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Enhancing Pavement Performance and Economy through Crumb Rubber Modified Bitumen: A Sustainable Engineering Approach

A.F.S. Ahad Rahman Khan*[,a], Nafisa Tabassum[b]

[a]Roads & Highways Department (RHD), Bangladesh

[b]Department of Civil Engineering, United International University, Dhaka 1212, Bangladesh

***Corresponding Author:** A.F.S. Ahad Rahman Khan (ahadrahman005@gmail.com)

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Abstract

The reuse of waste materials in infrastructure is a growing focus in materials engineering for enhancing both performance and sustainability. This study modified a conventional 60/70 penetration grade bitumen with crumb rubber derived from waste tires. Crumb rubber was incorporated in varying proportions (4%, 8%, 12%, 16% by weight of bitumen) using a controlled wet process at elevated temperature. The modified binders and resultant asphalt mixes were then evaluated through standard laboratory tests (penetration, softening point, ductility, flash/fire point) and Marshall mix design procedures. Results indicate that a 10% crumb rubber content is optimal, yielding significant improvements in binder properties and mix performance. The 10% Crumb Rubber Modified Bitumen (CRMB) exhibited a 25% reduction in penetration and 50% reduction in ductility (indicating increased stiffness), along with a 10–12% increase in softening, flash, and fire points, signifying enhanced thermal stability and safety. Marshall stability of the asphalt mix improved by about 25% with CRMB, while the optimum binder content was 0.6% lower than that of the control mix, reflecting more efficient binder usage. CRMB also showed superior viscoelastic behavior and a higher fatigue life compared to the unmodified binder, indicating better long-term performance under cyclic loading. Economically, the use of CRMB is advantageous: approximately 8% lower binder material cost was observed for a typical pavement section, owing to reduced bitumen requirements and the substitution of cheaper recycled rubber. These findings demonstrate that incorporating waste tire rubber can transform conventional bitumen into a more durable, thermally stable, and cost-effective paving material, contributing to sustainable infrastructure development.

Keywords: Crumb Rubber Modified Bitumen (CRMB), Bituminous Binder Modification, Sustainable Pavement Materials, Rheological Properties, Marshall Mix Design, Economic Analysis

Introduction

Each year, millions of end-of-life tires are discarded worldwide, creating a significant environmental burden, especially in rapidly urbanizing countries like Bangladesh. Due to their non-biodegradable nature and resistance to decomposition, waste tires accumulate in landfills or are incinerated, leading to severe air, soil, and water pollution [1,2]. In response to this challenge, the use of crumb rubber derived from waste tires as a bitumen modifier in flexible pavements has gained attention in recent decades. This approach not only diverts substantial waste from landfills but also enhances the performance characteristics of asphalt binders and mixtures [3–5]. Crumb Rubber Modified Bitumen (CRMB) is a sustainable and technically promising material that improves the engineering properties of conventional bitumen. Several studies have demonstrated that the inclusion of rubber particles significantly increases the binder's softening point, reduces its temperature susceptibility, and enhances its viscoelastic response, thereby improving rutting resistance and long-term pavement durability [6–9]. Additionally, the elastic recovery properties introduced by the rubber particles help mitigate cracking and fatigue under cyclic traffic loads which is a critical requirement for modern road infrastructure [10–12].

However, implementing CRMB in practice can present certain technical challenges, particularly in the local context of Bangladesh. The quality and consistency of locally sourced crumb rubber can vary (e.g. in terms of particle size distribution and rubber content), and mixing process constraints (such as adequate shearing and temperature control) can affect the uniformity and stability of the modified binder. Ensuring proper dispersion of the rubber within the bitumen and maintaining storage stability are practical concerns that must be addressed for field applications. The interaction mechanisms between crumb rubber and bitumen primarily through absorption of light fractions and physical swelling result in a modified binder with superior rheological and thermomechanical performance [13,14]. Studies have shown that CRMB exhibits enhanced resistance to thermal cracking at low temperatures and better deformation recovery at high temperatures, making it suitable for regions with variable climatic conditions [15,16]. Moreover, the improved binder-aggregate adhesion due to CRMB contributes to reduced stripping and enhanced moisture resistance [17]. Furthermore, while polymer-modified bitumens (e.g., using Styrene-Butadiene-Styrene (SBS) or Styrene-Butadiene Rubber (SBR) polymers) are known to greatly improve asphalt performance, their high cost and limited availability in developing regions hinder widespread use. CRMB offers a more accessible, low-cost alternative aligning with circular economy principles by utilizing local waste resources [18–20].

