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Carbon Nanotube Reinforced Polyisoprene Nanocomposites: A ComprehensiveReview of Mechanical and Thermo-Mechanical Properties

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Abstract- Polyisoprene is widely used in elastomeric applications due to its excellent elasticity and resilience. But its mechanical and thermo-mechanical performance is limited with conventional fillers. Carbon nanotubes (CNTs) have emerged as effective nanofillers because of their high aspect ratio, strength and ability to form interconnected networks at low loadings. This study critically analyzes CNT-reinforced polyisoprene nanocomposites which is focus on mechanical and thermo-mechanical behavior. It checks the influence of CNT type, loading, dispersion and interfacial bonding on stiffness, strength, flexibility and dynamic mechanical performance. Processing methods and percolation effects of CNT are discussed with challenges in large-scale processing, durability and structure–property relationships for advanced elastomeric applications.

Keywords- Carbon nanotubes; Polyisoprene; Elastomer nanocomposites; Mechanical properties; Thermo-mechanical behavior; Dynamic mechanical analysis; Filler network formation; Percolation phenomena
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1. INTRODUCTION

Polyisoprene is one of the most important elastomeric materials due to its exceptional elasticity with high resilience and ability to sustain repeated large deformations. These characteristics of Polyisoprene have ensured its continued relevance in applications. It is requiring for dynamic mechanical performance which includes tires, vibration control systems, seals and flexible engineering components. In spite of that, the intrinsic mechanical strength and thermo-mechanical resistance of neat polyisoprene are insufficient for many service environments particularly under cyclic loading and elevated temperatures making something necessary the use of reinforcing fillers (Kraus et al.; Heinrich et al.).

Carbon black has historically dominated elastomer reinforcement owing to its cost effectiveness and established processing technologies. While carbon black improves stiffness and strength, its reinforcing efficiency is limited by the relatively high filler concentrations required to achieve target properties, often resulting in increased hysteresis, reduced elasticity, and higher energy dissipation during dynamic deformation (Fröhlich et al.; Kraus et al.). Furthermore, the micro-scale nature of carbon black aggregates restricts control over filler network architecture and limits the ability to tailor viscoelastic behaviour for advanced applications (Heinrich et al.).

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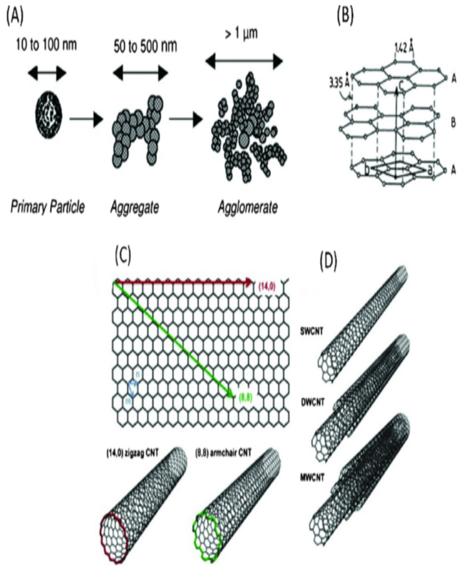

Figure 1. Schematic comparison of carbon black and carbon nanotube filler dispersion and reinforcement mechanisms in elastomer composites, illustrating the tendency of carbon black to form aggregated networks and carbon nanotubes to form interconnected load-bearing networks. *Adapted from Heinrich et al. (2008) and Kraus (2009)*

The emergence of carbon nanotubes has introduced new opportunities for elastomer reinforcement. Carbon nanotubes exhibit extremely high aspect ratios which is exceptional intrinsic mechanical properties and the ability to form continuous filler networks at very low loadings. In polyisoprene matrices, these characteristics enable efficient stress transfer and pronounced mechanical reinforcement without the substantial loss of extensibility typically associated with conventional fillers (Coleman et al.). As a result, CNT-reinforced poly-isoprene nano-composites have attracted increasing attention as next-generation elastomeric materials.

