

# Nanocomposites in Tire Development – Benefits, Challenges, and the Role of Carbon Nanotubes and Graphene

Xiang Zhang \*

Department of material science and engineering, Chengdu University of Technology, Chengdu, Sichuan, 610059, China

\* Corresponding Author Email: jwxy07@tzc.edu.cn

**Abstract.** In the rapidly evolving automotive industry, enhancing vehicle performance and sustainability through innovative materials is paramount. Nanocomposite materials, incorporating nanoparticles such as carbon nanotubes (CNTs), graphene, and silica, have emerged as key enablers in redefining tire technology with improved durability, efficiency, and environmental impact. This review discusses the integration of these nanocomposites into tire manufacturing, emphasizing their role in enhancing mechanical properties, wear resistance, and rolling efficiency while reducing environmental footprints. Challenges such as dispersion uniformity within the rubber matrix and economic considerations due to high material costs are examined, alongside future research directions aimed at scalability and cost reduction. The paper predicts a significant increase in the adoption of nanocomposite tires, driven by technological advances and the shift toward sustainable manufacturing practices. By detailing the synergistic effects of nanocomposites, this review highlights their potential to revolutionize tire performance and contribute to the next generation of green automotive technologies.

**Keywords:** Tire; nanocomposite; carbon nanotubes; self-healing.

## 1. Introduction

In the ever-evolving landscape of automotive engineering, the quest for innovative materials that enhance vehicle performance and sustainability is paramount. This review paper delves into the integration of nanocomposite materials in tire manufacturing, a pivotal development that promises to redefine the standards of tire durability, efficiency, and environmental impact. Nanocomposites, which encompass a myriad of nanoparticles such as carbon nanotubes (CNTs), graphene, and silica, are strategically embedded within polymer matrices to exploit their exceptional mechanical and thermal properties. The infusion of such materials not only enhances the structural integrity of tires but also contributes to significant advancements in wear resistance, rolling efficiency, and recyclability.

This discourse explores the multifaceted roles of these nanocomposites, from reinforcing the rubber matrix to introducing self-healing capabilities that extend tire life and facilitate recycling. By examining the latest research and technological breakthroughs, this paper aims to illustrate how nanocomposite technology not only meets but also exceeds current performance metrics, fostering a more sustainable automotive industry. Through detailed analysis of the properties and applications of these materials, the review will highlight the synergistic effects of nanocomposites in improving tire performance and their potential to drive the future of green automotive technologies.

## 2. Nanocomposite and Carbon Materials in Tire Treads and Components

### 2.1. Nanocomposites

In the quest for advanced tire technologies, the integration of nanocomposite materials has emerged as a pivotal strategy to enhance tire performance and sustainability. Nanocomposite materials, which involve the infusion of nanoparticles into a polymer matrix, offer significant improvements in mechanical properties, durability, and environmental impact. These materials are tailored to meet specific performance criteria required by different tire components such as treads,

sidewalls, and inner liners. This discussion delves into the types of nanocomposites used in the tire industry, including polymer nanocomposites, nanoclays, and silica nanoparticles, and explores their specific applications in enhancing the functionality and efficiency of tires.

Polymer nanocomposites in tire technology consist of a polymer matrix integrated with nanoparticles. These polymers are typically synthesized from monomers that offer flexibility, lightweight characteristics, and cost-effective production. Inorganic nanomaterials are added to impart specific properties like electrical conductivity, mechanocatalytic activity, and magnetism. For example, a blend of Styrene-Butadiene Rubber (SBR) and silica is commonly employed to enhance the performance of tire treads, improving properties such as abrasion resistance and grip [1].

Nanoclay composites, incorporating rubber as the continuous phase and clay particles dispersed at the nanometer scale, are notable for their mechanical and thermal enhancements. These composites are produced through methods like sol-gel processes, intercalation, or blending. The modification of nanoclay surfaces aids in their dispersion within the rubber matrix, resulting in improved interface bonding [2]. Notably, a nanoclay product containing Brominated Isobutylene-co-Para-Methylstyrene (BIMSM), developed by ExxonMobil, surpasses traditional halobutyl rubbers in air retention by approximately 50%. This substitution not only enhances performance but also reduces reliance on carbon black, thus diminishing the dependence on the fossil industry.

