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Graphene in Asphalt Materials: A Comprehensive Review A Summary of Application Research and Future Prospects

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ABSTRACT
Asphalt materials, as core components in road engineering and infrastructure construction, face critical challenges such as softening at high temperatures, cracking at low temperatures, and insufficient durability during long-term service. Graphene, with its exceptional mechanical, electrical, and thermal properties, has emerged as a promising modifier to address these limitations, opening new avenues for the development of high - performance asphalt materials. This review systematically synthesizes the latest research progress on graphene - modified asphalt. It first analyzes the research background and significance of graphene application in asphalt, then focuses on key research contents—including the effects of graphene on asphalt's physical and rheological properties, common preparation methods of graphene - modified asphalt, and its current application status in engineering. Finally, the review summarizes the existing achievements, identifies limitations in current research (such as poor graphene dispersion and high preparation costs), and proposes future research directions, including optimizing dispersion technologies, exploring molecular interaction mechanisms, and conducting long - term engineering monitoring. This work aims to provide a theoretical reference and technical support for the further development and large - scale promotion of graphene - modified asphalt materials.

KEYWORDS
Graphene; Asphalt materials; Material modification; Road engineering; Rheological properties; Preparation method

1 Introduction

Asphalt is a widely used viscoelastic material in transportation infrastructure, playing a crucial role in road pavements, airport runways, and bridge deck pavements. However, its inherent temperature sensitivity and poor durability have long plagued engineering applications:

High temperatures easily cause rutting and softening, while low temperatures lead to brittleness and cracking, significantly shortening the service life of pavements and increasing maintenance costs. With the rapid development of nanomaterial science, graphene—discovered in 2004—has attracted extensive attention in the field of material modification due to its unique two - dimensional (2D) planar structure and excellent comprehensive performance. Its high tensile strength (≈130 GPa), large specific surface area (≈2630 m^2/g), and good thermal conductivity (≈5000 W/(m·K)) make it a potential candidate to enhance asphalt performance [1].

This review is structured to systematically organize the research on graphene - modified asphalt. First, it clarifies the research background and significance by linking the performance defects of asphalt to the advantages of graphene. Second, it details the effects of graphene on asphalt's physical and rheological properties, compares the characteristics of different preparation methods, and summarizes practical application cases. Finally, it points out current research bottlenecks and prospects for future development, providing a comprehensive overview for researchers and engineers in related fields.

2 Research background and significance

2.1 Research background

2.1.1 Performance limitations of asphalt materials

In practical engineering, asphalt materials are constantly subjected to environmental factors (temperature changes, rainfall, ultraviolet radiation) and traffic loads (vehicle rolling, impact). These factors easily induce common pavement diseases:

· High - temperature softening: When ambient temperature exceeds 30° C, asphalt's viscosity decreases sharply, leading to rutting and permanent deformation under repeated vehicle loads. In some hot regions, the rutting depth of traditional asphalt pavements can reach up to 10 mm within a single summer season, seriously affecting driving safety and road flatness [5].

· Low - temperature cracking: At temperatures below 0°C, asphalt's molecular mobility is reduced, and its brittleness increases. Thermal stress accumulation often causes transverse or longitudinal cracks in pavements. In cold - climate areas, the number of cracks per kilometer of asphalt pavement can exceed 50 within a year of service, accelerating the deterioration of the pavement structure [5].

· Durability degradation: Long - term oxidation, aging, and water erosion further reduce asphalt's adhesion and cohesion, accelerating pavement damage. After 5 years of service, the adhesion strength of asphalt to aggregates in unmodified asphalt pavements can decrease by more than 30%, resulting in the detachment of aggregates and the formation of potholes [3].

These limitations not only affect driving safety and comfort but also increase the economic burden of road maintenance.

2.1.2 Unique advantages of graphene

Graphene's structural and performance characteristics address the inherent defects of asphalt:

· Mechanical enhancement: The 2D planar structure of graphene can form a "reinforcement network" in asphalt, improving its tensile strength and deformation resistance. Experimental studies have shown that adding 0.3% graphene by mass to asphalt can increase its tensile strength by about 25%, effectively enhancing the ability of asphalt to resist external forces [1].

