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Carbon Quantum Dots in Construction Materials: A Review and Thematic Analysis

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ABSTRACT

Carbon quantum dots (CQDs), also known as carbon nanodots, are a class of fascinating nanomaterials with unique optical, electrical, and chemical properties. Their small size (typically < 10 nm), low toxicity, cost-effectiveness, and tunable surface chemistry make them attractive candidates for various applications, including the modification of construction materials. This systematic review and thematic analysis explores the current state of research on the utilization of CQDs in cementitious composites, asphalt pavements, and other construction-related applications. Key themes identified include the synthesis methods of CQDs, their impact on the mechanical properties, durability, and functional performance (e.g., self-sensing, photocatalysis, corrosion inhibition) of construction materials, and the challenges and future perspectives in this field. The analysis synthesizes findings from recent studies to provide a comprehensive overview of the potential benefits and limitations of incorporating CQDs into construction materials, highlighting promising avenues for future research and development towards sustainable and high-performance infrastructure.

KEYWORDS: Carbon quantum dots, Construction materials, Cementitious composites, Asphalt, Nanomaterials, Mechanical properties, Durability, Functionalization, Review, Thematic analysis.

INTRODUCTION

The construction industry is continuously seeking innovative materials and technologies to enhance the performance, durability, and sustainability of infrastructure. Nanomaterials have emerged as promising additives due to their unique properties at the nanoscale, which can significantly influence the macroscopic behavior of conventional construction materials [8, 44]. Among the diverse range of nanomaterials, carbon-based nanomaterials, such as carbon nanotubes (CNTs), graphene, graphene oxide (GO), and carbon quantum dots (CQDs), have attracted considerable attention [78, 8, 77].

Carbon quantum dots (CQDs), typically defined as carbon nanoparticles with a size below 10 nm, possess distinct advantages over other carbon nanomaterials, including excellent photoluminescence, good biocompatibility, low toxicity, and ease of functionalization [4, 30, 38, 81, 95, 100]. These properties make them particularly interesting for applications in construction materials, where they can potentially improve mechanical strength, enhance durability, impart self-sensing capabilities, or enable photocatalytic activity [79, 90, 33, 87].

The utilization of various nanomaterials like nano-TiO$_2$, nano-Fe$_2O_3$, nanoclay, and nano-CaCO$_3$ in cementitious materials has been investigated for improving properties [1, 29, 70, 53]. Similarly, nanomaterials have been explored in recycled aggregate concrete to enhance mechanical properties and durability [5]. Graphene oxide has also been critically reviewed for its use in cement composites with recycled aggregates [6]. While other carbon-based nanomaterials like graphene and CNTs have seen significant research in construction [78, 21, 22, 69, 86, 94, 97, 98, 109], the application of CQDs in this field is a relatively newer but rapidly growing area.

This article provides a systematic review and thematic analysis of the current research on the utilization of CQDs in construction materials. It aims to synthesize findings from the literature, identify key research themes, and highlight the potential benefits, challenges, and future directions for incorporating CQDs into construction practices.

METHODS

This systematic review and thematic analysis was conducted by searching and analyzing relevant scientific literature focusing on the application of carbon quantum dots (CQDs) in construction materials. The search was primarily performed using academic databases, including but not limited to, those indexing journals in materials science, civil engineering, nanotechnology, and chemistry. Search terms included "carbon quantum dots," "carbon nanodots," "construction materials," "cement," "concrete," "asphalt," "mechanical properties," "durability," "photocatalysis," "self-sensing," and related keywords.

The identified literature was screened based on relevance to the topic, focusing on studies investigating the synthesis of CQDs for construction applications, the incorporation of CQDs into various construction materials, and the evaluation of the resulting material properties. Review articles providing broader perspectives on nanomaterials in construction or specific types of carbon nanomaterials were also included to provide context [8, 5, 6, 44, 78, 86].