The efficacy of silica nanoparticles in enhancing rubber durability is notable. By controlling their size or conducting surface modifications, the abrasion resistance of rubber can be significantly improved. The addition of nanosilica is known to decrease rolling resistance by 20%, increase road adhesion by 12%, and shorten braking distances by 10%. These enhancements contribute to fuel savings and heightened driving safety, potentially reducing environmental impact across the tire's lifecycle by 5-10%.

Nanocellulose, derived from wood-market pulp treated with sulfuric acid (to produce Cellulose NanoCrystals, CNC) or through mechanical treatments (to produce Cellulose NanoFibrils, CNF), is now more cost-effectively produced via biorefining. A variety of biomass sources, including hardwoods, softwoods, and agricultural residues, are utilized to generate nanocellulose [3]. Owing to its high strength and lightweight, CNF serves as an effective reinforcement in tires, providing an alternative to carbon black.

Research by Leibo Ji et al. explored the substitution of carbon black N660 with nano-clay in the sidewall compounds of steel-belted radial tires [4]. Findings indicate that replacing carbon black N660 with nano-clay does not significantly alter the processing or vulcanization characteristics. However, this substitution markedly enhances the tensile elongation and tear strength of vulcanized rubber. As the nano-clay content increases, the rubber's density also increases, while constant tensile stress decreases, improving flexural fatigue resistance. Furthermore, the enhanced dispersion of nano-clay filler contributes to the durability and performance of the tires, aligning with enterprise standards and reducing production costs.

## 2.2. Graphene and Carbon Nanotubes

CNTs possess a unique  $SP^2$  hybridization, where carbon atoms are arranged in a robust and efficient manner, lending exceptional mechanical, electrical, and thermal properties to the material [5]. The strategic addition of CNTs into tire compounds not only enhances durability but also improves elasticity when appropriately integrated through meticulous experimental design [6]. This enhancement in elasticity contributes to better handling and stability, reducing the tire's susceptibility to deformations under varying driving conditions.

Graphene, characterized as a two-dimensional crystal comprised solely of carbon atoms, exhibits a suite of outstanding properties. Its high conductivity, unparalleled strength, and remarkable elasticity make it a candidate for diverse applications including structural nanocomposites, electronic devices, optical lenses, and energy storage devices like fuel cells, batteries, and supercapacitors[7]. In the realm of tire technology, graphene's potential to enhance the performance of tire treads is significant. Despite the challenges associated with its high cost and difficulties in dispersion within

tire compounds, innovative solutions such as the development of a graphene rubber masterbatch (GRMB) have been proposed. As highlighted by Sujith S. Nair et al., GRMB can significantly enhance the mechanical properties of tires, particularly in terms of increased hardness and tensile modulus, which directly contribute to improved wear resistance and reduced rolling resistance [8].

Moreover, Rajan Krishna Prasad has suggested that graphene could serve as an alternative to certain functions traditionally fulfilled by carbon black [9]. This substitution not only promises to retain the desired properties but also to add new dimensions to the tire's performance, especially in terms of conductivity and thermal management.

The integration of these advanced nanomaterials into tires demonstrates a promising frontier in automotive technology, addressing both performance enhancements and environmental impacts. By leveraging the unique properties of CNTs and graphene, tire manufacturers are able to produce more durable, efficient, and sustainable tires, thereby setting new standards in the industry.

### 3. Advancements in Nanocomposites and Carbon Materials

The integration of nanocomposites into tire technology harnesses the unique properties of nanoparticles to revolutionize tire performance. Nanoparticles such as CNTs and graphene provide exceptional reinforcement for the rubber matrix used in tires. These materials integrate into the polymer structure, enhancing the mechanical properties through improved tensile strength and elasticity. This reinforcement is crucial for increasing the tire's durability and resistance to mechanical stresses. Furthermore, by incorporating CNTs and graphene, tires gain improved electrical and thermal conductivity. This feature is critical for dissipating the heat generated during tire operation more efficiently and preventing static build-up, which can be particularly problematic in dry environments. In addition, reduction of hysteresis loss can also be achieved by using nanocomposite, by optimizing the viscoelastic properties of the tire compounds, allowing them to quickly return to their original shape and reducing the energy lost as heat. This reduction directly improves the tire's rolling resistance and, consequently, the vehicle's fuel efficiency.

