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QUANTUM DOTS IN CEMENT COMPOSITES: A REVIEW OF SYNTHESIS, MECHANISM AND APPLICATIONS

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Abstract— The use of carbon-based nano materials in concrete has gained significant interest in recent years. Recently, carbon quantum dots (CQDs) and graphene quantum dots (GQDs) have become a promising nanomaterial for improving cementitious composite performance. This work provides an in-depth review of the recent research on the characteristics, impact, and synthesis methodologies of CQDs and GQDs, as well as their application to cement-based materials. The study examines the mechanism that facilitates the improvement of cement-based materials with the integration of CQDs and GQDs. The issues related to the utilization of CQDs and GQDs, including their dispersibility in cement composites and the cost-effective large-scale manufacture, have been addressed. This paper proposes a potential trajectory for the utilization of GQD and CQD technologies in the creation of sustainable, resilient, and intelligent building materials for future infrastructure.

Keywords— Carbon Quantum Dots, Cement, Graphene Quantum Dots, Hydration, Nanotechnology, Strength.

I. INTRODUCTION

Infrastructure and pavement technologies heavily rely on construction materials such as bitumen and cement. The demand for improved performance and durability, as well as the mitigation of deleterious environmental effects, is on the rise for concrete that is widely used in contemporary infrastructure. Traditional concrete and asphalt mixtures face challenges such as cracks, corrosion, limited electrical conductivity, and environmental impacts from manufacturing and handling (Prasittisopin et al. 2025; Rodrigues et al. 2021). The advancement of science and technology results in the continuous emergence of a diverse multitude of novel materials. Graphene and carbon quantum dots have emerged as a captivating class of nanomaterials with promising applications in a wide range of disciplines. Carbon dots are microscopic carbon nanoparticles that are present in aqueous solutions or other suspensions. The following categories can be broadly classified: (i) graphene quantum dots (GQDs); (ii) carbon nanodots (CNDs), which are composed of two subclasses: carbon nanoparticles (CNPs) and carbon quantum dots (CQDs); and (iii) carbonated polymer dots (CPDs) (Xia et al. 2019). The ongoing advancement of CQDs and GQDS stems from persistent research and development concentrated on organic components, improvements, and modifications within the domain of carbon-based materials.

Graphene quantum dots (GQDs) are nanoscale carbon particles that are distinguished by their zero-dimensional structure and distinctive luminescent properties. These particles are composed of one or a few graphene layers. GQDs are water-soluble and well-dispersed in aqueous solutions due to their hydrophilic properties, which is advantageous for applications that involve water interactions (Raj et al. 2024; Thwe et al. 2024a, 2024c). GQDs are composed of nanoscale graphite layers that exhibit anisotropy with a lateral dimension that exceeds their height, as well as surface and edge functional groups or interlayer defects. The dimensions of π-conjugated structural domains and the surface/edge configuration are the primary determinants of their optical properties(Yuegang Wang et al. 2025). The essential composition of carbon quantum dots is primarily sp^2 hybridized carbon, whereas the presence of sp^3 hybridized carbon in CQDs results from oxygen-containing functional groups. These nanoparticles consist of graphene and have diameters between 1 and 10 nm.(Review et al. 2022).

Carbon quantum dots (CQDs) and graphene quantum dots (GQDs) enhance the mechanical and durability characteristics of cement-based materials. Their nanoscale dimensions and numerous surface functional groups make them efficient nucleation sites for calcium–silicate–hydrate (C–S–H), accelerating hydration and producing denser microstructures. The enhancement increases compressive and flexural strength, particularly at initial stages. Quantum dots bridge nanoscale voids and enhance toughness and crack resistance, while simultaneously decreasing porosity and permeability. This results in enhanced resistance against chloride penetration, sulfate attack, and freeze-thaw cycles. Significantly, these improvements occur at low concentrations (<0.1 wt% binder), making them cost-effective compared to other nanomaterials. Multifunctional enhancements make CQDs and GQDs viable additives for next-generation high-performance and sustainability cementitious composites. This paper offers an in-depth review of graphene quantum dots (GQDs) and carbon quantum dots (CQDs) in cementitious composites. Initially, it discusses the primary synthesis methods, which are classified as top-down and bottom-up methods. Subsequently, it delves into the structural and functional characteristics of quantum dots. The paper subsequently investigates the mechanisms that are responsible for the performance enhancement of cement-based materials, with a particular focus on their impact on the fresh, mechanical, and durability properties. Furthermore, it addresses critical challenges, including the feasibility of large-scale production and dispersion in alkaline pore solutions. Lastly, the review emphasizes the potential for the application of CQD and GQD technologies to the development of next-generation, sustainable, and durable construction materials.

