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REVIEW PAPER

State of Art Review on Variants of Graphene on Properties of Concrete

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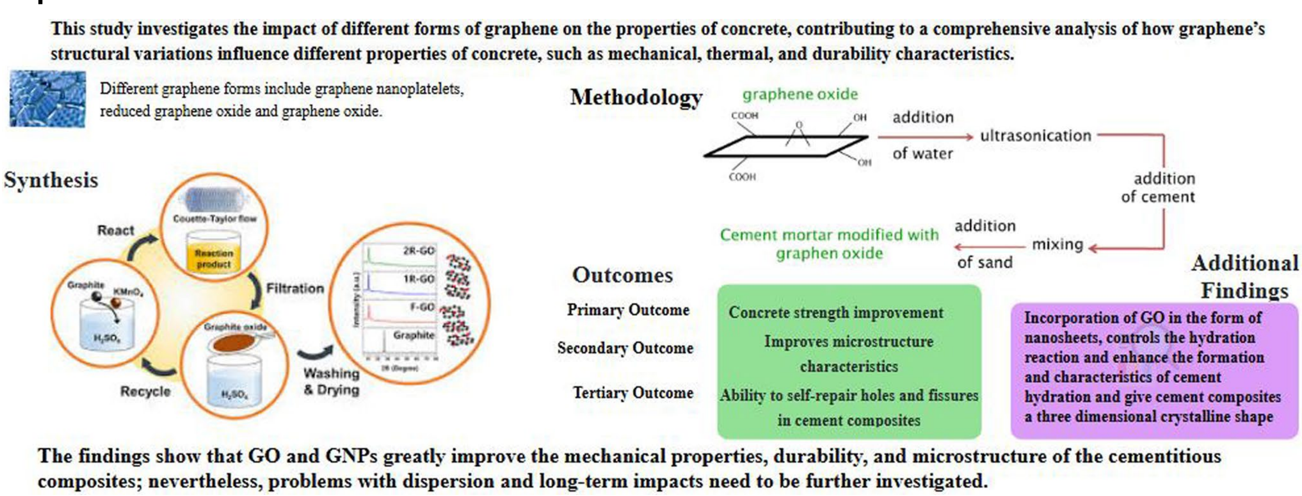
Abstract

This review critically examines the influence of different graphene derivatives graphene oxide (GO), reduced graphene oxide (rGO), and graphene nanoplatelets (GNPs) on the performance of cementitious composites. It systematically explores their synthesis methods, dispersion strategies, and effects on mechanical, durability, and microstructural properties of concrete. Notably, the incorporation of graphene has been shown to enhance compressive strength by up to 100% with just 0.01–0.1% dosage, improve flexural strength by 35–50%, and increase tensile strength by up to 20%, while also reducing porosity and enhancing resistance to chloride ingress, sulfate attack, and thermal degradation. Despite these promising outcomes, challenges such as agglomeration, cost, and compatibility with traditional concrete mix designs hinder practical scalability. The novelty of the review lies in comparing different graphene forms and their interaction with supplementary cementitious materials, providing insights into performance cost trade-offs and implementation potential. Research gaps related to long-term durability, environmental impact, and standardized dispersion techniques are also identified, highlighting future directions for the development of graphene-enhanced sustainable concrete.

Graphical Abstract



Keywords Graphene oxide · Reduced graphene oxide · Graphene nanoplatelets · Concrete strength and durability · Graphene dispersion techniques · Cement composites

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Abbreviations

GO	Graphene oxide
GNP	Graphene nanoplatelets
rGO	Reduced graphene oxide
AG	Aqueous graphene
CBN	Carbon-based nanomaterials

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PG	Powdered graphene
FLG	Few layer graphene
NM	Nanomaterials
CNT	Carbon nanotubes
EOGO	Edge–oxidized graphene oxide
HGM	Hollow glass microspheres
GON	Graphene oxide nanosheets/platelets
3DG	Three-dimensional graphene
NGP	Nano graphite platelets
GND	Graphene nano derivatives
NA	Nano alumina
GSNS	Graphene sulfonate nanosheets
PC	Polycarboxylate
PCE	Polycarboxylate ether
RHA	Rice husk ash
TBP	Tributyl phosphate
MO	Methyl orange
GMP	Graphene monolayer prepreg
MP	Monolayer prepreg
PCE	Perchloroethylene

