TRANSFORMING BITUMINOUS MIXTURES: A STUDY ON REINFORCEMENT WITH VARYING SIZES OF HEAVY WEIGHT AUTOMOBILE WASTE TIRES AND EVALUATION OF THEIR FATIGUE LIFE

Abstract

This study addresses the deteriorating condition of road structures due to escalating challenges from increased servicetraffic, higher axle loading, and inadequate maintenance. Focusing on enhancing traditional bitumen's performance attributes, particularly resistance to deformation and fatigue cracking, the research aims to prolong flexible pavement life and reduce surface damage. While previous studies explored bituminous binder modification, this paper advocatesfor environmentally friendly alternatives, such as crumb rubber modified bitumen (CRMB), to improve binder qualities and durability. The environmental impact of used tire disposal prompts exploration of recycling and reusing tire rubber. The study highlights the benefit of rubberized bitumen binders, emphasizing the use of crumb rubber as a rheology enhancer. The paper examines interaction mechanisms, emphasizing particle size's impact on bituminous mixture performance. The study also addresses limited exploration of modifiers, focusing on waste tire powder obtained from heavy automobile. Investigating crumb rubber doses, the study assesses Marshall and indirect tensile strength, and fatigue life impact. Emphasizing the importance of understanding crumb rubber (CR) particle size for optimizing bituminous mixture attributes, the research aims to provide insights for sustainable asphalt pavements.

Keywords: Crumb rubber (CR), Fatigue, Resilient Modulus, Indirect tension, Loading frequency.

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I. INTRODUCTION

With increasing traffic density, high axle loading, and inadequate maintenance services, pavements have degraded more quickly over time. Traditional bitumen's performance-related attributes, Resistance to persistent deformation (rutting) and fatigue cracking are two examples, must be enhanced to decrease pavement surface damage and increase the longevity of flexible pavement. In recent years, bituminous binder modification has been researched to improve the performance attributes of road pavements. However, the use of alternative materials, such as CRM, would surely be favorable to the environment, and it will not only improve the bitumen binder qualities and durability, but it may also be cost effective (Li et al., 2022). The increasing disposal of used tires has raised significant environmental concerns, primarily due to the risk of fires and the creation of habitats for pests and rodents (Presti et al., 2012). Despite their long lifespan, vehicle and truck tires contain a substantial amount of non-recycled rubber. Unlike thermoplastic polymers, rubber cannot be remolded through reheating due to its thermosetting nature. To address this issue, a viable solution lies in recycling and reusing discarded tire rubber to both mitigate environmental risks and recover raw rubber resources (Singh et al., 2013). Recent studies have highlighted several benefits of utilizing rubberized bitumen binders. These advantages encompass enhanced resistance of bitumen to rutting due to its heightened viscosity and softening point, along with improved resilience. Additionally, these binders contribute to increased resistance against surface-initiated cracks, reduced fatigue and reflection cracking, lowered temperature susceptibility, and cost-effective savings in road pavement maintenance (Vishnu et al., 2020). Crumb rubber, comprising natural rubber and styrene- butadiene rubber, is employed as a rheology enhancer in bitumen for rubberized bitumen production. Utilizing wet or dry methods, crumb rubber has been tested for modifying bitumen in pavement and roofing applications. Wet processes involve additive blending to achieve favorable bitumen property adjustments, while dry processes struggle with chemical changes due to challenges like bond cleavage or additive stabilization (Wambura et al., 1999). By incorporating crumb rubber into bitumen, temperature sensitivity is reduced while resistance to rutting, low-temperature cracking, fatigue, and aging is increased. Rubber type, composition, ratios, particle size, carbon black, and processes all influence improvement. Limited chemical changes in vulcanizate network during bitumen blending. Cross-linked crumb rubber leads to sedimentation in storage stability testing. (Cetin, 2013). Incompatibility due to low interfacial force, affecting rheological properties of base bitumen (Ghafari et al., 2023). It is reported that the two primary modes of contact are fluid phase and the particles of the binder matrix (Ghavibazoo et al.,2013). The fine particles' greater surface area relative to their weight or volume enhances their capacity to swell in the presence of the binder and form a bond with it. Instead of the conventional grinding process, swelling/pump regeneration of rubber produces better properties related to storage stability and low viscosity (Ibrahim et al., 2013). The blend of crumb rubber-modified bitumen (CRMB) offers enhanced elasticity, higher softening point, delayed oxidation, increased strength, and improved flow compared to regular crumb rubber-modified bitumen. This improvement is attributed to radical deactivation from partial devulcanization of crumb rubber. Milling breaks down swollen crumb rubber for smooth mixing with bitumen. The paper focuses on the performance of bitumen modified with crumb rubber concentrate (Nanjegowda and Biligiri, 2023). The microstructure, phase miscibility, and wettability of the concentrate in bitumen were all investigated. The activated CRMB's properties were compared to those of the conventional crumb rubber system, addressed in respect to both conventional and rheological criteria, and evaluated considering commercial specification requirements. A study by (Qian et al., 2020) found that the performance of hot mix asphalt is improved against moisture sensitivity, alligator cracking, and permanent deformation by adding crumb rubber and recovered asphalt pavement (RAP).. High RAP content combined with crumb rubber yields these benefits. Fine crumb rubber is suggested for better fatigue performance, while moisture susceptibility resistance is also improved. Limited research has explored the effects of diverse modifiers like fibers, crumb rubber, polymers, and natural rubber on asphalt mixtures. Among these, polymers stand out as the most effective for asphalt modification. Polymer-modified asphalt mixtures exhibit enhanced properties such as rutting resistance, temperature sensitivity, and fatigue time period. This study specifically investigates the impact of incorporating waste tire powder, sourced from several vehicles, on the indirect tensile strength, Marshall strength, and fatigue time period of the asphalt mixture (Tahami et al., 2019, Zhang et al., 2023). This study examined crumb rubber doses between 5% and 11%. Adding crumb rubber to asphalt shows potential for enhancing pavement durability and sustainability. Success hinges on factors like crumb rubber's particle size, which substantially influences bituminous mixture attributes like stability, stiffness, and crack resistance. (Mashaan, 2022). Therefore, understanding the effect of particle size on the performance of bituminous mixtures is crucial for optimizing the design and construction of bituminous pavement.