II. SYNTHESIS OF GRAPHENE AND CARBON QUANTUM DOTS

This section provides a concise and precise summary of the diverse methodologies that are implemented to synthesize CQDs and GQDs. In the synthesis of CQD and GQD, all processes are conventionally classified as either bottom-up or top-down synthesis as depicted in figure 1.

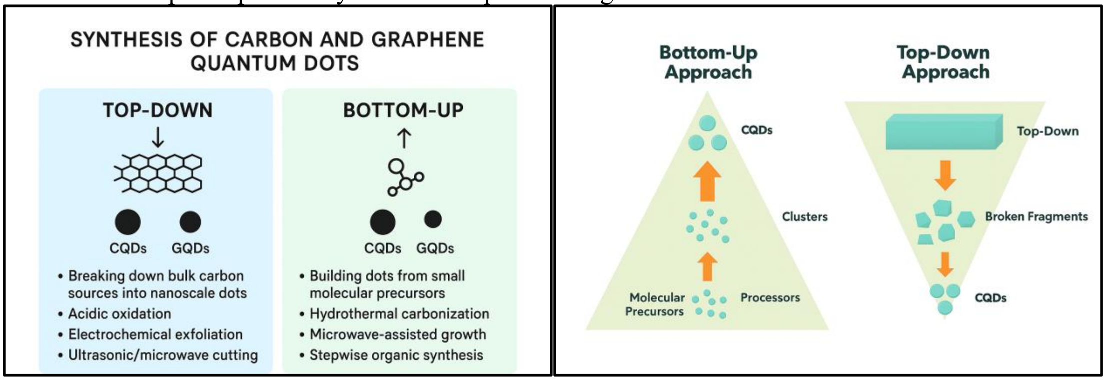

Fig. 1 Synthesis of Graphene and Carbon Quantum Dots(Online et al. 2022)

A. TOP - DOWN APPROACHES FOR SYNTHESIS

Top-down methods break down large carbon molecules like graphene into small quantum dots using physical or chemical approaches. Top-down production of CQDs and GQDs uses massive carbon sources such nano-cellulose carbon soot, graphene, nano-diamonds, carbon fibers, , and silicon carbide(Momina et al. 2024; Prasittisopin et al. 2025). The top-down preparation techniques include arc discharge, electrochemical and acid oxidation, and laser ablation, among others. This approach provides perfect control over the size, shape, and structure of the fluorescent carbon dots; however, the synthesis procedure is relatively complex.

Carbon and Graphene quantum dots are generated by electrochemical oxidation of carbon source materials, with carefully regulated reaction parameters including voltage and current. (Gurel et al. 2024) created GQDs top-down electrochemically. Electrodes were two graphite rods in ultrapure water without electrolytes. Exfoliation and oxidation of graphite into GQDs occurred at 30 V for 120 hours under stirring. Pure GQDs were obtained by centrifuging, filtering through 0.45 µm → 0.2 µm → 0.1 µm membranes, and freeze-drying the solution. GQDs were synthesised from multiwalled carbon nanotubes (MWCNTs) in a two-step electrochemical procedure. The MWCNT-coated electrode underwent anodic oxidation (+1 V) in propylene carbonate with $LiClO_4$, causing tubes to unzip, followed by cathodic reduction (–1 V) to exfoliate oxidized pieces into nanoscale GQDs. Particle size was influenced by reaction conditions such temperature and oxidation duration (3-8 nm at 90 °C; ~23 nm at 30 °C). Dialysis purified the stable green photoluminescent GQDs for future use(Nanotubes, Shinde, and Pillai 2012).

Laser ablation use high-energy laser pulses to irradiate the surface of a target material. Thermodynamic processes produce elevated temperatures and pressures, resulting in the fast heating, melting, and vaporization of the material into plasma. The cold induces the condensation of vapors, resulting in the formation of nanoparticles. Regulating laser strength, frequency, wavelength, and more parameters is essential during the procedure. Following ablation, carbon quantum dots can be isolated from the resultant products (Technology 2005; Kong et al. 2024).