1 Introduction

Concrete is one of the fundamental building materials that has been used for over a thousand years due to its high strength and durability. However, it has some drawbacks, such as its brittle nature, susceptibility to cracking, and low tensile strength. The self-recovery of the damaged concrete is considered as the major factor that concerns the energy-saving parameter and environmental mitigation. Thus nanomaterial-based self-healing concretes have been exploited in a wide range (Ghasan Fahim Huseien et al. 2019). The production of cement, which is the binder material in concrete, contributes to 8% of global CO_2 emissions. In response to this challenge to reduce the environmental impacts, researchers have turned their attention to incorporating additives and materials that can improve the performance of concrete.

In this regard, graphene, a single-layered two-dimensional honeycomb structure of carbon atoms, has emerged as a promising candidate for incorporation into concrete (Karla P Bautista-Gutierrez et al. 2019). It possesses excellent mechanical properties, such as tensile strength above 130 GPa and surface area approximately equal to 2630 m^2/g, which has brought interest in using this material to improve concrete properties (Yusaf et al. 2022). Graphene oxide (GO) is easily dissolved in aqueous solutions and can form a chemical bond with the cement matrix (Fonseka et al. 2024). However, Qureshi and Panesar (2019) have found GO to be hydrophilic agglomerates, resulting in poor dispersion within the cementitious matrix. Nowadays, reduced graphene oxide (rGO), extracted by the reduction of graphene oxide, has gained attention due to its greater electrical conductivity and mechanical properties with better dispersion than GO in the matrix (Wang et al. 2023a).

Graphene can improve the mechanical properties of concrete, such as compressive strength, tensile strength, and flexural strength, even at extremely low dosages (Basquiroto et al. 2022). According to Ramanjit Kaur et al. (2023), the service life of concrete structures may be extended with the incorporation of graphene oxide, as it presents better resistance to sulfate attacks and chloride ingress. It can also prevent concrete from environmental degradation and cracking, improving the cement paste and aggregate bond. Additionally, Nilofar Asim et al. (2022) showed that the inclusion of graphene resulted in the improvement of the thermal conductivity of cementitious composites, which may be helpful in enhancing the resistance of the material to thermal shock and energy efficiency in building applications. However, the addition of graphene to concrete provides a number of benefits and increased sustainability (Neha Singh et al. 2024). In addition long term exposure to graphene derivatives may cause decreased neuromuscular coordination and locomotor activity, as well as an accelerated ageing process at the bodily level (Wang et al. 2017). Graphene can be applied to walls and other surface coatings to improve their antibacterial and long lasting qualities. These coatings promote a healthier environment by preventing bacterial growth in addition to providing protection against wear and tear (Srimaneepong et al. 2022). Furthermore, buildings can be better insulated with graphene-based coatings, which lowers the amount of energy needed for heating and cooling (Malisz and Świeczko-Żurek 2023). Saeed et al. (2020) studied the market and stated that although the cost of producing graphene is still somewhat high, it should go down as production techniques advance. Chemical vapour deposition (CVD) is the most widely used technique for creating graphene.

Despite the potential benefits, the challenges related to large-scale implementation of graphene in concrete, including dispersion and cost, still pave the path for research in this sector. This study sheds light on the following parameters:

- Different forms of graphene and its properties.
- Techniques adopted for graphene dispersion.
- Effect of graphene on strength and durability properties.
- Microstructural effects of graphene in concrete.

