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Advancements in sustainable pavement materials: a literature review

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Abstract. This paper reviews the research progress of sustainable pavement materials, focusing on the urgent need to reduce carbon emissions and improve the recyclability of road construction materials. Traditional materials such as asphalt and cement contribute significantly to greenhouse gas emissions due to their reliance on fossil fuels. This study explores innovative solutions including bio-based asphalt substitutes, recycled aggregates, and industrial by-products that comply with circular economy principles and offer similar or better mechanical properties. Integrating these materials into road construction can not only solve environmental problems but also support global climate governance efforts. Despite the progress made, challenges remain, such as the need for a comprehensive life cycle assessment framework and improved performance evaluation systems. This paper emphasizes the importance of building a multi-dimensional collaborative innovation research framework to overcome the technological bottleneck and promote the sustainable development of green infrastructure.

Keywords: sustainable construction, Recycled Asphalt Pavement (RAP), carbon footprint reduction, circular economy, green infrastructure

1. Background

Considering that the construction, operation, and demolition phases of new and existing buildings together contribute to more than 20% of total global greenhouse gas emissions under the framework of building life cycle carbon emissions assessment [1]. It is imperative to develop innovative strategies to mitigate these emissions. In the field of traditional road-building materials, asphalt and cement materials are the main contributors to the total carbon emissions of global transport infrastructure due to their dependence on fossil fuels in the production process [2]. In the case of asphalt mixture, its carbon emissions per ton in the production stage reach 120-180 kg CO_2 equivalent, 70% of which comes from aggregate drying and asphalt heating energy consumption. This situation highlights the urgent need to develop new environmentally friendly road materials such as bio-based asphalt substitutes and low-carbon cementing materials. The development of sustainable paving materials has become a vital technical path to cope with environmental deterioration and promote the utilization of waste resources, and its large-scale application is directly related to the achievement of the climate goals of the Paris Agreement.

In recent years, studies have been oriented towards the development of materials that reduce the carbon footprint, improve recyclability, and take advantage of industrial or post-consumer waste, for instance, the research by Hossain et al. [3]. The research and development on a novel, ultra-high-performance, low-carbon cement derived from solid waste (fast-setting/hardening high-belite sulfoaluminate cement) has established an innovative paradigm for synergizing solid waste resource utilization with eco-friendly construction materials. This technology employs bulk industrial solid wastes—such as fly ash, blast furnace slag, industrial by-product gypsum, and alkali-activated slag—as the primary raw materials, achieving a substantial increase in solid waste recycling efficiency. Compared to conventional Portland cement and traditional sulfoaluminate cement, this system demonstrates superior sustainability and performance metrics. The calcination temperature is reduced by 150~200 ℃ and 50 ℃, respectively, and the carbon emission intensity is only 30%~60% and 50%~80% for the two cements, achieving a major breakthrough in energy saving and emission reduction in the calcination process. The engineering application of such cementified materials marks the key technological progress in the construction of the "solid waste - building materials - carbon emission reduction" collaborative development system in China, and provides a demonstration path for the innovative application of sustainable recycled materials in the field of road engineering.

2. Recycled materials in pavement construction

Under the strategic framework of coping with environmental crisis and promoting global climate governance, the research and development and application of environmentally friendly paving materials has become the core path to balance the needs of ecological protection and infrastructure construction. By reconstructing the material metabolism model of “resource-production-application”, such innovative materials not only achieve the dual goals of waste resource utilization and ecosystem restoration but also promote the deep alignment of the concept of green and low-carbon development with the international climate action program at the practical level [4].

