly placed on a plate. These samples with molds are cooled in the air and then in water bath at 25°C temperature. Three replicates of neat and other modified binders were tested for their ductility test, elongation in cm were averaged for all the binders. The results are showed in the **figure 9.**

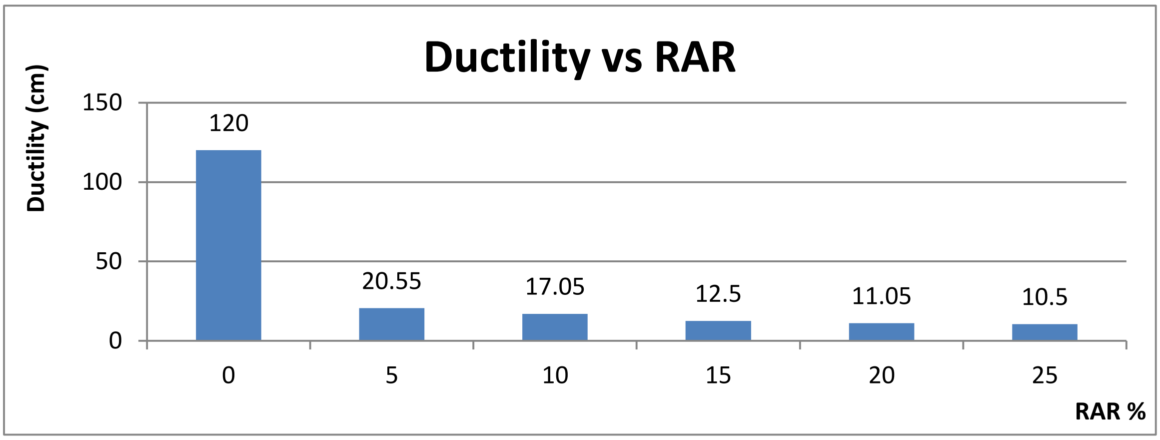

Figure 9: Ductility vs RAR %

The collected data form the fig showed that the modification of neat bitumen is sensitive for ductility test whatever the percentage of RAR. A decrease by 83% of ductility just for 5% of RAR, where the greatest decrease was showed for 25% of RAR by 91%. The analyzed trend is showing that slight changes in ductility of the modified binders have been seen. The optimum RAR content would be 5% of RAR. Better ductility could be seen for less RAR contents than 5%.

5.1.4 Elastic recovery -EN 13398-

The elastic recovery is a measure of the tensile properties of the polymer modified asphalt cement. The elastic recovery is measured by the percentage to which the asphalt cement residue will recover its original length after it has been elongated to a specific distance at a specified rate of speed and then cut in half. The distance to which the specimen contracts during a specified time is measured and the elastic recovery is calculated.

Three replicates for neat and modified bituminous binders were tested for their elastic recovery, the following **fig10** showed the results.

