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EFFECTIVE UTILIZATION OF CRUMB RUBBER FROM WASTE TYRE AS A MODIFIER OF BITUMEN FOR ASPHALT MIXES WITH IMPROVED RESISTANCE AGAINST RUTTING AND CRACKING FOR LOCAL OMANI ROADS

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ABSTRACT

Crumb rubber serves as a modifier for bitumen in the production of asphaltic aggregates, utilizing either the dry or wet process. When incorporated through the wet process, crumb rubber-modified bitumen demonstrates enhanced road performance, including increased resistance to rutting and cracking, as well as a higher resilience modulus. In this study, crumb rubber was subjected to thermal pre-treatment and blended with bitumen at temperatures between 160 °C and 180 °C. Physical properties such as viscosity, softening point, penetration value, and ductility were measured. The results reveal that the addition of crumb rubber increases viscosity and elevates the bitumen's softening point. A reduction in penetration value further improves rutting resistance. However, excessive reduction in ductility may compromise resistance to low-temperature cracking. Analytical techniques, including FTIR, SEM, and DSC-TGA confirmed the improved performance of crumb rubber-modified bitumen with respect to rutting and cracking resistance.

KEYWORDS: Crumb Rubber, Modified bitumen, Rutting, Cracking, Asphalt Mixes

1. INTRODUCTION

The widespread use of tire compounds presents a significant environmental pollution challenge, particularly regarding their disposal. Tire waste is recognized as one of the most prevalent and hazardous forms of polymer waste due to its abundance and durability [1]. The management of industrial waste has emerged as a major global concern. Considerable attention has been directed toward the use of crumb rubber, produced from recycled tire rubber, in asphalt modification. Crumb rubber is a granular material obtained by processing scrap tires into small particles, generally ranging from 0.425 mm to 4.75 mm, with optimal performance achieved at particle sizes below 1 mm [2]. This material is utilized in a variety of applications, such as construction fillers, sports surfaces, and asphalt modification. Effective utilization of crumb rubber in these contexts depends on a thorough understanding of its chemical composition and physical characteristics, including particle size and morphology. Additionally, crumb rubber maintains its inherent elasticity, imparting flexibility and impact resistance to materials, which is particularly beneficial for flexible pavements and sports surfaces [3].

The ongoing rise in vehicle registrations has resulted in a substantial increase in used tire generation, with the total number of vehicles from December 2024 to the present surpassing 1,753,872 [4]. The Sultanate of Oman is currently experiencing an accumulation of used tire waste, highlighting the necessity for local recycling initiatives. The Environment Authority of Oman (EAO) has suspended the issuance of permits for exporting this waste, with the objective of enhancing the domestic utilization of used tires [5].

Extensive research has investigated the recycling and reuse of scrap tyres in various forms, including whole, shredded, and granulated tyres [6]. Crumb rubber (CR), produced from recycled tire rubber, has attracted considerable interest for its application in asphalt modification. Modified binders demonstrate enhanced rheological and performance properties. In Oman, incorporating modified bitumen into road construction can extend pavement lifespan by providing increased resistance to rutting, bleeding, and cracking, thereby reducing construction and maintenance costs [7,8]. In the present study, crumb rubber was thermally pre-treated and blended with bitumen at 160-180 °C. The resulting modified bitumen was subsequently evaluated for various properties.

2. METHODOLOGY

Crumb rubber samples were sourced from the MARN Flexible Rubber Factory in Al-Nahdah. Penetration grade bitumen 60/70 was obtained from Muscat International Bitumen LLC, located in Al Qurum, Muscat, Sultanate of Oman.

2.1 Thermal Activation of Crumb Rubber

Crumb rubber was thermally activated in a muffle furnace at 160-180°C for 30 minutes. This process improves the surface and internal structure of the rubber particles, thereby enhancing their compatibility and reactivity with bituminous binders.

2.2 Experimental Procedure:

Initially, 96 grams of bitumen were heated to 180°C using a high-shear homogenizer. Subsequently, 4 grams of crumb rubber were gradually introduced into the hot bitumen under continuous stirring, facilitating swelling and partial dissolution of the rubber. The resulting mixture was dispersed at 3,500 rpm for 60 minutes. After mixing, the modified binder was allowed to cool to room temperature prior to further testing. This preparation procedure was repeated for different ratios of bitumen and crumb rubber for preparation of CRMB.

