Dean&Francis
ISSN 2959-6157

Research on the application of graphene in material reinforcement to improve material properties

Ruixuan Xu

Abstract:
In this study, the physical properties of graphene were altered and reinforced by mixing it with different types of materials. This was achieved through experimental procedures and analyses, informed by relevant literature and course materials. It was found that graphene not only retains the excellent physical properties of the original material when compounded with most materials, but also endows the composite material with the unique properties of graphene, which significantly enhances the overall performance of the material.

Keywords: graphene reinforcement, material properties, composites, physical properties, strength.

1. Introduction

Graphene, one of the most extraordinary and profoundly significant carbon materials discovered after the turn of the millennium, holds an unshakable position in the field of materials development. Since its discovery in 2004 by Andre Geim and Konstantin Novoselov, graphene has garnered significant attention in the materials science community due to its exceptional properties. Its potential to enhance composite materials is particularly intriguing, attributed to its remarkable thermal conductivity, tensile strength, and exceptional stability. Graphene is a two-dimensional material composed of carbon atoms arranged in a hexagonal lattice. Structurally, it consists of a single layer of carbon atoms organized in a two-dimensional crystalline lattice, forming a honeycomb-like hexagonal network. This distinctive two-dimensional structure grants graphene numerous unique electrical, optical, and mechanical properties. Despite being only one atom thick, graphene exhibits extraordinary strength and elasticity, making it a material of immense scientific and industrial value.

2. Graphene-Enhanced Non-Metallic Matrix Materials

The reinforcement of asphalt mixtures using graphene is a prominent application of graphene in the field of material strengthening. This approach aims to enhance the strength, durability, and crack resistance of asphalt mixtures. Numerous research teams worldwide have focused on developing graphene-modified asphalt mixtures and have conducted detailed experimental evaluations of their mechanical and durability properties.

Typically, researchers introduce graphene into asphalt mixtures through methods such as chemical reduction and physical blending. The resulting materials are then subjected to a variety of performance assessments, including tensile tests, compaction tests, and dynamic shear tests. For instance, graphene-reinforced rubber-modified asphalt mixtures and SBS-modified asphalt mixtures exhibit excellent water stability, high-temperature stability, and low-temperature crack resistance. Compared to SBS-modified asphalt binders, graphene-reinforced rubber provides more significant improvements in water stability and high-temperature stability, although its effects on low-temperature crack resistance are relatively modest.

The incorporation of graphene into asphalt materials substantially increases their strength, addressing challenges in paving roads in harsh environments. This advancement demonstrates the potential of graphene to revolutionize infrastructure materials in regions with demanding conditions.

3. Graphene-Enhanced Metallic Matrix Materials

Graphene also holds remarkable promise for reinforcing alloys and metal materials. The use of carbonaceous materials for metal reinforcement began in the early stages of developing carbon-based materials, initially leveraging carbon nanotubes as reinforcement phases to strengthen metals. These studies built upon earlier experiments where carbon nanotubes were used to reinforce polymers. With the gradual scaling of graphene production and improved control over its quality and layer thickness, research into graphene-based composites has gained considerable attention worldwide. Scholars have sought to determine whether graphene's high-performance characteristics can be transferred to various metal materials through blending or novel preparation techniques. However, integrating graphene into metals remains challenging due to its low density, poor dispersibility, and weak interfacial tension with molten metals. These issues complicate the incorporation of graphene into metallic matrices. Consequently, current mainstream methods for combining graphene with metals include powder metallurgy, chemical deposition, hydrothermal synthesis, and sol-gel techniques. These approaches aim to overcome the limitations of traditional carbonaceous reinforcements, paving the way for graphene-enhanced metallic materials with superior properties and broader applications.