This study examines how crumb rubber particle size impacts bituminous mixture stability, offering valuable guidance for creating sustainable, resilient asphalt pavements. Asphalt pavements are vital for safe and reliable transportation, but growing traffic and environmental factors like temperature changes and water infiltration can harm them, resulting in safety risks, higher maintenance expenses, and shorter lifespans (Ziari et al., 2021). To address these challenges, researchers and practitioners have been exploring various techniques to improve the performance and durability of asphalt pavement. Recycling materials like crumb rubber into bituminous mixtures holds promise. Crumb rubber, derived from processed scrap tires, enriches asphalt properties- bolstering crack resistance, flexibility, and rutting resistance. (Nanjegowda and Biligiri, 2023). This sustainable practice curbs waste and lessens demand for new materials. Success depends on factors, notably crumb rubber's particle size, which significantly shapes mix stability, stiffness, and crack resistance. Appreciating this impact is vital for fine-tuning asphalt pavement design and construction (Narani et al., 2020). Therefore, understanding the effect of particle size on the performance of bituminous mixtures is crucial for optimizing the design and construction of asphalt pavement (Jdayil et al., 2016).

II. EXPERIMENTAL INVESTIGATION

1. Materials Used

- **Crumb Rubber (CR):** CR obtained from Srivastava Petro Carbons Private Limited, Khajekalan, Patna, India. The crumb rubber was shredded into four different sizes of 0.30 mm, 0.60 mm, 1.18 mm and 2.36 mm (shown in Figure 1) and sourced from heavy weight automobile tire.

