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Graphene Oxide in Construction: A Comprehensive Review on the Prospects, Challenges, and Sustainable Cement Reinforcement

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Abstract

The growing demand for cement production to support the rapid growth of the construction industry has resulted in a significant contribution to global carbon emissions due to the high energy requirements of cement production. Addressing this issue requires the development of eco-friendly cement modifiers/additives. Graphene, known for its exceptional properties, has emerged as a versatile material in various domains, including construction. Its incorporation into cement has exhibited promising prospects, surpassing geopolymer performance and enhancing cement quality. Nevertheless, challenges persist, such as inadequate dispersion in concrete mixtures and quality control issues during large-scale production. Harnessing the potential of graphene oxide can revolutionize cement performance and contribute to a more sustainable construction industry. Addressing dispersion challenges and ensuring successful large-scale production are pivotal steps towards realizing these benefits. This comprehensive review investigates the potential of graphene oxide in the construction sector, specifically focusing on its capacity to reinforce cementitious composites and highlighting the associated implementation challenges, paving the way for more sustainable cement production with a touch of scientific excellence.

Keywords: *Cementitious composites, graphene, graphene oxide, sustainable cement reinforcement*

Abstrak

Meningkatnya permintaan produksi semen untuk mendukung pesatnya pertumbuhan industri konstruksi berkontribusi signifikan terhadap emisi karbon global karena kebutuhan energi yang tinggi dari produksi semen. Untuk mengatasi masalah ini diperlukan pengembangan modifier/aditif semen yang ramah lingkungan. Grafena, yang dikenal karena sifatnya yang luar biasa, merupakan bahan serbaguna di berbagai bidang, termasuk konstruksi. Penambahannya ke dalam campuran semen meningkatkan kualitas semen dan menunjukkan prospek menjanjikan, yang melampaui kinerja geopolimer. Namun, masih ada tantangan dalam penerapannya di lapangan seperti dispersi yang tidak memadai dalam campuran beton dan masalah kontrol kualitas pada produksi skala besar. Potensi grafena oksida dapat dimanfaatkan untuk revolusi kinerja semen dan berkontribusi pada industri konstruksi yang lebih berkelanjutan. Mengatasi tantangan mengenai dispersi dan memastikan keberhasilan produksi skala besar merupakan langkah penting untuk mewujudkan manfaat ini. Tinjauan komprehensif ini menelisik potensi grafena oksida di sektor konstruksi, dengan fokus pada perannya menambah kekuatan komposit semen dan membahas tantangannya dalam implementasi di lapangan,meretas jalan bagi produksi semen yang lebih berkelanjutan dengan sentuhan keunggulan ilmiah.

Kata kunci: *Komposit semen, grafena, grafena oksida, perkuatan semen berkelanjutan*

Introduction

The global construction industry has witnessed substantial growth, leading to a significant rise in cement and concrete consumption. In 2021, annual cement production worldwide reached 4.4 billion metric tons, marking a 5% increase from the previous year (US Geological Survey, 2022). Cement production is a major contributor to global warming due to its high energy requirements and

CO_2 emissions, responsible for emitting 5-8% of global CO_2 emissions (Ellis et al., 2020). Each ton of cement produced releases 0.628 to 0.92 tons of CO_2 emissions (Ige et al., 2022), Therefore, it is imperative to explore environmentally friendly alternatives to cement.

One proposed solution is to reduce clinker manufacturing (Maglad et al., 2022), and use supplementary cementitious materials (SCM) instead (Antunes et al., 2022; Juhart et al., 2021). SCM enhances concrete quality, reducing maintenance and the need for early replacement Geopolymers, with their superior availability, easier processing, and reduced energy consumption and emissions (Liu et al., 2020; Maglad et al., 2022), represent a promising option, with consideration for the environmental impact of their raw materials.

