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ASSESSMENT OF GROUND TYRE RUBBER IMPACT ON STIFFNESS MODULUS AND CRACKING RESISTANCE OF BITUMINOUS MIXTURES

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Abstract

The objective of this study was to evaluate and characterize the performance of ground tire rubber (GTR) modified dense graded asphalt mixtures to recommend a suitable GTR content to produce a mix that provides superior pavement performance characteristics. The research effort encompassed investigation of stiffness and cracking resistance of six dense graded asphalt mixtures, including one conventional and five modified mixes covering 42 samples. Addition of GTR using wet process showed decrease in stiffness during loading. Cracking resistance of GTR modified mixtures increased with higher levels of dosages regardless of the base binder. An increase in the GTR dosage from 0 to 10% did not result in a significant change in fracture energy but a further increment to 25% increased the fracture energy. The laboratory Results indicated that 10% GTR was showed as the optimal content for the stiffness modulus and 25 % GTR as better content that provides better cracking resistance.

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

1. INTRODUCTION

The increase in the carbon dioxide (CO2) and other greenhouse emissions has contributed to the thinning of the ozone layer, which is thought to be responsible for the global warming and the increased occurrence of natural disasters such as increasing in Planet temperature which results in rising water levels due to melting of glaciers(Tsunami) [2], one of the scientific approaches is to reduce the CO2 emission by maximizing the use of recycled materials in construction of new roads or rehabilitation of the existing roads such reclaimed asphalt pavement and recycled tire rubber….etc [26]., GTR has been used in bituminous industry using two principal methods, called Dry Process and Wet

Process, in dry process, the GTR is incorporating directly in the mixture by replacing a quantity of aggregates, while in the wet process, the GTR is blended with bituminous binder before producing the mixture, this method requires a special equipment and high cost comparing to the dry process but also it is expected to provide high performance and tests results returning to dry process[1].

The original wet process was introduced in the United States in the 1960s and is often termed ‘the McDonald process’ [3]. Wet process rubber modification involves mixing the tire rubber with a binder in mixing tanks and allowing them to react for a set time (45 to 60 min) and at a set temperature (175 to 200°C (350 to 400 °F)) [1,3], GTR-modified binder results when rubber absorbs asphalt binder and swells at a high temperature. The addition of rubber to form a theoretical, continuous homogenous phase with a binder will increase the viscosity of the binder blend, making it stiffer and thereby increasing the rut resistance of the mixture [4]. At the same time, the softened rubber grains enhance the toughness of the binder system, leading to an increased resistance to various cracking forms [5].

Terminally blended GTR denotes crumb rubber modification at an asphalt blending terminal, requiring subsequent transportation to job sites. Terminology at the California Department of Transportation(Caltrans) refers to terminal blends as a wet-process-no-agitation binder since it supposedly does not require any agitation after its production stage [10,11], However, researchers have reported cases of settlement in the trucks used for transportation of terminal blends, thus affecting the performance of the end product [15]. Consequently, a few state agencies have either mandated or used additional modifiers such as Vestenamer, a trans-poly-octenamer rubber (TOR) (Missouri Department of Transportation (DOT), Pennsylvania DOT), and extender oils (Caltrans, Oregon DOT, NJDOT) in an effort to avoid such constructability issues and to enhance mixture performance [6–7].

In recent years, there have been many research studies and publications on crumb rubber. The topics addressed include (1) the influence of crumb rubber on the moisture susceptibility of bituminous mixes [18.19.20]. (2) the effect of crumb rubber on mix resistance to plastic deformation [27] and (3) the environmental benefits derived from its use [23.24.25]. The results of this study provide more data regarding the addition of crumb rubber (the wet method) to a bituminous mix and its effect on properties such as the stiffness modulus (closely related to bearing capacity).

The present research study tested the stiffness modulus and direct tensile strength of ground tire rubber modified (GTR) bituminous mixes. The addition of

GTR was analyzed to see how it affected the bearing capacity and cohesion of the mix.

As explained in the methodology, this study analyzed six bituminous mixes of similar characteristics. The reference mix was manufactured with conventional bitumen, and the other five mixes were manufactured with the same bitumen but modified with ground tire rubber at different percentages. The main objective of this study is to evaluate and examine the effect of Ground Tyre Rubber on the laboratory performance of bituminous mixtures.

2. METHODOLOGY

2.1 Materials

2.1.1 Ground Tyre Rubber

An ambient GTR was considered in this study, GTR has been recycled from waste tyres (80% of truck tyres and 20% of car tyres) with a gradation of 0/0.6 mm and Density of 1.15 t/m^3. **Fig 1** shows the gradation of the used GTR.

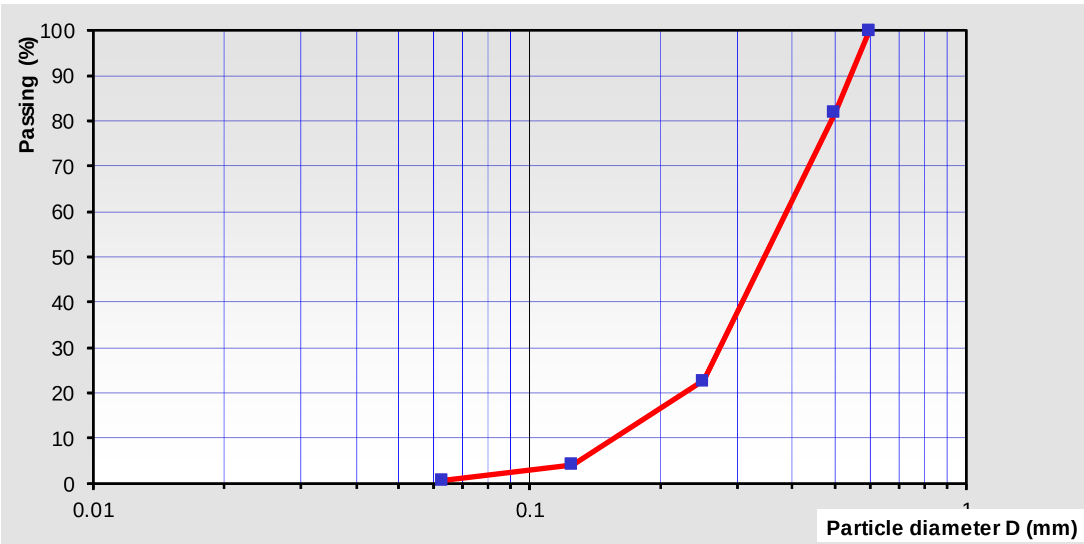

Figure 1: Gradation of Ground Tyre Rubber

2.1.2 Binders

The base binder utilized in this study was 35/50 penetration grade bitumen, commonly used for pavement construction in Algeria. This binder was sourced from NAFTAL, a national bitumen contractor, ensuring consistency and local relevance in material selection. To prepare the modified GTR binders, the base bitumen was heated to 180°C. Ground Tire Rubber (GTR) was then incrementally added at different percentages relative to the weight of the binder—5%, 10%, 15%, 20%, and 25%. These mixtures were blended using a high-shear mixer at 3000 rpm for 45 minutes [1-19]. A high-precision laser thermometer monitored and maintained the mixing temperature consistently at 180°C. Comprehensive physical testing was conducted on both the unmodified and GTR-modified binders to assess their performance characteristics. The tests included: Measuring the consistency of the bitumen which indicated a decrease in penetration values with increasing GTR, suggesting enhanced stiffness due to the GTR interaction during the mixing process determining the temperature at which the bitumen reaches a specific softening state. A notable increase in the softening point was observed, with the highest GTR content (25%) reaching 74.8°C, reflecting the increased viscosity and thermal stability of the modified binders.