A comparative look at other modification methods shows that properly formulated CRMB can deliver performance on par with conventional polymer-modified binders in many aspects. For example, field studies have found that asphalt mixtures with crumb rubber modified binders can achieve similar in-service performance to those with SBS-modified binders over several years of heavy traffic. Such findings suggest that the performance gap between waste-tire rubber and virgin polymer modifiers can be minimal when formulations are optimized. Notably, a recent industry survey reported that 50% of surveyed agencies observed rubber-modified asphalt performing as well as or better than SBS-modified asphalt, with only 8% perceiving it to be inferior. Moreover, multiple studies have reported net life-cycle cost savings when using rubber-modified asphalt in place of conventional mixtures. In contexts like Bangladesh where SBS must be imported, replacing a portion of expensive bitumen or polymer additives with abundant domestic waste rubber can yield economic benefits. The addition of waste tire rubber not only lowers raw material costs but also reduces the need for virgin polymer and bitumen, thereby contributing to both cost efficiency and sustainability.

Beyond mechanical performance, the environmental and economic implications of CRMB have become a focal point of recent research. By partially substituting bitumen with recycled rubber, CRMB helps reduce the consumption of non-renewable resources and the environmental impact of tire waste. Life-cycle assessment studies indicate that although the initial processing of CRMB may require additional energy (for grinding rubber and blending), the improved pavement longevity and reduced maintenance frequency can offset these costs and lead to overall savings. Agencies are increasingly considering these sustainability benefits alongside engineering performance.

In recent years, research efforts have been directed toward optimizing CRMB formulations and understanding their behavior. Researchers have identified roughly 10–20% crumb rubber by weight of bitumen as an effective range for performance improvement without compromising workability [21,22]. Wet process blending (where rubber is pre-mixed into hot bitumen) has been found more effective than dry process (adding rubber directly into asphalt mix) for achieving uniform modification. Field trials and long-term studies further validate the positive impact of CRMB on pavement performance under diverse traffic and climate conditions [23–25]. For example, a field performance study in Spain observed that high-volume road sections paved with CRMB showed aging and mechanical performance very similar to those paved with traditional SBS-modified asphalt over a 5-year period. Such evidence of long-term success in the field builds confidence that CRMB can reliably extend pavement life. Another focus has been the effect of crumb rubber particle size and processing on binder quality. Fine rubber particles (e.g., ≤0.5 mm) tend to disperse more uniformly and improve the storage stability of the binder, whereas larger particles can increase stiffness and rut resistance but may pose blending and segregation challenges [26-27]. Overall, the literature suggests that with proper material selection and mixing protocols, CRMB can significantly enhance pavement performance while contributing to waste recycling and cost reduction. This study seeks to contribute to this growing body of knowledge by evaluating the physical and mechanical performance of CRMB prepared through the wet process, focusing on identifying the optimum crumb rubber content for flexible pavement applications in Bangladesh. The goal is to assess whether a moderate addition of crumb rubber (on the order of 10% by bitumen weight) can yield substantial benefits in laboratory measures of binder and mix performance, and to discuss the broader implications for sustainable pavement engineering.

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Relevance of CRMB in the Bangladeshi Context

Bangladesh is grappling with two pressing issues: deteriorating road infrastructure and mounting solid waste, particularly from used tires (Figure 1). With over 90% of the country's roads built using flexible pavements [28], extreme weather conditions like intense heat, heavy monsoons, and high moisture quickly take a toll, causing rutting, cracking, and reduced road safety.

At the same time, the country produces more than 90,000 tons of waste tires every year [29]. These tires, due to their tough, cross-linked structure, are difficult to dispose of and often end up in landfills or are burned, both options being harmful to the environment [30].

