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Sustainable Road Construction in India: A State-of-the-Art Assessment of Waste Tyre Rubber Modified Bitumen

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Abstract
Globally, approximately 9–10 kg of waste tyres are discarded per person annually, with minimal landfill usage. The large-scale production and disposal of waste tyres have raised significant environmental concerns. Various recycling and reuse strategies have been explored, including agricultural applications, tyre-derived fuel, sports applications, incorporating waste tyre rubber in new tyre production, and civil engineering uses, such as adding waste tyre rubber powder to bituminous mixes for road construction. The use of waste tyre rubber in bituminous mixes is expected to rise as its benefits gain recognition. Rubber-modified bitumen has been employed globally for the past five decades, with the "wet process" as a common preparation technique. Despite some drawbacks, research indicates that road pavement performance can be significantly enhanced with waste tyre rubber-modified bitumen. This study examines existing technologies, specifications, and methods for the production, handling, and storage of waste tyre rubber, as well as the latest applications in road construction. However, the global adoption of this technology remains limited due to insufficient information, lack of training, and inadequate government policy support. The primary aim of this study is to promote widespread adoption by highlighting its advantages.

Keywords: *Waste tyre rubber, bitumen modification, road construction, sustainable infrastructure, environmental impact*

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I. Introduction

The number of vehicles on roads is rapidly increasing in both industrialized and developing nations. This has led to a surge in global tyre demand, which reached over 3 billion units in 2020 and is projected to grow at a compound annual rate of 4% by 2026, potentially reaching 4 billion units. According to IMARC research, the Indian tyre market reached approximately 179 million units in 2020, ranking fourth globally after China, Europe, and the United States, and is expected to reach 211 million units by 2026.

These tyres can eventually be discarded as waste. In India, more than 1.5 billion tyres are generated annually, with India accounting for 6% of this waste[1]**.** Given the anticipated increases in vehicle quantity and traffic volume, the amount of waste tyres is expected to increase accordingly. The large-scale production and long-lasting nature of these waste tyres create a significant waste management challenge. Improper disposal, such as pyrolysis, illegal dumping, or stockpiling, can pose serious environmental risks, including fire hazards, threats to human health from mosquito breeding, and harbour rodents.

Tyre

Tyre design is a harmonious blend of chemistry, physics, and engineering, all of which work towards the ultimate goal of providing a safe and comfortable driving experience. A tyre is composed of three main materials: an elastomeric or rubber compound, fabric, and steel. The fabric and steel form the structural skeleton of the tyre, while the rubber constitutes the "flesh" of the tyre, shaping the tread, sidewall, apexes, liner, and shoulder wedge [2]. The transformation of natural rubber through engineering processes is essential to ensure good performance, safety, and durability. Natural rubber exhibits varying physical properties depending on the temperature: it is brittle and opaque at low temperatures, soft and resilient at 20°C, and plastic and sticky at 50°C, as shown in Table 1. Vulcanization is necessary to produce a high degree of elasticity in rubber, as it enables the formation of cross-links between the polymer chains, allowing them to move independently and undergo deformation under stress while returning to their original shape upon release of stress. Tyres are typically composed of a blend of natural rubber, synthetic rubber, steel, nylon, silica, polyester, carbon black, and petroleum-derived components. The unique combination of raw materials and manufacturing processes employed by different tyre producers results in diverse performance attributes across the range of tyres available in the market[3] .According to a report published in 2019, the production of automobiles was estimated to be 95 million units globally, and it is anticipated to reach 110 million units by the year 2025 [4].

Table 1: Effect of temperature on natural rubber.

Temperature	**Property**
-10 ^{0} C	Brittle and opaque
20 ^{0} C	Soft, resilient and translucent
50 ^{0} C	Plastic and sticky
120 ^{0} C to 160 ^{0} C	Vulcanised when agents e.g., sulphur are added
182 ^{0} C	Break down as in the masticator
200 ^{0} C	Decomposes

Generally, tyres contain 40-48% rubber/elastomers, and the percentage of natural rubber is high in truck tyres [2,5] . A typical composition of passenger and truck tyres can be seen in Table 2

Table 2: Typical composition of passenger and truck tyres [5]

Composition	**Passenger tyre**	**Truck tyre**
Natural rubber	14%	27%
Synthetic rubber	27%	14%
Carbon black	28%	28%
Steel	14-15%	14-15%
Fibre, fillers, accelerators, antiozonants, etc	16-17%	16-17%