Figure 2 illustrates these changes, showing how the incorporation of GTR significantly alters the physical properties of the binders, enhancing their suitability for more demanding pavement applications.

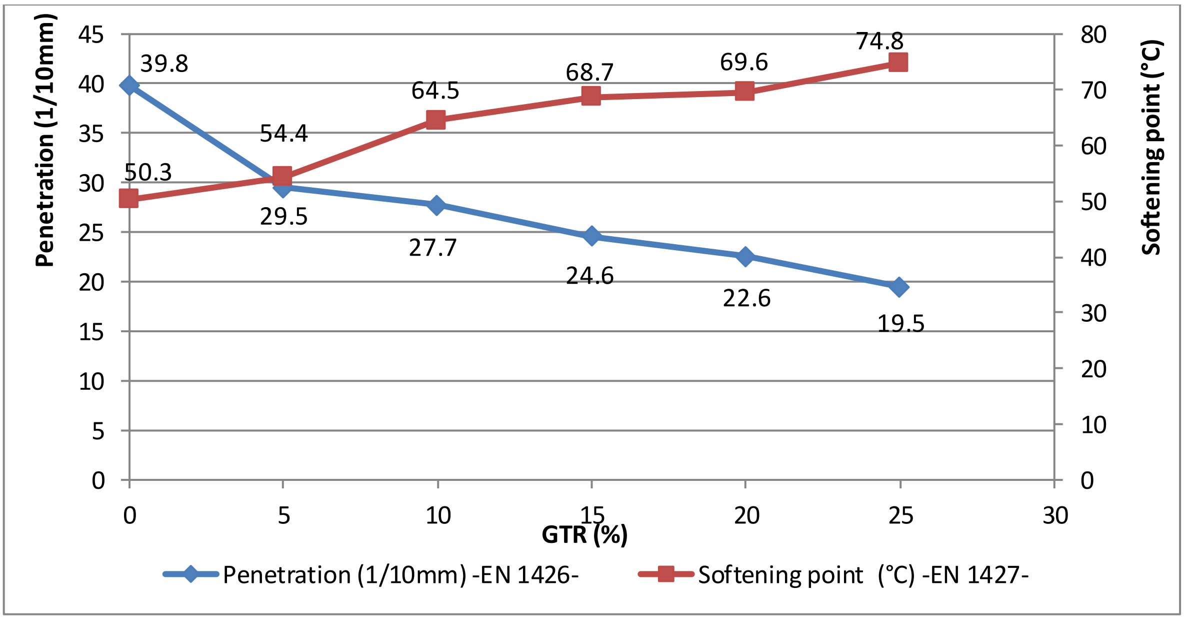

Figure 2: Penetration and softening point results of base and GTR binders

The modification of bitumen with Ground Tire Rubber (GTR) resulted in a notable decrease in ductility, a trend that aligns with expectations given the increased viscosity observed with higher GTR contents [9-10]. This relationship is depicted in Figure 3, illustrating how the viscosity of the binder escalates as more GTR is incorporated, thereby reducing its ductility. Particularly at higher GTR contents, specifically 20% and 25%, the loss in ductility becomes more pronounced. This behavior suggests that while GTR enhances certain performance characteristics like stiffness and temperature susceptibility, it also makes the binder less capable of elongating without breaking, a critical property in applications where flexibility under stress is required.

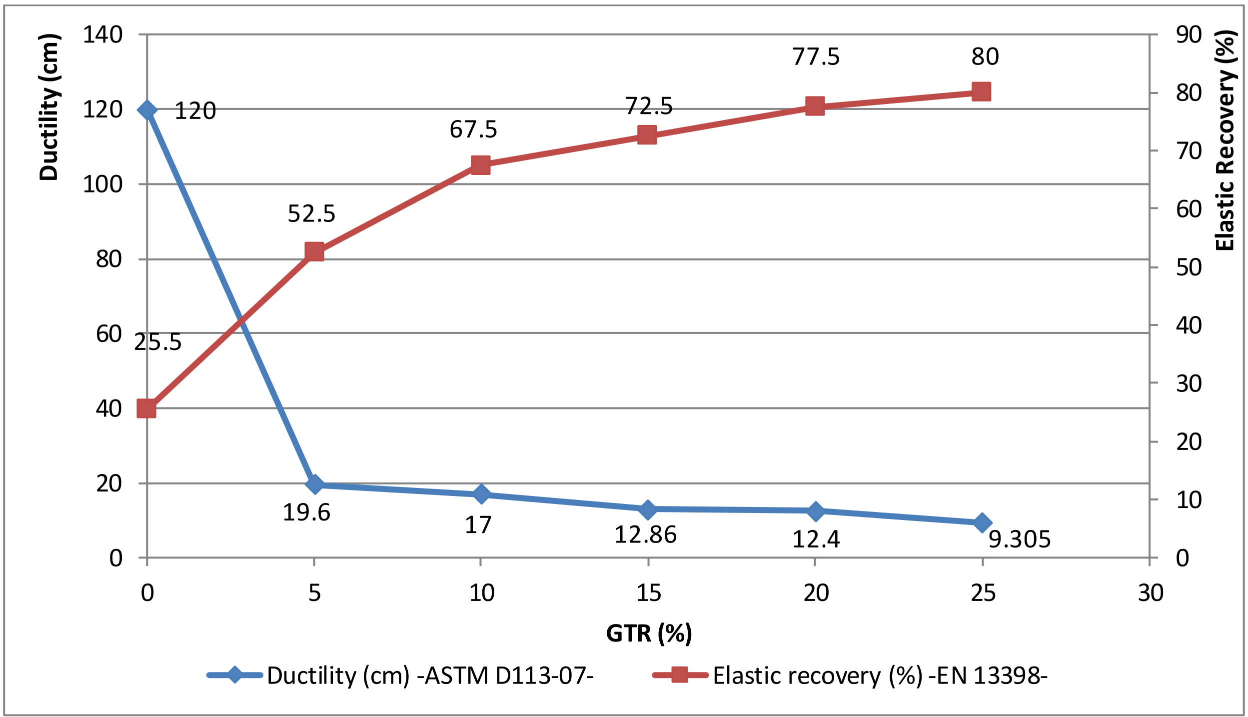

Figure 3: Ductility and Elastic recovery versus GTR content

The conducted elastic recovery tests revealed enhanced performance of GTR-modified bitumens compared to the unmodified binder. As illustrated in Figure 3, the addition of GTR not only improved the elastic properties of the bitumens but also showed progressive increases in elasticity with higher GTR contents. Notably, the maximum enhancement in elastic recovery was observed at 25% GTR content. This significant improvement in elasticity is likely to contribute to better rutting resistance in the modified mixtures, indicating potential for improved pavement performance under repetitive traffic loading[13-14].