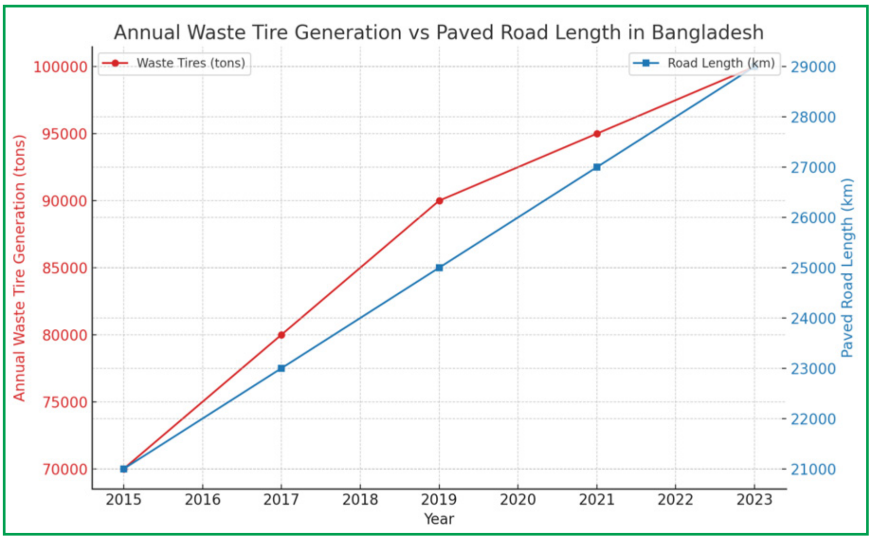

Figure 1. Annual waste tire generation vs paved road length in Bangladesh

Crumb Rubber Modified Bitumen (CRMB) offers a practical, sustainable solution to both problems. By blending recycled tire rubber into bitumen, CRMB strengthens road surfaces, making them more resistant to damage, while also giving new purpose to waste tires. For Bangladesh, CRMB is not just an engineering upgrade, it's a smart, eco-friendly strategy that boosts pavement performance and supports waste recycling efforts.

Materials and Methods

Methodology

This study was designed to evaluate the potential of crumb rubber as a performance-enhancing and sustainable modifier for conventional asphalt binder used in flexible pavement construction. A structured experimental program was carried out, comprising the preparation of crumb rubber modified binders, laboratory characterization of their physical properties, and performance testing of asphalt mixtures using the Marshall mix design method. The overall approach was to first produce CRMB at various rubber concentrations and test the binder properties, and then to incorporate the optimum binder into asphalt concrete samples to assess improvements in mixture performance relative to an unmodified binder control.

Materials

The base bituminous binder used in this study was a 60/70 penetration grade paving bitumen, which is commonly utilized for flexible pavements in Bangladesh. Representative bitumen samples were obtained from the Transportation Engineering Laboratory of the Bangladesh University of Engineering and Technology (BUET). The modifier, crumb rubber, was sourced from waste tire vulcanizing workshops in Dholaikhal, Dhaka – a local hub for recycled rubber. To ensure consistency, only rubber particles that passed through a No. 30 sieve but were retained on a No. 50 sieve were collected and used (see Figure 2). This particle size corresponds to approximately 0.3 mm. The choice of a 0.3 mm crumb size was deliberate: finer rubber particles tend to disperse more uniformly into the hot bitumen and facilitate a more stable modification (reducing phase separation) [31]. This size range is also readily available in the local market, ensuring the approach remains practical for wider implementation.