Liu Haizhou et al. highlighted the challenges associated with traditional carbon black fillers in rubber reinforcement materials, notably the issue of heat buildup which can lead to increased energy consumption in automobiles [10]. To address this, their research explores an innovative approach using graphene oxide (GO) through a precipitation method. By incorporating GSi (Graphene-Silica) filler directly into natural rubber (NR) via the standard mechanical mixing processes used in tire manufacturing, they leverage the synergistic effects of cross-linking and covalent bonding between the GSi and NR matrices. This method not only enhances abrasion resistance and tensile strength, achieving a maximum tensile strength of 30.7 MPa, but also maintains low heat buildup, thus optimizing energy efficiency without compromising mechanical properties.

In a parallel advancement, Li Shuaiqi et al. focus on the enhancement of rubber composites through silica modifications [11]. They noted that traditional silica nanoparticles tend to agglomerate due to hydrogen bonding and van der Waals forces, which adversely affects tire performance. By employing silane coupling agents to modify silica, they improved the dispersion of silica particles within the rubber matrix. Utilizing a novel coupling agent, AEOX-M2, to replace traditional ethoxy Si69, they shortened the polyether chain on the AEO, enhancing tire wear resistance. This modification not only improves wear resistance but also reduces rolling resistance and increases wet slip performance. The shorter the polyether chain, the more pronounced these benefits, illustrating a direct correlation between chain length and tire performance enhancement.

These studies underscore the transformative potential of nanocomposites in tire technology, particularly through the strategic modification of traditional materials like carbon black and silica. By integrating graphene and advanced silica modifications, tire manufacturers can achieve superior performance metrics, including enhanced durability, better energy efficiency, and improved safety features, thus driving forward the evolution of tire technology.

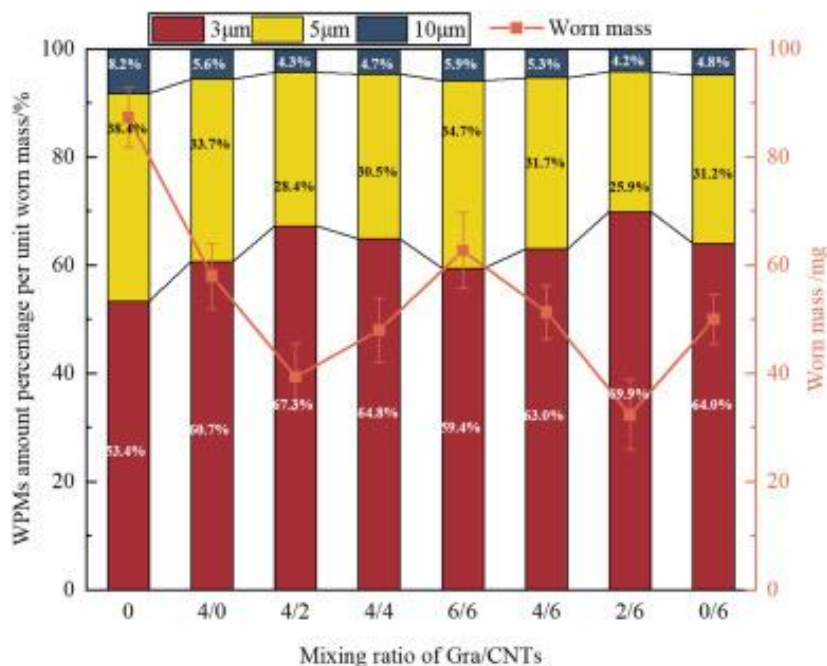
## 4. Long-term Durability and Recyclability

### 4.1. Long-term Durability

The longevity and durability of tires are critical factors in automotive safety and efficiency. Recent advancements in material science, particularly through the use of nanocomposites, have shown significant promise in extending tire life. This paper examines how the incorporation of nanomaterials such as CNTs, graphene oxide (GO), and silica (SiO<sub>2</sub>) within the rubber matrix can alter the wear properties of tires, thus enhancing their durability.

Wear Particle Measurement (WPM) is a common method used to estimate tire wear and, by extension, tire life. However, it is essential to recognize that WPM alone does not comprehensively predict wear rates, as demonstrated by various studies. For instance, despite higher wear levels, some tires may not necessarily produce a proportional amount of WPM.