The result is divided into three phases: buoyant, suspended, and precipitate, as a result of submerged arc discharge in water (SADW). MWCNT-enriched precipitate and CNO-enriched floating materials are evident, while the water-suspended material is primarily composed of CQD and contains minimal graphene oxide (GO) flakes. After synthesis, the floating material is eliminated, and the water is permitted to settle for 24 hours to settle larger particulates. The precipitate is meticulously cleaned of suspended debris in the water. This CQD suspension is employed to observe cell cultures in their natural state. For the purpose of characterization, the material may be progressively concentrated or dried. Although this method generates carbon quantum dots with exceptional fluorescence, its low yield and nonuniform particle sizes render it unsuitable for large-scale production. This preparation method is rendered ineffectual due to the introduction of contaminants that compromise product performance and stability, which may be a result of the high temperatures and energy of the arc discharge method (Youfu Wang and Hu 2014; Ge et al. 2014). The exploration of greener and more efficient bottom-up alternatives is motivated by the fact that, despite the fact that top-down methods offer a straightforward route to carbon and graphene quantum dots with controllable sizes, they frequently encounter challenges such as low yield, harsh processing conditions, and limited surface functionality.

B. BOTTOM – UP APPROACHES FOR SYNTHESIS

The bottom-up strategy incorporates the synthesis of nanomaterials from organic molecules or polymer precursors utilizing hydrothermal/solvothermal, microwave, or chemical oxidation methods as shown in figure 2.CQDs and GQDs are produced by the combination of complex chemical constituents, including citric acids, amino acids, sugars, and carbohydrates, with a variety of aromatic molecules (Prasittisopin et al. 2025).

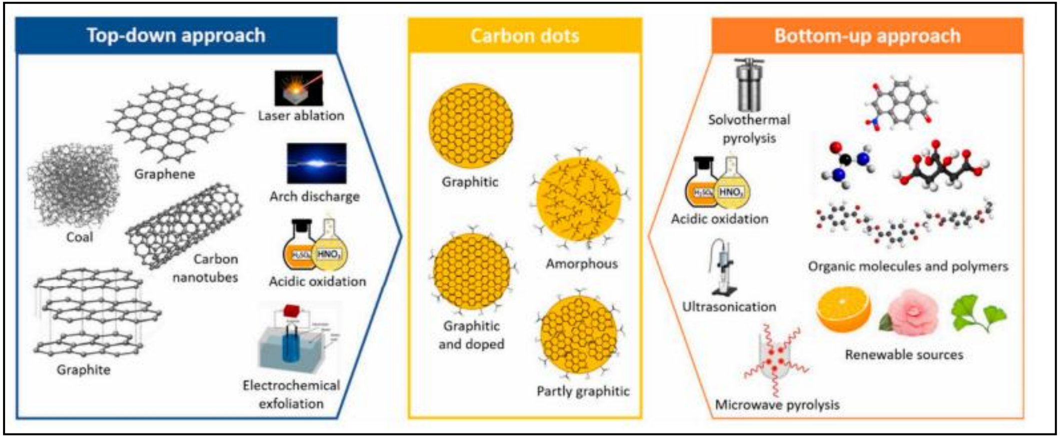

Figure 2 : Top- down and Bottom-up Approaches for synthesis of Quantum Dots(Yuegang Wang et al. 2025)