Figure 2. Different type of crumb rubber based on particle size

Preparation of Crumb Rubber Modified Bitumen (CRMB)

The bitumen modification was performed using the wet process, which involves blending the crumb rubber directly into the hot liquid bitumen. Approximately 500 g of the base bitumen was heated in a clean, open-top metal container to a fluid state (around 160°C) before adding the rubber. Crumb rubber was introduced to the bitumen at the target proportions of 4%, 8%, 12%, and 16% by weight of the binder. The blending was executed in two stages for each batch:

- **Manual Mixing:** Initially, the rubber was stirred into the hot bitumen manually for about 3–4 minutes at 160°C to ensure even dispersion and wetting of the particles.
- **Mechanical Shearing:** This was followed by high-speed mechanical mixing using a lab-scale impeller mixer at 1200 rpm for 50–60 minutes. During this period, the temperature was maintained between 160–170°C. Care was taken to avoid overheating or local scorching of the

rubber. The prolonged high-shear mixing allows the rubber particles to swell and interact with the bitumen's lighter oily fractions, promoting a homogeneous modification.

After mixing, the crumb rubber modified binders were cooled to room temperature and stored in airtight containers for subsequent testing. The wet process adopted here is compatible with standard laboratory equipment and procedures, and it mirrors methods reported in literature for producing CRMB with good performance attributes.

Bitumen Characterization Tests

A series of standard laboratory tests was conducted on both the unmodified (neat) bitumen and the CRMB samples to quantify the effects of crumb rubber on key binder properties. Five primary tests were performed, each following ASTM and AASHTO standard methods, as listed below:

- **Penetration Test (ASTM D5 / AASHTO T49):** Measures the hardness/consistency of bitumen by the depth a standard needle penetrates at 25°C under a 100 g load for 5 seconds.
- **Softening Point Test (Ring-and-Ball, ASTM D36 / AASHTO T53):** Determines the temperature at which the binder softens enough to allow a steel ball to drop a specified distance, indicating thermal susceptibility.
- **Ductility Test (ASTM D113 / AASHTO T51):** Measures the elongation capacity of bitumen by pulling a briquette of binder apart at 25°C and noting the length at which it breaks (reported in cm), indicating flexibility.
- **Flash and Fire Point Tests (Cleveland Open Cup, ASTM D92 / AASHTO T48):** Determine the temperatures at which the binder emits vapors that can ignite (flash point) and sustain combustion (fire point), related to safety in handling and high-temperature performance.
- **Specific Gravity Test (ASTM D70 / AASHTO T228):** Determines the density of the binder, useful for converting volume–mass in mix designs.

These tests provided insights into the binder's hardness (penetration), thermal behavior (softening point, flash/fire point), tensile ductility, and overall consistency. By comparing results across the range of rubber contents, the influence of crumb rubber on binder stiffness, temperature susceptibility, elasticity, and safety could be assessed.

Marshall Mix Design

In addition to binder-level tests the performance of CRMB was further assessed using the Marshall Mix Design method, employing the Marshall Test Apparatus as illustrated in Figure 3. This procedure was carried out for both the unmodified and the optimum CRMB binder (10% rubber) to determine the mixture properties and optimum binder content (OBC) in each case. A dense-graded aggregate blend suitable for wearing course (surface layer) construction was used for all mixes. The aggregate gradation and preparation followed local pavement specifications, kept constant to isolate the effect of binder type.

Figure 3. Marshall stability test apparatus

Standard Marshall cylindrical specimens (101.6 mm diameter × 63.5 mm height) were compacted with 75 blows per side using a Marshall hammer, per ASTM D6926. For each binder type, a series of specimens was prepared at varying binder contents around the expected optimum (approximately 4–6% by weight of mix for the control, with adjustments for CRMB). The Marshall stability and flow values were measured for each specimen following ASTM D6927. Stability (maximum load sustained) indicates the mix's strength, while flow (deformation at failure) indicates its flexibility. Bulk specific gravity of the compacted mixes, along with theoretical maximum density (ASTM D2041), were used to compute volumetric parameters: air void content (Va), voids in mineral aggregate (VMA), and voids filled with bitumen (VFB). The OBC for each binder was determined by the standard Marshall criteria (typically the binder content that achieves 4% air voids while satisfying stability and flow requirements). This procedure was done separately for the conventional binder mix and the CRMB mix.

By conducting a parallel Marshall design, we obtained a direct comparison of how the crumb rubber modification alters the mix requirements and performance metrics. Key outcomes recorded included the Marshall stability (kN), flow (0.25 mm units), bulk density, and the resulting OBC for each case. These results were later used to quantify improvements in load-bearing capacity and material economy (binder saving) due to CRMB.