2.1.3 Mixtures

To select the aggregate gradation of the mixture to be evaluated in this study, the gradations of aggregates of dense graded GTR 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 4 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, 45% manufactured sand 0/3mm. The mechanical characteristics of aggregates are summarized in the Table 1 (which comply with the Algerian technical specification for road construction), it is noted that the mix design was targeted to construct a new bituminous pavements. The binder content was selected based on shear gyratory compactor for an air void 5-9% for all mixes.

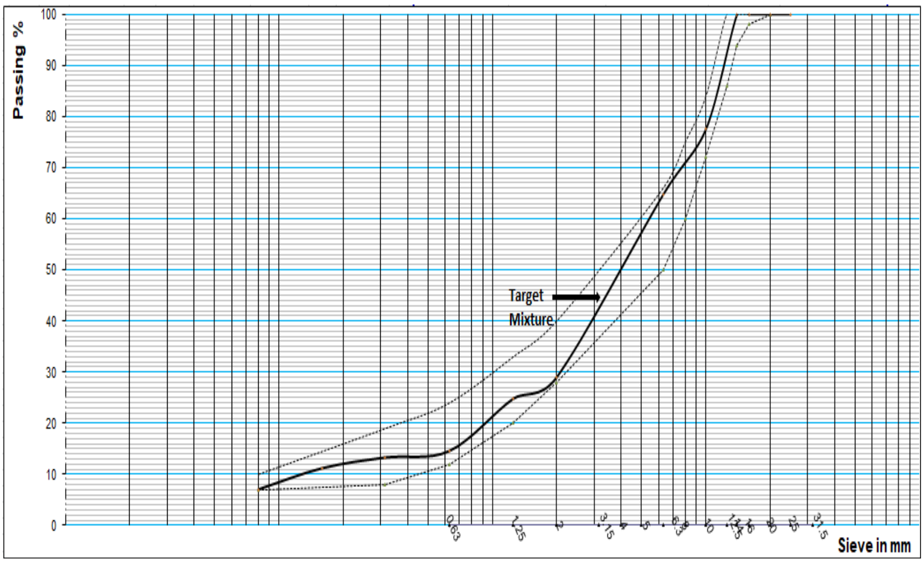

Figure 4: Gradation of target mixture BBSG 0/14 according to EN13108-1

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
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
coarse aggregate angularity(%)	EN 933–5	-	100	100

The aggregates were pre-heated to 180°C and maintained at this temperature for four hours to ensure proper temperature homogeneity. Following this, the modified bitumens were blended with the heated aggregates at the same temperature of 180°C. The mixing process lasted for four minutes to guarantee a homogeneous mixture. To account for short-term aging, the mixture was then left in the oven at 180°C for an additional one and a half hours[12]. Table 2 details the binder content for each of the seven different mixtures, where the base binder content was consistently maintained across all mixtures. This approach was adopted to specifically isolate and evaluate the effects of varying GTR contents on the properties of the mixtures.

Table 2: Different bitumen contents for different GTR binder content

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

2.1.4. Mixtures Testing

A laboratory testing program was performed to evaluate the performance of the control and the GTR 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 ground tire 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 160°C for conventional and 180°C for GTR modified mixes. The manufacturing temperature for the conventional 35⁄50 reference mix was 160–165°C. The CRM mixes were elaborated at a slightly higher temperature because the addition of ground tire rubber increased mix viscosity. The higher temperature thus guaranteed the workability of the mix.

The mixes 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, In a hot bituminous mix, the mineral skeleton (aggregates) provides the compression strength, and the bitumen and mastic cohesion provide the tensile strength (and also the adhesion bitumen/aggregates). One of the main problems with hot crumb rubber mixes is low cohesion attributable to a poor interaction between the crumb rubber and the bitumen [13]. This weakness may reduce tensile strengths and cause pathologies, e.g., stripping, pot holes. For this purpose, the direct tensile strength test [Fénix approach] was used because it directly measures the tensile strength in the mix and is thus a way to calculate mix cohesion [13]. This test entailed the manufacture of two test cylinders compacted with 75 blows on each side by a Marshall hammer. These test specimens had a diameter of 101.6 mm and heights ranging from 55 to 64 mm. As part of the test, they were subjected to direct tensile loads between two loading plates at a constant velocity of 1 mm⁄ min Fig. 6. This load produced a relatively uniform tensile stress along the vertical diametric axis.

Finally, to analyze the bearing capacity of each mix, an indirect tensile stiffness modulus test (ITSM) as described in standard EN 12697-26 (Annex C) was performed. The stiffness modulus is a very important performance characteristic of the pavement. This test defines the viscoelastic performance of bituminous mixes. Two extremely influential factors are the volumetric composition of the mix and its bitumen modulus. For this reason, the mixes in the present study had an identical mineral skeleton and the same type of bitumen. This made it possible to exclusively focus on the influence of the crumb rubber on the mix properties.

2.4.1 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 [8]. Basically, the term stiffness refers to stress divided by corresponding strain [9]. 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 [12]. 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:

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

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.

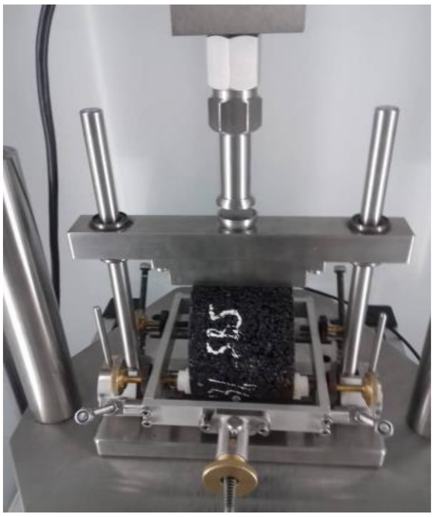

Figure 5: Indirect Tensile Stiffness Modulus Machine

The ITSM measures the load-spreading ability of the bituminous layers and controls the traffic-induced tensile strains at the underside of the roadbase, which are responsible for fatigue cracking, along with the compressive strains induced in the subgrade that can lead to permanent deformation [21]. A base layer of high stiffness can protect the soil foundation by decreasing soil shear stress. However, this brings a risk that the base layer itself may crack [22].