4. Applications of Graphene in Enhancing the Properties of Composite Materials

4.1 Composite Reinforcement in Non-Metallic Matrix Materials

The increasing demand for infrastructure development in frontier and geologically challenging regions has heightened requirements for road surface torsional resistance, hardness, and tensile performance. Conventional asphalt and traditional road construction materials often fail to meet these stringent demands. Graphene-composite asphalt materials offer a promising solution. The exceptional strength, thermal conductivity, and chemical stability of graphene significantly enhance these properties in asphalt, without complicating the paving process. This enables the optimization of material performance under various environmental conditions by leveraging graphene's superior properties. For instance, Russo and colleagues in Italy developed a graphene-modified asphalt mixture by incorporating hard plastic into the composite. Their research revealed that the performance enhancements in strength, tensile resistance, and thermal stability varied with the type of asphalt used. In comparison with conventional SBS PmB-modified asphalt, mixtures containing recycled plastic asphalt modifiers exhibited higher stiffness modulus. Studies also confirmed that under medium to high-temperature conditions, which are critical for road longevity, these composite materials performed better than conventional SBS materials. Technologically, they demonstrated greater resistance to permanent deformation and longer projected lifespans [1]. Despite its benefits, challenges such as reduced viscosity, difficulty in application, and melting issues arise in practical paving scenarios [2]. Furthermore, graphene oxide (GO), a precursor to solid graphene sheets, not only serves as an intermediary for graphene production but also enhances composite performance when integrated with polymers or ceramics. For example, Xu and his team significantly improved the thermal stability and corrosion resistance of PVA by blending it with GO in an oxygen-rich and aqueous environment. This GO-PVA composite increased corrosion resistance in gasoline pipelines by 35.35% [3]. Similarly, in ceramic matrix materials, graphene primarily enhances material density. Chen et al. combined graphene suspensions with ceramic powders to form composite powders. These were processed using various ceramic sintering techniques, resulting in significant density improvements across all graphene concentrations and sintering methods [4].

4.2 Composite Reinforcement in Metallic Matrix Materials

Graphene also exhibits remarkable capabilities in strengthening alloys and metallic materials. Early research into carbon-based materials for metal reinforcement employed carbon nanotubes as a reinforcing phase. With ad-

ISSN 2959-6157

vancements in graphene production, its composites have gained significant attention, aiming to replicate graphene's high-performance attributes in metal materials through innovative blending and fabrication methods.

However, challenges such as graphene's low density, poor dispersibility, and weak interfacial tension with molten metals hinder its integration into metallic matrices. To address these issues, methods like powder metallurgy, chemical deposition, hydrothermal synthesis, and sol-gel techniques are commonly used [5]. For example, Wang et al. from Shanghai Jiao Tong University used powder metallurgy to produce graphene-reinforced aluminum alloys with a tensile strength improvement of over 62% compared to conventional aluminum alloys. Similarly, Zhu J's team at Harbin Institute of Technology employed chemical vapor deposition (CVD) to deposit Sn-Co nanoparticles onto graphene films, enhancing electrical conductivity and reducing resistance. While traditional conductive materials such as Cu and Ag are commonly used, graphene offers superior performance at lower costs, making it a preferred alternative [6]. The impact of graphene's weight fraction on aluminum-based composites has also been extensively studied. Results indicate that increasing graphene content correlates with significant strength improvements in aluminum-based materials. For example, Seretis et al. utilized mechanical stirring to create graphene-reinforced aluminum composites, demonstrating substantial strength gains compared to standard aluminum materials [7]. Li et al. developed graphene-aluminum composites using high-energy ball milling and vacuum hot pressing, while Khan et al. employed ball milling and powder metallurgy. Their findings suggest that uniform graphene dispersion and material densification are key factors in improving composite hardness [8][9].

Overall, the uniform dispersion of graphene within metallic matrices significantly enhances the hardness and overall mechanical properties of the composites, paving the way for broader industrial applications.

5. Research Content and Innovation

The study of graphene-modified asphalt mixtures constitutes a significant aspect of this project. We aim to introduce graphene into asphalt using chemical reduction and physical blending methods. Through tensile tests, compaction tests, and dynamic shear tests, we will comprehensively evaluate the mechanical and durability properties of these composites, including high-temperature stability, low-temperature crack resistance, and water stability.

In addition, our research extends to graphene-metal composites. Employing methods such as powder metallurgy, chemical deposition, hydrothermal synthesis, and sol-gel techniques, we will combine graphene with metals like aluminum, copper, and silver. The performance of these composites, including tensile strength, electrical conductivity, and resistance, will be rigorously tested and optimized. For graphene-polymer and graphene-ceramic composites, we will prepare graphene suspensions, conduct surface modifications, and integrate graphene with polymers (e.g., PVA) and ceramic matrix materials. The focus will be on evaluating thermal stability and density, exploring graphene's potential to enhance the properties of these materials.