Results

Effect of Crumb Rubber on Bitumen Properties

The incorporation of crumb rubber into 60/70 grade bitumen led to significant modifications in its physical characteristics. Five standard tests: penetration, softening point, ductility, flash and fire point, and specific gravity were conducted to evaluate these effects. The test outcomes are presented in Table 1.

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Table 1. Bituminous test results

Crumb Rubber %	Penetration (0.1 mm)	Softening Point (°C)	Ductility (cm)	Flash Points (°C)	Fire Points (°C)	Specific Gravity
0%	67	49.7	100+	275	325	1.037
4%	64	52.5	76	282	330	1.044
8%	61	54.5	62	287	334	1.052
12%	58	57.3	50	295	342	1.06
16%	52	60	45	305	360	1.064

A consistent trend was observed as crumb rubber content increased from 0% to 16%. Penetration values decreased by approximately 25%, indicating a stiffer binder that is more resistant to deformation under load. Similarly, ductility a measure of the binder's elasticity declined by about 50%, reflecting a reduced ability to stretch but increased rigidity, which is desirable in hot climates where pavement softening is a concern.

In contrast, parameters related to high-temperature performance showed marked improvement. The softening point increased by 10–12.5%, indicating enhanced resistance to flow at elevated temperatures. Flash and fire points also rose within the same range, which contributes to improved safety during construction. Although specific gravity increased slightly with added rubber, the change was not as substantial as other parameters.

Based on a comprehensive review of these test results and existing literature, a 10% crumb rubber content by weight of bitumen was selected as the optimum content shown in Figure 4 for further investigation [32-34]. This proportion offers a balanced trade-off between stiffness and workability, making it a practical choice for Marshall Mix Design analysis.

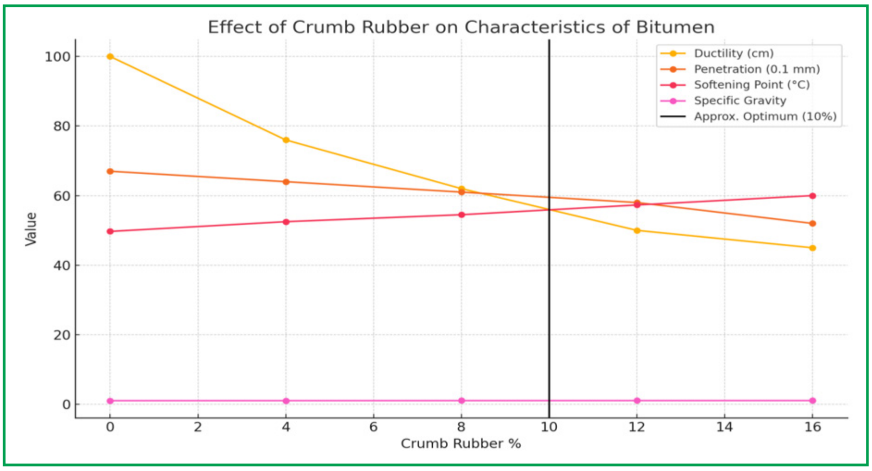
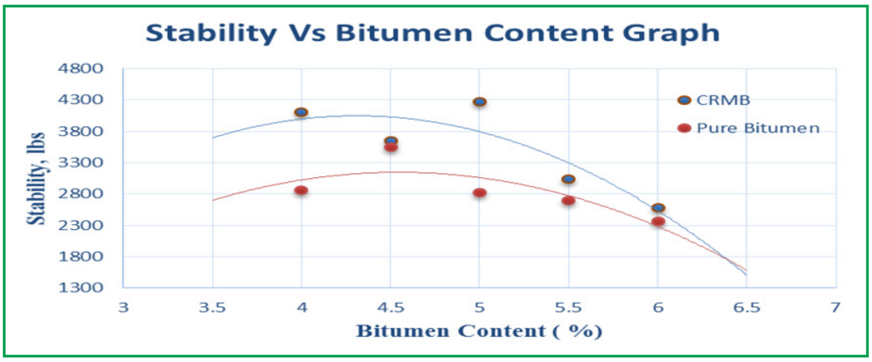