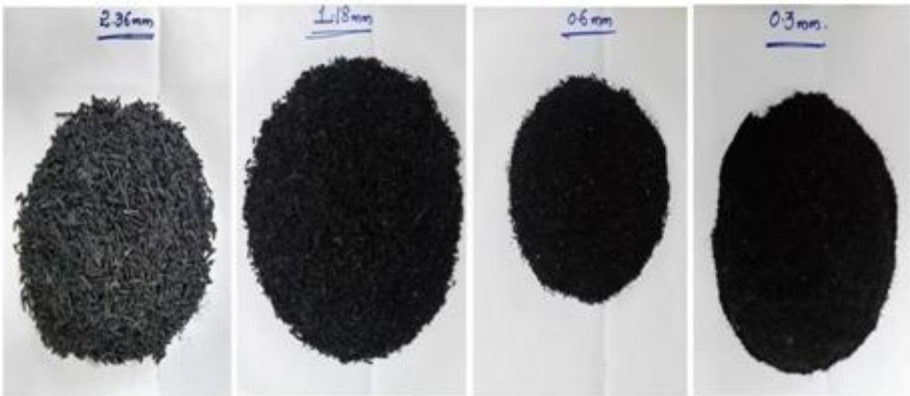

Figure 1: Different sizes of crumb rubber used in the study.

- **Bitumen:** Viscosity grade 30 (VG 30) bitumen and crumb rubber modified (CRMB) was used in this study. The VG 30 bitumen was obtained from PLR constructions Pvt. Ltd., Andhra Pradesh, India. The CRMB bitumen was produced by mixing crumb rubber of different sizes (2.36 mm, 1.18 mm, 0.60 mm, 0.30 mm) to the VG 30 grade of bitumen

- **Aggregates:** Fine aggregates, very strong coarse aggregates (AIV 10%) and fillers (stone dust) were used for the study. A combination of seven different sizes of aggregates, 13.2 mm, 9.5 mm, 4.75 mm, 2.36 mm, 1.18 mm, 0.15 mm, 0.6 mm, 0.3 mm and 0.075 mm for the Marshall mix was used. The aggregates were of granite category, which typically refers to plutonic rocks with a coarse grain.

2. Elements of CR

The CR of different sizes was sourced from the heavy weight automobile tires. The main reason behind the selection of heavy automobile tires was the comparatively better chemical constituents in proportions of hydrocarbons, ash content and carbon black (Vishnu et al., 2020). The chemical composition of the CR from heavy weight automobile tire is given in Table 1.

Table 1: Chemical properties of heavy weight automobile waste tire.

Heavy weight automobile tires	**Carbon black (%)**	**Rubber hydrocarbon (%)**	**Acetone extract (%)**	**Ash (%)**
	47.5	33	11.8	7.6

III. RESULTS AND DISCUSSION

1. Optimum Binder Content (OBC) for Normal Bituminous Mix

To determine the optimum binder content of the mix produced with conventional bitumen (VG 30) the Marshall mix design method was adopted. The results of the Marshall stability test reflect the performance evaluation of the bituminous mixture. The word 'stability' in the Marshall stability test means the maximum load bearing capacity of the bituminous mix. The aggregate gradation was chosen from the MORTH (5th revision) for bituminous concrete (BC) grading 2 from Table 500-17 (page-189). The bituminous mixture was prepared using various binder percentage (5%, 5.5% and 6%) to trace out the OBC for the mix. Binder percentages were chosen according to the Asphalt Institute manual MS-2 specifications. The OBC of a mix depends directly on the various physical properties of the aggregates used such as, gradation, percentage of water absorption, shape, texture and percentage of air voids (Panda et al. 2017). A change in these properties largely affects the OBC of the mix. It was observed from the results in Figure 2 that the OBC of the mix was found to be 5.5%.