A thematic analysis approach was employed to synthesize the findings from the selected literature. Key themes were identified by systematically reading and coding the content of the articles. These themes included:

1. Synthesis of CQDs: Methods used for preparing CQDs, including top-down and bottom-up approaches, and the use of various carbon sources, including waste materials [8, 10, 13, 19, 27, 28, 51, 57, 68, 80, 83, 92, 103, 104, 107].
2. Impact on Mechanical Properties: The effect of CQD incorporation on the compressive strength, tensile strength, flexural strength, and other mechanical properties of cementitious composites and asphalt mixtures [79, 90, 41, 40, 77, 97, 98, 109].
3. Influence on Durability: How CQDs affect the durability aspects of construction materials, such as resistance to chloride ingress, sulfate attack, and freeze-thaw cycles [40, 42, 64, 82, 90, 109].
4. Functionalization and Smart Properties: The use of CQDs to impart functional properties to construction materials, including self-sensing for structural health monitoring, photocatalytic activity for self-cleaning and pollutant degradation, and corrosion inhibition [21, 22, 33, 87, 94, 101, 105, 106].
5. Microstructural Effects: The influence of CQDs on the microstructure of cementitious materials, including cement hydration, pore structure, and the interfacial transition zone (ITZ) [20, 29, 35, 36, 53, 70, 77, 97, 98, 109].
6. Challenges and Future Perspectives: Identification of the current limitations, challenges, and future research directions in the field of CQD-modified construction materials [8, 19, 54, 68, 83, 92, 107].

The findings related to each theme were synthesized and are presented in the Results section. The Discussion section provides an interpretation of these findings, highlights the interconnections between themes, and outlines future research needs and potential applications.

RESULTS

The review of the literature revealed a growing body of research on the application of CQDs in construction materials, primarily focusing on cementitious composites and asphalt pavements.

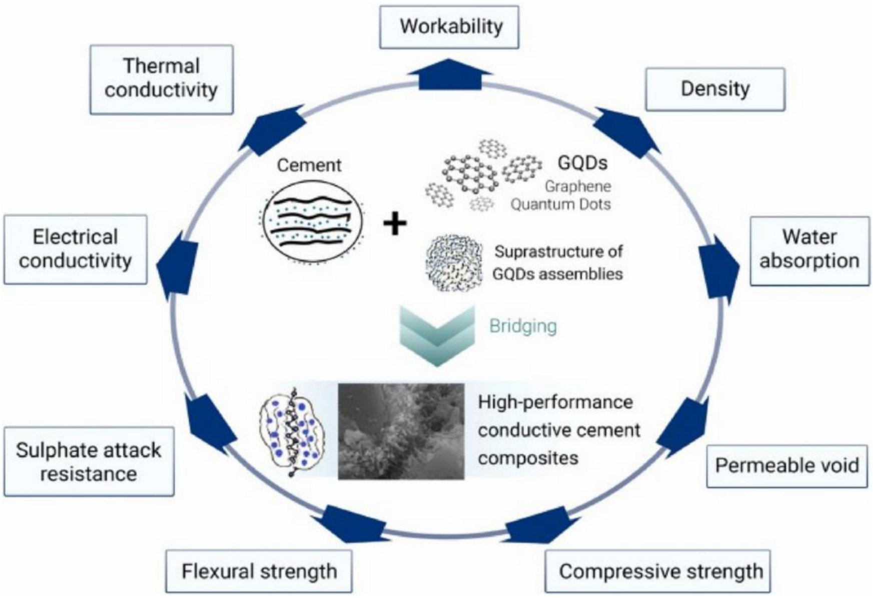
Synthesis of CQDs for Construction Applications

Various methods have been employed for the synthesis of CQDs, broadly categorized into top-down and bottom-up approaches [8, 13]. Top-down methods involve breaking down larger carbon structures, such as graphite or carbon fibers, into smaller CQDs using techniques like arc discharge, laser ablation, or electrochemical exfoliation [57, 51]. Bottom-up methods involve the carbonization of molecular precursors, often organic compounds, through techniques like hydrothermal synthesis, thermal pyrolysis, or microwave irradiation [10, 19, 27, 28, 68, 80, 83, 92, 103, 104].

A notable trend is the increasing use of sustainable and cost-effective carbon sources, including various types of biomass and waste materials, for CQD synthesis [19, 28, 68, 83, 92, 103, 104]. This aligns with the broader goal of promoting a circular economy in the construction sector [60, 76]. For instance, studies have reported the synthesis of CQDs from agricultural waste like rice husk [92] and other biomass sources [24, 107]. The choice of synthesis method and precursor significantly influences the size, morphology, surface chemistry, and optical properties of the resulting CQDs, which in turn affect their performance in construction materials [4, 10, 27, 38, 46, 81, 95, 100]. Functionalization of CQDs during or after synthesis is often performed to improve their dispersion in the construction material matrix and enhance their interaction with the hydration products of cement or the components of asphalt [46, 40, 42, 97, 98, 109].