For the performance of the complete test, three test cylinders were manufactured for each of the mixtures studied. The final value of the stiffness modulus of each specimen is the mean value of both diameters. The stiffness modulus of each mix is the mean value of the results obtained for the three test cylinders. Furthermore, to compare the results of the cylinders, a stiffness modulus that had been weighted for a load factor value of 0.60 was calculated. This was the value used in the analysis of the results.

2.4.2 Cracking Resistance

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 [13]. 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 [14]. The testing device can be seen in Figure 6 [13]. 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).

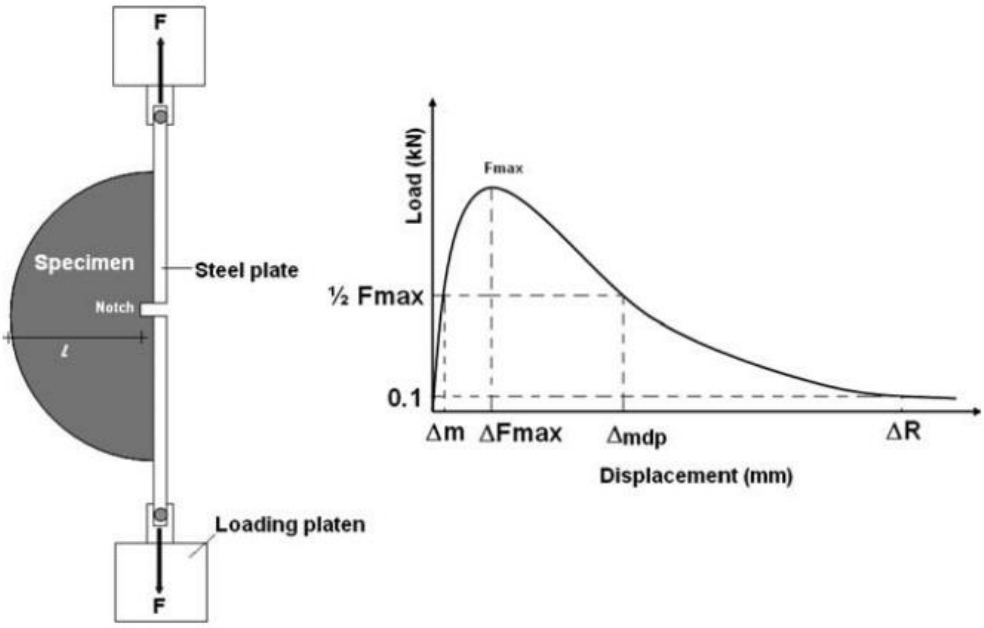

Figure 6: Fénix Test Setup and load-displacement output Curve [13].

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 [13]. 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 2 [16]:

$$G_F = \frac{\int_0^{df} F(u)\,.\,du}{S} \quad (2)$$

where
GF: fracture energy (J/m^2)
F: load (kN)

u: displacement (mm)
S: 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 [16], and it is related to the mixture modulus. It is obtained using Equation3 :

$$\text{IRT} = \frac{0.5Fmax - 0.25Fmax}{d0.5Fmax - d0.25Fmax} \quad (3)$$

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. (4) [16]:

$$\text{TI} = \frac{\int_{dfmax}^{df} F(u)\,.\,du}{S}\,.\,(d_{0.5PostFmax} - d_{Fmax}) \quad (4)$$

where
TI: toughness index ($J.mm/m^2$)
F: load (kN)
u: displacement (mm)
S: fracture surface (m^2)
d_{Fmax} and $d_{0.5PostFmax}$: 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 [17].

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 GTR 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.

3. RESULTS AND DISCUSSION

3.1 Indirect Tensile Stiffness Modulus.

The ITSM results at 15°C, as depicted in Figure 7, indicate that the stiffness modulus of the bituminous mixtures generally increases with the addition of ground tire rubber (GTR), though there are some fluctuations at higher percentages. Here’s a breakdown of how the GTR content impacts the stiffness modulus:

Analysis of ITSM Results:

- Control Mixture: The stiffness modulus for the control mixture (no GTR added) is measured at 10,247 MPa.
- 5% GTR: Adding 5% GTR results in an increase in the stiffness modulus to 11,028 MPa. This suggests that even a small percentage of GTR can significantly enhance the stiffness of the mixture.
- 10% GTR: At this level, the stiffness modulus further increases to 11,714 MPa, indicating continued improvement in the mixture's ability to resist deformation under stress.
- 15% GTR: The stiffness modulus slightly decreases to 11,292 MPa. This dip could be due to the variability in how the rubber interacts with the bitumen binder at different concentrations.
- 20% GTR: Increases again to 11,525 MPa, suggesting that higher GTR content continues to enhance the bitumen binder's performance up to this point.
- 25% GTR: There's a notable increase to 13,199 MPa, showing a significant rise in stiffness, which could be beneficial in high-stress applications where deformation resistance is critical.

As GTR percentage increases, the rubber particles contribute to a more rigid matrix within the bitumen, enhancing its ability to bear loads without deforming. Optimal GTR Content: The results suggest that higher GTR contents generally improve stiffness, but the specific optimal content for maximum performance efficiency might depend on specific use-case scenarios, including traffic load and environmental conditions.