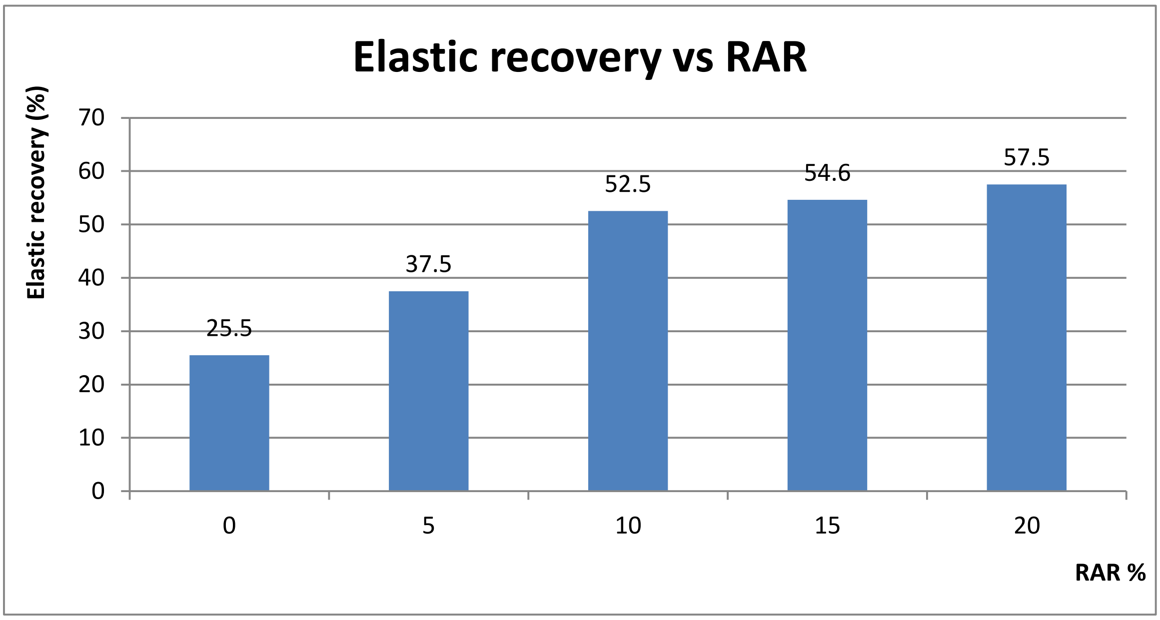

Figure 10: Elastic recovery vs RAR %

The collected data showed that the addition of reacted and activated rubber (RAR) has an effect on the elastic properties of modified bitumen binders, by increasing its elastic recovery. As it can be seen from the fig, the RAR content should not be equal or greater than 25% (elastic recovery not available). The optimum RAR content for 35/50 neat bitumen is 20%, higher elastic recovery may be reached for RAR content between 20 and 25%. The addition of RAR to neat bitumen improves the elastic properties.

5.2 Mixtures Testing Results

5.2.1 Shear Gyratory Compaction

We can find that the compactability of neat mixture when mixing temperature is 160℃ is equivalent to that of hot RAR mixtures when its mixing temperature is 180℃ for 5 and 10% RAR.

From the below fig 11, we can show that the apparent density and air voids of the control, 5 and 10 RAR is approximately the same, this is due to the low un-dispersed swelled RAR contents (low weight) and the difference in viscosity also of the modified bitumens. So it is clearly that the effect of un-dispersed RAR particles and viscosity of modified bitumens play a role very important on the apparent density of the mixtures.

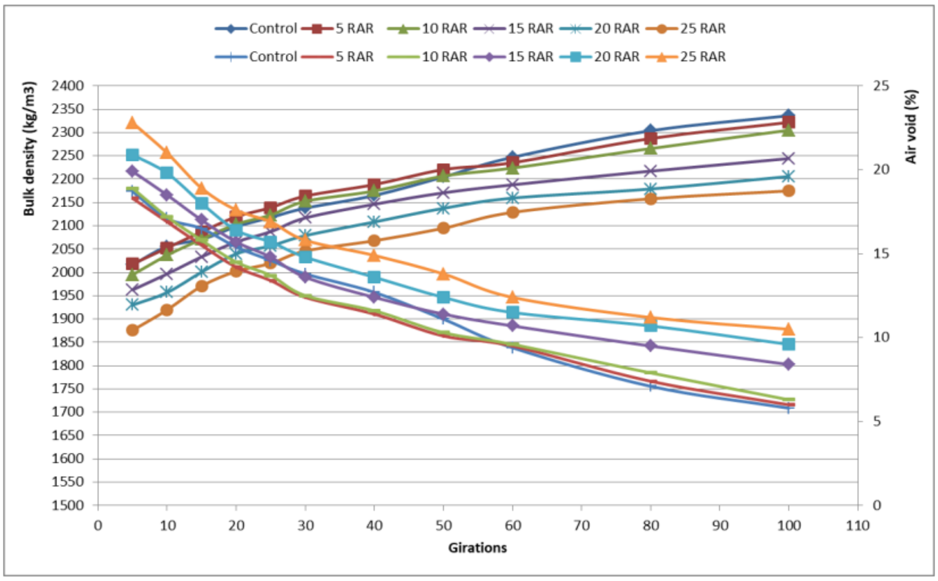

Figure 11: Effect of RAR content on the Apparent Density and air voids of the Mixtures

For 15, 20 and 25% RAR, we see lower densities and higher air voids of the mixtures respectively which is expected because of the high RAR contents that increase considerably the viscosity, for example, at 80 gyrations the lowest density is 2150kg/m^3 (25% RAR) and the highest one is 2200kg/m^3 (15% RAR)which confirms previous comments. So, starting from 15% RAR, the compactability become an issue due to the increase in viscosity. For 25% RAR the density decreased considerably because of the increase in viscosity.