· Thermal stability regulation: Graphene's high thermal conductivity helps to uniformize temperature distribution in asphalt, reducing thermal stress caused by temperature gradients. In a simulation test, when graphene was added to asphalt, the temperature difference within the asphalt layer under the same heat source was reduced by 15% - 20%, alleviating the thermal stress concentration problem [8].

· Interface adhesion improvement: Graphene's large specific surface area enhances its interaction with asphalt molecules, reducing the risk of delamination between asphalt and aggregates. The adhesion work between graphene - modified asphalt and aggregates is 30% - 40% higher than that of traditional asphalt, significantly improving the overall stability of the asphalt - aggregate system [1].

2.1.3 Feasibility of graphene - modified asphalt

Early experimental studies have confirmed that adding a small amount of graphene (usually 0.05%–0.5% by mass) can significantly improve asphalt's high - temperature stability and low - temperature toughness without increasing its viscosity excessively. For example, when 0.2% graphene was added to 70# base asphalt, the softening point increased by 3 - 5°C, and the low - temperature brittle point decreased by 2 - 4°C [1]. This feasibility lays the foundation for the industrial application of graphene - modified asphalt.

2.2 Research significance

2.2.1 Engineering application value

Improving the service life of asphalt pavements is the core goal of this research. By enhancing asphalt's high - temperature anti - rutting and low - temperature anti - cracking performance, the maintenance cycle of pavements can be extended from 5–8 years to 10–15 years. In a practical project in a high - temperature area, the use of graphene - modified asphalt reduced the rutting depth by 50% - 60% after 5 years of service compared with traditional asphalt, reducing maintenance costs by 30%–50% and alleviating the impact of road construction on traffic [3].

2.2.2 Promotion of graphene industrialization

Graphene, as a representative of 2D nanomaterials, has long faced the challenge of "laboratory - to - industry" transformation. The application of graphene in asphalt materials (a large - volume civil engineering material) provides a broad market space for graphene production. It is estimated that with the large - scale application of graphene - modified asphalt, the annual demand for graphene in the road construction industry alone could reach hundreds of tons in the next decade, promoting the development of the entire graphene industry chain [4].

2.2.3 Theoretical innovation significance

The interaction between graphene (nanoscale) and asphalt (macroscale viscoelastic material) involves multi - scale mechanisms such as interface physics and molecular chemistry. Studying this interaction can enrich the theoretical system of nanomaterial - modified composite materials. For instance, through molecular dynamics simulations, it has been found that graphene forms strong π - π interactions with asphalt molecules, which provides new insights into the modification mechanism at the molecular level and can provide a reference for the modification of other polymer materials [8].

3 Key research contents of graphene - modified asphalt

3.1 Research objectives

The research on graphene - modified asphalt focuses on two core objectives:

(1) Systematically clarify the influence mechanism: Summarize the quantitative relationship between graphene content, dispersion state, and asphalt performance (such as softening point, creep stiffness, and complex shear modulus), and establish a theoretical model for performance prediction. For example, research has shown that within a certain range of graphene content (0 - 0.5%), the complex shear modulus of asphalt shows a nearly linear increase with the increase of graphene content, and a semi - empirical model has been proposed based on this relationship [1].

(2) Summarize preparation and application status: Classify and evaluate the technical characteristics of existing preparation methods, sort out practical application cases in engineering, and provide a basis for the optimization of modification processes and the promotion of application technologies.

3.2 Effects of graphene on asphalt properties

3.2.1 Physical properties

(1) High - temperature stability: The softening point test (T&R method) shows that adding graphene can significantly increase the softening point of asphalt. For example, when 0.2% graphene is added to 70# base asphalt, the softening point increases by 3–5°C, and the high - temperature anti - deformation ability is improved by 20%–30% [1]. In a real - world scenario, a road section paved with 0.2% graphene - modified asphalt in a high - temperature region had a rutting depth of only 2 - 3 mm after 3 years of service, while the adjacent section paved with unmodified asphalt had a rutting depth of 5 - 6 mm [3].

This is because graphene's 2D structure hinders the flow of asphalt molecules at high temperatures, increasing the material's resistance to viscous deformation.

(2) Low - temperature toughness: The low - temperature brittle point test and bending beam rheometer (BBR) test confirm that graphene can reduce the brittle point of asphalt by 2–4°C. When the temperature is - 10°C to - 20°C, the creep stiffness of graphene - modified asphalt decreases by 15%–25% compared with base asphalt, and the recovery rate increases by 10%–20% [1].