1.1 Timeline of Evolution of Graphene

This timeline highlights the progression from fundamental research to practical applications, demonstrating the growing interest and potential of graphene in revolutionising the

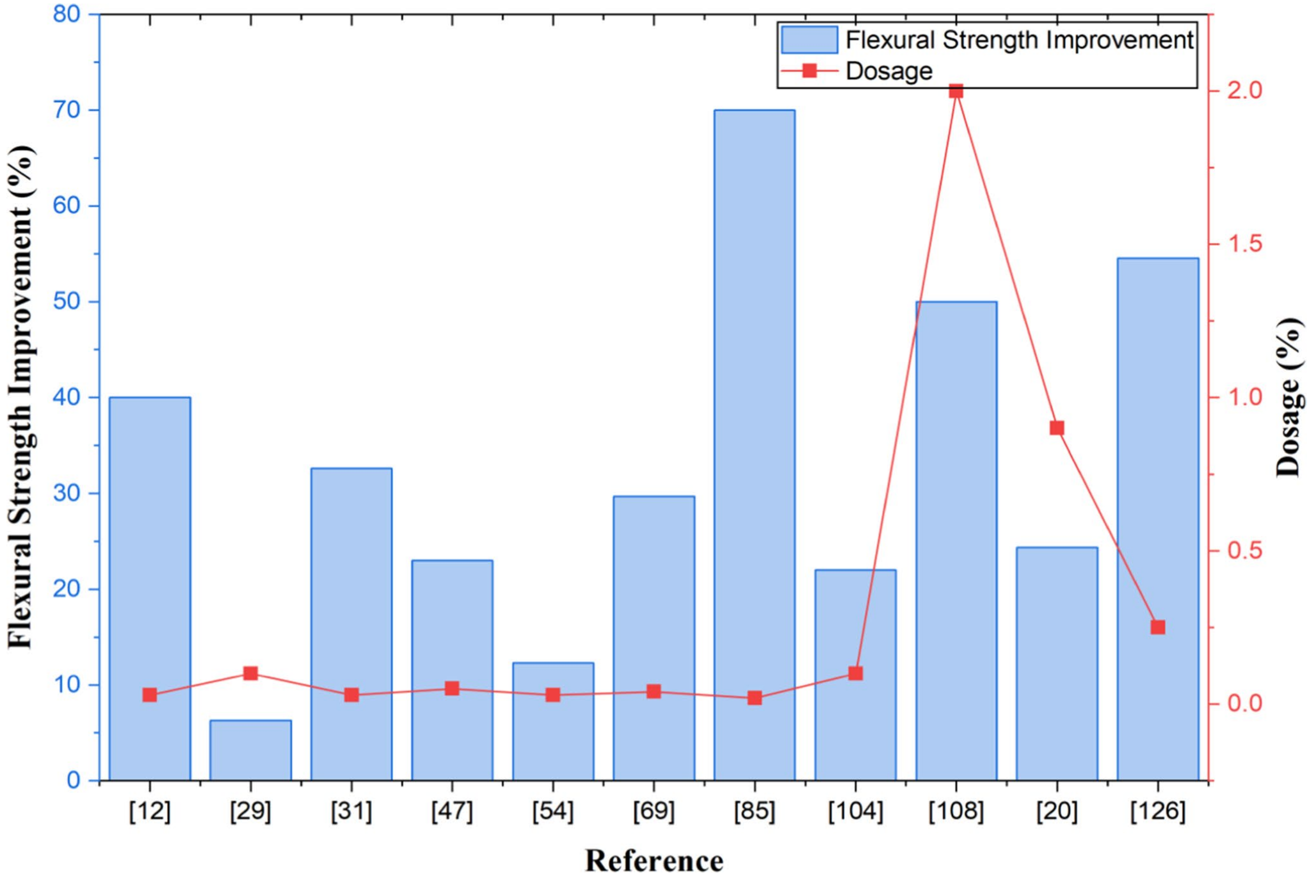

Fig. 4 Flexural strength improvement of graphene concrete

emphasis on synthesis methods, dispersion strategies, and structure–property relationships. The findings highlight promising developments, but also underscore the challenges that hinder widespread adoption.