2.3 Viscosity Test:

The viscosity of crumb rubber-modified bitumen (CRMB) was measured in accordance with ASTM D4402. The binder was heated in an oven to 135°C until a uniform consistency was achieved, then transferred to a preheated rotational viscometer sample chamber, ensuring the absence of air bubbles. The chamber was placed in a temperature-controlled bath to achieve thermal equilibrium. The appropriate spindle was immersed to the specified depth at 20 rpm, and the test was initiated. Once the torque reading stabilized, the viscosity value indicated by the instrument at that temperature was recorded [9].

2.4 Softening point test:

The softening point of CRMB was determined according to ASTM D36 using the Ring-and-Ball apparatus. The binder was heated and poured into two clean brass rings, which were then allowed to cool. Excess binder was trimmed to produce smooth, flush discs. The rings were suspended in a water bath, and standard steel balls were placed centrally on each binder disc. The bath temperature increased at a constant rate until each softened disc allowed its ball to drop 25 mm. The temperature at the point of ball drop was recorded [10].

2.5 Penetrometer test:

The penetration value of CRMB was determined in accordance with ASTM D5. The binder was heated to

a fluid state, poured into standard penetration cups, and allowed to cool. A standard needle with a total load of 100 g was placed on the binder surface and released to penetrate vertically for 5 seconds. The depth of penetration, measured in 0.1 mm increments, was recorded from the instrument display [11].

2.6 Ductility Value test:

The ductility of B-CRMB was measured in accordance with ASTM D113. The binder was heated to a liquid state and poured into standard brass ductility molds, which were positioned on a leveled plate. The molds were cooled at room temperature, then conditioned in a water bath at 25°C, ensuring complete submersion. Following conditioning, the molds were removed from the base plate, the ends were trimmed, and the briquettes were attached to the clips of the ductility testing machine, which was maintained at 25°C. The machine pulled the clips apart at a uniform rate until the samples broke, and the distance to failure was recorded in centimeters as a measure of the B-CRMB's ductility.[12]

2.7 Fourier Transform Infrared Spectroscopy (FTIR) Analysis:

The PerkinElmer Spectrum Two FT-IR Spectrometer was used to identify molecular structures and functional groups in CRMB samples by measuring infrared absorption in the mid-infrared region (4000–400 cm^{-1}) at scan rates exceeding 10 kHz.

2.8 Scanning Electron Microscopy (SEM) Analysis:

The surface morphology and microstructure of activated crumb rubber and crumb rubber-modified

bitumen were examined using a Jeol JSM-7600F Field Emission Scanning Electron Microscope. This instrument provides a resolution of up to 1.0 nm at 15 kV, a magnification range from 8× to over 1 million times, and an operating voltage range of 0.2 to 30 kV. It is equipped with both secondary and backscattered electron detectors to enable detailed imaging of surface features [13].

2.9 DSC-TGA Analysis:

DSC-TGA analysis was conducted using a Julia DSC 500 to evaluate the thermal stability and composition of CRMB samples. The instrument operates over a temperature range of 150°C to 700°C, facilitating the investigation of thermal transitions, melting points, degradation, and weight loss [14].

3. RESULT AND DISCUSSION

The incorporation of crumb rubber (CR) into bitumen leads to an increase in viscosity shown in figure-1. As the CR content increases from 0% to 20%, the viscosity of the modified bitumen rises, producing a stiffer binder that exhibits reduced workability at standard temperatures. This viscosity enhancement is attributed to the swelling of CR particles, which absorb lighter fractions of bitumen and create a more elastic, gel-like network within the binder. The magnitude of this effect is greater at higher CR ratios and is further influenced by factors such as particle size, mixing temperature, and mixing duration [15]. Elevated viscosity enhances rutting resistance and durability at high temperatures but necessitates higher mixing and compaction temperatures. However, excessive CR content above 15% or 20% can result in an overly viscous binder, leading to significant workability challenges.