As it can be seen from the above fig 11, the effect of increasing gyrations number result in reducing the Air voids for all Mixtures, for example, for 25% RAR the higher air voids was 22.625% for 5gyrations and 10.057% for 80 gyrations which is considerable.

While the trend was not observed for 15, 20 and 20% of RAR mixtures, the results showed the effect of viscosity of these ;mixtures on their compactability by showing less densities and higher air voids which is expected as these mixtures need higher compaction temperatures above 180°C. At 80 gyrations, the 25, 20 and 15% RAR have the lowest densities and highest air voids respectively as shown in the fig 11 which confirms the comments.

5.2. 2Indirect Tensile Stiffness Modulus.

Figure 12 shows the ITSM results for temperature of 15 °C. The results showed that the stiffness modulus apparently increases with the increasing percentage from 10 to 25% RAR. The modified mixture showed an increase of stiffness modulus with highest value for 15% RAR. Meanwhile, this is due to the hardening of the bituminous binder as RAR percentage increased. For higher contents of RAR typically 25% there is improvements in the stiffness regarding the conventional but lower than 10, 15 and 20% RAR.

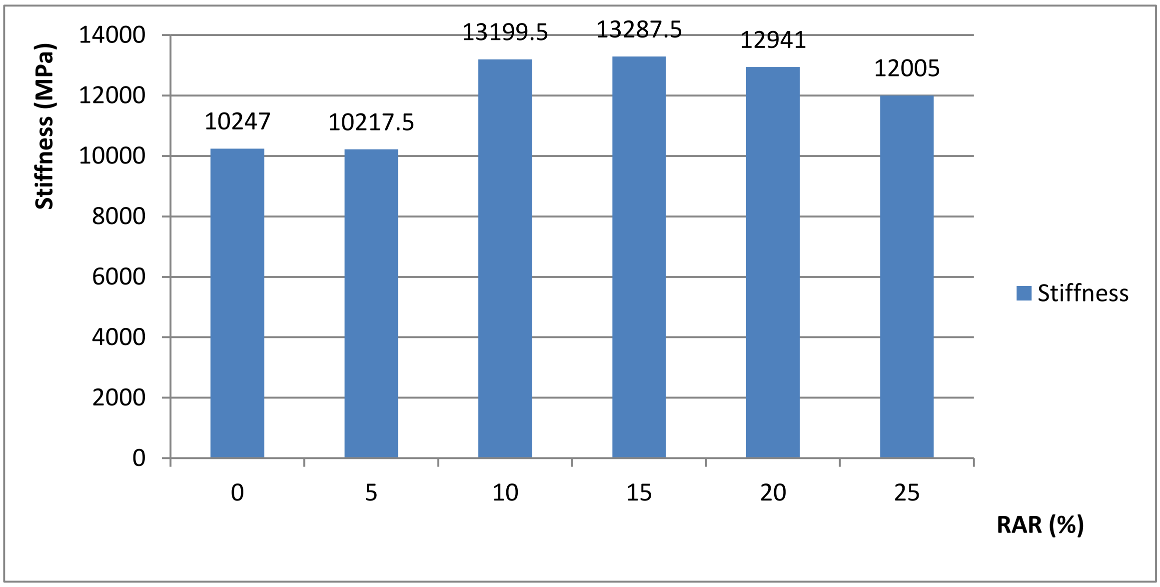

Figure 12: Effect of RAR content on the Stiffness Modulus of bituminous mixtures at 15°C.

Finally, to determine the effect of the reacted and activated rubber on the bearing capacity of the mixes, an indirect tensile stiffness modulus test were performed (see figure 11), the RAR mixes had a higher stiffness modulus value than the reference mix. In fact, this may even be dangerous because an excessive increase in mix stiffness can cause crack reflection in the pavement.

The results also showed that the addition of RAR increases the stiffness of the mixtures, this is converged with physical results of the modified binders especially the penetration, ductility and softening point. That means that RAR modified mixtures would have better rutting resistance and bleeding.