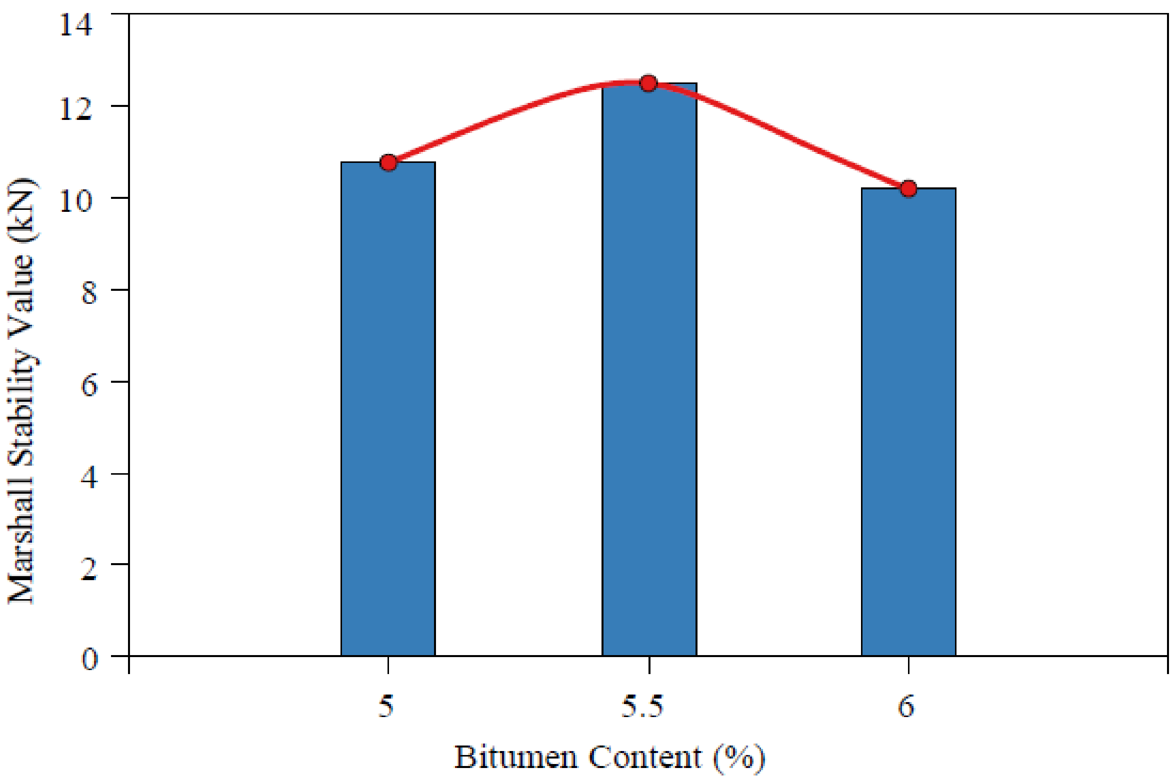

Figure 2: Variation of stability with different percentages of bitumen.

2. Optimum Crumb Rubber Content for Modified Bituminous Mix

The percentage dosage of the crumb rubber (CR) that corresponded to the maximum stability value was taken into consideration in order to estimate the ideal CR content for the bituminous mix. (Vishnu et al., 2020). The crumb rubber modified bituminous (CRMB) mix was prepared by mixing VG 30 grade of bitumen with shredded crumb rubber of four different sizes (2.36 mm, 1.18 mm, 0.60 mm and 0.30 mm) which were obtained from heavy weight automobile tires. The crumb rubber (CR) was added in the mix in five different percentages 8%, 8.5%, 9%, 9.5% and 10% by weight of the binder in the mix. The trial dosage of the CR was selected based on the study by Vishnu et al., where maximum stability was obtained at 9% (between tested values of 7% and 11%) (Vishnu et al., 2020). The Marshall stability test was conducted with all different sizes modified sample with the above-mentioned percentage dosage as shown in Table 2. It was observed that the maximum stability was found at 9.5% dosage of 0.30 mm size of CR. The stability of the bituminous mixture with 9.5% of 0.30 mm size CR was found to be 21.70 KN that is 71% greater than the stability value of the original bituminous mix which is 12.70 KN. The addition of smaller size CR in the bituminous mix have shown an increasing trend in the stability value which is shown in the Figure 3.

Table 2: Variation of Marshall Stability with different sizes and dosages of crumb rubber.

Size (mm)	Marshall Stability value with Crumb Rubber Content (KN)				
	8.00%	**8.50%**	**9.00%**	**9.50%**	**10.00%**
0.3	18.78	19.52	20.8	21.7	21
0.6	14.8	15.46	15.75	17.95	16.8
1.18	10.2	10.9	11.65	14.8	12.97
2.36	9.16	9.82	10.08	13.86	12.65