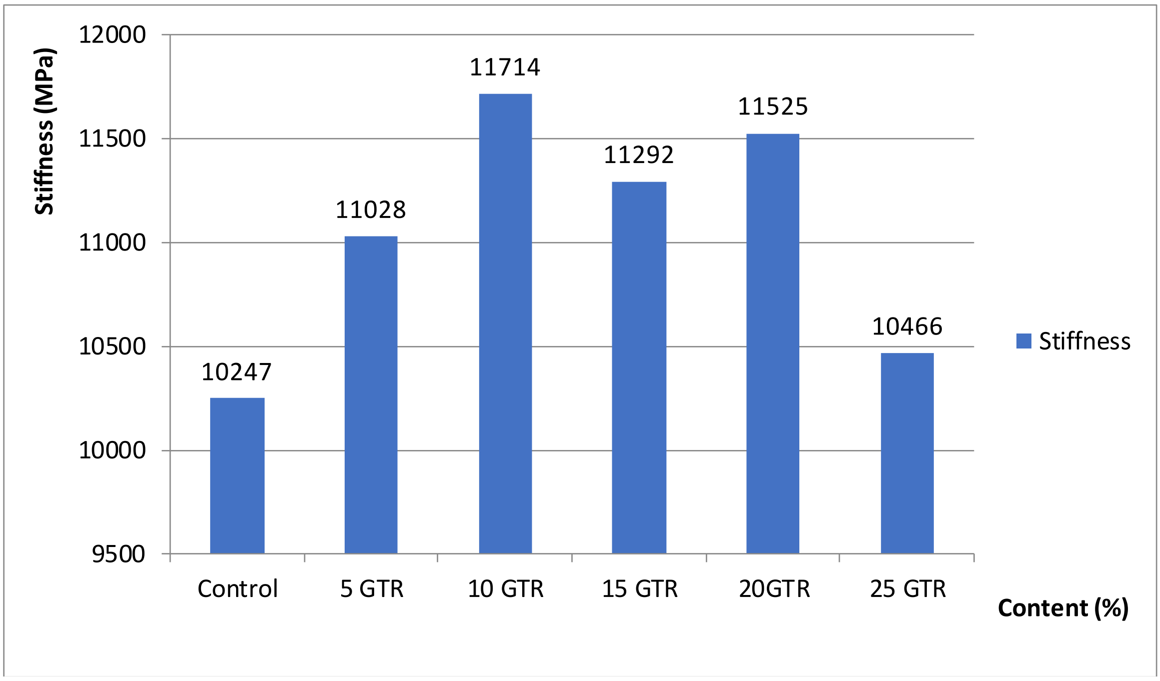

Figure 7: Effect of GTR content on the Stiffness Modulus of bituminous mixtures at 15°C.

The integration of ground tire rubber (GTR) hardens the mix by reducing the penetration of the bitumen. This increased hardness results in a higher stiffness modulus, which is beneficial for supporting heavy traffic loads.

While an increased stiffness modulus is generally desirable for durability, it can also make the bituminous mix less flexible. This reduced flexibility can lead to increased susceptibility to cracking, especially in environments subject to temperature fluctuations or where the bitumen undergoes frequent or high-magnitude stresses.

The addition of elastic rubber particles from GTR can introduce an interesting dynamic to the mix's behavior under load. Even though the bitumen becomes harder and the overall stiffness increases, the rubber particles can provide a mechanism for energy dissipation. This dissipation can potentially counteract some of the negative effects of increased stiffness, such as brittleness and susceptibility to cracking.

At 15°C, an increase in stiffness might not detrimentally affect performance due to the elastic nature of the rubber particles. These particles help absorb and dissipate the energy from traffic loads, which can reduce cracking despite the harder bitumen.

Further studies might focus on how GTR-modified bitumen behaves across a broader range of temperatures, particularly extremes that are likely to challenge the material's mechanical properties.

Longitudinal studies could evaluate how these mixtures perform over time, considering factors like fatigue life and resistance to various types of cracking. Identifying the optimal GTR content that provides the best balance between increased stiffness and maintained flexibility could be critical for tailoring bituminous mixtures to specific environmental conditions and traffic patterns.

3.2 Cracking Resistance

3.2.1 Tensile Forces

Figure 8 revealing the detailed behavior of the GTR modified mixtures under load at 25°C provides crucial insights into how GTR concentration impacts the mechanical properties of the bitumen. The results suggest about the mixture, stiffness and Brittleness: The initial slope of the load-displacement curve indicates stiffness, with a steeper slope suggesting a stiffer mix. The rapid decline in the post-peak part of the curve signals brittleness, where the material fails to maintain integrity under continued stress[13].

Increased Peak Force at 10-15% GTR: The notable increase in peak force within this range suggests that the mixtures achieve an optimal balance between stiffness and ductility, potentially offering the best structural integrity and load-bearing capacity. Decreased Peak Force at 20-25% GTR: The significant drop in peak force for these higher GTR contents points to excessive brittleness. This implies that while the mixtures are initially stiffer, they are more prone to rapid failure once their peak stress threshold is exceeded, likely due to the increased rigidity and reduced elasticity of the binder.

Optimal GTR Content: The findings indicate that while a moderate amount of GTR (around 10-15%) can enhance the stiffness and load-bearing capacity of bituminous mixtures without overly compromising ductility, higher levels (20-25%) introduce too much brittleness. This excessive brittleness can lead to earlier onset of cracking and potentially lower overall pavement life due to reduced ability to accommodate stresses from traffic and thermal variations.

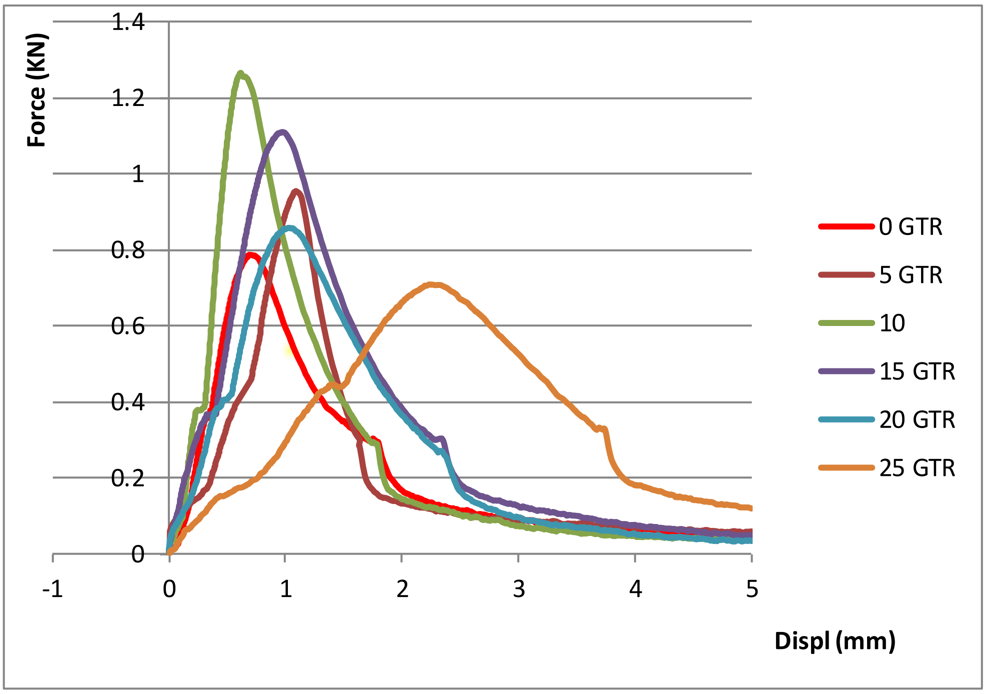

Figure 8: Load-displacement curve at a test temperature of 25°C

The analysis of the output curve from the test provides critical insights into the mechanical properties of the bituminous mixtures, especially concerning their cracking behavior under load. The parameters interpret the performance of the asphalt mixtures:

This parameter measures the amount of energy required to propagate a crack through the material. Higher fracture energy values indicate a mixture's ability to resist crack initiation and propagation, enhancing its durability under repeated traffic loads and environmental stress. The IRT reflects the slope of the stress-displacement curve between 25% and 50% of the peak load. It is an indicator of the mixture's modulus of elasticity. Higher IRT values suggest that the mixture is stiffer, which can be advantageous for bearing capacity but may also imply a higher susceptibility to cracking under tensile stress. This index measures the energy dissipation during the post-peak phase of the test and is indicative of the mixture's ability to endure and dissipate energy after the peak load has been reached. A higher toughness index means better resistance against the propagation of cracks, suggesting a more ductile mixture that can deform without failing immediately after reaching critical stress levels. This measures the deformation capacity of the mixture after reaching 50% of the peak load. Lower values here might indicate a more brittle material that loses its load-bearing capacity more quickly after peak stress, while higher values suggest better deformability under stress.