Figure 4. Effect of crumb rubber on the characteristics of bitumen

Comparative Performance: Pure Bitumen vs. 10% CRMB Mix

Marshall test results were conducted to evaluate and compare the performance of conventional bituminous mixes and those modified with 10% crumb rubber. The CRMB mix demonstrated a 25% increase in Marshall stability, indicating significantly enhanced load-bearing capacity. Despite this improvement in stiffness, flow values remained within the acceptable range, suggesting that flexibility was not adversely affected. Additionally, the CRMB mix exhibited higher bulk density, pointing to improved compaction and structural consistency. Notably, the optimum binder content was reduced by 0.6% in the CRMB mix compared to the unmodified mix, implying more efficient binder utilization and improved aggregate coating. These findings collectively suggest that CRMB not only enhances the mechanical properties of the mix but also offers potential material savings, making it a viable and sustainable alternative for flexible pavement construction. A comparative analysis of the six Marshall properties is illustrated in Figure 5.



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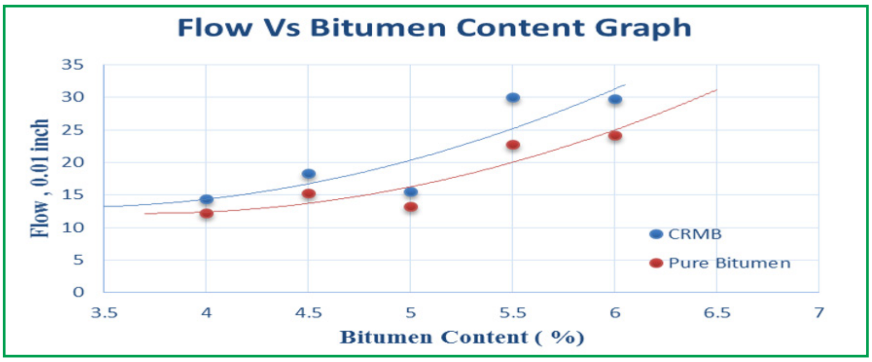

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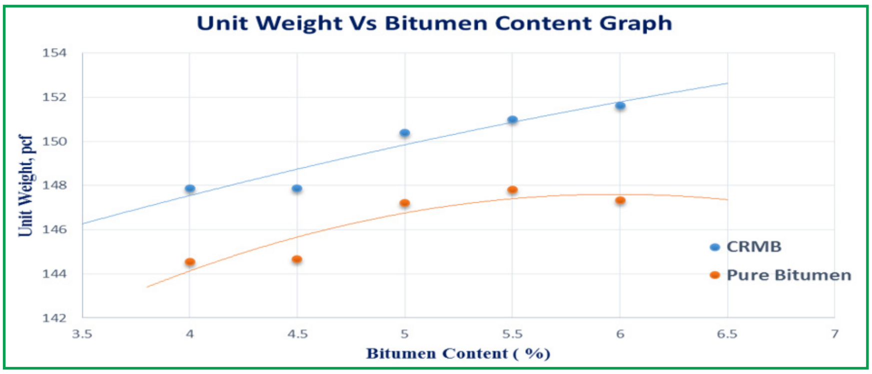

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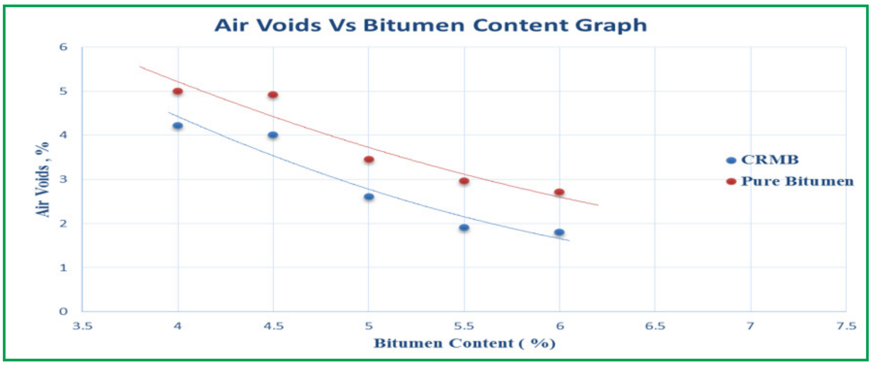