In a cold - region experiment, the number of cracks in a pavement section paved with graphene - modified asphalt was 40% - 50% less than that of a section paved with unmodified asphalt after a winter with multiple freeze - thaw cycles [3]. This is due to graphene's ability to improve the flexibility of asphalt molecular chains and reduce the accumulation of thermal stress at low temperatures.

3.2.2 Rheological properties

Rheological properties directly reflect asphalt's deformation and recovery behavior under load, which is the key to evaluating its road performance. The dynamic shear rheometer (DSR) test shows that:

· *Complex shear modulus (G)**: After adding graphene, G* of asphalt increases by 15%–30% (at 60°C), indicating that the material's ability to resist shear deformation is enhanced. In a study on different graphene - modified asphalt samples, when the graphene content was 0.3%, the G* value at 60°C increased from 1.5 kPa in the base asphalt to 2.0 - 2.2 kPa [1].

· Phase angle (δ): δ decreases by 5° – 10°, meaning the elastic component of asphalt increases and the viscous component decreases, improving the pavement's ability to recover from deformation after load removal. For example, in a cyclic loading test, the permanent deformation of graphene - modified asphalt was 20% - 30% less than that of unmodified asphalt under the same loading conditions [2].

In addition, the bending beam rheometer (BBR) test shows that the low - temperature creep stiffness (S) of graphene - modified asphalt is lower, and the creep rate (m - value) is higher, which means the material has better low - temperature flexibility and crack resistance [1].

3.3 Preparation methods of graphene - modified asphalt

At present, the main preparation methods of graphene - modified asphalt include melt blending, solution blending, and in - situ polymerization modification. Each method has its own characteristics, and the comparison is shown in Table 1.

Table 1

Preparation Method	Core Process	Advantages	Disadvantages	Application Scenarios
Melt Blending	Heat base asphalt to 160–180° C (molten state), add graphene, and stir at high speed (1000–3000 rpm) for 30–60 minutes [2].	Simple operation, low equipment requirements, suitable for on - site construction [2].	Poor graphene dispersion, easy agglomeration (reducing modification effect); high stirring speed may cause asphalt aging. In a melt - blending experiment, when the stirring speed was 2000 rpm, the average size of graphene agglomerates in asphalt was about 5 - 10 μm, which affected the performance improvement effect [2].	Emergency maintenance of pavements, small - batch modification projects [2].
Solution Blending	Dissolve asphalt and graphene in an organic solvent (such as toluene or xylene), stir to form a uniform solution, and then evaporate the solvent under vacuum [2].	Good dispersion of graphene (uniform distribution in asphalt matrix); controllable modification process. The average size of graphene particles in asphalt after solution blending can be controlled within 1 - 2 μm [2].	Complex process (solvent recovery required); organic solvents are toxic and polluting; high cost (solvent and recovery equipment) [2].	Laboratory research, high - precision modification projects (such as airport runways) [2].
In - Situ Polymerization Modification	Mix graphene with asphalt monomers (such as styrene and butadiene) and initiators, and carry out polymerization reaction at 80–120℃ to form graphene - polymer composite modified asphalt [4].	Strong interaction between graphene and asphalt; excellent modification effect (G^* increases by 30%–50%); good long - term stability. In a long - term aging test, the performance of in - situ polymerization - modified asphalt changed less than that of other modified asphalts after 500 hours of aging [4].	Harsh reaction conditions (strict control of temperature and pressure); high cost (initiators and monomers); long reaction time [4].	High - performance pavement projects (such as bridge decks, heavy - duty road sections) [4].

3.4 Application status of graphene - modified asphalt

3.4.1 Road engineering

In recent years, graphene - modified asphalt has been applied in trial sections in many regions:

· High - temperature areas: In Guangdong and other southern provinces, trial sections of graphene - modified asphalt pavements have been built. After 2 years of operation, the rutting depth is less than 3 mm (far lower than the national standard limit of 5 mm), and the high - temperature stability is significantly better than that of ordinary asphalt pavements. In a large - scale trial in Guangdong, a 5 - kilometer road section paved with 0.3% graphene - modified asphalt showed excellent performance, with the rutting depth remaining stable at around 2 mm even during the hottest months [3].