Thread, Sidewalls, bead, tyre casing, and belt system are the main components of the tyre structure shown in figure 1. Rubber materials experience various types of wear and tear influenced by contact forces, environmental conditions, and material properties. Abrasion wear occurs when a harder surface rubs against rubber, removing material. Fatigue wear results from repeated deformation under stress, causing cracks and material breakage. Sharp objects can cut or tear rubber surfaces. Ozone exposure degrades rubber, forming cracks perpendicular to the stress direction. Chemical degradation from certain substances can cause rubber to swell, soften, or become brittle, impacting its wear resistance [6]. Thread is the part that is in contact with the ground and is supported by Carcass and sidewalls which gives it a specific shape [7]**.**

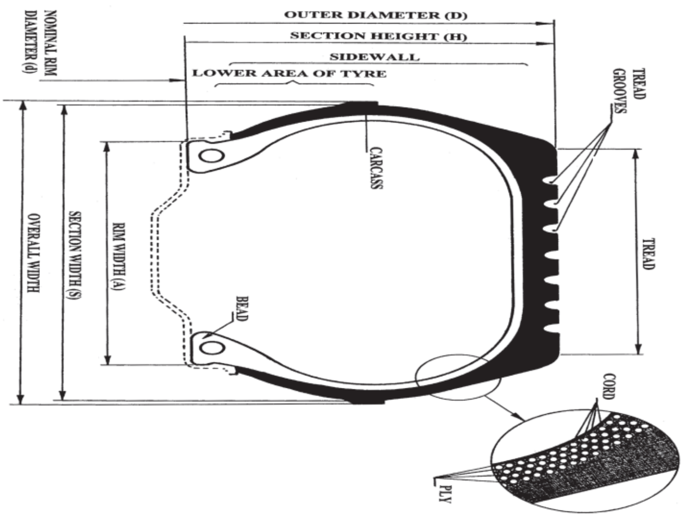


Figure 1: Structure of tyre [7]

Tyre recycling in India

In India, formal recycling of waste tyres is conducted by a limited number of industries. However, informal recycling practices are prevalent to a significant degree. Approximately 4-5% of scrap tyres are repurposed for use in brick kilns. The rubber recycling industry in India is second in size to that in China within Asia, though the difference in volume is substantial. Across the country, there is a lack of comprehensive monitoring measures for the disposal of used tyres [8]. There are several methods for recycling waste tyres, including regrooving and retarding, shredding or crumb rubber modification, and pyrolysis of tyre-derived fuel. Worn-out tyres can be reused directly through regrooving and re-treading. If the tyre cannot be reused, it can be mechanically modified by converting it into crumb rubber or shredded rubber pieces. Estimates indicate that 3-5% of rubber crumbs and approximately 10% of reclaimed rubber are utilized in tyre manufacturing[9]. There are various methods of recycling tyres which includes mechanical recycling, chemical recycling and various other methods[10]. Pyrolysis, the thermal decomposition of rubber at elevated temperatures in the absence of oxygen, provides valuable insights into the degradation mechanisms of its primary constituents under thermal stress. This process elucidates the thermal decomposition characteristics of rubber's key components[11]. Numerous studies have investigated the potential utilization of products obtained from the pyrolysis of end-of-life tyres, such as recovered carbon black, as feedstock for novel rubber compounds[12,13]. The pyrolysis process also segregate the carbon black and metal components. The metal can then be resold, whereas carbon black or charcoal can be utilized for industrial and commercial purposes. However, the use of scrapped rubber and waste tyres as cheap fuels for brick manufacturing kilns is problematic, as the burning of tyres releases harmful gases that can significantly impact the environment and human health. Additionally, it is estimated that approximately 60% of waste tyres in India are either dumped or stockpiled, leading to land pollution, increased mosquito breeding, and providing a habitat for rodents.

II. Waste tyres to crumb rubber modifier

Waste tyres and other rubber are processed into uniform granular particles by segregating the reinforcing materials within the tyres, such as steel and fiber. These uniform granular particles, typically approximately 400 microns in size, are referred to as crumb rubber. Generally, a standard waste tyre comprises approximately 70% recoverable rubber, 15% steel, 3% fiber, and 12% extraneous materials, such as dust, glass, and stone pieces[14]. Various technologies are employed to convert waste tyres into crumb rubber modifiers, including

a. Ambient grinding
b. Cryogenic grinding
c. Wet-grinding
d. Hydro jet size reduction