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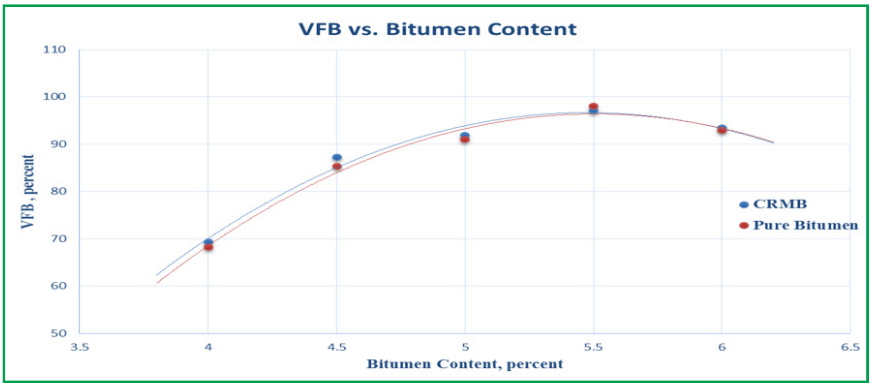

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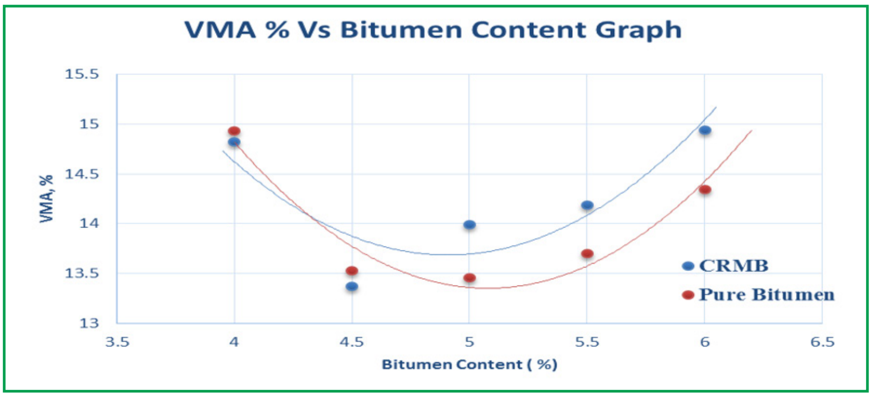

(f)

Figure 5. Comparison between Marshall property curves

Rheological and Mechanical Enhancements in CRMB

The performance evaluation of Crumb Rubber Modified Bitumen (CRMB) demonstrated notable improvements in temperature susceptibility, viscoelasticity, and fatigue resistance—key factors for enhancing pavement durability in Bangladesh's variable climate. The Newtonian viscosity ratio between 25°C and 60°C revealed that CRMB binders are less sensitive to temperature changes compared to unmodified binders. This reduced temperature susceptibility is particularly advantageous for tropical regions like Bangladesh, where pavements are exposed to significant thermal variations between dry and monsoon seasons.

The penetration index (PI) of CRMB binders further confirmed improved thermal stability, indicating a shift toward more elastic and less temperature-sensitive behavior, which is critical for long-term rutting resistance.

From a rheological perspective, the incorporation of crumb rubber introduced pronounced viscoelastic characteristics to the binder, enabling both immediate and delayed recovery under loading conditions. This dual-phase viscoelasticity plays a vital role in resisting fatigue cracking and permanent deformation, especially under repetitive traffic loads. Fatigue testing using indirect tensile strength methods revealed a characteristic three-phase response in CRMB mixes. Phase I is marked by a rapid drop in modulus due to the initiation of micro-cracks, followed by Phase II, which shows a relatively linear and gradual reduction in modulus, indicating controlled crack propagation. Phase III corresponds to the final failure stage, where a sharp decline in stiffness occurs [35].