· Low - temperature areas: In Heilongjiang and other northern provinces, the low - temperature cracking rate of graphene - modified asphalt pavements is reduced by 40%–60% compared with ordinary pavements, and the service life is extended by 3–5 years. In a project in Heilongjiang, a section of highway paved with graphene - modified asphalt had only a few minor cracks after 3 winters, while the adjacent section paved with traditional asphalt had numerous cracks [3].

3.4.2 Special engineering fields

(1) Airport runways: Airport runways have high requirements for asphalt's high - temperature stability (resisting aircraft tire friction heat) and low - temperature crack resistance. Graphene - modified asphalt has been used in the expansion project of a domestic airport. The test shows that its high - temperature softening point is above 65°C, and it can withstand the repeated impact of large aircraft without rutting. In an airport runway project, the graphene - modified asphalt used could maintain its integrity and performance even after thousands of aircraft take - offs and landings, with no visible rutting or cracking [6].

(2) Bridge deck pavements: Bridge decks are prone to cracking due to structural deformation and temperature changes. Graphene - modified asphalt, with its good flexibility and adhesion, has been applied in the deck pavement of a highway bridge in Jiangsu. After 1 year of operation, no cracking or delamination has occurred, and the structural stability is excellent. In the Jiangsu bridge project, the adhesion strength between the graphene - modified asphalt pavement and the bridge deck was 40% - 50% higher than that of traditional asphalt pavements, ensuring the long - term stability of the pavement structure [3].

4 Summary and future prospects

4.1 Research summary

4.1.1 Significant performance improvement effects

Graphene significantly modifies asphalt: it raises the high-temperature softening point by 3–5°C, lowers the low-temperature brittle point by 2–4°C, and increases the complex shear modulus by 15%–30% [1]. These improvements address asphalt's core defects (high-temperature softening, low-temperature cracking). For example, 0.2% graphene-modified 70# asphalt showed 28% less permanent deformation under cyclic loading at 60°C and 32% higher low-temperature fracture energy at -15°C [1].

4.1.2 Trade-offs in preparation methods

Each preparation method has pros and cons: melt blending is convenient but has poor dispersion (30%–40% agglomeration under conventional stirring) [2]; solution blending reduces agglomeration to <10% but has high solvent recovery costs (40%–50% of total cost) [2]; in-situ polymerization has excellent effects but is expensive. Selection depends on engineering needs and budgets.

4.1.3 Broad application prospects

Graphene-modified asphalt adapts to diverse environments and scenarios. In Guangdong's high-temperature road project, it cut annual maintenance from 2 to 0.5 times, boosting per-kilometer economic benefits by ~120,000 yuan [3]. Airport runways using it are expected to have a 15-year service life—5 years longer than ordinary asphalt [6].

4.2 Future research prospects

4.2.1 Optimize graphene dispersion technology

Poor dispersion limits application. Future research should:

· Develop green dispersants (e.g., soybean oil-based surfactants) to improve dispersion uniformity by 25%–30% with no toxic emissions [9].

· Use physical methods (e.g., 20–30 kHz ultrasonic dispersion) to reduce graphene agglomerate size to 1–2 μm, with only 5%–8% asphalt aging (vs. 15%–20% for high-speed stirring) [10].

4.2.2 Deepen the study of interaction mechanisms

Current understanding of graphene-asphalt interaction is macro-level. Future work should:

· Use molecular dynamics to reveal atomic-level binding: graphene's hydroxyl groups form hydrogen bonds with asphaltenes (binding energy 20–30 kJ/mol), enhancing interface adhesion [8].

· Establish a multi-scale model: Li et al.'s (2023) model predicts complex shear modulus with <10% error for precise formulation design [11].

4.2.3 Conduct long-term engineering application monitoring

Most cases have <5 years of service. Future efforts should:

· Set up 10–15-year monitoring for 12 trial sections (high/low temperature, high humidity) with annual data updates [12].

· Address environmental impacts: under strong UV (annual dose >1000 kWh/m^2), graphene-modified asphalt has 15%–20% higher performance retention than ordinary asphalt; adding 0.5%–1% UV absorbers improves this by 10%–15% [13].

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