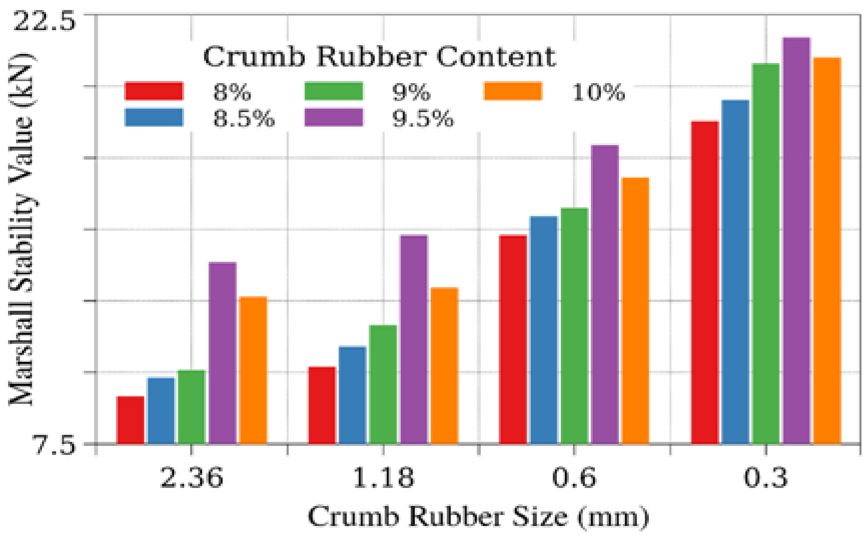

Figure 3: Variation of stability with crumb rubber sizes and dosages.

3. Evaluation of Tensile Strength of the Bituminous Mix

The bituminous samples, conventional mixture and modified CR mix was subjected to indirect tensile strength (ITS) following the ASTM D 6931-07 to find the tensile strength ratio (TSR). The test was carried out for both conditioned (wet condition) and un-conditioned (dry condition) at a temperature of 25 °C with a deformation rate of 50.8 mm/min in order to later arrive at the moisture susceptibility of the mix. Firstly, the un-conditioned CR modified samples were tested at room temperature (25 °C) and observed that the addition of CR dosages in the bitumen increases the tensile strength up to a dosage of 9.5% and then gradually reflects a falling tendency. It was observed from the Figure 4 that the tensile strength of the bituminous mix with 0.30 mm size of CR showed 794 Kpa which is 39% higher than the ITS as observed for the conventional mix which was found to be 571 Kpa as given in Table 3.

Table 3: Changes in the ITS of bituminous mixture in relation to varying sizes and quantities of crumb rubber.

Size (mm)	Indirect Tensile Strength with Crumb Rubber Content (Kpa)				
	8.00%	**8.50%**	**9.00%**	**9.50%**	**10.00%**
0.3	780	782	790	794	788
0.6	775	777	785	789	783
1.18	767	769	777	781	775
2.36	760	762	770	774	768

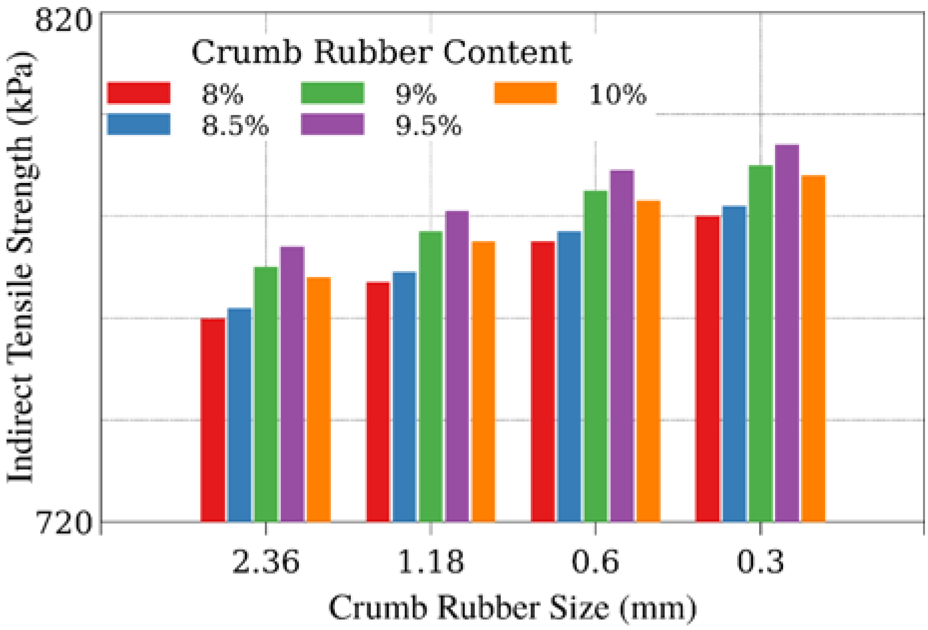

Figure 4: Change in ITS of bituminous mix with different sizes and dosages of crumb rubber.