Economic Analysis

One of the motivations for using waste tire rubber in bitumen is the potential cost savings from reduced bitumen usage and the relatively low cost of the recycled modifier. Table 2 presents a comparison of the estimated binder material costs for constructing 1 km of asphalt pavement (surface course) using conventional versus 10% CRMB binder. The analysis considers the unit costs of materials in Bangladesh and the binder contents determined from the Marshall mix design. Both cases assume a similar pavement layer thickness and volume.

Table 2. Comparison of cost

Basic Item of Surface Course	Conventional Bituminous Road Construction	10% CRMB Bituminous Road Construction
Cost of bitumen per kg (BDT)	82	82
Cost of crumb rubber per kg (BDT)	15	15
Bitumen required in per Km Road (kg)	10*1000	9*1000
Crumb Rubber required in per Km road (kg)	0	1*1000
Total Cost Per Km (BDT)	8,20,000	7,53,000
Saving Per Km Road (BDT)	67,000	
Saving Per Km Road (%)	8.17	

The cost analysis presented demonstrates a clear economic advantage of using 10% Crumb Rubber Modified Bitumen (CRMB) over conventional bitumen. For a 1 km road surface layer, the conventional mix requires approximately 10,000 kg of neat bitumen, costing about 820,000 BDT at 82 BDT/kg. In contrast, the CRMB mix benefiting from a reduced optimum binder content requires only 9,000 kg of bitumen and 1,000 kg of crumb rubber, totaling around 753,000 BDT. This yields a binder cost saving of approximately 67,000 BDT per kilometer, or about 8.2%. These savings arise not only from the reduced bitumen requirement but also from the significantly lower cost of crumb rubber, a recycled material priced at roughly 15 BDT/kg.

Beyond initial construction costs, the long-term economic benefits of CRMB are potentially even greater. Its improved resistance to rutting and cracking is

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expected to reduce maintenance frequency and life-cycle costs. Studies have shown that rubberized asphalt can offer comparable or superior performance to polymer-modified alternatives at a lower overall cost [36-37]. Field reports from U.S. highway agencies also confirm the cost-effectiveness of CRMB, with reductions in asphalt mix costs of $2–$4 per ton when using engineered crumb rubber instead of traditional polymers [38]. These findings underscore the dual benefit of CRMB in enhancing pavement performance while achieving material cost efficiency.

Conclusion

This study highlights the potential of crumb rubber as a sustainable and effective modifier for 60/70 grade bitumen in flexible pavement construction. The inclusion of 10% crumb rubber significantly improved key binder properties—reducing penetration by 25%, lowering ductility by 50%, and increasing softening, flash, and fire points by 10–12.5%—indicating enhanced stiffness and thermal resistance. In the Marshall mix design, the CRMB mix showed a 25% increase in stability and required 0.6% less binder, reflecting better performance and material efficiency. Rheological evaluations further revealed improved temperature susceptibility, elastic recovery, and fatigue resistance, making the modified mix well-suited to Bangladesh's challenging traffic and climatic conditions. Additionally, reusing discarded tires in road construction addresses environmental concerns while contributing to the circular economy.

However, the study has certain limitations. Only one particle size (0.3 mm) of crumb rubber was used, leaving out the effects of finer or coarser particles. The research also focused solely on the wet process and a limited rubber content range, without exploring other techniques such as the dry process or blended modifiers. All tests were conducted under laboratory conditions, without real-world exposure to traffic or environmental stresses. Therefore, while the findings are promising, further field trials and long-term monitoring are necessary to validate the practical durability of CRMB. Nonetheless, this study offers valuable insights into the technical and economic viability of rubberized asphalt in the context of sustainable road infrastructure.

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Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

A.F.S. Ahad Rahman Khan: conceptualization, methodology, software. **Nafisa Tabassum:** data curation, writing, visualization, reviewing and editing.

Data Availability Statement

The data used to support the findings of this study are included within the article.

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