- A balanced combination of these values represents an optimal mixture design that can resist cracking while still providing sufficient stiffness and load-bearing capacity.
- Mixtures with high fracture energy and a high toughness index are particularly desirable for roads subjected to heavy and repeated traffic loads as they can better resist the initiation and spread of cracks.
- The tensile stiffness index needs to be optimized to ensure the mixture is neither too stiff nor too flexible, aligning with the specific requirements of the pavement design.

3.2.2 Displacement at 50% post-peak load

The observation of increased maximum load at 5% and 10% GTR content, as shown in Figure 9, highlights the impact of moderate levels of GTR on the stiffness and ductility of the bituminous mixtures. Here’s a breakdown of what this finding implies:

1. The addition of GTR at these levels enhances the stiffness of the binder, which contributes to an increased load-bearing capacity of the asphalt mixtures. This stiffening effect is beneficial for supporting heavier traffic loads and improving the overall structural integrity of the pavement.
2. Despite the increased stiffness, the mixtures with 5% and 10% GTR still maintain adequate ductility. This is critical because it means that while the mixtures are stiff enough to bear greater loads, they are also flexible enough to accommodate some degree of deformation without cracking. Ductility is essential for bituminous pavements to withstand various stresses caused by traffic, temperature changes, and settling of the underlying materials.
3. The parameter d0.5PostFmax serves as an indicator of how the mixtures behave under stress after reaching half of the maximum load capacity. An increase in this value in the context of higher GTR contents would typically indicate better fracture behavior, suggesting that the pavement can endure larger deformations post-peak load before failing.

The increased maximum load at 5% and 10% GTR signifies an optimal balance between stiffness and ductility, making these concentrations potentially ideal for achieving durable and resilient bituminous pavements. Ensuring that bituminous mixtures retain ductility while increasing stiffness is crucial for preventing premature failures such as cracking under operational conditions. Further testing and analysis could explore how variations in GTR content above 10% influence the fracture behavior and long-term durability of the mixtures, particularly focusing on the trade-offs between increased stiffness and the potential for reduced ductility at higher rubber contents.

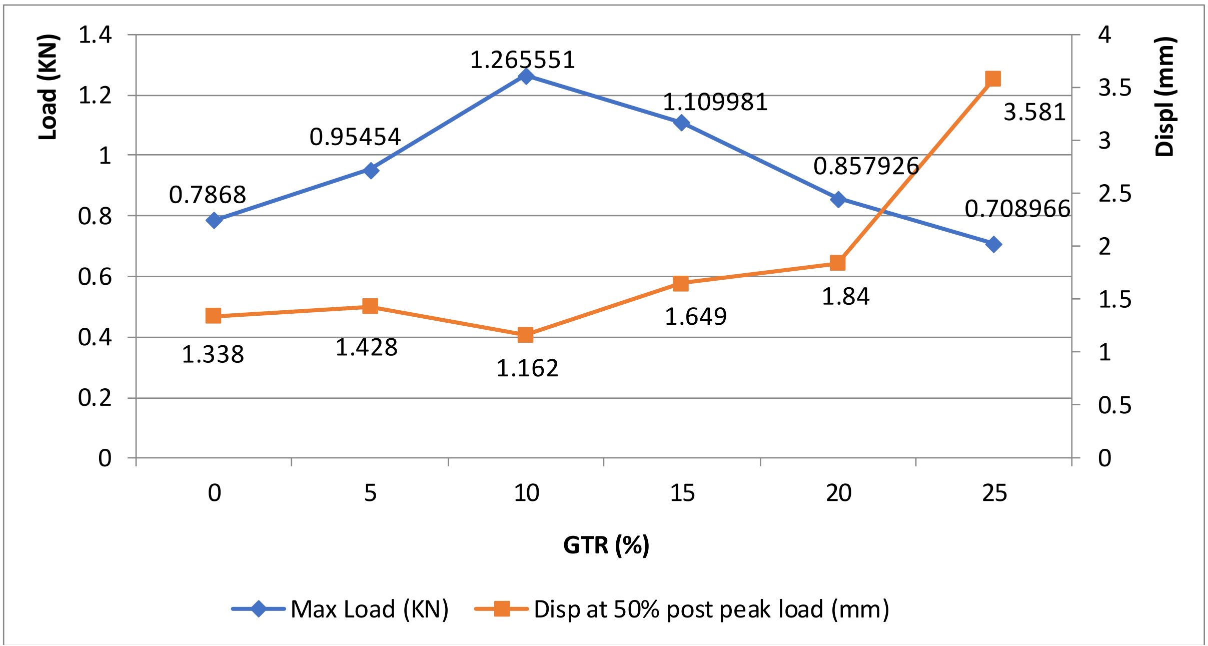

Figure 9: Max load and displ at 50% post peak load versus GTR content

As the GTR content increases beyond 15%, the maximum load that the mixtures can withstand continues to decrease, reaching the lowest value at 25% GTR. This trend indicates that although the binder becomes more consistent or viscous, it may also become overly stiff and brittle, reducing its ability to withstand load without fracturing. The increasing displacement at 50% post-peak load observed with higher GTR contents suggests a reduction in the ductility of the mixtures. This means that while the mixtures may be able to deform more before completely failing, they are also more likely to crack under less strain compared to mixtures with lower GTR contents. High stiffness and low displacement at post-peak loads typically indicate a material that is brittle and prone to cracking under stress. In pavement materials, while stiffness is needed to support loads, excessive stiffness can lead to reduced fatigue life and increased susceptibility to cracking, especially under dynamic loading conditions such as traffic or thermal fluctuations.

The results suggest that a balance needs to be found in the GTR content to optimize both stiffness and ductility. While lower GTR contents (around 10%) improve stiffness without significantly reducing ductility, higher contents might lead to diminished performance due to increased brittleness.

It might be beneficial to investigate the interaction between GTR particles and the bitumen matrix more closely, particularly at higher GTR contents. Understanding the microstructural changes within the binder with increased GTR could provide insights into managing the adverse effects of high ground tyre rubber content. For practical applications, choosing the appropriate GTR content will depend on the specific requirements of the pavement performance. If higher load-bearing capacity is essential without a significant loss in ductility, maintaining GTR content at or below 10% might be advisable.