Microwave-assisted synthesis carbonizes organic precursors such as citric acid, glucose, or biomass under microwave irradiation, yielding highly functionalized carbon quantum dots (CQDs). A study by (Allah et al. 2023) synthesised CQDs using a cost-effective, eco-friendly, and one-step approach that involved microwave heating of several biomass and cellulose sources, including urea, bagasse, cellulose, and carbon-rich carboxymethyl cellulose. CQDs were manufactured by dissolving 0.03 g of carbon sources in 0.07 g of NaOH and 2.4 g of urea, which was followed by overnight freezing to obtain a homogenous solution. After reaching ambient temperature, the dissolved mixture was subjected to ultrasonication for 2 minutes and then microwaved at 700 W for 7 minutes, resulting in yellow/brown crude CQD solids. The synthesized CQDs were assessed using various spectroscopic techniques to investigate the influence of carbon purity on the adsorption efficacy of CQDs.
The hydrothermal approach generates carbon and grapheme quantum dots by carbonizing organic precursors within a sealed autoclave at elevated temperature and pressure. (Krishnaiah et al. 2025; Yuegang Wang et al. 2025) synthesized 4 nm CQDs utilizing flufenamic acid for fluorine and carbon and thiourea for nitrogen and sulfur in a one-step hydrothermal process. The mixture of precursor compounds was heated for 8 hours in a Teflon-lined stainless steel autoclave. A 160 ◦C reaction temperature was selected. The light-yellow solution was centrifuged at 10^4 rpm for 30 minutes to remove precipitates. A dialysis bag was used to dialyze the fluid for 24 hours. CQDs thus obtained have excellent water solubility, pH stability, and ionic strength. A green hydrothermal method was used to synthesis GQDs from eucalyptus leaves (Saud, Saleem, and Munira 2023).The dried, ball-milled leaf powder was extracted with ethanol, centrifuged, and filtered. The extract slurry was hydrothermally treated at 300 °C for 480 min to make nanoscale GQDs. After ethanol washing, filtration, and drying, crystalline GQDs (2–5 nm) with high photoluminescence were obtained. This sustainable, low-cost process produces high-quality GQDs. Chemical oxidation refers to the oxidative transformation of organic raw materials into CQDs by dissolving the carbon source in a chemical oxidant solution and executing a chemical reaction. Chemical oxidation is a viable and mass-produced synthesis process that requires no specific equipment and diverse, easy-to-obtain carbon sources. Strong oxidants are expensive and can contaminate the environment (Kong et al. 2024). (Peng and Travas-sejdic 2009)developed a simple carbon quantum dot synthesis technique. Carbonaceous materials were produced by dehydrating carbohydrates with strong sulfuric acid. By treating carbonaceous materials with nitric acid, carbogenic nanoparticles were formed. Passivation of carbogenic nanoparticles with amine-terminated chemicals produced luminous carbogenic dots. The emission wavelength of carbon quantum dots can be altered by varying the precursor material and the exposure time to nitric acid. Bottom-up approaches offer adaptable, scalable, and environmentally sustainable methods for modifying the dimensions, surface chemistry, and optical characteristics of carbon and graphene quantum dots, rendering them exceptionally promising for many applications in sensing, energy, and cementitious materials.

III. PROPERTIES OF GRAPHENE AND CARBON QUANTUM DOTS

CQDs have a wide range of features, such as water solubility, environmental compatibility, non-toxicity, tunable fluorescence, and high stability, because of the variety of raw materials and synthetic techniques. The physical, chemical, and optical characteristics of CQDs and GQDs will be covered in this section.

A. PARTICLE SIZE & MORPHOLOGY

CQDs are typically quasi-spherical nanoparticles with diameters ranging from ~1-10 nm, depending on synthesis route. GQDs have planar or disk-like morphology, lateral dimensions of 2-20 nm, and thicknesses corresponding to one or more graphene layers. Nanoscale dimensions provide strong quantum confinement effects, therefore modest size changes can greatly affect optical and electrical performance(Kong et al. 2024). Compared to more amorphous CQDs, the two-dimensional graphene lattice in GQDs provides anisotropic geometries, potentially more defined edges, and a planar structure(Ansari 2022).

B. CRYSTAL STRUCTURE & CARBON HYBRIDIZATION

CQDs are typically composed of sp^2-hybridized carbon centers that are interspersed with sp^3 domains that are the result of oxygen-containing groups or structural defects. This results in a composite structure that consists of graphitic and disordered carbon regions(Elugoke et al. 2024). In contrast, GQDs maintain the crystalline graphene lattice structure, which consists of hexagonal networks of sp^2 carbon. Edge defects, such as zigzag or armchair defects, and functionalization are likely to occur at the margins or defects(C. Liu 2024). In general, the retention of graphitic domains in GQDs results in more continuous π-conjugation and superior structural ordering than in numerous CQDs(Sharma et al. 2025)

C. SURFACE CHEMISTRY & FUNCTIONAL GROUPS

The complex surface chemistry of both CQDs and GQDs is one of their distinguishing features. Typical functional groups consist of hydroxyl (–OH), carboxyl (–COOH), carbonyl (–C=O), amino ($–NH_2$), and other oxygen or nitrogen moieties, among others, contingent upon the precursor and synthesis conditions.

D. OPTICAL (PHOTOLUMINESCENCE) PROPERTIES

CQDs and GQDs demonstrate pronounced photoluminescence (PL), frequently excitation-dependent, due to the synergistic influences of quantum confinement, surface state emission, and defect states. The emission wavelengths of CQDs generally change to longer wavelengths with an increase in size or surface states(Sharma et al. 2025). Quantum yields range from 5% to over 70%, with GQDs having smaller emission peaks due to well-defined conjugated domains(C. Liu 2024). These optical properties reveal their structure and enable multipurpose applications in smart and self-sensing cementitious composites(Elugoke et al. 2024).