Ambient grinding

This is the most common method in which the grinding or processing of waste tyre is done at or above room temperature. The ambient grinding process consists of a series of machines to separate rubber, steel, fiber, and other components of tyre. In the primary stage, the material is reduced to small chips after which the rubber is separated from steel and fiber, and in the last stage, the material will be ground to the desired specification. After each stage, the shifting screens are used to return the oversized pieces to the granulator or mill for further processing. Steel wire and other metal contaminants are removed by using magnets. fiber is removed by air separators. This method of grinding provides irregularly shaped particles having rough texture, large surface area with size around 600 microns[14]. The process of ambient-temperature comminution of waste tyre rubber can yield fine particles suitable for incorporation into novel rubber formulations. Furthermore, thermal decomposition can facilitate the extraction of valuable chemical substances and carbon black materials[12,15]. A typical ambient grinding system is shown in Figure 2[14]

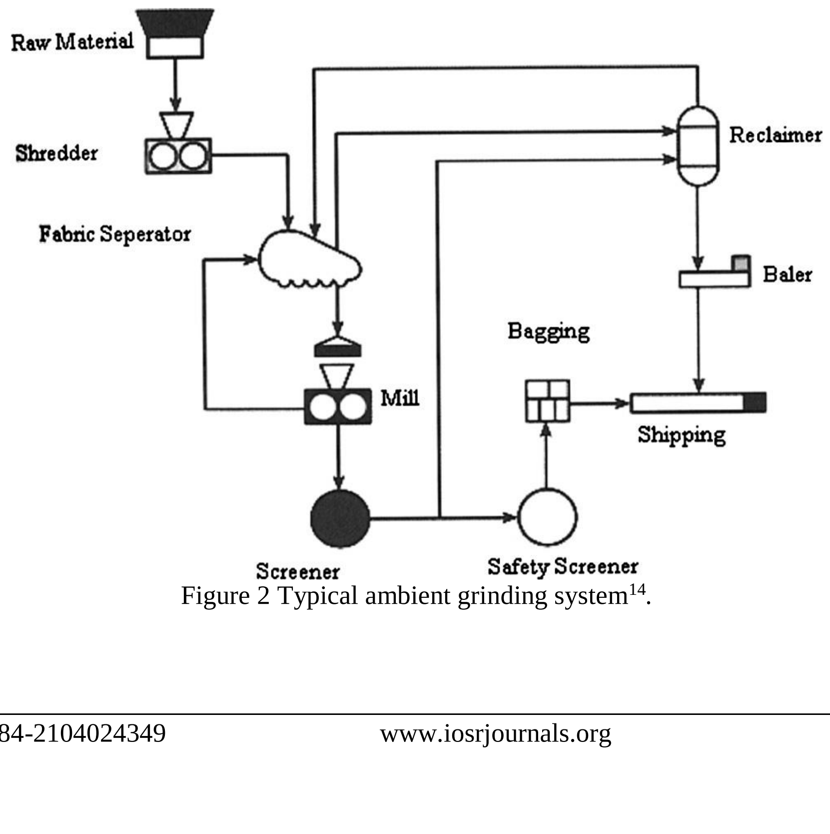


Figure 2 Typical ambient grinding system[14].

Cryogenic grinding

In the cryogenic grinding method, tyre chips are subjected to freezing using liquid nitrogen prior to being processed through a hammer mill. This approach mitigates the heat-induced degradation of the rubber. At cryogenic temperatures, the rubber becomes brittle and fractures along smooth planes, resulting in particles with a uniform texture. The surface area of these particles is reduced compared to that generated through the ambient grinding process. The crumb rubber produced by cryogenic grinding typically exhibits a size range of 600 microns to 6 millimeters. Magnetic separation is employed to remove the steel, while the fiber fraction is eliminated through aspiration and screening. The figure 3 explains the process of cryogenic grinding system[14].