- Quantitative evidence from recent literature reveals the following average improvements in concrete properties upon the incorporation of graphene derivatives. The Compressive strength increased by 25–100%, with optimum increase typically observed at 0.01–0.1% dosage by weight of cement. The Flexural strength improved by 20–50%, particularly with functionally graded GNP and GO additions. The Tensile strength enhanced by 9–20%, due to crack-bridging and matrix densification effects. Improved resistance to sulfate attack, chloride ingress, and freeze–thaw cycles has been consistently reported.
- Despite these performance benefits, several critical limitations must be addressed before graphene-modified concrete becomes viable for large-scale construction:
- While physical and chemical dispersion techniques (e.g., ultrasonication with superplasticizers) are effective, they are resource-intensive and may not be feasible for field applications. Poor dispersion leads to agglomeration, negatively impacting both workability and strength.
- Most existing concrete formulations are not directly compatible with nano-additives. GO provides better dispersion and chemical interaction with hydration products, whereas rGO exhibits higher conductivity but reduced bonding capacity due to fewer functional groups.
- Although graphene incorporation reduces cement consumption and promotes sustainability, potential health risks due to airborne nanoparticle exposure and the environmental impact of graphene synthesis remain concerns.
- Future research must prioritize the development of cost-effective, scalable, and environmentally benign dispersion methods. The Field-scale validation through pilot projects and long-term durability assessments under real environmental conditions. Life-cycle analyses (LCA) and techno-economic assessments to quantify the true sustainability potential of graphene-enhanced concrete. Exploration of hybrid approaches (e.g., combining GO with supplementary cementitious materials or fibers) to balance performance and cost.

Table 9 Graphene and its effects on cement hydration

Main Study	Improvement	Causes and effect of GO	References
Microstructure	Improves hydration, densifies microstructure	Due to oxygen functional groups	Reddy and Ravi Prasad (2022)
FA-Cement Hydration	Improves primary and secondary hydration	Refines CH crystals and pore structure	Wang et al. (2019a)
Mechanical strength	Increases strength and hydration speed	General performance enhancement	Yang et al. (2017a), Li et al. (2017b) and Horszczaruk et al. (2015)
Microstructure	Forms 3D GO network in cement	Direct chemical reactions observed	Wang et al. (2016)
Hydration kinetics	Speeds up hydration, reduces moisture loss	Affected by curing conditions	He et al. (2018)
Synergistic Effect (GO+NA)	Improves hydration and mechanical traits	Microstructure refinement	Li et al. (2017c)
Particle Dispersion	Enhances dispersion, accelerates hydration	Particle-level interaction	Lee et al. (2020)
Alite Hydration	Slight acceleration	Functional group stability critical at high pH	Ghazizadeh et al. (2017)
Durability	Enhances hydration and CO_2 resistance	Broad species interaction	Mohammed et al. (2018a)
Concrete Durability	Enhances density and durability	Hydration is the key mechanism	Sanglakpam Chiranjiakumari Devi and Rizwan Ahmad Khan (2020)
Product Aggregation	Promotes aggregation of hydration products	Leads to stronger matrix	Wang et al. (2024c)
ITZ Improvement	Improves interfacial transition zone	Enhances bonding quality	Dong et al. (2024)
rGO & Pore Structure	Optimizes pore structure and hydration heat	Depends on rGO content	Zhai et al. (2021)

- Future research should focus on a detailed comparative assessment of graphene variants, particularly evaluating cost-performance trade-offs, scalability, and compatibility with existing concrete formulations, to guide their practical adoption in the construction industry.

The graphene-enhanced concrete represents a transformative advancement in the construction materials sector. However, its practical deployment necessitates overcoming current technical, economic, and environmental barriers. With focused interdisciplinary research, this technology holds promise for transitioning from laboratory innovation to sustainable, field-ready construction solutions.