Graphene and graphene oxide (GO) have found extensive applications in various fields, (Dideikin & Vul', 2019) including medicine (Ławkowska et al., 2022), biomedical applications (Blessy Rebecca et al., 2022), wastewater treatment (Obayomi et al., 2022; Paton-Carrero et al., 2022), energy storage (Velasco Davoise et al., 2022), and water filtration (Barker et al., 2020; Gayen et al., 2023; Khaliha et al., 2022; Zambianchi et al., 2022). In construction, graphene oxide can address the shortcomings of cement-based materials, such as brittleness and high permeability, and enhance mechanical strength up to 120 GPa (Xu, 2018). Moreover, graphene oxide can stabilize silty soil and soft clay for building foundations, making it a promising material for construction projects (Fattah et al., 2021; Mahmood et al., 2021; Yuan et al., 2023)

Nevertheless, graphene, like other carbon-based nanomaterials, is water-insoluble, posing challenges for even distribution in cement mixes (Suo et al., 2022; Zhao et al., 2020a). In contrast, graphene oxide (GO), composed of single-layer sp2-hybridized carbon atoms with oxygen-containing groups, exhibits good hydrophilicity and cost-effectiveness, making it a popular choice for concrete mixes (Krystek et al., 2021; Aliyev et al., 2019; Suo et al., 2022). The presence of oxygen-containing groups enhances GO's dispersibility, reducing van der Waals forces between GO sheets (Wang & Yao, 2020).

However, industrial-scale production of high-quality graphene is challenging, and most graphene nanoplatelets (GNP) derived from graphite are in the form of flake graphene or low-quality graphite microplatelets (Zhu et al., 2018). The degree of functionalization and size diversity of GO products can impact their dispersibility and interfacial bonding, influencing the mechanical durability of GO-reinforced cementitious composites (GRCC) (Backes et al., 2020; Santhiran et al., 2021). Thus, it is essential to develop cost-effective methods for using graphene-based nanoparticles as reinforcement in cementitious composites, balancing performance and product properties for practical infrastructure development.

This paper offers a comprehensive overview of graphene oxide's characteristics, multifunctional properties, and its reinforcement mechanism in cementitious composites. It also explores the opportunities and challenges of utilizing graphene oxide in the construction industry.

Method

Analyzing 150 publications from 2013 to 2023 across various academic databases (e.g., Google Scholar, Science Direct, MDPI, Research Gate, IOP Science, and NCBI), this study underscores GO's hydrophilic and cost-effective attributes as a valuable means of enhancing cementitious composite mechanical and durability properties. The paper also delves into the opportunities and challenges in construction applications and suggests potential research directions.

Graphene Oxide (GO)

As a nanomaterial, GO, with dimensions under 100 nm, consists of a single layer of carbon, oxygen, and hydrogen atoms, featuring additional hydroxyl groups attached to its carbon network (Murali et al., 2022). This single-layer substance results from oxidizing graphite crystals, creating oxygenated graphene sheets with various oxygen-containing groups (C=O, –OH, –COOH, and –CH(O)CH) that modify van der Waals forces between GO particles (Suo et al., 2022; Wang et al., 2017). GO exhibits remarkable properties, including a high tensile strength (up to 120 GPa), a large specific surface area (2630 m^2/g), and high thermal conductivity (5300 W/m^2K), making it a state-of-the-art nanomaterial (Lu et al., 2018). Compared to traditional reinforcement materials, GO effectively manages nanoscale crack propagation (Pan et al., 2015). Unlike carbon nanofibers and nanotubes, GO can act as a chemical modifier for cement hydration, enhancing composite properties beyond traditional cementitious composites.

Dispersion

Graphene nano-platelets (GNP) tend to aggregate due to van der Waals interactions stemming from their substantial specific surface area, potentially harming composite quality. To alleviate this, GNP must be uniformly dispersed within the cement matrix (Zhu et al., 2017). High-shear mixing, although time-consuming and less effective, can mechanically separate graphene sheets, while other methods like ultrasonic treatment, ball milling, shear mixing, calendaring, and intense agitation are also employed (Kang et al., 2017; Zhu et al., 2017). However, GO, which possesses superior dispersibility compared to GNP, is more commonly used (Zheng et al., 2017).