The use of this technique also reduced bitumen penetration, which hardened the mix and increased the stiffness modulus. Nonetheless, it should be underlined that an overly stiff mix can cause the road surface to crack. Because the pavement is not as elastic which is not the case, crack propagation energy is dissipated to a much lesser extent. It was observed that in this climate (15°C), the stiffness modulus of the mix increased. Even though the bitumen is slightly harder (with lower penetration), the elastic rubber particles dissipate the energy applied by traffic loads. Consequently, it had a lower stiffness response (and thus a better performance under temperature-induced stresses and strains).

5.2.3 Cracking Resistance

5.2.3.1 Tensile Forces

Figure 13 shows the difference in behavior between tested mixtures. The initial increased slope of the load-displacement curve represents the stiffness while the rapidly dropping post-peak curve provides a sense of the brittleness of the binder [13]. Thus, it can be observed that the 15 RAR modified binder reflects the higher stiffness and brittleness at a test temperature of 25°C. The figure also showed that 15 % of RAR the peak force was increased considerably, therefore for 20 and 25 % of RAR this force was decreased by much of 50% and 60% respectively because of the such stiffness that they have reached.

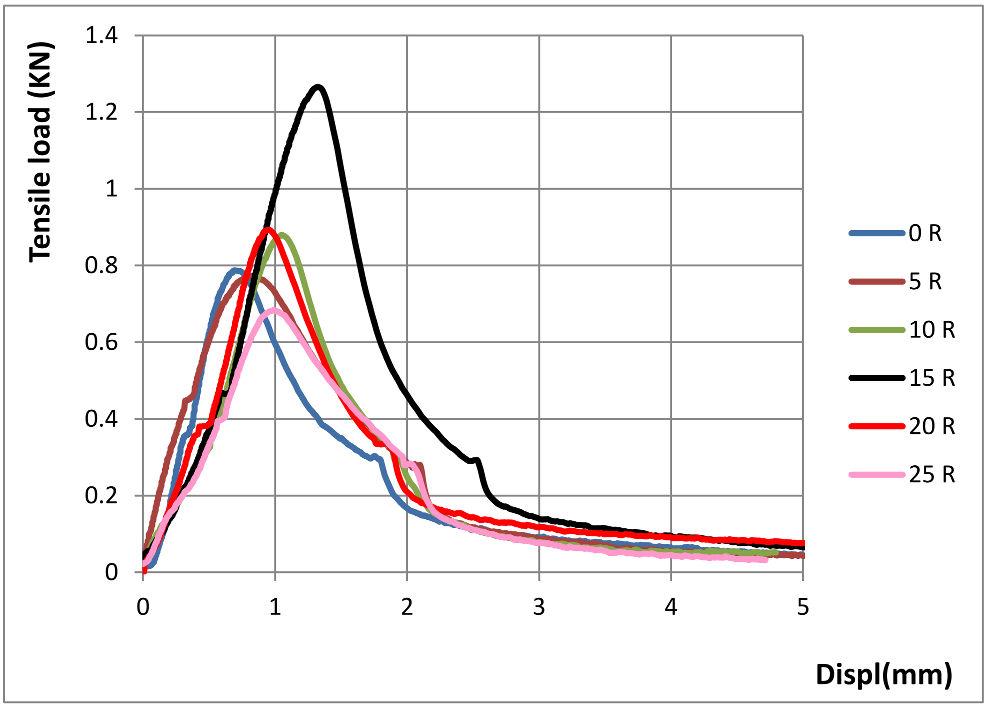

Figure 13: Load-displacement curve at a test temperature of 25°C

Based on this output curve, the parameters involved in the cracking process are obtained. The mean values for fracture energy, tensile stiffness index, toughness index and displacement at 50% post-peak load were obtained from three individual results.

The maximum tensile load was recorded for 15% of RAR which is expected returning to the hard bitumen used (35/50) and considerable decrease in these tensile forces for higher contents of RAR.

5.2.3.2 Fracture energy (G_f)

Figure 14 illustrates the change in fracture energy, which represents the work required for crack initiation, with RAR content for all the tested mixtures: conventional and RAR-MB. The fracture energy clearly varies on the basis of the content of RAR incorporated in the binder.