Table 10 Tests carried out for microstructure studies

Test	References
Atomic Force Microscopy (AFM)	He et al. (2022), Yang et al. (2017a, b) and Lv et al. (2016)
Dynamic mechanical analysis (DMA)	Udeze et al. (2024)
Energy Dispersive Spectrometer (EDS)	Alagawani et al. (2024), He et al. (2022), Reddy and Ravi Prasad (2022), Zheng et al. (2017), Mohammed et al. (2018a) and Indukuri et al. (2020)
Focused Ion Beam (FIB)	Udeze et al. (2024)
Mercury intrusion porosimeter (MIP)	Hongjian and Pang (2015), Dalal et al. (2022), Yang et al. (2017b), Wang et al. (2016), Li et al. (2017a), Murugan et al. (2016) AND Sanglakpam Chiranjiakumari Devi and Rizwan Ahmad Khan 2020)
Nanoindentation (NI)	Udeze et al. (2024)
Nuclear Magnetic Resonance spectroscopy (NMR)	Udeze et al. (2024)
Raman Spectroscopy	He et al. (2022), Dalal et al. (2022), Yang et al. (2017a, b)
Scanning Electron Microscopy (SEM)	Alagawani et al. (2024), Dung et al. (2023), He et al. (2022), Shanmuga Priya et al. (2021), Reddy and Ravi Prasad (2022), Yang et al. (2017a), Yang et al. (2017b), Wang et al. (2016), Li et al. (2017a), Suo et al. (2020), Chintalapudi and Pannem (2020), He et al. (2018), Lv et al. (2016), Mohammed et al. (2018a), Murugan et al. (2016), Indukuri et al. (2020) and Ying and Xi 2022)
Transmission electron microscopy (TEM)	Udeze et al. (2024)
Thermogravimetric Analysis (TGA)	Wang et al. (2016), Snigdha Sharma and Kothiyal (2016), He et al. (2018), Murugan et al. (2016) and Sanglakpam Chiranjiakumari Devi and Rizwan Ahmad Khan (2020)
Three-dimensional computed tomography (XCT),	Udeze et al. (2024)
UV Spectroscopy	Dung et al. (2023), Dalal et al. (2022) and Sheng et al. (2021)
X-Ray Diffraction (XRD)	Dung et al. (2023), He et al. (2022), Dalal et al. (2022), Yang et al. (2017a), Yang et al. (2017b), Suo et al. (2020), Wan and Zhang 2020), He et al. (2018), Murugan et al. (2016), Indukuri et al. (2020) and Sanglakpam Chiranjiakumari Devi and Rizwan Ahmad Khan (2020)

Table 11 Tests carried out on various properties

Properties	Test	References
Mechanical properties	Compressive strength	Bautista-Gutierrez et al. (2019), Qureshi and Panesar 2019), Alagawani et al. (2024), Dung et al. (2023), Shanmuga Priya et al. (2021), Cho et al. (2019), Suo et al. (2020), Li et al. (2017b, c), Liu et al. (2018, 2021), Lee et al. (2020), Sheng et al. (2021), Wang et al. (2024a), Kang et al. (2017), Lv et al. (2016), Mohammed et al. (2016b, c), Chu et al. (2017) and Indukuri et al. (2020)
	Split tensile strength	Alagawani et al. (2024), Shanmuga Priya et al. (2021), Liu et al. (2021) and Mohammed et al. (2016c)
	Flexural strength	Alagawani et al. (2024), He et al. (2022), Shanmuga Priya et al. (2021), Liu et al. (2021), Liu et al. (2018), Lv et al. (2016), Indukuri et al. (2020) and Mohammed et al. (2016c)
Fresh properties	–	Dung et al. (2023), Cho et al. (2019), Indukuri et al. (2020) and Ying and Xi (2022
Electrical resistivity	–	He et al. (2022), Jang and Park (2018), Chintalapudi and Pannem (2020), Snigdha Sharma and Kothiyal (2016) and Li et al. (2017c)
Chemical properties	–	Hongjian and Pang (2015), He et al. (2018), Sheng et al. (2021), Ying and Xi (2022) and Sanglakpam Chiranjiakumari Devi and Rizwan Ahmad Khan (2020
Hydration	Isothermal calorimetry	Lee et al. (2020) and Ghazizadeh et al. (2017)

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Conflict of Interest The authors declare no competing interests.

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