In addition to static mechanical enhancement, CNT incorporation significantly alters the viscoelastic and thermo-mechanical behaviour of polyisoprene. Dynamic mechanical studies have demonstrated that CNT networks strongly influence storage modulus, damping behaviour, and temperature-dependent mechanical stability which is particularly in the vicinity of the mechanical percolation threshold (Bokobza & Bruneel et al.). These effects arise from the formation, deformation and partial disruption of CNT networks under applied strain. Thisgoverns energy dissipation and hysteresis behaviour (Rapoport et al.).

Even after many detailed experiments, the relationship between structure and properties in CNT-reinforced polyisoprene nanocomposites is still not fully understood till now. It was reporteddiscrepancies in mechanical and thermo-mechanical performance have been reported in various studies. These differences are often traced to variations in CNT type, dispersion state, processing route and interfacial interactions Which makes direct comparison between studies difficult (Chen et al.). In addition, the key issues such as how the CNT network develops during repeated deformation and how stable the material remains under long-term thermal and mechanical stress and whether advanced dispersion methods can be effectively scaled up are still not fully understood.

This study review aims to provide a well-organized and analyticalexamination of carbon nanotube which reinforced polyisoprene nanocomposites with emphasis on mechanical and thermo-mechanical properties. The effects of CNT characteristics, dispersion quality, and processing techniques are analyzed. These factors influence tensile behaviour, viscoelastic response, and dynamic mechanical performance. Current limitations are identified and future research directions are proposed to support the rational design of high-performance polyisoprene/CNT nanocomposites.

II. CARBON NANOTUBE REINFORCED POLYISOPRENE NANO-COMPOSITES

Carbon nanotubes are cylindrical nanostructures derived from graphene sheets and exist in different structural forms which includes single-wall, double-walland multiwall configurations. The structural characteristics of CNTs strongly influence their dispersion behavior, network formation and reinforcement efficiency in polyisoprene matrices.

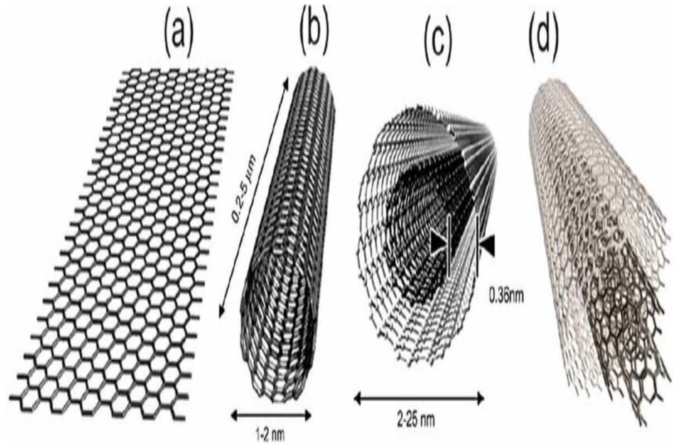

Figure 2. Structural representation of (a) graphite sheet, (b) single-wall carbon nanotube (SWCNT), (c) double-wall carbon nanotube (DWCNT), and (d) multiwall carbon nanotube (MWCNT). *Adapted from Coleman et al., 2006; Bokobza, 2008.*

A. Influence of CNT Characteristics and Filler Content

The reinforcing efficiencyof carbon nanotubes in polyisoprene is closely related to their structural parameters which includes aspect ratio, degree of entanglement and aggregation tendency. Carbon nanotube which is made of many layers of carbonare most frequently employed in elastomer systems since they have suitable properties togetherbetween reinforcement efficiency and processability (Bokobza et al.). Even at low concentrations, CNTs can induce substantial increases in modulus and tensile strength

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which reflects their ability to form mechanically effective filler networks (Bokobza & Rahmani et al.).

Mechanical percolation plays a central role in CNT-reinforced polyisoprene. As CNT concentration approaches the percolation threshold, a pronounced increase in stiffness and storage modulus is commonly observed which indicates the formation of a continuous load-bearing network (Rahmani et al.; Zhou et al.). Beyond this threshold, further CNT addition yields diminishing returns and may adversely affect extensibility due to increased filler–filler interactions and agglomeration (Chen et al.).