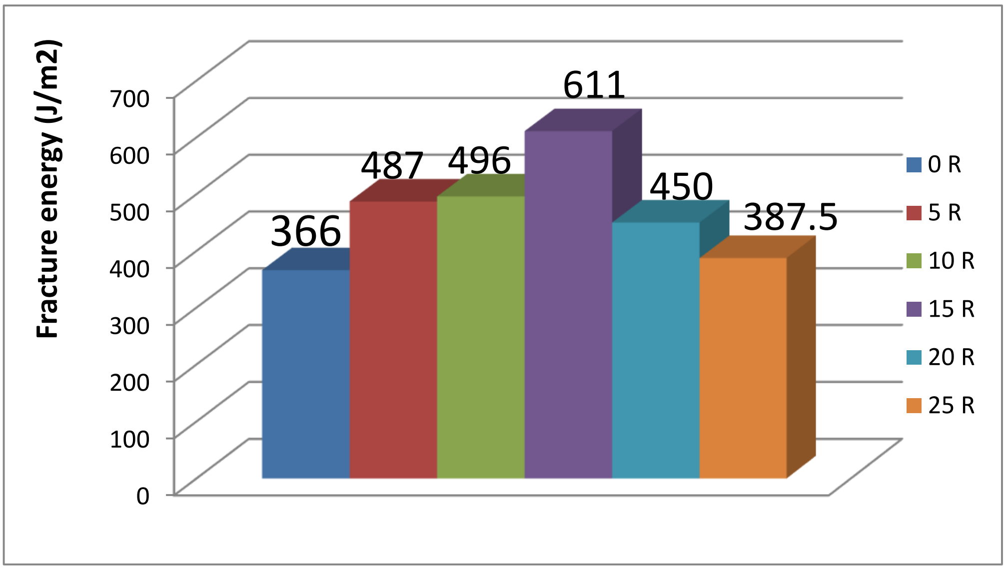

Figure 14: Fracture energy versus RAR content at 25°C

It is observed that asphalt binders reach a maximum of the fracture energy at 15 of RAR. An increase is observed in the fracture energy as RAR content increase for 5, 10 and 15% because these modified binders have reached a better stiffness with low decrease in ductility, this stiffness increased considerably for 20 and 25% of RAR in such a way the binder became stiffer and it lost of ductility which results in lowest fracture energy. The high stiffness and loss of ductility are the two reasons that make the 20 and 25 RAR modified binders more susceptible to thermal cracking.

5.2.3.3 Displacement at 50% post-peak load

The displacement at 50% post-peak load (d0.5PostFmax) has been considered as a parameter directly related to the ductility of the mixture, since it allows evaluating the type of fracture [22], fig15 showed an increase in max load for 10, 15 and 20% RAR because of the stiffening of the binder after modification while keeping some ductility