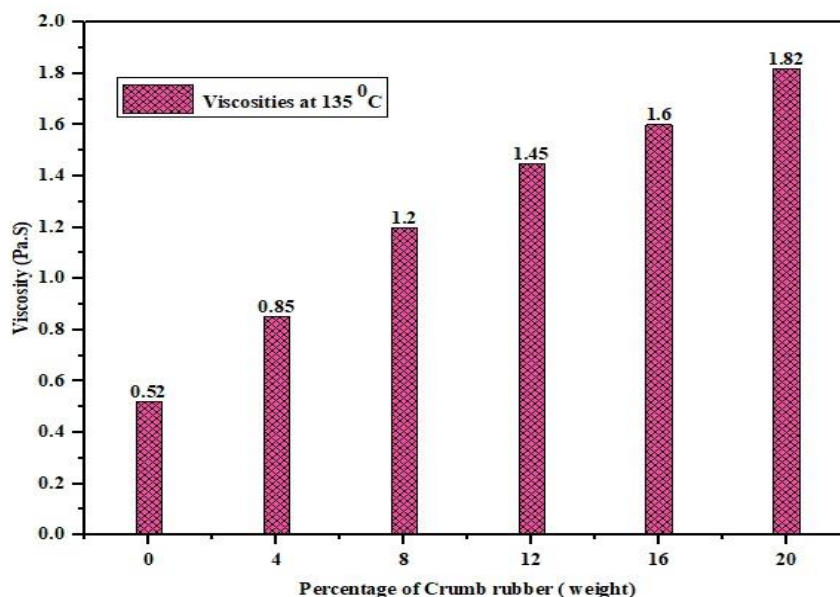


Figure 1: Viscosity of crumb rubber modified bitumen at various weight percentages of crumb rubber.

Increasing the crumb rubber (CR) ratio in modified bitumen results in a higher softening point, thereby enhancing resistance to deformation at elevated temperatures. These results demonstrate that as CR content increases from 4% to 20% by weight, the softening point rises from 53 °C to 65 °C as shown in figure-2. This trend indicates improved thermal stability and stiffness in the modified bitumen.

The penetration value, which reflects bitumen hardness, decreases as the crumb rubber (CR) content increases, indicating a harder, less penetrable binder. For example, adding 4%, 8%, 12%, 16%, and 20% CR yields penetration values of 56, 49, 45, 41, and 39, respectively shown in figure-3. This reduction in penetration value signifies increased stiffness, thereby enhancing the bitumen's resistance to deformation and making it more suitable for high-temperature and heavy-load conditions.