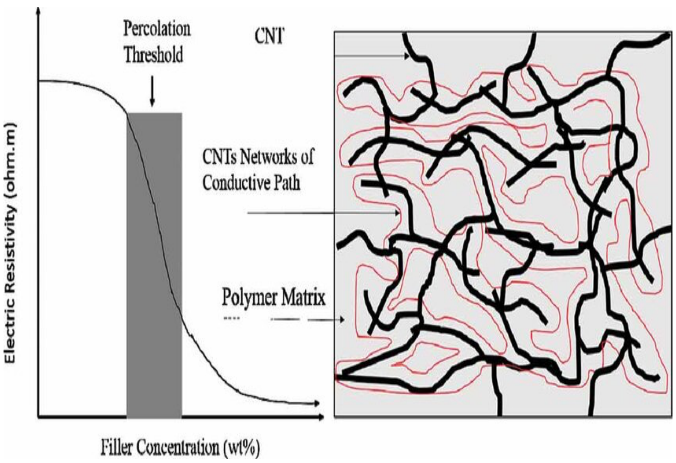

Figure 3. Illustration of percolation threshold showing transition from isolated CNTs to continuous network in a rubber matrix. *Adapted from Rahmani & Bokobza, 2014; Bokobza & Bruneel, 2016; Zhou et al., 2019.*

B. Dispersion State and Interfacial Interactions

Achieving a homogeneous CNT dispersion within the polyisoprene matrix is essential for maximizing reinforcement efficiency. It is an inadequate dispersion which leads to CNT agglomerates that act as stress concentrators and reduce effective load transfer (Pötschke et al.; Bokobza et al.). These strong interfacial interactions between CNT surfaces and polyisoprene chains promote stress transfer and restrict chain mobility. This can contribute to enhanced stiffness and improved thermo-mechanical stability (Heinrich et al.).

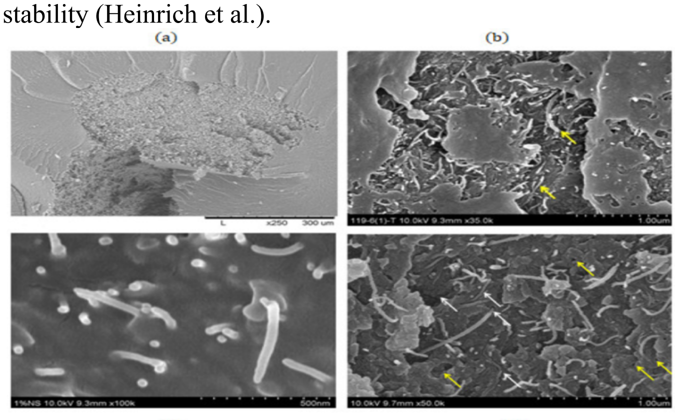

Figure 4. SEM characterization of CNT-reinforced polymer composite with 4 wt% CNTs: (a) CNT agglomeration; (b) high-magnification view of CNT agglomerates; (c) interfacial adhesion between CNTs and epoxy resin; (d) CNTs and porosity distribution. Yellow arrows represent porosity, and white arrows point to CNTs.
Source: Tamayo et al., *The Effect of Agglomeration on the Electrical and Mechanical Properties of Polymer Matrix Nanocomposites Reinforced with Carbon Nanotubes* (2022).

CNT surface modification has been explored as a strategy to improve dispersion and interfacial adhesion. While functionalization can enhance compatibility with the elastomer matrix.It may also disrupt CNT–CNT interactions and modify network formation which can influence viscoelastic behaviour (Bokobza & Belin et al.; Zhang et al.). Consequently, an optimal balance between dispersion quality and network integrity must be achieved.

C. Mechanical Properties

CNT-reinforced polyisoprene nanocomposites exhibit significant improvements in tensile modulus, tensile strength, and tear resistance. These properties are higher compared to unfilled and conventionally filled systems.At comparable filler contents, CNTs provide higher reinforcement efficiency than carbon black which reflects their superior aspect ratio and network-forming capability (Bokobza et al.; Bokobza & Zhang et al.). The Improved mechanical performanceis primarily attributed to the presence of a percolated CNT network that supplements the elastomer matrix in load bearing (Rahmani et al.)