Recent advances in nanotechnology have highlighted the potential of carbon-based quantum dots, particularly Carbon Quantum Dots (CQDs) and Graphene Quantum Dots (GQDs), in enhancing cementitious materials. Owing to their ultrafine size (<10 nm), high specific surface area, abundant surface functional groups, and superior photo luminescent and redox properties, CQDs can act as nucleation sites during hydration, accelerating the formation of C–S–H gel and refining pore structure. GQDs, with their sp^2-hybridized domains and tunable oxygen-containing functionalities, not only promote hydration kinetics but also enhance interfacial bonding within the cement matrix, leading to improved mechanical strength, reduced permeability, and higher resistance to chloride ingress. Moreover, both CQDs and GQDs exhibit excellent dispersibility in aqueous media, enabling uniform incorporation in concrete without agglomeration, which is a common limitation with conventional nanoparticles. These unique physicochemical properties position CQDs and GQDs as promising nano-modifiers for developing durable, high-performance, and multifunctional concretes in line with sustainable construction demands.

IV. Table I : Properties of CQDs and GQDs

Property	**CQDs**	**GQDs**
Size	<10 nm (typically 2–8 nm)	<20 nm (typically 3–15 nm)
Structure	Amorphous or partially crystalline carbon core with functionalized surface	Crystalline graphene sheets (few atomic layers) with sp^2-hybridized domains
Surface Chemistry	Rich in oxygen-, nitrogen-, and hydroxyl-containing groups	Oxygen-containing functional groups, carboxyl, hydroxyl, epoxy
Optical Properties	Strong photoluminescence, excitation-dependent emission	High photoluminescence, tunable band gap
Electrical Properties	Moderate conductivity	Higher conductivity due to sp^2 domains
Hydration Effect	Accelerates hydration by acting as nucleation seeds for C–S–H gel	Enhances hydration kinetics and promotes growth of denser microstructure
Durability Effect	Improves chloride resistance and reduces microcracking by refining pores	Provides barrier against chloride ingress, enhances resistance to carbonation
Dispersibility	Excellent water dispersibility due to surface groups	Also good dispersibility, but slightly more prone to restacking
Applications in Concrete	Early strength gain, durability enhancement, self-sensing materials	Mechanical reinforcement, durability improvement, multifunctional (electrical/optical) concretes

IV. EEFFECT OF GRAPHENE AND CARBON QUANTUM DOTS ON CEMENT COMPOSITES

GQDs and CDQs exhibit a combination of advantageous properties for cementitious materials. The hydration process and microstructure development are influenced by their high surface area and small size, which facilitate interaction with cement hydrates. The following advantageous effects are observed: the workability of composites is improved by utilizing their hydrophilic functional groups on the surface to attract water, the materials are made more dense by reducing voids, the mechanical strength is increased, the ability to absorb water is improved, the resistance to damage caused by sulfate is enhanced due to their structure(Prasittisopin et al. 2025).

A. DISPERSIBILITY AND MECHANICAL PROPERTIES

CQDs and GQDs are fundamentally simpler to maintain in a dispersed state than larger graphene derivatives due to their small size and abundant surface functional groups. However, cement pore solutions significantly promote agglomeration. The following are the methods for achieving reliable dispersion in cement systems: (a) selecting the appropriate surface chemistry (oxygenated / doped CQDs/GQDs), (b) utilizing compatible dispersants or polycarboxylate ether (PCE) superplasticizers (including GO-PCE hybrids), and (c) integrating controlled sonication with immediate mixing or pre-grafting practices(Thwe, Raengthon, and Prasittisopin 2024). The dispersion of quantum dots is difficult in cement pore solutions for the following reasons:-

The cement pore solution has a high alkalinity (pH ~12–13) and comprises Ca^{2+}, Na^{+}, and K^{+} ions, which mitigate electrostatic repulsion and induce sheet and particle flocculation(Gao et al. 2024).

GO/graphene fragments and inadequately functionalized dots will rapidly precipitate or form aggregates in minutes to hours, as Ca^{2+} frequently causes charge neutralization and bridging between negatively charged oxygenated groups(B. Liu et al. 2022).

Compared to larger graphene oxide sheets, CQDs/GQDs have higher colloidal stability in water and simulated pore solutions due to their zero-dimensional size (<10-20 nm) and oxygen/nitrogen functional groups. Small dots have noticeable dispersity and enhanced transport/durability effects. This advantage depends on surface chemistry (hydrophilicity, charge) and ionic environment(Reddy et al. 2024).Some of the strategies to improve/maintain dispersion of quantum dots as used by researchers is given in table below.