The use of recycled materials in road construction has significant environmental and economic benefits. However, in view of the long-term service performance of recycled materials from different regions and different sources, it is still necessary to construct a comprehensive performance evaluation system that includes multi-factor coupling effects such as freeze–thaw cycle, dry and wet alternations, and dynamic load, and develop supporting modification and enhancement technologies to meet engineering reliability requirements. It is suggested that a life cycle database of recycled materials based on big data analysis should be established to provide a scientific basis for the formulation of differentiated application technical guidelines [5]. Fortunately, Zhang et al. [6] found that that California Load Bearing Ratio (CBR) values do not reliably predict frost heave sensitivity, and the RPCC/RAP mix exhibits balanced performance and relatively low CBR reduction after freeze–thaw cycles, underscoring its potential for pavement based on applications. The study also revealed no direct correlation between frost heave and thawing sensitivity, highlighting the complexity of freeze–thaw dynamics. In addition, Kazmee et al. [7] demonstrated that 60-40% recycled concrete aggregate and RAP materials are the most satisfactory improved subgrades. These findings not only help to develop durable and recyclable pavement materials, but also contribute to the sustainable development of the construction industry [6].

3. Bio-based binders and alternative materials

The application of Recycled Asphalt Pavement (RAP) has seen substantial growth in terms of the construction and rehabilitation of resilient road surfaces, optimizing the utilization of finite natural resources, and bio-oil—derived from Waste Cooking Oil (WCO) and soybean oil—has emerged as a viable rejuvenator for alleviating the rigidity of asphalt binders and mixtures containing elevated levels of Recycled Asphalt Pavement (RAP). This approach addresses the challenges posed by high-RAP formulations while aligning with sustainable material practices. The significant potential of bio-oil lies in its ample availability and its capacity to improve the functional characteristics of asphalt binders and composite mixtures incorporating substantial Recycled Asphalt Pavement (RAP) content, and research has shown that bio-oil modification effectively enhances critical performance metrics in Hot-Mix Asphalt (HMA). Experimental findings confirm that treated binders achieve superior mechanical durability and workability compared to unmodified high-RAP formulations [8]. Bio-binder-modified mixtures exhibit enhanced low-temperature fracture resistance compared to conventional mixtures of the same performance grade, despite having lower fracture resistance overall [9]. Moreover, the study by Lusher et al. [10] mentioned that the dwindling availability of liquid bitumen and the growing concerns over the adverse health effects linked to petroleum-derived recycling agents have spurred interest in bio-based substitutes as safer and sustainable solutions. Among these alternatives, guayule (Parthenium argentatum), a drought-tolerant shrub native to the arid regions of the Southwestern United States, has garnered attention for its potential to yield premium-grade resin and natural rubber. This plant-based resource not only circumvents toxicity risks but also aligns with ecological preservation goals. Consideration has been also given to the cost, availability, and environmental consequences associated with the use of petroleum-derived materials, and alternative asphalt adhesives for flexible pavements have been developed [11].

4. Industrial by-products and innovations

Over the past decade, considerable advancement and application of eco-friendly pavement materials have taken place in contemporary infrastructure practices. A recent study by Hoy et al. [12] demonstrates the feasibility and performance merits of integrating recyclable alternatives (such as the removal of debris, industrial residues, and plant-based hemp fibers) to replace traditional primary aggregates in roadworks. These materials not only comply with circular economy principles, but also exhibit mechanical properties comparable to or better than traditional solutions, supporting their application in sustainable pavement systems. The integration of industrial by-products into road construction has demonstrated feasibility in maintaining structural integrity and functional performance. Notably, steel slag and bottom ash—the abundant residues obtained from metallurgical and combustion processes—exhibit properties suitable for use as sustainable alternatives to conventional aggregates, thereby reducing reliance on virgin materials while addressing waste management challenges. The results indicate that both materials possess considerable potential as aggregates for asphalt mixtures [13]. Moreover, semiconductor photocatalytic materials possess photocatalytic properties that enable the generation of free electron–hole pairs when exposed to ultraviolet or visible light irradiation. These materials exhibit strong photocatalytic REDOX capabilities and demonstrate oxidative decomposition effects on various organic compounds as well as certain inorganic substances. Primary pollutants are found in automobile exhaust. The photocatalytic oxidation process effectively converts pollutants including hydrocarbons, Nitrogen Oxides (NO_x), and carbon oxides into benign inorganic compounds such as Carbon Dioxide (CO_2), water (H_2O), and mineralized salts. This degradation pathway demonstrates high efficiency in neutralizing hazardous emissions through advanced oxidation mechanisms [14].