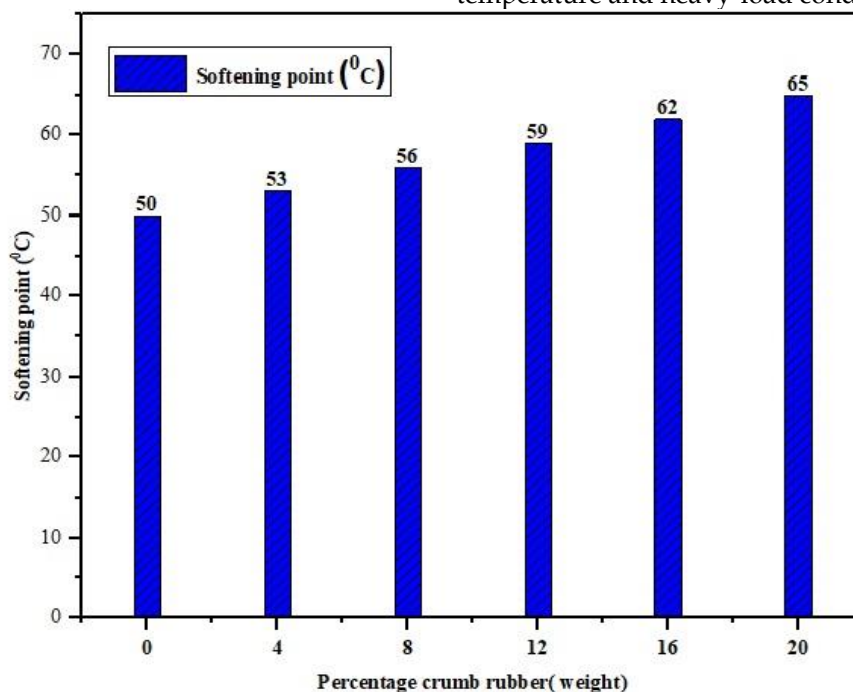


Figure 2: softening point of CRMB at various weight percentages of crumb rubber

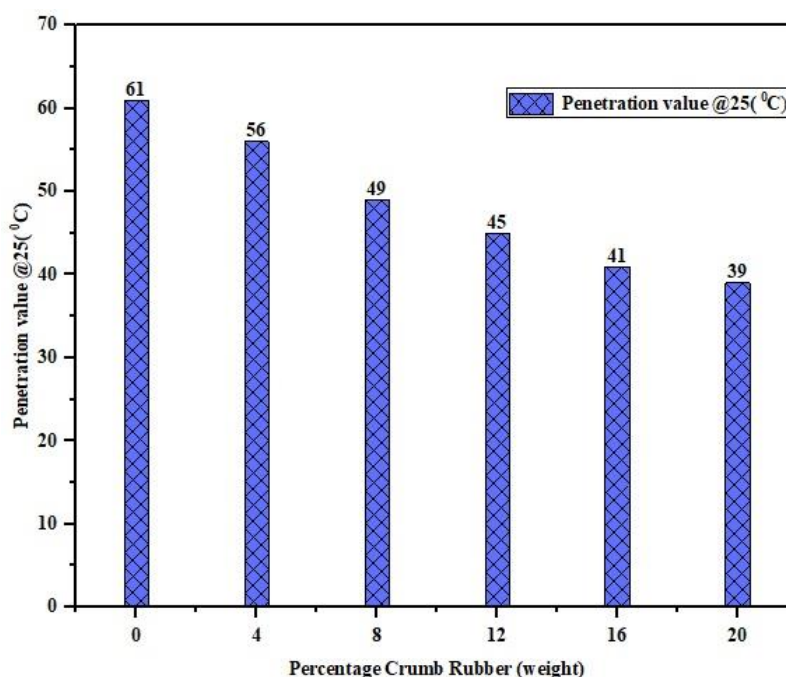


Figure 3: Penetration value of crumb rubber modified bitumen at various weight percentages of crumb rubber

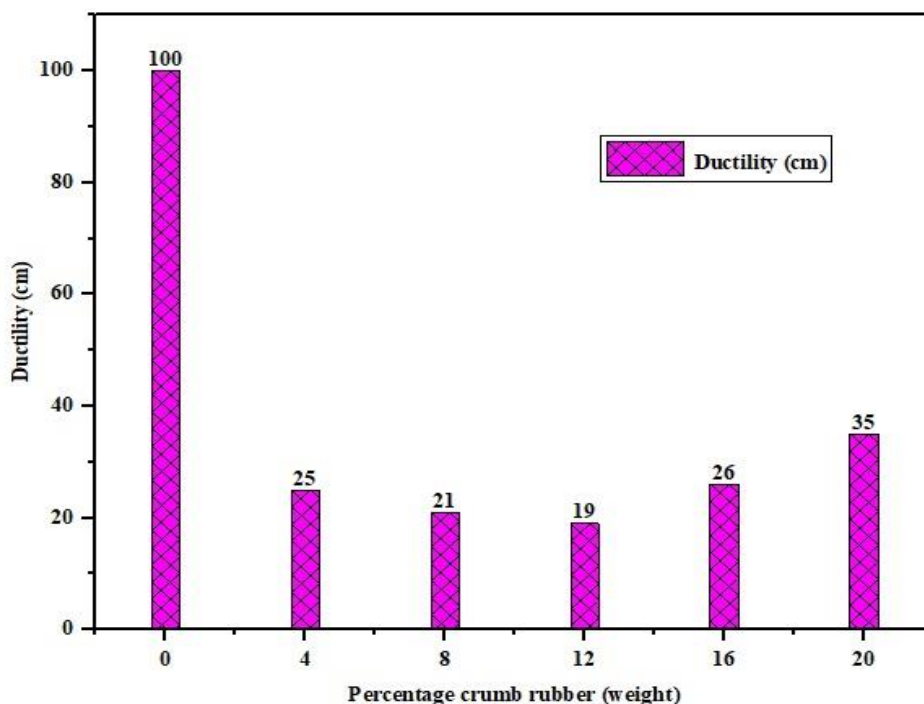


Figure 4: Ductility of crumb rubber modified bitumen at various weight percentages of crumb rubber.

The addition of crumb rubber (CR) to bitumen in proportions up to 10% generally leads to a decrease in ductility compared to unmodified bitumen. This reduction is attributed to the stiffening effect of the rubber and its absorption of lighter bitumen fractions, which restricts the binder's flexibility at low temperatures. However, when the CR content increases from 12% to 20%, ductility tends to

improve, likely due to the development of a more elastic network within the bitumen. This enhanced elasticity increases the material's capacity to deform without cracking, especially under low-temperature conditions.