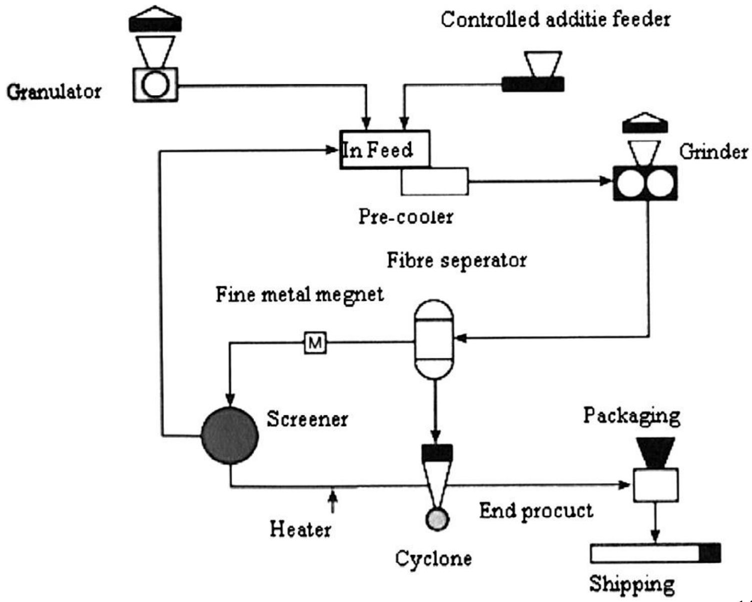


Figure 3 Typical cryogenic grinding system[14]

Wet-grinding

Wet grinding, also known as the micro-milling technique, utilizes water to grind the rubber to a finer particle size compared to traditional methods. In this process, the crumb rubber particles are combined with water to form a slurry, which is then fed through equipment comprising two closely spaced grinding wheels. This alloweds the particles to be reduced to a size below 400 µmmicrons.

Hydro jet size reduction

The Hydro jet size reduction technique employs a high-pressure water jet to reduce waste tyre rubber into fine particles. This process utilizes extremely high-pressure water jets (approximately 2000-3000 bars) rotating in spin arrays to produce clean rubber crumbs devoid of wire. The resultant particles measure less than 200 microns in size. Furthermore, this method facilitates devulcanization by disrupting the majority of sulfur-containing molecular structures, affecting approximately 70% of the rubber particles[15] . Scanning electron microscope images, presented in Figures 4 and 5, illustrate the distinct internal structures between the high-pressure water jet crumb rubber and the mechanically ground crumb rubber. The Wwater jet-processed particles exhibit a more homogeneous morphology with smaller radii compared to the mechanically ground particles[16].

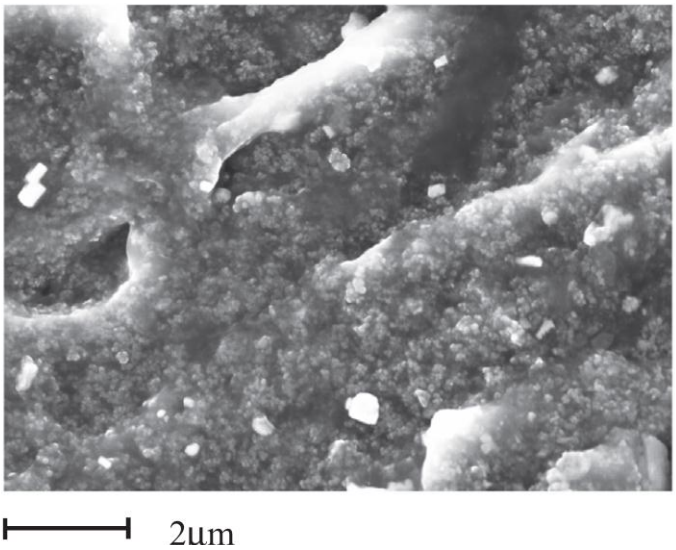


Figure 4 SEM images of High Pressure Water Jet crumb rubber[16]

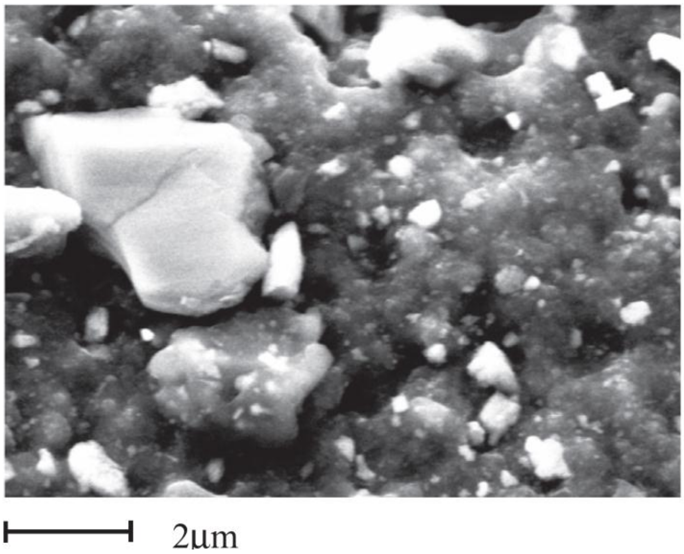


Figure 5 SEM image of crumb rubber produced through mechanical grinding[16]