Key challenges include graphene's poor dispersibility, weak interfacial compatibility, and the feasibility and economic viability of fabrication processes. To address these issues, we will conduct extensive experiments and analyses to optimize graphene dispersion techniques. Furthermore, we aim to improve the interfacial bonding between graphene and substrate materials to enhance the overall performance of the composites. Developing cost-effective, industrially scalable production processes for graphene composites will be a central focus of our research. The study will utilize both experimental and theoretical methodologies. Laboratory tests and performance analyses of graphene composites will be complemented by theoretical modeling and computational simulations to predict and explain experimental outcomes.

5.1 Technical Approach

Graphene-Modified Asphalt: Using chemical reduction and physical blending methods, followed by mechanical and durability testing.

Graphene-Metal Composites: Employing powder metallurgy and chemical deposition methods, with subsequent performance testing and optimization.

Graphene-Polymer and Ceramic Composites: Preparing graphene suspensions, conducting surface modifications, and synthesizing composites, with thermal stability and density testing.

5.2 Experimental Design

Prepare asphalt samples with varying graphene concentrations and assess their mechanical and durability properties.

Fabricate metal samples with different graphene concentrations and evaluate their mechanical and electrical properties.

Develop polymer and ceramic samples with various graphene concentrations to test their thermal stability and density.

5.3 Feasibility Analysis

The relative maturity of graphene composite fabrication techniques suggests high feasibility. By validating performance enhancement through experiments, this study will provide robust data to support practical applications.

5.4 Innovative Contributions

The project focuses on developing high-performance graphene composites to enhance the physical properties of substrate materials. By exploring and optimizing fabrication techniques, we aim to overcome challenges such as poor graphene dispersion and interfacial compatibility. The findings of this study have broad application prospects in areas such as road construction, aerospace, military, and civil engineering, improving the lifespan and performance of materials. This research holds substantial practical significance and theoretical value.

6. Conclusion

Over two decades of research and innovation in graphene have yielded significant achievements in its integration with various materials. However, challenges remain in the large-scale industrial production and application of graphene and graphene composites. The road to fully realizing graphene's potential in composite materials necessitates further breakthroughs. Continued exploration of the relationships and applications between graphene and diverse materials is essential for advancing this promising field.

References

[1] Zheng Q.Q., Guo R., Huang Y., Chen J., Yuan W., Wang W., Liu Y.H. Performance Analysis of Graphene Composite Rubber-Modified Asphalt SMA Mixtures [J]. *Modern Transportation Technology*, 2023, 20(2): 20-24.

[2] *The Graphene Handbook*. Graphene-Info.com, 2019.

[3] Xu J.Y., Hu Y., Song L., et al. Preparation and Characterization of Poly(vinyl alcohol)/Graphite Oxide Nanocomposite [J]. *Carbon*, 2002, 40(3): 450-451.

[4] Chen C., Yun C., Yang J., et al. Research Progress on Graphene/Ceramic-Based Composite Materials [J], 2017.

[5] Wang J., Li Z., Fan G., et al. Reinforcement with Graphene Nanosheets in Aluminum Matrix Composites. *Scripta Materialia*, 2012, 66(8): 594.

[6] Zhu J., Wang D., Liu T., et al. Preparation of Sn-Co-Graphene Composites with Superior Lithium Storage Capability [J]. *Electrochimica Acta*, 2014, 125: 347.

[7] Seretis G.V., Kouzilos G., Polyzou A.K., et al. Effect of Graphene Nanoplatelet Fillers on Mechanical Properties and Microstructure of Cast Aluminum Matrix Composites [J]. *Nano Hybrids and Composites*, 2017, 15: 26-33.

[8] Li G., Xiong B. Effects of Graphene Content on Microstructures and Tensile Properties of Graphene-Nanosheets/Aluminum Composites [J]. *Journal of Alloys and Compounds*, 2017, 697: 31-33.

[9] Khan M., Amjad M., Khan A., et al. Microstructural Evolution, Mechanical Profile, and Fracture Morphology of Aluminum Matrix Composites Containing Graphene Nanoplatelets [J]. *Journal of Materials Research*, 2017, 32(11): 2055-2066.