In addition, innovative technologies for improving the properties of materials used in pavement involve increasing road strength and durability. Emerging advancements in sustainable construction materials encompass innovations such as polymeric and geopolymeric composites for concrete, photovoltaic modules for energy harvesting, secondary cementitious binders, autonomous repair systems, shape-adaptive metallic alloys, and photoluminescent cementitious matrices. These materials collectively redefine the boundaries of durability, functionality, and environmental compatibility in modern infrastructure [15].

5. Challenges and research gaps

In the process of achieving sustainable road paving technology, temperature control is the key process parameter. From the Hot-Mix Asphalt mixture (HMA) production stage, the heating temperature of the raw aggregate, Recycled Asphalt Pavement material (RAP), and asphalt binder needs to be precisely controlled [16].

Furthermore, the global road engineering field is accelerating the transformation to the circular economy model. Industry statistics show that the proportion of alternative environmental protection materials such as recycled aggregate and industrial waste in the pavement structure layer has been significantly increased when compared with that ten years ago, and this transformation is due to the realistic pressure of the increasingly scarce natural aggregate resources, but it has also benefited from the policy drive of countries to promote carbon neutrality. However, systematic obstacles such as the lack of material performance database, non-uniform regeneration process standards, insufficient economic performance evaluation and imperfect certification system of the whole industry chain still restrict the large-scale application of such materials. To overcome these bottlenecks, it is necessary to build a four-body collaborative innovation system of “material research and development—engineering specifications—quality certification—policy incentives” [17].

While current research has achieved breakthroughs in key technical bottlenecks and theoretical system construction, it is crucial to establish a multi-dimensional collaborative innovation research framework. Firstly, a multi-field coupled accelerated simulation platform should be developed to replicate extreme climatic conditions and overloaded freight traffic, enabling the systematic analysis of material performance degradation and interfacial failure mechanisms. Secondly, a comprehensive life cycle assessment model integrating resource cycling indices and ecological benefit factors needs to be established, focusing on elucidating the molecular restructuring mechanisms of bio-rejuvenators due to UV–moisture–thermal synergistic aging, the damage evolution pathways of recycled interfaces in thermal cyclic loading, and the nano-scale effects of bio-oil functional group distribution on material durability. Concurrently, an intelligent decision-making system based on multi-source heterogeneous data should be constructed and validated through distributed fiber optic sensing monitoring in full-scale test sections to bridge laboratory-field performance correlations. This integrated approach aims to formulate a new-generation low-carbon road construction technology system that integrates structural reliability with environmental friendliness [12].

6. Summary

In the field of road engineering, the use of recycled materials to replace original resources for pavement construction not only creates a new path for the resource utilization of construction waste, but also provides an innovative solution to achieve the sustainable development goal of green infrastructure. By constructing a closed-loop material circulation system of “raw material - construction - maintenance - regeneration”, this material substitution strategy can effectively promote the efficient utilization of resources and the coordinated development of ecological environment in the whole life cycle of roads [18].

It is worth noting that environmental conditions such as high temperature, ultraviolet radiation, and humidity can cause serious deterioration of the asphalt present in pavement materials [19]. Throughout the life of the pavement, the interaction between the vehicle and the pavement changes the characteristics of the pavement surface [18]. In the current mechanical evaluation system of asphalt mixture, it is suggested to establish a correlation analysis model between vibration molding process parameters and unconfined mechanical properties and to establish a differentiated test procedure based on the vibration energy transfer mechanism. This process–performance linkage evaluation method can not only overcome the technical bottleneck of traditional density field perception but also provide material constitutive model support for the construction of a digital intelligent compaction system and achieve the collaborative optimization of construction technology and structural performance [20].

New sustainable road materials such as waste-plastic-based modifiers and recycled aggregate technologies are promoting the transformation of road engineering to “solid waste recycling - low-carbon construction” [21].

However, the current assessments of the environmental and economic performance of innovative eco-friendly paving materials across their entire life cycle still exhibit research gaps [18]. It is imperative to develop a comprehensive evaluation framework covering the full spectrum of “raw material acquisition-production and transportation-construction and maintenance-demolition and recycling”.

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