3.1 Fourier Transform Infrared Spectroscopy

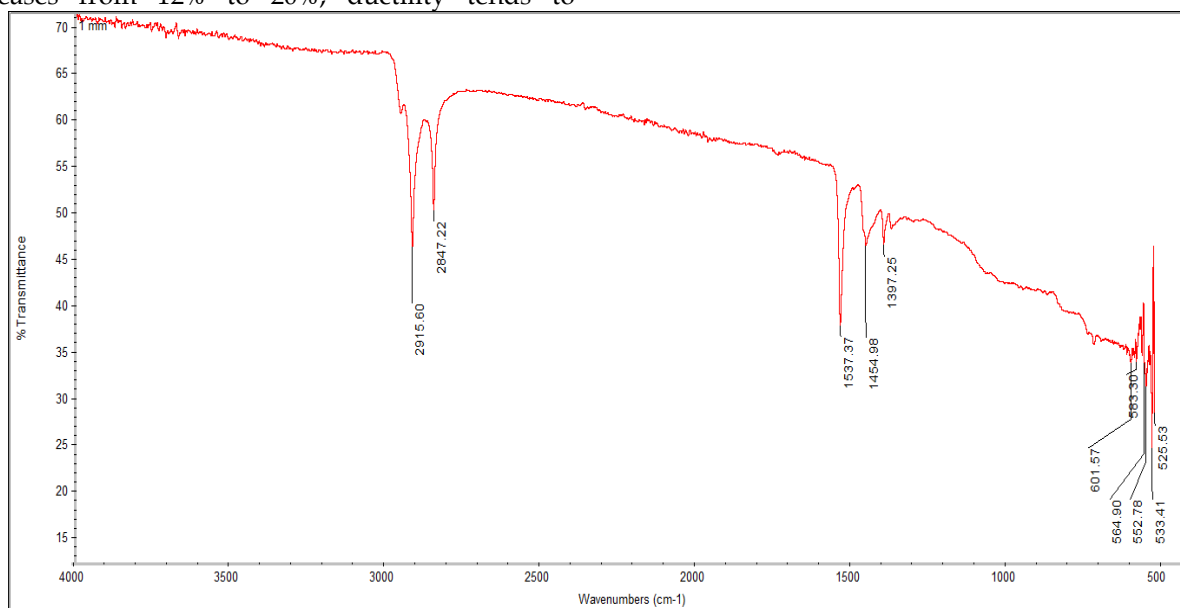


Figure 5: FTIR spectra of crumb rubber modified bitumen activated by thermal activation

Figure 5 presents the FTIR analysis of crumb rubber activated by the thermal method. The spectra display peaks at 2915.60 cm^{-1} and 2847.22 cm^{-1} , which correspond to C-H stretching in aliphatic

compounds, as well as peaks near 1537.37 cm^{-1} and 1454.98 cm^{-1} , attributed to C=C stretching. Peak intensities decrease as sample thickness increases, which is likely a result of infrared light attenuation

through thicker samples and the consequent reduction in transmittance[16]. The spectra overall indicate the presence of similar functional groups,

with only minor variations attributable to differences in sample thickness.

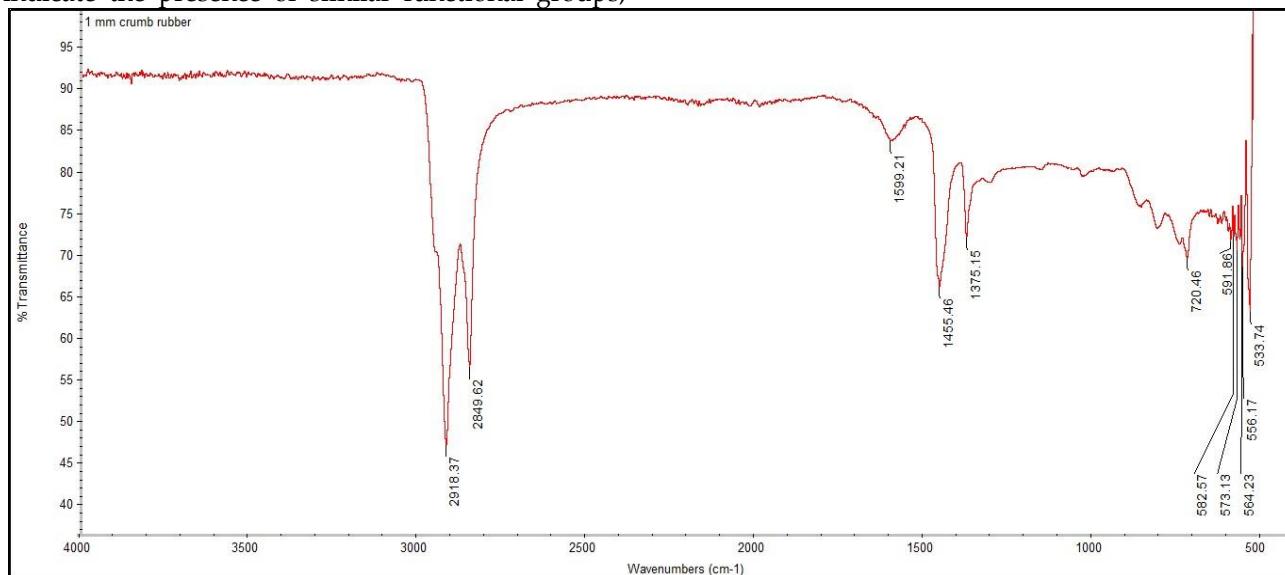


Figure 6: FTIR spectra of crumb rubber modified bitumen activated by thermal activation