Table II : Strategies to improve dispersion of quantum dots

Technique employed	Reference	Findings
Polycarboxylate ether (PCE) superplasticizers	(B. Liu et al. 2022)	PCEs are frequently employed to stabilize GO and GQDs in alkaline cement solutions. They either adsorb onto GO/GQD surfaces or are chemically affixed to produce GO@PCE / PCE-stabilized dispersions that maintain fluidity and resist Ca^{2+} bridging. Several experimental studies have demonstrated that the use of PCE (or GO-modified PCE) results in enhanced dispersion, workability, and mechanical improvements.
Surface functionalization / doping	(Reddy et al. 2024)	The hydrophilicity and electrostatic stabilization of dots are enhanced by the introduction of oxygenated groups, carboxylates, or N-doping. Hydrothermal oxidation, acid oxidation, or heteroatom modification were employed to optimize the surface chemistry of CQDs/GQDs for improved compatibility with aqueous cement systems.
Pre-mixing and pre-dispersion protocols	(Thwe, Raengthon, and Prasittisopin 2024)	Disperse dots in deionized water using probe or bath sonication for 5 to 30 minutes, depending on volume and concentration. Optionally, incorporate a dispersant (PCE) during sonication, and subsequently add the dispersion to the mixture immediately or after brief controlled storage at 4 °C. Numerous investigations underscore the necessity of preparing dispersions immediately before to utilization for pore-solution assessments.
Use of small doses and ratio control	(Thwe, Raengthon, and Prasittisopin 2024)	Minimal dosages of dots (often cited as 0.01–0.2 wt% of binder for CQDs/GQDs) reduce the possibility of agglomeration; combining with appropriate PCE levels (specific to the paper, frequently several times the mass of GO/GQD) enhances workability and dispersion.

When well dispersed, CQDs and GQDs consistently enhance the mechanical properties of cement-based composites, including compressive, flexural, splitting tensile strength, and toughness. These improvements are observed from early ages through long-term curing and are attributed to the nucleation of hydration products, pore refinement, and nanoscale crack-bridging. The gains are significantly influenced by particle size, surface chemistry, dispersion protocol, and dosage. The compressive and flexural strength of concrete are substantially enhanced by the addition of GQDs. In comparison to concrete without GQDs, the compressive strength increased by approximately 20–70%, while the flexural strength increased by approximately 30–110%. GQDs can enhance the 7-day compressive and flexural properties of cement mortar by approximately 28–34% and 13–25%, respectively, when combined with graphene oxide and calcined layered double hydroxide (He et al. 2024). The incorporation of CQDs significantly enhanced the mechanical performance of cement mortars, with the effect strongly dependent on dosage. Compressive strength showed a remarkable increase, reaching up to 73% improvement at 56 days when 0.025 wt% CQDs were added, while flexural strength improved by nearly 59% at the same dosage and age(Reddy et al. 2024**).** Table below gives results obtained by various researchers.

Table III : Effect of quantum dots on mechanical properties of cement composites

Reference	**Nanomaterial & Dosage**	**Curing Age(s)**	**Reported Improvements**
(Raj et al. 2024)	GQDs, 0.3 wt% of cement	28 d	Compressive increased by 18%, tensile strength improved by 15%, dynamic modulus improved.
(Shi et al. 2025)	GQDs, 0.12 wt%	7, 28 d	+26.4% compressive (7 d)**,** +20.9% compressive (28 d)**;** +27.7% splitting tensile at 28 d. Better retention under elevated temperature (≤600 °C).
(Thwe et al. 2024b)	Supra-GQDs, , 1 wt%	28 d	Compressive strength increased by 40%, Flexural Strength increased by 108%.
(Raj et al. 2025)	GQDs, 0.3 wt%	28 d	Both compressive & flexural increased by nearly 15%; reduced performance loss in recycled aggregate concrete.

B. DURABILITY PROPERTIES

Several durability-related properties of cementitious materials can be significantly enhanced by both carbon quantum dots (CQDs) and graphene quantum dots (GQDs) when they are well dispersed and used at optimized low concentrations, according to recent experimental study. Improved freeze-thaw performance, enhanced resistance to sulfate attack and high-temperature exposure, reduced permeability and sorptivity, and lower chloride ingress are the most consistently reported benefits. These enhancements are inextricably linked to microstructural modifications: The nano-filling and pore-blocking effects of QDs reduce critical pore sizes and connectivity, thereby slowing the transport of aggressive substances, and they function as nanoscale nucleation sites that accelerate and refine C–S–H formation.