Junhao Qu et al. reported that the properties of rubber could be modified to varying extents through the rational addition of CNTs and graphene (GRAs)[12]. As shown in Figure 1, their research found that a specific mixing ratio of graphene to CNTs (2:6) resulted in the lowest coefficient of friction (COF) and a significant reduction in WPM by 41.2% compared to rubber without nanofillers, indicating a lower mass loss. A subsequent study highlighted that while a larger amount of WPM per unit of wear mass generally reflects better abrasion resistance, this is not the case with WPM 3.0. Moreover, a lower COF does not necessarily correlate with reduced fine WPM per unit of wear mass, challenging some conventional understandings of tire wear dynamics.



**Fig 1.** Wear particle measurement of the rubber with different ratios of CNT and graphene [12].

Yiwen Cui's research further explored the use of GO as a primary filler in natural rubber (NR) composites[13]. Through the latex co-precipitation method, the study investigated the effects of various layers and concentrations of GO on the mechanical properties of NR. The findings indicated that composites with three parts filler exhibited the least wear, attributed to the more concentrated stress in graphene with fewer layers, resulting in fewer cracks. In NR/GO/SiO<sub>2</sub> composites, the synergistic interactions among hydrogen bonding, electrostatic forces, and chemical bonds—facilitated by ultrasonic dispersion and electrostatic adsorption—significantly enhanced the durability (Figure 2). Moreover, when 2-mercapto-1-methylimidazole (MMI) was used as both a reducing and modifying agent for GO, it was found to improve the dispersion of the filler within the rubber matrix substantially. The enhanced dispersion led to better immobilization of rubber molecular chains, thus minimizing wear in NR/MMI-GO composites (Figure 3).

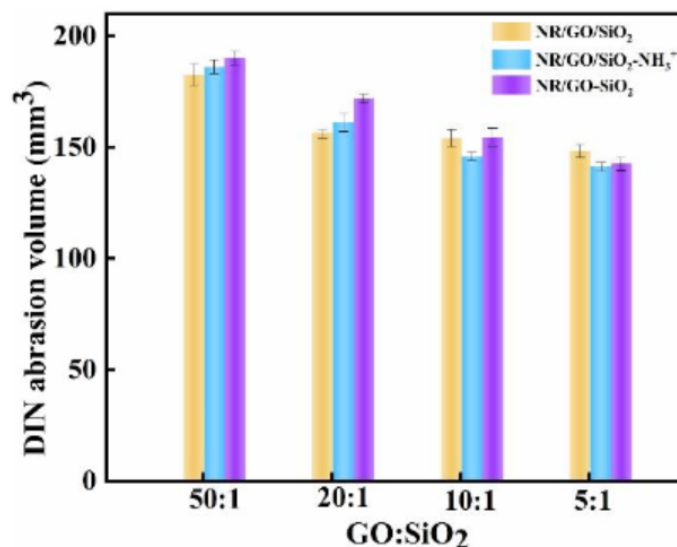


Fig 2. Abrasion volume diagram of NR/GO/SiO<sub>2</sub>, NR/GO/SiO<sub>2</sub>-NH<sub>3</sub><sup>+</sup>, and NR/GO-SiO<sub>2</sub> [13].

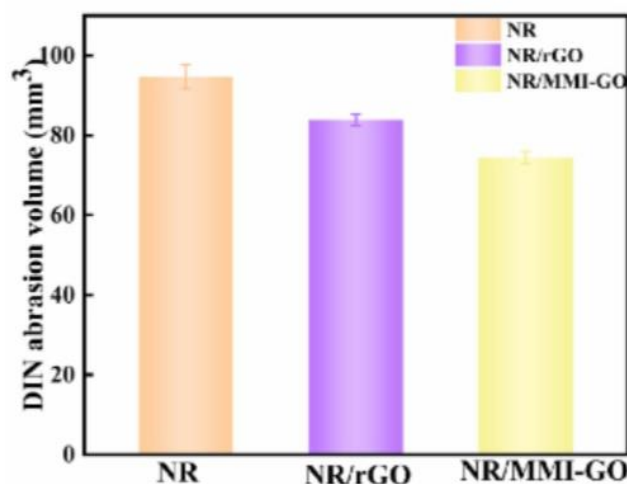


图 4-11 NR、NR/rGO 和 NR/MMI-GO 的磨损体积图

Figure 4-11 Abrasion volume diagram of NR, NR/rGO and NR/MMI-GO

Fig 3. Abrasion volume diagram of NR, NR/rGO, and NR/MMI-GO [13].