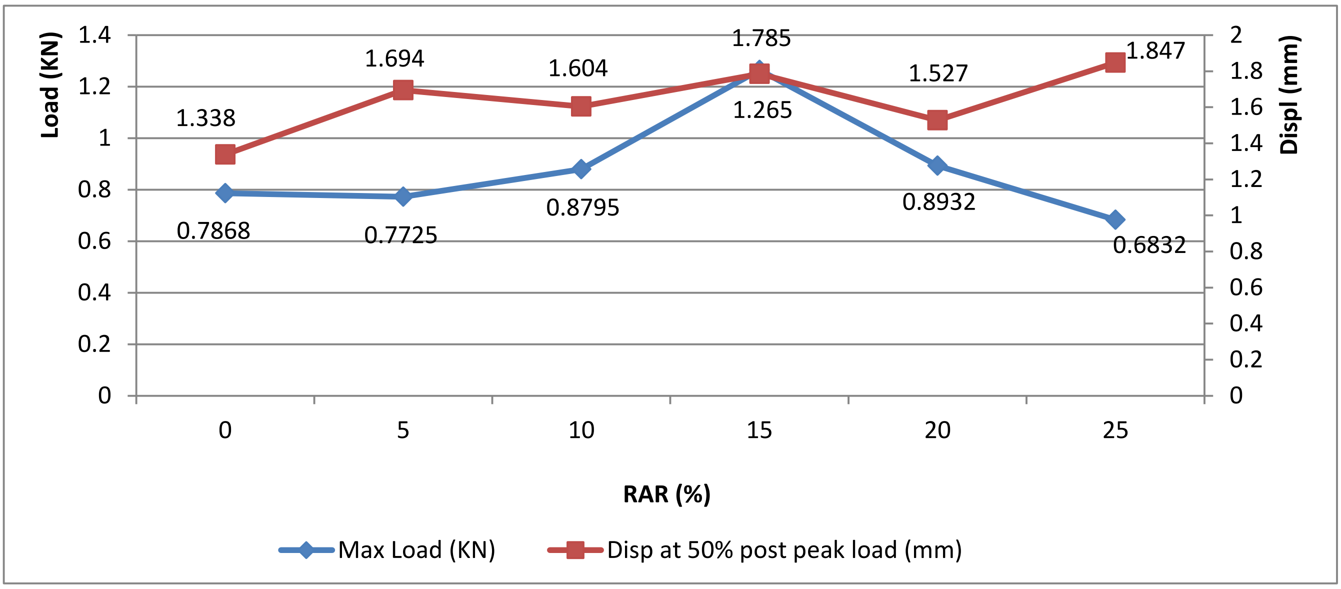

Figure 15: Max load and displ at 50% post peak load versus RAR content

From 15% RAR, the max load was still decreasing until it got the lowest value for 25% RAR, this is expected due to the increasing in consistence of the binder for all RAR percentages, displacement at 50% post peak load is increasing which means a decrease in ductility, this hypothesis is confirmed with previous results on binders for ductility test, it should be mentioned that high max load values and low displacements at 50% post peak load did not mean better performance.

5.2.3.4 Tensile stiffness index (IRT)

The tensile stiffness index assesses the tested specimen modulus or the stiffness of the mixture. Tensile stiffness index values strongly decrease with increasing of RAR content for all asphalt binders. The obtained results are clear not converged with ITSM previous results (**Figure 16**).

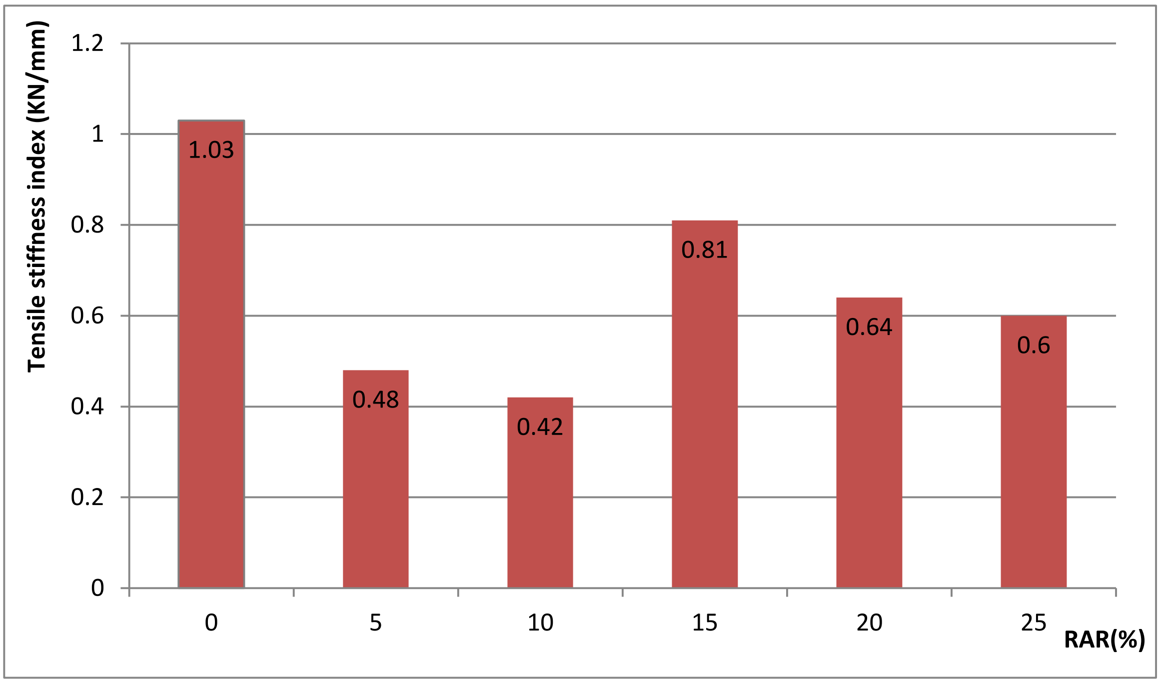

Figure 16: Tensile stiffness index versus RAR content at 25°C

The same trend is observed for all the tested mixtures. The results don't coincide with penetration grade tests as it indicates the increase of consistency with RAR content increase except for 25% of RAR which shows a decrease in the stiffness for non-explanation.