3.2.3 Fracture energy (G_f)

The increase in fracture energy with higher GTR contents (particularly at 20% and 25%) suggests that these mixtures can absorb more energy before cracking. This property is typically beneficial for materials subjected to dynamic loads, as it indicates better resistance against crack initiation and propagation. As GTR content increases, the elasticity of the binders also increase. While these properties enhance the binder's ability to resist deformation and recover its shape, they can also lead to increased brittleness, particularly at higher rubber contents. This brittleness, while enhancing fracture energy, reduces the ductility of the binder, making it less able to accommodate strains without cracking.

The lower GTR contents (5% and 10%) exhibit lower elasticity, which, while making these binders less brittle, also makes them more susceptible to thermal cracking. Thermal cracking often results from a material's inability to tolerate stress caused by temperature changes, which could be more problematic in binders with lower elastic responses.

The findings in fig 10 suggest that while higher GTR contents can improve certain properties like fracture energy, they also introduce challenges like increased brittleness. Therefore, selecting an optimal GTR content that balances these factors is crucial. Based on your data, while 25% GTR offers the highest fracture energy, it may not be the best choice for all pavement conditions due to its reduced ductility.

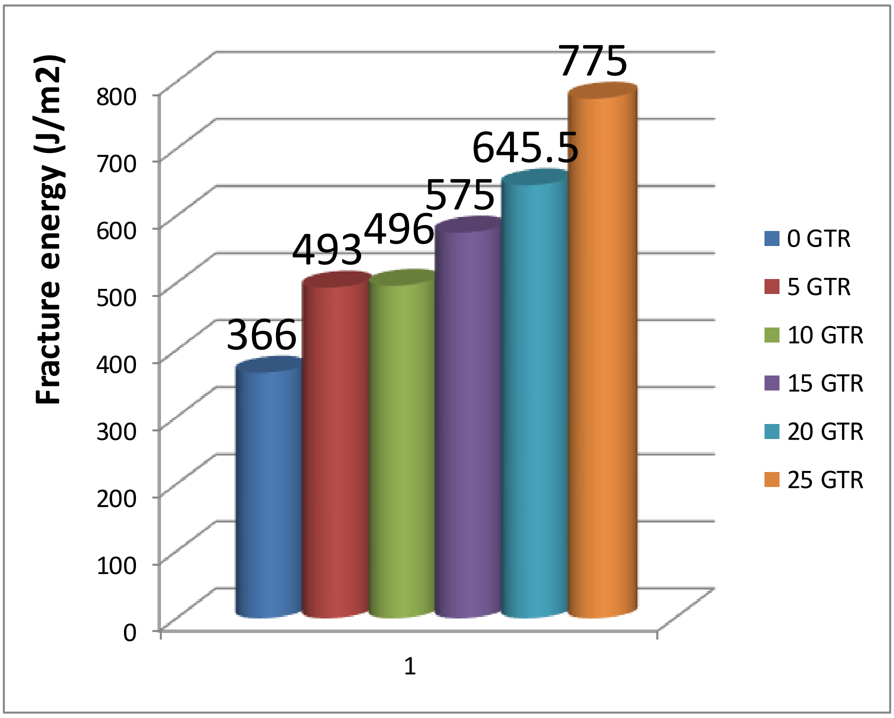

Figure 10: Fracture energy versus GTR content at 25°C

For applications where high fracture energy and stiffness are required, higher GTR contents might be beneficial. However, for environments where thermal cracking is a concern, or where pavements are subjected to frequent temperature fluctuations, lower GTR contents might be more appropriate.

To refine the use of GTR in bituminous mixtures, further studies could explore the long-term durability of these mixtures under real-world conditions. Additionally, looking into modifiers that could enhance the ductility without compromising the increased viscosity and elasticity at higher GTR levels could be beneficial.

In conclusion, while increasing GTR content in bituminous binders enhances certain mechanical properties, it also necessitates careful consideration of the resultant trade-offs in material behavior, especially concerning ductility and susceptibility to thermal cracking.

3.2.4 Tensile stiffness index (IRT)

The increase in TSI at 10% GTR indicates a notable hardening effect of the binder (fig 11). This stiffness suggests that the binder is more resistant to deformation under load, which can be particularly beneficial for pavements exposed to heavy traffic where deformation resistance is critical. The increase in stiffness at 10% GTR suggests that this may be an optimal point for balancing increased stiffness without excessively compromising other properties like ductility and workability. It implies a threshold where GTR begins to significantly influence binder behavior.

Increased stiffness in the binder typically leads to better performance in terms of rutting resistance. As the binder becomes harder, it can better resist the forces that cause rutting, which are prevalent in areas with high temperatures and heavy traffic loads. While increased stiffness is beneficial for certain performance aspects like rutting resistance, it is also associated with increased brittleness. This means the pavement may be less able to accommodate stresses from thermal contraction and expansion, possibly leading to increased cracking risks under certain conditions.

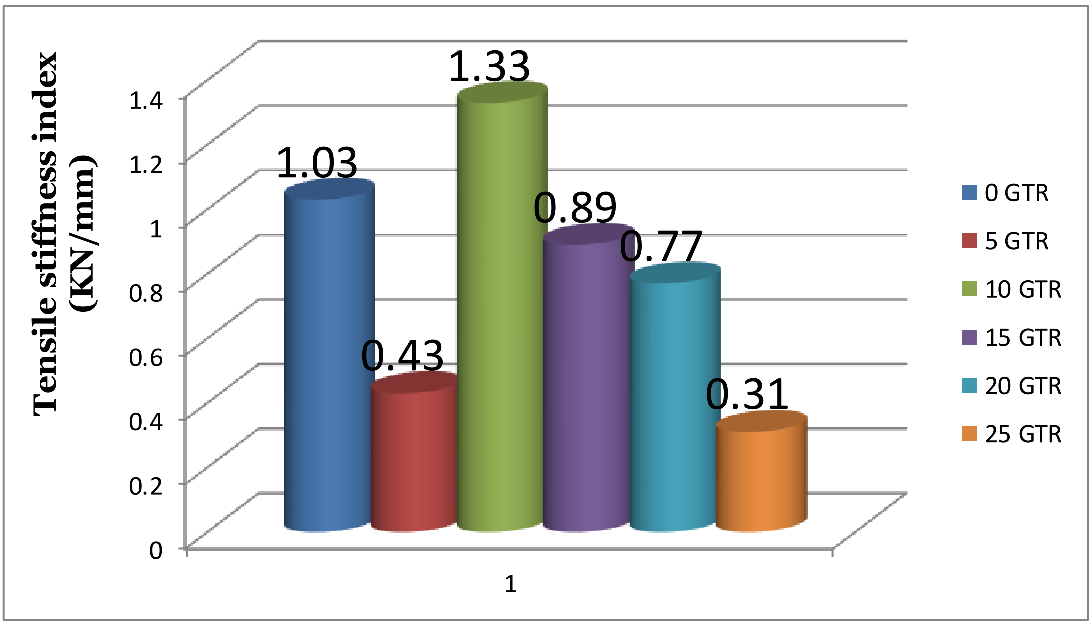

Figure 11: Tensile stiffness index versus GTR content at 25°C

Using a 10% GTR content may be particularly advantageous for pavements in regions with high traffic loads. However, this should be balanced with considerations of the environmental conditions, such as temperature extremes that might necessitate a more ductile binder.