Figure 6 displays characteristic peaks observed in all samples, including those at 2850 cm^{-1} , 1600 cm^{-1} , $1455\text{--}1375\text{ cm}^{-1}$, and 720 cm^{-1} . These peaks indicate consistent C-H stretching, aromatic C=C stretching, and bending vibrations within the rubber. A slight increase in intensity with greater thickness suggests higher concentrations of functional groups within the infrared beam path. The observed increase in peak width results from the interaction between crumb rubber and bitumen.

SEM imaging as shown in figure 7 demonstrates that, following swelling in bitumen, crumb rubber particles increase in size, develop more complex and rougher surfaces, and exhibit a larger specific surface

area compared to their original state. The presence of sticky, cohesive, and de-agglomerated swelled crumb rubber particles indicate strong interaction with the bitumen matrix. These microstructural changes are essential for improving mechanical properties, as they promote enhanced dispersion and bonding within the bitumen.

SEM analysis in figure 8 indicates that swelling crumb rubber in bitumen leads to significant microstructural changes, which are directly associated with enhanced elasticity and improved high-temperature performance of crumb rubber modified bitumen.

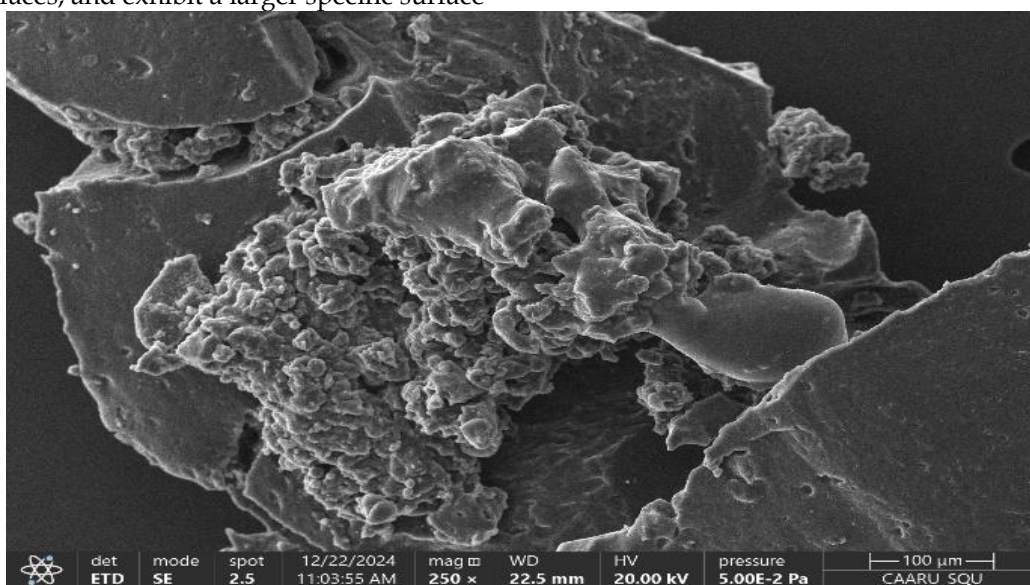


Figure 7: EM image of thermally treated crumb rubber

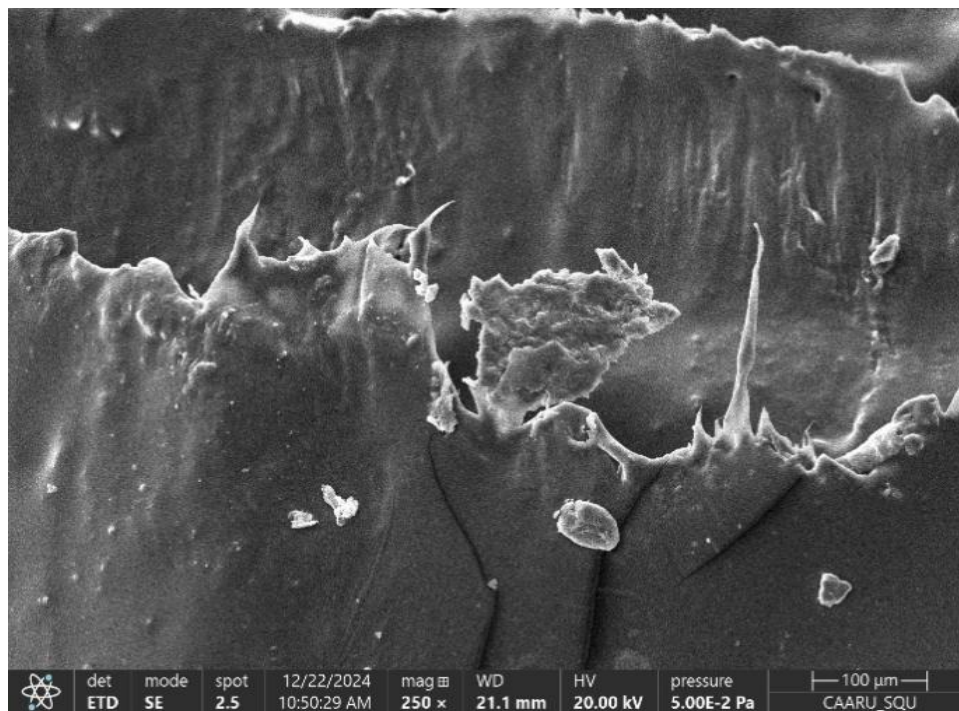


Figure 8: SEM image of crumb rubber modified bitumen.

3.2 Differential Scanning Calorimetry (DSC) And Thermogravimetric Analysis (TGA)

Important information regarding the effects of crumb rubber on the temperature-dependent stability and decomposition of bitumen was obtained through thermal analysis methods such as

Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA). By monitoring changes in weight as temperatures increase, these techniques reveal the thermal resistance and degradation profile of bitumen that has been modified with crumb rubber.

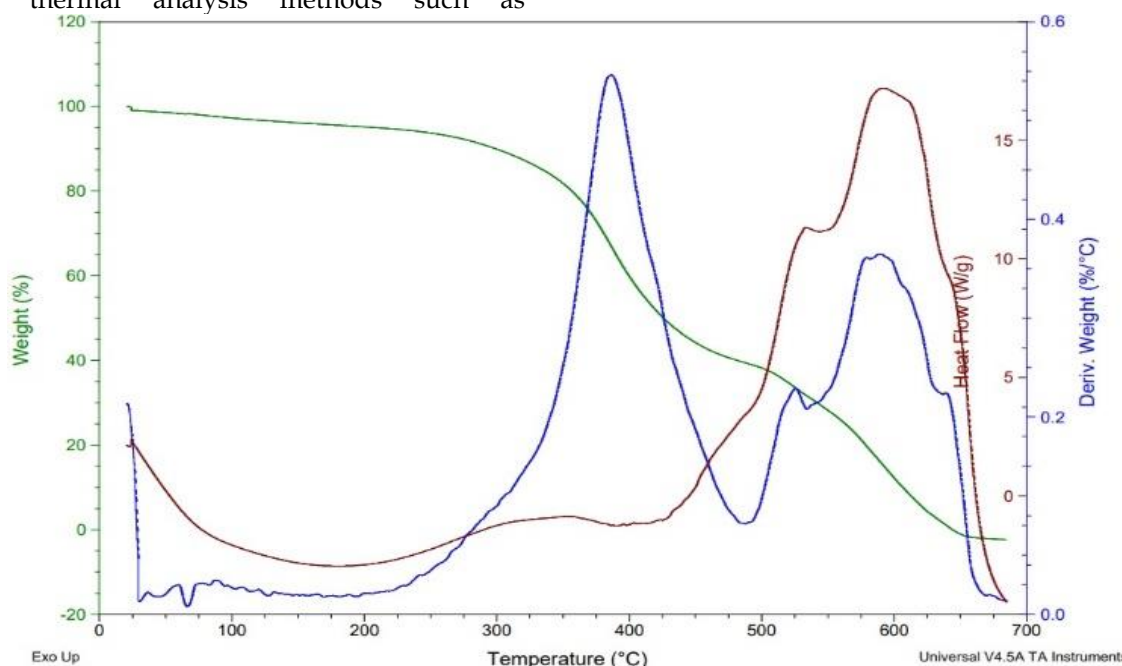


Figure 9: DSC-TGA image of Bitumen

Thermogravimetric analysis (TGA) of thermally activated crumb rubber revealed a minor weight loss below 150 °C as shown in figure 9, which is attributed to the removal of surface moisture and volatile