5.2.3.5 Toughness index (TI)

The toughness index gives a measure of the ability of the binder to resist cracking fracture after reaching maximum resistance. In other words, it assesses whether the type of fracture is more or less ductile.

Indeed, the toughness index is defined as the fracture energy after achieving the peak load weighted by a post-peak displacement. For this reason, the obtained patterns are consistent with the energy fracture patterns.

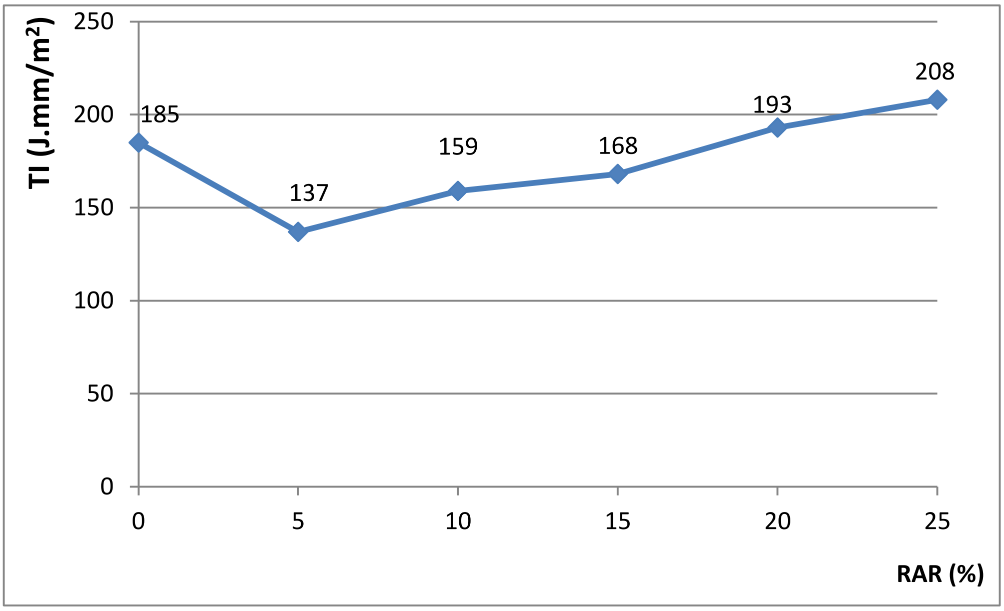

Figure 17: Toughness index versus RAR content at 25°C

Results indicate that high penetration binders (low RAR content) become tougher and more ductile at intermediate temperatures, although at 25°C the toughness index is not highest for 05 RAR content due to the hardening process that leads to a reduction in binder ductility that leads to a brittleness fracture. Where the lowest value of TI was recorded to 05% of RAR modified mixture (**fig 17**).

Conclusion

From this modest research, it can be said that the reacted and activated rubber (RAR) as an alternative solution to enhance the mechanical performance of bituminous mixtures by modifying the base bitumen and gain high mechanical performance over conventional bituminous mixtures, incorporating the RAR through dry process in our road pavements participates in recycling end of life tires from landfill and develops a sustainable solutions to environment by find a practical ways to deal with end of life tires pollution problem.

The main conclusions and findings that can be warranted based on the analysis presented in this paper are as follows:

1. The modification of bitumens by reacted and activated rubber can enhance the physical and mechanical properties of binders and mixtures.
2. The modification by reacted and activated rubber enhances the physical properties of the binders by decreasing its penetration and increasing softening point, it also enhances the elastic properties by increasing the elastic recovery.

3. The modification by reacted and activated rubber affects the ductility of the binder considerably by decreasing this ductility at lowest and highest contents of RAR.
4. The modification by reacted and activated rubber affects the compactability of mixtures. Especially for high RAR contents while no effects have been seen for lower RAR contents.
5. The Stiffness of the RAR mixtures is increased above the conventional; this is due to the increase in consistency of RAR modified bitumens as showed by Penetration and softening point results.
6. The RAR modified mixtures increase the tensile forces of binders which are translated to better cracking resistance of bituminous mixtures.
7. From the results of Fénix test, the RAR modified mixtures increase the fracture energy of binders which are translated to better cracking resistance of bituminous mixtures.
8. 15% RAR is the most suitable content for this hard bitumen returning to previous results.

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