#### 4.2. Recyclability of nanocomposite materials

In the realm of tire technology, enhancing the longevity and durability of rubber is crucial for advancing automotive performance and sustainability. Recent scientific endeavors have focused on developing self-healing rubbers, which promise significant advancements in tire life by enabling materials to automatically repair themselves after damage. This innovative approach primarily revolves around two mechanisms: extrinsic healing involving external agents and intrinsic healing rooted in the rubber's chemical structure.

Self-healing in rubber can be achieved through two primary methods[14]. The first, extrinsic healing, utilizes external healing agents encapsulated within tiny vessels or networks mimicking biological systems, which release their contents upon rupture. The second method, intrinsic healing, exploits the inherent properties of elastomers, such as reversible dynamic bonds and supramolecular interactions, enabling them to mend autonomously without additional interventions.

Natural rubber (NR), due to its chemical structure, typically lacks self-healing properties. However, researchers have developed functional variants like epoxidized natural rubber (ENR) and brominated

natural rubber (BNR) that exhibit enhanced reactivity conducive to self-repair mechanisms. Xu et al. introduced ionic interactions in NR to promote self-healing[15]. Their approach utilized peroxide-induced controlled vulcanization to form a network rich in ionic cross-links via the polymerization of zinc dimethacrylate (ZDMA). By optimizing the vulcanization conditions, they created a supramolecular structure dominated by ionic bonds, allowing the NR chains to move and self-repair effectively. Remarkably, this method achieved up to 95% recovery of tensile strength after just five minutes at room temperature, albeit at lower stress levels.

Building on conventional techniques, Hernandez-Santana et al. explored sulfur-based vulcanization common in NR formulations[16]. Their research focused on the dynamic behavior of disulfide and polysulfide bonds, which facilitated self-healing and the recovery of mechanical properties at moderate temperatures (below 70°C). This process demonstrated potential in enhancing the durability of rubber without fully curing the initial material.

Mandal et al. developed a method to introduce ionic structural domains in ENR, evaluating variousazole derivatives and ethylenediamine through rheological studies[17]. The interaction between the ethylene oxide ring and 1H-imidazole was found to be particularly effective, forming a network of covalent and ionic bonds that supported self-healing. This configuration allowed the material to regain up to 90% of its tensile strength and maintain considerable elasticity, demonstrated by an elongation at break of approximately 700%.

Although the application of self-repairing elastomers in the automotive sector is still emerging, their potential to significantly impact the industry, particularly in the context of sustainability and reduced material waste, is immense. As the automotive industry shifts towards greener practices, the development of self-healing tires could align well with environmental goals, offering a pathway to reduce tire waste and enhance vehicle efficiency.

## 5. Challenges and Future Perspectives

Integrating nanocomposites like CNTs and graphene into tire manufacturing presents technical challenges, particularly in achieving uniform dispersion within the rubber matrix and maintaining compatibility with existing production processes. These challenges require innovative processing techniques to ensure consistent product quality and performance. The adoption of nanocomposite materials is economically challenging due to the high costs of raw materials and advanced processing technologies. Balancing these costs with the benefits of enhanced tire durability and efficiency is crucial for widespread market acceptance.

Future research should focus on reducing the costs of nanocomposite production and improving the integration techniques to enhance the scalability of this technology. Developing tires with advanced self-healing capabilities and improved recyclability will also be key areas of focus. The adoption of nanocomposite tires is expected to increase as the automotive industry advances towards more sustainable practices. With improvements in cost-efficiency and material processing, nanocomposite tires are likely to become more prevalent, especially in electric and autonomous vehicles, over the next decade.

## 6. Conclusion

This Paper has comprehensively explored the integration of nanocomposite materials into tire technology, highlighting their potential to significantly enhance tire performance and sustainability. The use of nanoparticles like CNTs, graphene, and silica has shown promising results in improving the durability, efficiency, and environmental footprint of tires. While there are challenges in terms of cost and technical integration, ongoing research and technological advancements are likely to overcome these barriers, facilitating broader adoption in the automotive industry. Future research will play a pivotal role in optimizing the production processes and further exploring the self-healing capabilities of tires, ultimately leading to more sustainable automotive practices. As the industry

continues to evolve towards greener solutions, nanocomposite tires stand at the forefront, promising to transform tire manufacturing and vehicle performance in the coming decades.

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