Impact on Mechanical Properties

The incorporation of CQDs has shown promising results in enhancing the mechanical properties of cementitious composites. Studies have reported improvements in compressive strength, tensile strength, and flexural strength of cement paste, mortar, and concrete with the addition of small dosages of CQDs [79, 90, 41, 40, 77, 97, 98, 109]. The reinforcing effect of CQDs is attributed to their ability to act as nucleation sites for cement hydration products, leading to a denser and more homogeneous microstructure, and their role in bridging cracks and inhibiting crack propagation [79, 41, 77, 97, 98, 109]. The size of the CQDs has been found to influence their impact on the mechanical performance of cement composites [41].



In asphalt mixtures, CQDs and related graphene quantum dots (GQDs) have been explored as modifiers to improve properties such as thermal conductivity and aging resistance [7, 39, 65, 66, 84, 93]. While the primary focus in asphalt has been on other carbon nanomaterials like carbon black and CNTs for conductivity and self-heating applications [78, 67], CQDs are emerging for their potential to enhance UV aging resistance and potentially contribute to energy harvesting applications in pavements [39, 16, 56].

Influence on Durability

CQDs can positively influence the durability of cementitious materials by refining the pore structure and reducing the permeability to aggressive substances like chlorides and sulfates [40, 42, 64, 82, 90, 109]. The denser microstructure resulting from improved hydration in the presence of CQDs contributes to enhanced resistance against the ingress of deleterious ions, thereby mitigating issues like chloride-induced steel corrosion in reinforced concrete structures [40, 42, 64, 82, 109, 74]. Studies have shown that CQDs can enhance the chloride binding performance of cement [42, 64, 82]. The use of CQDs as novel inhibitors for carbon steel against chloride corrosion is also being investigated [64].

Functionalization and Smart Properties

One of the exciting areas of research is the use of CQDs to impart smart functionalities to construction materials. Due to their fluorescence properties, CQDs can potentially be used for structural health monitoring, for instance, by embedding them in cementitious materials to detect crack formation or monitor strain through changes in fluorescence intensity or wavelength [94]. GQDs have also been explored for monitoring structural strain and cracks based on their fluorescence response [94].

CQDs, particularly when combined with photocatalytic materials like TiO$_2$, can enhance the self-cleaning and pollutant degradation capabilities of cementitious coatings and surfaces [33, 87, 12]. This is due to the ability of CQDs to act as electron donors or acceptors, improving the efficiency of photocatalytic reactions [73].

Furthermore, the electrical conductivity of certain types of CQDs or composites containing CQDs can be leveraged for self-sensing applications, where changes in electrical resistance can indicate stress, strain, or crack development in the material [21, 22, 67, 78]. This is particularly relevant for smart infrastructure applications [34, 102, 67]. CQDs have also been investigated for their potential in energy harvesting applications within pavement structures [16, 56].

Microstructural Effects

The presence of CQDs influences the hydration kinetics and microstructure of cementitious materials. CQDs can act as heterogeneous nucleation sites, promoting the formation of calcium-silicate-hydrate (C-S-H) gel, the main binding phase in cement paste [20, 35, 36, 77, 97, 98, 109]. This leads to a more refined pore structure and a reduction in the porosity of the hardened cement matrix [79, 77, 97, 98, 109]. The interaction between CQDs and cement hydration products, particularly at the interfacial transition zone (ITZ) between aggregates and the cement paste, is crucial for improving mechanical properties and durability [77, 97, 98, 109]. Studies have investigated methods to improve the dispersion of 2D nanomaterials, including those related to CQDs, to effectively promote cement hydration [43]. The effect of nano calcium carbonate, another nanomaterial, on hydration and microstructure has also been reviewed [29, 53].