Influence of Moisture on Bituminous Mixture

Flexible pavements are very susceptible to moisture damage which is one of the fatal parameters considered during the design of pavements (Hamedi GH, 2018). The moisture inclusion deteriorates the asphalt mixture. Generally, the moisture is induced in the asphalt mix because of insufficient bond between the binder and the aggregates and sometimes, due to the loss of binder cohesion. In order to look into the moisture susceptibility of the bituminous mixture the tensile strength test (TSR) was conducted following the ASTM D6931standard. The samples were tested for both wet and dry condition and subsequently the TSR was calculated by dividing the ITS $_{wet}$ by ITS $_{dry}$ multiplied by 100 i.e.,

$$\text{TSR}\ (\%) = \frac{ITS_{wet}}{ITS_{dry}} \times 100$$

Where, ITS $_{wet}$ = indirect tensile strength in wet condition. ITS $_{dry}$ = indirect tensile strength in dry condition.

The resistance to moisture susceptibility in the bituminous mix increases with the inclusion of smaller particle size of the CR (0.30 mm) as shown in Table 4 up to a dosage of 9.5% and shows a falling trend beyond this which is shown in Figure 5.

Table 4: Variation of Tensile Strength Ratio (TSR) with different sizes and dosages of crumb rubber.

Size (mm)	Tensile Strength ratio with Crumb Rubber Content(%)				
	8.00%	**8.50%**	**9.00%**	**9.50%**	**10.00%**
0.3	84	87	90.1	92.15	88
0.6	83.6	86.5	89.52	91.1	86.52
1.18	83.1	86.12	87.1	89.56	86.14
2.36	82.92	85.91	88.5	89.05	85.95

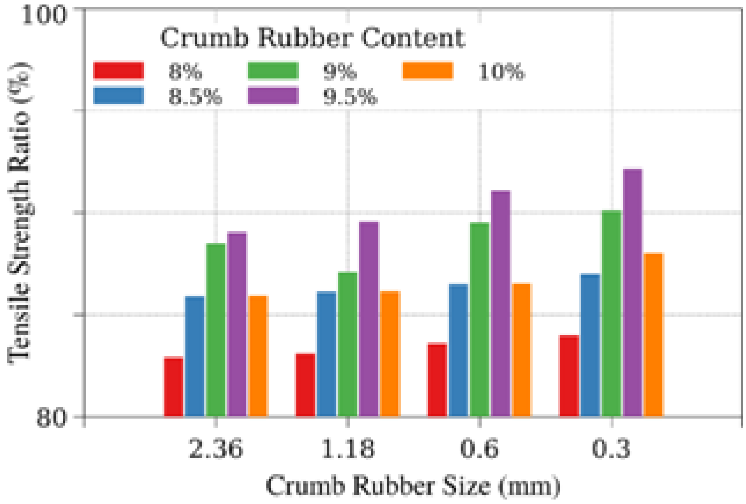

Figure 5: Change in tensile strength ratio to different crumb rubber sizes and dosages.

4. Assessment of Fatigue Characteristics of the Bituminous Mix

For accessing the fatigue properties of the bituminous mix, the indirect tension test (IDT) was examined under repetitive loading to simulate field traffic condition and data collected with controllable loading frequencies and magnitude and vertical and horizontal deformations in the bituminous specimen was measured with the help of LVDTs. The bituminous specimens were prepared by mixing the aggregates and binder together at optimum mix temperature with a compaction of 75 blows on both sides of the specimen using Marshall hammer following the Marshall mix design approach at OBC. The specimen was held in the cabinet between two steel strips and subjected to a steady repeated load with a 0.1 s loading period and a 0.9 s rest interval (Vishnu et al., 2020). The loading continued till the failure of the sample and for each loading cycle, the vertical and horizontal deformations were correctly noted down. With the help of this data, the resilient modulus (M_R) of samples (conventional and modified bituminous mixture) were found as per ASTM:D-4123 1995.