Chloride penetration is a substantial concern for reinforced- concrete structures, as it leads to the corrosion of steel reinforcements. GQDs have the potential to enhance chloride resistance by promoting the formation of denser hydration products along with functioning as physical barriers(Fahim et al. 2019). The presence of Friedel's salt or AFt phase development within the confined cavities resulted in an expansion effect resulting from the rise in volume, in terms of chloride resistance. The addition of suprastructured graphene quantum dots (S-GQDs) enhanced the durability of high-strength cement composites by reducing the pore volume by 30% and improving pore connectivity. Densifying the microstructure reduced chloride ion and water intrusion, improving degradation resistance. S-GQDs are promising additives for durable, high-performance cement composites due to hydration acceleration, nano-void filling, and strong interfacial bonding with hydration products(Thwe et al. 2024b). (Raj et al. 2024)and (Thwe et al. 2024b)showed that GQDs improve cementitious composite durability at different doses. (Raj et al. 2024) reported a nearly 30% reduction in chloride penetration, as well as decreases in porosity, water absorption, and sorptivity, after incorporating 0.3 wt% GQDs into concrete. Hydration acceleration and GQD nano-filling enhanced pore structure and reduced aggressive ion transport channels, improving these results. In contrast,(Thwe et al. 2024b). found that greater dosages of S-GQDs in high-strength cement composites resulted in a 30% reduction in total pore volume , limiting chloride intrusion and water permeability.

Concerning chloride ion resistance, (Long et al. 2024)manufactured CQDs by a microwave method and employed them as economically viable corrosion inhibitors. Simulation results of concrete pore solution indicated that a concentration of 400 mg/L on carbon steel might enhance inhibition efficiency by over 99%. CQDs form a protective layer by complexing their many surface groups with Ca^{2+}, thereby retarding hydration.

C. MECHANISMS OF GQD AND CQD INTERACTION WITH CEMENT

The interaction between GQDs/CQDs and the cement hydration product is the reason for the positive impact of GQDs/CQDs on concrete properties. The following are potential mechanisms (Prasittisopin et al. 2025):

ucleation effect : GQDs and CQDS can act as sites for the formation of calcium-silicate-hydrate (C–S–H) gel, the principal binding agent in cement(Thwe et al. 2024b). This promotes rapid hydration and a denser microstructure. The hydration reactions appear to progress more rapidly.

Nano-filling effect: Graphene quantum dots can fill the voids inside the cement matrix, resulting in a denser and more resilient structure. Numerous studies have demonstrated that very fine pores can be decreased, resulting in a reduction of permeability voids at macro sizes by up to 50%(Reddy et al. 2024).

Enhanced interfacial bonding: The interaction between the cement matrix and aggregates can be enhanced by the presence of functional groups on CQDs, resulting in improved mechanical performance. Additionally, the nucleation sites on a variety of materials and additives, such as aggregates and fibers, are improved by the superhydrophobic properties of CQDs.(Ying-ting Wang et al. 2025), resulting in improved aggregation and increased bonding within the interfacial transition zone (ITZ) of cement and particles. (X. Wang et al. 2022) also contended that nanoparticles can reduce micropore content and low-density calcium silicate hydrate (LD C–S–H), subsequently enhancing the levels of high-density C–S–H (HD C–S–H) and ultrahigh-density C–S–H (UHD C–S–H).

V.CHALLENGES AND FUTURE DIRECTIONS

Despite the positive results, challenges continue to impede the widespread adoption of CQD and GQD for cementitious materials. This incorporates the cost-effectiveness of the production of CQDs. The application of carbon/graphene nanomaterials is already the subject of investigation by a number of researchers due to their high cost, and carbon quantum dots (CQDs) are significantly more costly. The top-down strategy has been employed in numerous studies to reduce the particle size of acetic acid obtained from biomass, as indicated in the literature. This approach is purportedly advantageous from an economic standpoint. Utilizing an amine solution and carbon-capture technology, a cost-effective bottom-up approach is employed to generate an atomic crystalline carbon structure. This technology is similarly cost-effective than the use of nano-silica or silica particulate in high-strength concrete. Additional research is necessary to assess the potential for cost reductions associated with the procurement of basic materials and the implementation of energy-efficient processes. It is imperative to optimize the yield from production, assess the carbon credit of CQD materials across a variety of regions with varying environmental conditions, and implement them in a large-scale manufacturing process in order to assess the feasibility of their use in the construction sector.