components. A significant decomposition event occurred between 250 and 500 °C, corresponding to the degradation of rubber polymer chains and additives. This process resulted in a residual char,

indicating the formation of a thermally stable carbonaceous structure. Differential scanning calorimetry (DSC) revealed an endothermic region corresponding to the evaporation of physically adsorbed water and low-molecular-weight species. This was followed by broader thermal transitions related to the softening and degradation of the rubber

matrix. Together, thermogravimetric analysis (TGA) and DSC results indicate that thermal activation removes volatile components, enhances carbon content, and generates a more stable and porous structure appropriate for subsequent applications.

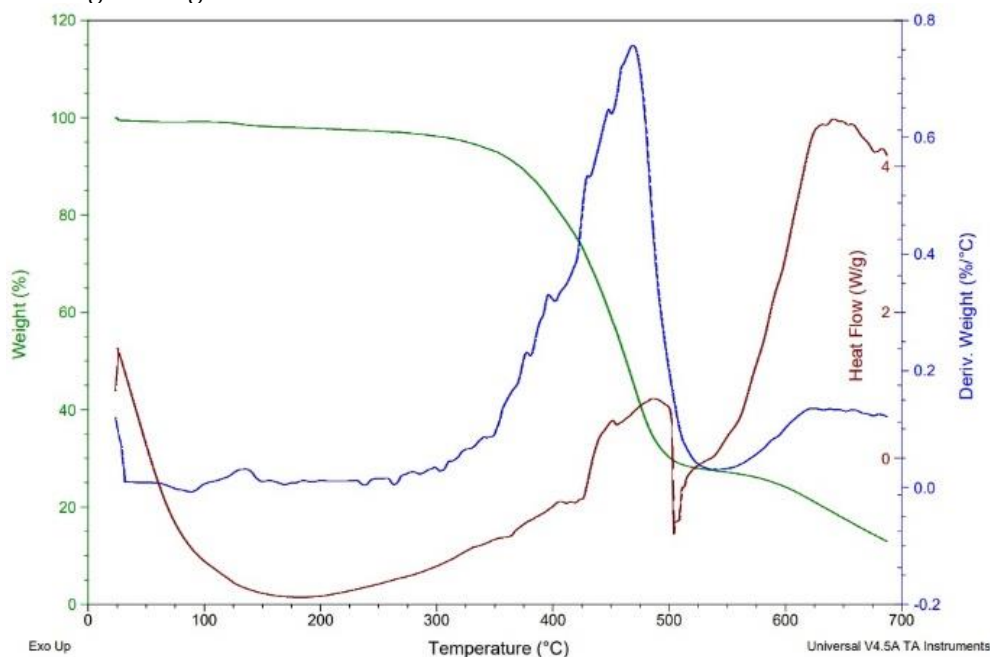


Figure 10: DSC-TGA image of crumb rubber modified bitumen.

TGA curves as shown in figure10 indicate that crumb rubber modified bitumen (CRMB) begins to decompose, as evidenced by weight loss, at higher temperatures (above 400°C) compared to unmodified bitumen. This observation suggests enhanced thermal stability. The main weight loss occurs within the temperature range where volatile components and crumb rubber degrade. Additionally, the total weight loss of CRMB is generally lower than that of base bitumen at equivalent temperatures, underscoring the stabilizing influence of crumb rubber.

Furthermore, CRMB exhibits a lower rate of weight loss, indicating slower and more controlled degradation process. The increased decomposition temperature and reduced total weight loss demonstrate that CRMB possesses greater resistance to high-temperature degradation, making it suitable for use in demanding pavement environments.

4. CONCLUSIONS

This study demonstrates that chemically activated crumb rubber derived from waste tires can effectively modify bitumen properties, thereby increasing its suitability for asphalt applications. The incorporation of thermally activated crumb rubber into bitumen produces significant chemical and structural

changes, as confirmed by FTIR, SEM, and TGA analyses. The study indicates that thermally activated crumb rubber improves compatibility with bitumen, resulting in enhanced performance of crumb rubber-modified asphalt. These results underscore the potential of this sustainable approach for utilizing waste tires in road construction, providing both environmental and practical advantages.

5. DECLARATION OF COMPETING INTEREST

The authors declare that they have no competing interests. This research was supported by The Research Council (TRC), Ministry of Higher Education, Research and Innovation, Sultanate of Oman, grant number "MoHERI/BFP/UTAS/2023,

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