Table 3: Comparison of Ambient, cryogenic, wet grinding and hydro jet

Physical property	Ambient	Cryogenic	wet grinding	hydro jet
Specific gravity	Same	Same	Same	Same
Particle shape	Irregular	Irregular	Irregular	Irregular
Fibre content	0.5%	Nil	Nil	Nil
Steel content	0.1%	Nil	Nil	Nil

III. Bitumen

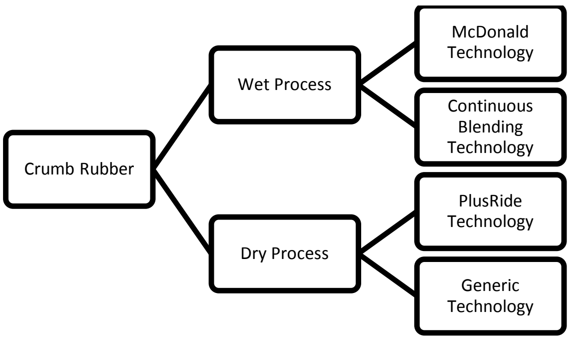
History

The experimentation-based utilization of natural rubber in bitumen started approximately 180 years ago in 1840. The use of waste tyre rubber as a secondary material in bitumen was introduced in the early 1960s by McDonald[17]. There are two primary processes, the wet and dry processes, which have been employed to incorporate rubber into bitumen and hot-mix asphalt. In India, the Indian Road Congress has provided guidelines for the use of polymer and rubber-modified bitumen in road construction, with the initial guidelines issued in IRC: SP:53-1999 in December 1999 and subsequent revisions published as IRC: SP:53-2010 in December 2011. Additionally, the Bureau of Indian Standards has incorporated standard specifications for crumb rubber and modified crumb rubber-based bitumen in IS 15462:2004 Polymer and Rubber Modified Bitumen. The wet process has emerged as the most widely adopted technique globally and has been successfully demonstrated through the construction of roads over the past 30 years.

Interaction Process

The crumb rubber modification process can be performed using either wet or dry methods. In the wet process, crumb rubber was blended with bitumen for 45 min to 1 h in a tank, thoroughly mixing the two components to enhance the engineering properties of the resulting blend when combined with aggregates. The two technologies that utilize the wet method are McDonald’s method and Continuous Blending. McDonald's technology incorporates 15-22% of crumb rubber particles ranging from 2 mm to 600 µm, whereas the Continuous Blending technology employs 5-25% of finer crumb rubber particles between 150-200 microns. The mix design and construction practices are consistent for both McDonald's and the Continuous Blending technologies

The dry process, first introduced in Sweden in the 1960s, involves thoroughly blending crumb rubber with mineral aggregates before incorporating them into a bituminous mix. This approach is employed in two distinct technologies: PulseRide and Generic. PulseRide technology incorporates a blend of granulated crumb rubber particles ranging from 6 to 2 mm, as well as ground crumb rubber, which are combined with mineral aggregates of the desired gradation. Conversely, generic technology utilizes finer crumb rubber at a lower percentage compared to the PulseRide method.



The wet process for incorporating crumb rubber into bitumen has been found to be more effective than the dry process in enhancing performance characteristics. This is because the wet method enables a more intimate interaction between crumb rubber and bitumen. In addition, wet processes have been shown to reduce the incidence of premature pavement failure.

Properties of rubberized bitumen

The key properties of rubberized bitumen that are improved compared to conventional bitumen are:
The increased viscosity of the rubberized bitumen enhances its resistance to permanent deformation[18,19,20]. Higher softening point, which improves its resistance to rutting and shoving. Furthermore, the improved ductility provided by the crumb rubber in bitumen enhances the flexibility of the pavement, leading to an extended fatigue life[18]. The addition of crumb rubber also improved the resistance to low-temperature cracking, as shown by the increased penetration index values[18,19].

IV. Conclusion

The use of waste tyre rubber in the modification of bitumen has significant potential in India to produce rubberized bitumen with improved engineering properties. Extensive research has been conducted to understand the influence of crumb rubber addition on the rheological and mechanical properties of modified bitumen. The wet process was found to be more effective in improving the performance characteristics than the dry process owing to the better interaction between the crumb rubber and bitumen.

Hence, the wet process is preferred over the dry process for the construction of Indian roads. Proper guidelines and standards from regulatory bodies would further facilitate the widespread adoption of rubberized bitumen in India.

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