$$M_R = \frac{P\ (0.27 +\ \mu_R)}{H_R h}$$

Where,

P is the repeated load

μ_R is the Poisson's ratio

H_R is the horizontal deformation and h is the specimen height in millimeter

As per ASTM: D-4123 1995, the recoverable tensile strain after a loading cycle of 50 to 200 is known as the initial tensile strength of the mix. This parameter indicates the bituminous mixes performance under repetitive loading. To find out the maximum initial horizontal tensile strain of the bituminous mix (in micro-strain) was calculated following the equation

$$\varepsilon_{max} = \sigma_{max} \frac{1 + 3\mu_R}{M_R}$$

Where,

σ_{max} is the maximum tensile strain at the mid-section of the sample specimen.

5. Change in Fatigue Life (Nf) for Different Percentage and Different Sizes of Crumb Rubber

After conducting the fatigue test, it was noticed that the size of crumb rubber (CR) greatly affects the fatigue life (Nf) of the bituminous mixture. The results of the fatigue life and the initial micro-strain has been given in the Table 5 and Figure 6. It is observed that fatigue life of the bituminous mix increases with the increase of the dosage of the CR (0.30 mm) up to 9.5% and shows a falling trend after that. Also, the smaller particle sizes of the CR showed high fatigue life compared to the largely sized CR particle. It is to be noted that apart from the source of origin of the CR, the size and dosage of the CR in the bituminous mix greatly influences the fatigue life of the mix. The table reflects that for a relatively smaller particle size of the CR i.e., 0.30 mm, the fatigue life was 8850 cycles. This shows a 97.54% increment of the fatigue life compared to the normal bituminous mix which was 4469 cycles.

Table 5: Fatigue properties of unaltered and adapted bituminous blends incorporating diverse crumb rubber sizes.

Mixture of Bitumen + Crumb Rubber (%)	**Crumb Rubber size (mm)**							
	0.3		**0.6**		**1.18**		**2.36**	
	Fatigue Life (Cycles)	**Micro-strain**	**Fatigue Life (Cycles)**	**Micro-strain**	**Fatigue Life (Cycles)**	**Micro-strain**	**Fatigue Life (Cycles)**	**Micro-strain**
0	4480	190	4480	190	4480	190	4480	190
8	8235	142	7968	143.5	7718	144.1	7468	145
8.5	8400	136	8125	137.1	7896	138.2	7636	139.5
9	8721	129	8486	131.5	8140	133.1	7835	134.1
9.5	8850	145	8559	147.1	8268	148.2	7948	150.1
10	8578	162	8289	163.2	8026	164.1	7750	165.6

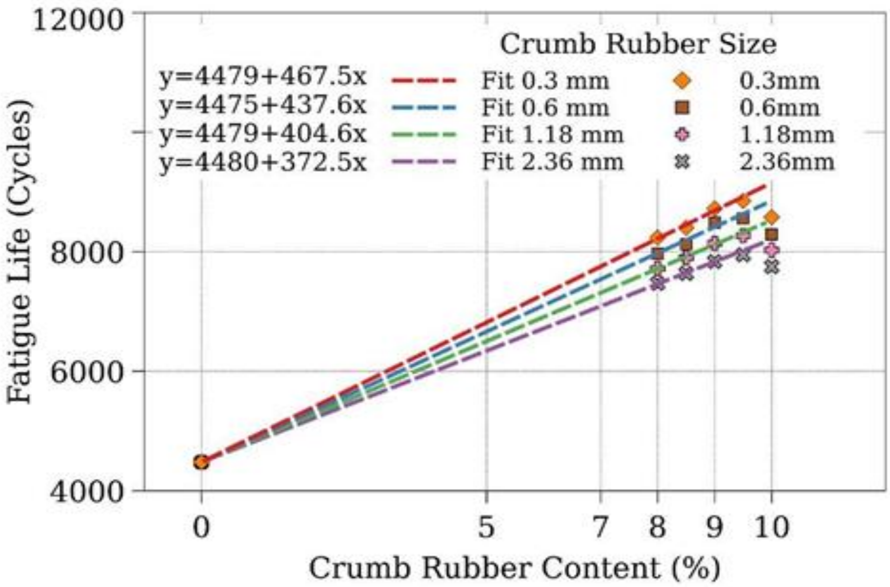

Figure 6: Fatigue life (cycles) with respect to different crumb rubber sizes and dosages.