However, the increased stiffness of CNT-reinforced polyisoprene nanocomposites is often accompanied by a reduction in elongation at break which is especially at higher CNT loadings. This shows the need to carefully control CNT content and dispersion for applications that require both high strength and large reversible deformation (Wang et al.; Kim et al.).

D. Thermo-Mechanical and Dynamic Mechanical Response

The Dynamic mechanical analysis has provided valuable insight into the viscoelastic behaviour of CNT-filled polyisoprene. This incorporation of CNTs leads to a marked increase in storage modulus over a broad temperature range which indicates improved resistance to dynamic deformation (Bruneel et al.; Wang et al.). Changes in loss factor reflect modifications in energy dissipation mechanisms associated with CNT network formation and polymer chain confinement (Bokobza & Rapoport et al.).

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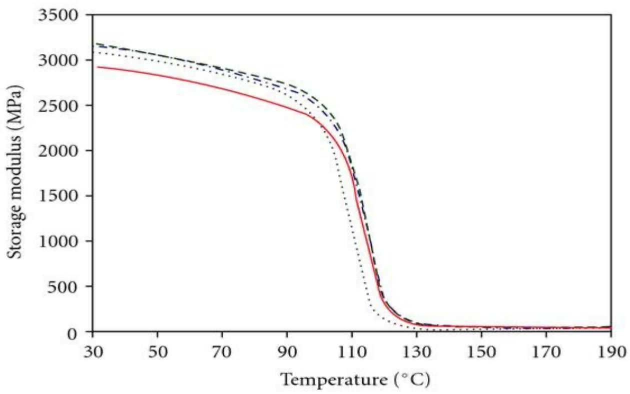

Figure 5**.** Dynamic mechanical analysis of CNT-filled polyisoprene composites showing (a) storage modulus (E′) and (b) loss factor (tan δ) as a function of temperature, illustrating enhanced thermo-mechanical stability with increasing CNT content. *Adapted from Wang et al. (2018).*

Under cyclic deformation, CNT networks exhibit strain-dependent breakdown and partial recovery which directly influence hysteresis and fatigue behaviour. Electrical and mechanical measurements suggest reversible network rearrangement. however, direct experimental observation of these processes in polyisoprene systems remains limited (Alig et al.).

E. Processing Methods and Structure–Property Relationships

Processing route selection strongly influences CNT dispersion and network development. Melt mixing gives industrial relevance but often results in incomplete dispersion due to high melt viscosity and limited shear efficiency (Pötschke et al.; Zhao et al.). this Solution processing enables improved dispersion but suffers from scalability and environmental concerns (Bokobza et al.).

Latex-based processing has emerged as a particularly effective method for achieving uniform CNT distribution and strong filler–matrix interactions in polyisoprene nanocomposites. This approach has demonstrated superior mechanical and thermo-mechanical performance at low CNT loadings.Although, these challenges related to large-scale implementation remain unresolved (Bokobza & Zhang et al.; Zhao et al.).

III. CONCLUSION AND FUTURE OUTLOOK

Carbon nanotube reinforced polyisoprene nanocomposites represent a significant advancement in elastomer technology which offers enhanced mechanical strength and thermo-mechanical stability at substantially lower filler contents than conventional systems. The formation of interconnected CNT networks within the polyisoprene matrix plays an important and decisive role. It governs tensile behavior, viscoelastic response, and dynamic mechanical performance. While considerable progress has been made in understanding reinforcement mechanisms, key challenges remain.

Future research should prioritize direct and in-situ characterization of CNT network evolution under cyclic and dynamic loading. Itestablishesa clear links between network structure and macroscopic performance. In the Long-term thermo-mechanical aging and fatigue behaviour must be systematically correlated with network stability to ensure reliable performance in real-world applications. Further, the developmentof predictive structureproperty models which is capable of integrating dispersion state, percolation behaviour and viscoelastic response would greatly facilitate material design.

In practical terms, thescalable processing strategies that preserve CNT dispersion and reinforcement efficiency are essential for industrial adoption. Greater attention should also be directed toward application-specific optimization, multifunctional elastomer concepts and environmentally sustainable processing routes. Knowing these challenges will enable the rational design of next-generation polyisoprene/CNT nanocomposites for advanced elastomeric applications.

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