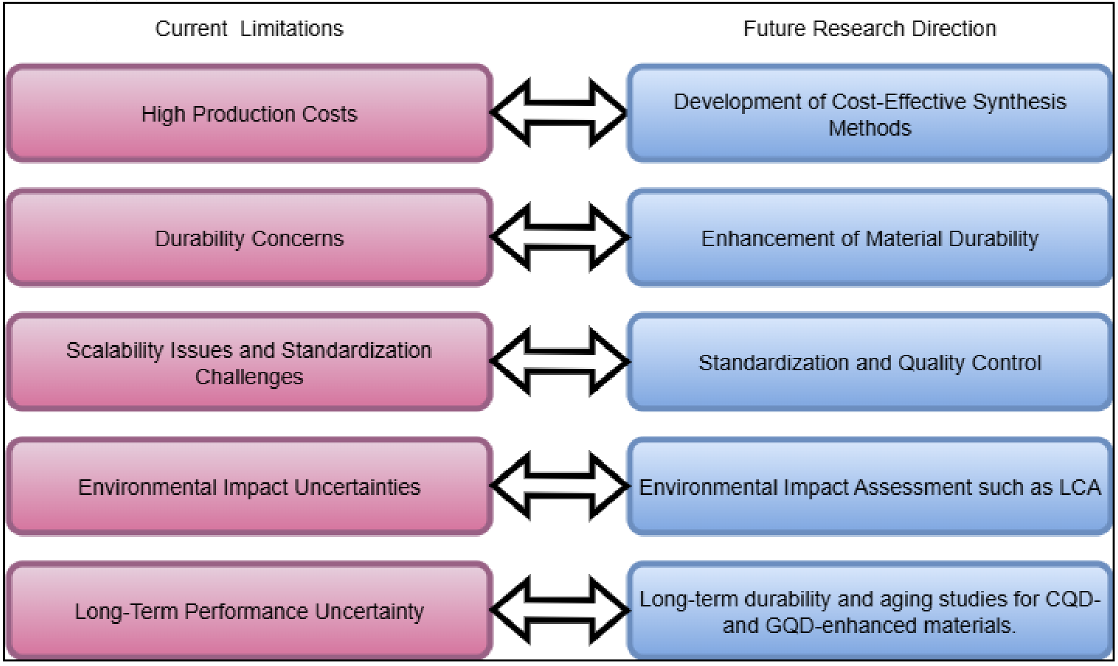

Figure 3: Current Limitations and future research direction for use of Carbon and Graphene Quantum Dots in Cement Composites

VI.CONCLUSIONS

New green nanomaterials and atomic materials, such carbon dots (CQD), aim to enhance performance and minimize environmental effect. CQDs and GQDs in cement and concrete are examined in this systematic review. This review examines the entire impact of these materials, including production methods, distinctive properties, and their impact on mechanical, thermal, and durability factors. The review offers earlier research, enabling scholars to explore the subject area and comprehend its mechanisms and interactions.

1. CQDs and GQDs are an innovative category of carbon-based nanomaterials, exhibiting exceptional optical, structural, and surface characteristics that render them particularly advantageous for cementitious applications.

2. The manufacturing of CQDs and GQDs has been documented using both bottom-up and top-down synthesis methods. Although bottom-up methods (hydrothermal, solvothermal, microwave, chemical oxidation) are more environmentally conscious and scalable, top-down methods (arc discharge, electrochemical oxidation, laser ablation) offer superior particle size control but are characterized by high energy requirements and low yield.
3. The integration of CQDs and GQDs in cement composites notably improves mechanical properties, such as compressive, flexural, and tensile strengths, due to their nucleation impact, nano-filling capabilities, and enhanced interfacial bonding with hydration products.
4. CQDs and GQDs enhance the durability properties of cementitious materials by optimizing pore structure, decreasing permeability, alleviating chloride ingress, and improving resistance to sulfate attack, freeze-thaw cycles, and high-temperature exposure.
5. In comparison to larger graphene derivatives, their nanoscale dimensions and abundance of functional groups facilitate superior dispersibility. Nevertheless, the maintenance of stable dispersion in alkaline pore solutions remains a challenge that necessitates surface functionalization, dispersants, or optimized mixing protocols.
6. Acceleration of hydration, densification of the microstructure, pore refinement, and stronger interfacial transition zones (ITZ) are among the mechanisms that contribute to performance enhancement. These mechanisms result in multifunctional enhancements, including enhanced durability and self-sensing.
7. Notwithstanding encouraging laboratory-scale outcomes, issues of cost-effective large-scale production, energy efficiency, and dispersion stability must be resolved prior to the widespread adoption of CQDs and GQDs in the construction sector.
8. Future research must prioritize eco-friendly, cost-effective synthesis techniques, the incorporation of carbon-capture technologies, and life-cycle assessments to determine the sustainability potential of CQD and GQD-based cementitious composites.

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