Additional tests should be conducted to evaluate other properties such as fatigue life, moisture susceptibility, and long-term aging. These properties will provide a more comprehensive view of how GTR-modified binders perform over time and under various stress conditions.

Given the increase in stiffness, adjustments in mix design may be necessary to optimize the overall performance of the pavement. This might include altering aggregate gradation, modifying mixing and compaction temperatures, or incorporating other additives that can enhance the ductility and flexibility of the mix. The findings provide valuable insights into the specific effects of GTR on asphalt mixture performance and pave the way for targeted adjustments in mix design to leverage these benefits while mitigating potential drawbacks.

3.2.5 Toughness index (TI)

The toughness index offers a detailed view of the binder's behavior post-peak load. It essentially measures the material's ability to absorb energy after reaching its maximum load capacity, which is critical in understanding how it might behave under repeated traffic loads that cause microcracks to form and propagate. A higher toughness index indicates that the material not only reached a high peak load but also managed to dissipate significant energy before failure, which correlates to more ductile fracture behavior. This ductility is beneficial for pavement performance in environments subject to temperature fluctuations and dynamic loads, reducing the likelihood of brittle fractures. The challenge in pavement material design, especially with the incorporation of modifiers like ground tire rubber (GTR), is balancing increased stiffness (for rut resistance) with sufficient ductility (to avoid brittle fractures). The toughness index helps quantify this balance, providing a metric to optimize the mix design.

Since the toughness index reflects the energy absorption capacity of the material after peak load, it can be a predictor of how well the pavement will perform over time, particularly in resisting fatigue and reflective cracking. The changes in toughness index with varying percentages of GTR can guide the optimal content of rubber in the mixture. If the toughness index significantly decreases at higher GTR contents, it may indicate an over-hardened mix that could be prone to cracking under certain conditions.

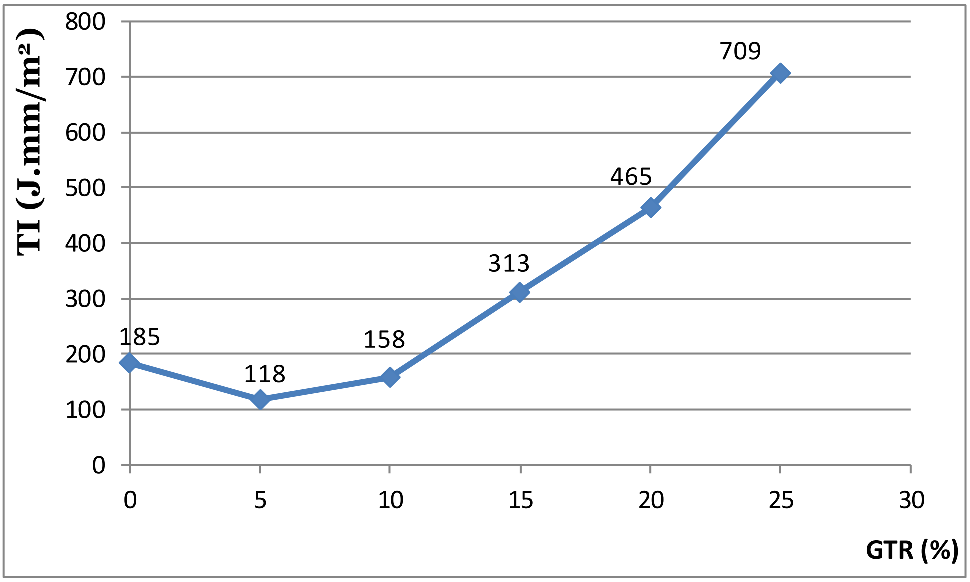

Figure 12: Toughness index versus GTR content at 25°C

The increase in TI at 25% GTR indicates that while the binder becomes harder and potentially more brittle due to reduced ductility (fig 12), it also possesses a higher capacity to absorb energy post-peak load. This phenomenon suggests that despite the binder's brittleness, its ability to withstand further deformation without fracturing is enhanced at this GTR content. At 5% GTR, the binder remains more ductile and less brittle, which is beneficial for low-temperature performance but may not be ideal for high-temperature or heavy-load conditions where stiffness and rut resistance are critical. The low TI at this level implies a reduced ability to absorb energy post-peak, suggesting a quicker transition to failure once the peak load is exceeded.

For environments with frequent high-temperature conditions or heavy traffic, increasing the GTR content to enhance stiffness and toughness may be beneficial. However, care must be taken to balance these properties with sufficient ductility to prevent premature cracking.

Since the toughness index varies significantly with temperature, it's vital to consider the typical climate of the pavement location. In cooler climates, lower GTR contents may be preferable to avoid brittleness, while hotter areas might benefit from higher GTR levels.

4. CONCLUSION

The use of GTR leads to stiffer and more consistent bitumen, which can be beneficial for high-temperature performance and rutting resistance. This modification helps in sustaining pavement integrity under heavy traffic conditions and in warmer climates.

- Enhanced Elastic Recovery: The improvement in the elastic properties suggests better performance under cyclic loading conditions, which is crucial for roads subjected to constant and varying loads. This property helps in the durability and longevity of pavements.
- Decreased Ductility: While the reduction in ductility suggests a loss in flexibility, which could potentially increase susceptibility to cold temperature cracking, the overall balance of properties might still favor the use of GTR, especially in moderate to warm climates.
- Cracking Resistance: Increased fracture energy indicates that GTR-modified mixtures are more resistant to crack propagation. This quality is particularly important for enhancing the lifespan of road surfaces under dynamic loading and environmental stresses.
- Fatigue Performance: Although the increased stiffness could negatively impact fatigue resistance, the overall benefits of GTR such as enhanced crack resistance and better elastic recovery could offset some of these effects. This aspect might require further optimization of GTR content to balance stiffness and flexibility.
- Environmental Sustainability: Utilizing GTR in asphalt mixtures promotes recycling and reduces landfill waste, addressing environmental concerns associated with tire disposal. This approach not only helps in conserving natural resources by reducing the demand for new raw materials but also mitigates pollution.
- Economic Benefits: Incorporating recycled materials like GTR can potentially reduce the costs associated with the production of new bituminous mixtures and the disposal of used tires.

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