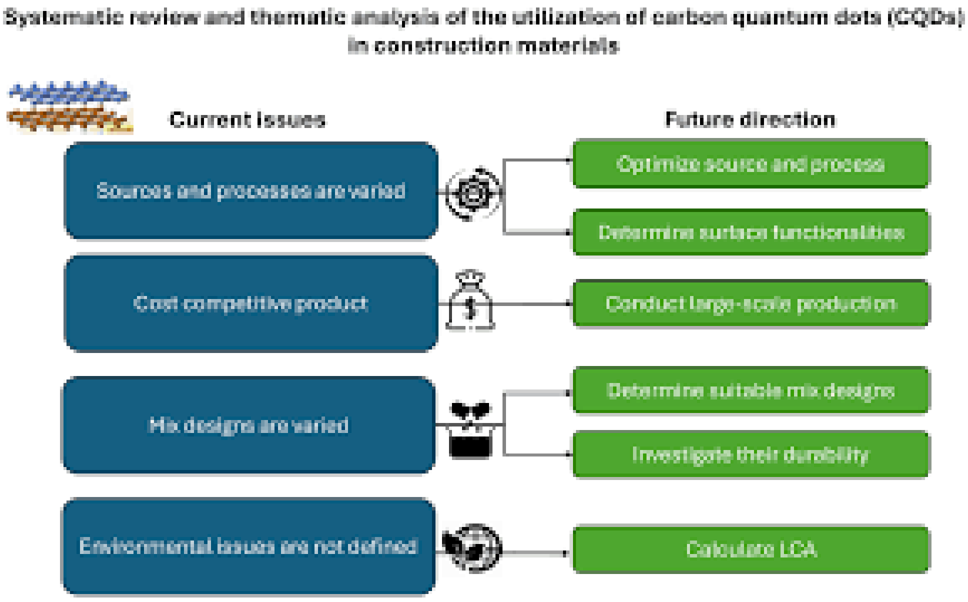
Challenges and Future Perspectives

Despite the promising results, several challenges need to be addressed for the widespread application of CQDs in construction materials. Scalable and cost-effective synthesis methods for producing large quantities of high-quality CQDs are essential [8, 19, 54, 68, 83, 92, 107]. Ensuring uniform dispersion of CQDs within the complex matrix of construction materials, especially in concrete with larger aggregates, remains a technical challenge [79, 43]. The long-term stability and durability of CQDs within the harsh alkaline environment of cementitious materials or under the demanding conditions of asphalt pavements require further investigation [40, 64, 82, 90, 109].

Future research directions include exploring novel synthesis routes, particularly those utilizing waste materials, to improve sustainability and reduce costs [19, 28, 68, 83, 92, 103, 104]. Developing effective strategies for dispersing and stabilizing CQDs in different construction material matrices is crucial [43]. More comprehensive studies on the long-term performance and durability of CQD-modified materials under realistic environmental conditions are needed [40, 64, 82, 90, 109]. Further exploration of the potential of CQDs in imparting advanced functionalities, such as self-healing, energy harvesting, and advanced sensing, will pave the way for the next generation of smart and sustainable construction materials [44, 16, 56, 34, 102, 67]. The integration of machine learning approaches could also aid in predicting the performance of CQD-based composites [69].

DISCUSSION

The thematic analysis reveals that carbon quantum dots hold significant potential for revolutionizing the construction industry by enhancing the performance and sustainability of conventional materials. The ability to synthesize CQDs from various carbon sources, including waste, aligns with the growing emphasis on circular economy principles in construction [60, 76]. The observed improvements in mechanical properties and durability of cementitious composites are particularly noteworthy, suggesting that CQDs can contribute to building more resilient and long-lasting structures [79, 90, 40, 41, 42, 64, 77, 82, 97, 98, 109].



The potential to impart smart functionalities, such as self-sensing and photocatalysis, opens up exciting possibilities for developing intelligent infrastructure that can monitor its own condition, self-clean, and potentially interact with its environment [21, 22, 33, 87, 94, 101, 105, 106]. This aligns with the global trend towards smart cities and sustainable urban development [34, 102, 67, 75, 96].

However, the field is still in its nascent stages, and several challenges need to be overcome before CQD-modified construction materials can be widely adopted. The scalability of synthesis, cost-effectiveness, and ensuring uniform dispersion in large-scale applications are critical factors that require significant research and development effort. Furthermore, a deeper understanding of the long-term interactions between CQDs and the complex chemical environment of construction materials is essential to ensure their long-term performance and safety.

Future research should focus on developing standardized and cost-efficient synthesis methods, exploring surface modification techniques to enhance dispersion and compatibility with different matrices, and conducting comprehensive long-term performance and life cycle assessments. The potential environmental impact of using nanomaterials in construction also warrants careful consideration and research [69]. As research in this area progresses, CQDs are poised to become a key enabler for the development of high-performance, durable, and smart construction materials, contributing to a more sustainable built environment.

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