Change in Resilient Modulus (M_R) with Different Percentage and Different Sizes of Crumb Rubber.

The ratio between the applied stress to the recoverable strain is the resilient modulus of the mix. The size and dosage of crumb rubber (CR) greatly influences the resilient modulus of the bituminous mixture. It has been witnessed from the work that, the inclusion of smaller particle size crumb rubber (0.30 mm) till a dosage of 9.5% increases the resilient modulus after which it seems to decrease. The gradual incremental size (0.60 mm, 1.18 mm, 2.36 mm) of the CR when added to the bituminous mix tends to decrease the resilient modulus of the mix which has been depicted in Table 6 and Figure 7.

Table 6: Resilient Modulus of un-modified and modified bituminous blends incorporating different crumb rubber size.

Mixture of Bitumen + Crumb Rubber (%)	Crumb Rubber size (mm)							
	0.3		0.6		1.18		2.36	
	Resilient Modulus (Mpa)	Micro-strain	Resilient Modulus (Mpa)	Micro-strain	Resilient Modulus (Mpa)	Micro-strain	Resilient Modulus (Mpa)	Micro-strain
0	3121	190	3121	190	3121	190	3121	190
8	4550	142	4436	143.5	4328	144.1	4226	145
8.5	4579	136	4486	137.1	4385	138.2	4329	139.5
9	4722	129	4598	131.5	4512	133.1	4398	134.1
9.5	4814	145	4689	147.1	4596	148.2	4506	150.1
10	4705	162	4590	163.2	4469	164.1	4391	165.6

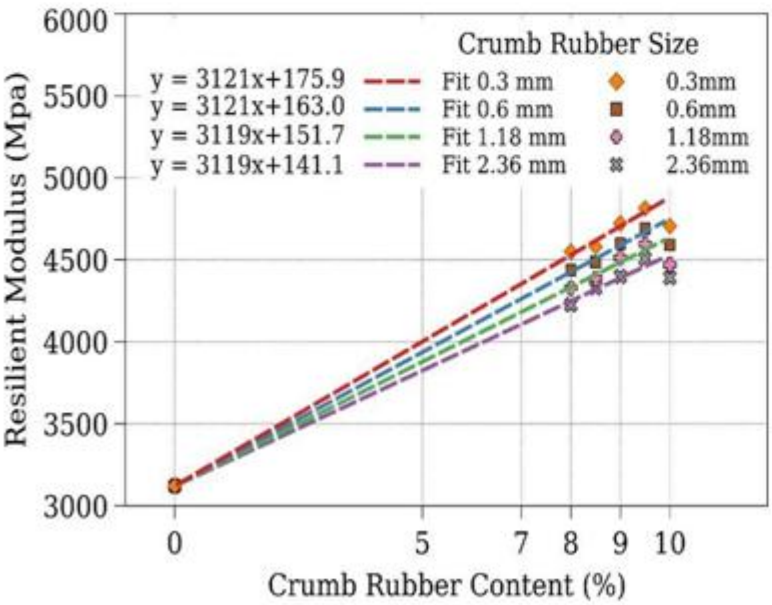

Figure 7: Resilient Modulus (Mpa) with respect to different crumb rubber sizes and dosages.

IV. CONCLUSIONS

From the experimental study, the following major conclusions can be comprehended as follows.

- The optimum crumb rubber content was determined to be 5.5% by weight of the overall mix and 9.5% with respect to the binder weight.
- Once the bituminous mixture's crumb rubber content was increased to a dose of 9.5%, it exhibited a declining trend in both its indirect tensile strength and stability. In comparison to the traditional bituminous mix, it was discovered that the sample's indirect tensile strength had improved by 39% and its stability value had risen by 71%.
- The resistance to moisture susceptibility as observed was 56% higher than that of the conventional bituminous mix.
- Among the different particle size of crumb rubber used for the study the remarkable increase in the fatigue life was observed with the least size of crumb rubber (0.30 mm).
- The fatigue life of the bituminous mixture modified with 0.30 mm size of crumb rubber showed an increment of 98% as compared to the conventional bitumen mix.
- The resilient modulus of the bituminous mix modified with 0.30 mm size of crumb rubber showed an increase of 50%.

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