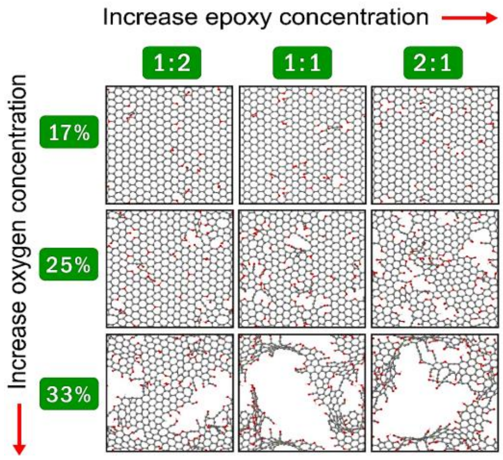

Figure 1. The relation of the oxygen and epoxy/hydroxyl ratio variation in a 3 by 3 matrix. Balls illustrate structures that stick with carbon (grey), oxygen (red), and hydrogen atoms (white) (Adapted from Lin & Grossman, 2015).

The presence of oxygen-containing functional groups on GO sheets enhances their water solubility, as depicted in Figure 1, resulting in a stable dispersion primarily composed of single-layered sheets (Aliyev et al., 2019; Hou et al., 2015; Suo et al., 2022; Lin & Grossman, 2015).

Synthesis method

Graphene can be synthesized from graphite using various methods (Figure 2), including chemical, electrochemical, microbial, and chemical vapour deposition (CVD) (Brisebois & Siaj, 2020; Tene et al., 2020). Hummer's Method (HM) is the most widely employed approach for producing graphene oxide (GO) by oxidizing graphite crystals with potassium permanganate, sulfuric acid, and sodium nitrate (Brisebois & Siaj, 2020, Ikram et al., 2020; Jiříčková et al., 2022). While HM has drawbacks, including the generation of toxic gases and ion residues in wastewater, modifications such as nitrate-free, two-step, co-oxidant, and low-room-temperature methods have been proposed (Ikram et al., 2020) (Yu et al., 2016; Chen et al., 2019). However, HM remains suitable for large-scale GO production (Brisebois & Siaj, 2020; Jiříčková et al., 2022).

At the industrial level, factors such as reaction conditions, raw materials, purification, and quality control require attention (Ikram et al., 2020; Lowe & Zhong, 2016). Strategies involve modifying production techniques to control the degree of oxidation, shorten reaction time, and enhance the number of oxygen functional groups in GO, thereby reducing production costs (Yu et al., 2016; Liu et al., 2016; Park et al., 2017). Sonochemical and electrochemical methods offer faster, manageable large-scale production alternatives (Ikram et al., 2020).

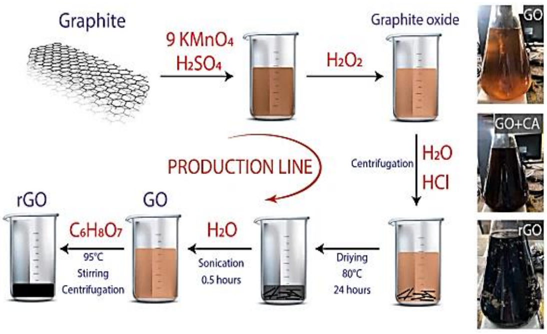

Figure 2. Production scheme using graphite powder as initial material. The provided image shows graphene oxide (GO), graphene oxide with citric acid (GO+CA), and reduced graphene oxide (rGO) (Tene et al., 2020)

Reinforcing Mechanism of Graphene Oxide

Extensive research has examined the impact of graphene oxide (GO) on cementitious materials, uncovering its capacity to enhance mechanical properties through distinct mechanisms. These encompass the establishment of nucleation sites, decreased permeability through void-filling, and the fortification of the C-S-H matrix through interfacial bonding (Table 1).

Nucleation Effect

Graphene oxide (GO), with its nanoscale dimensions and large surface area, creates multiple nucleation sites on cement particles, promoting hydration product development (Figure 3) (Meng et al., 2021). This is facilitated by GO's small size and high specific surface area (Pan et al., 2015; Wu et al., 2021). During cement hydration, the carbon-carbon sp2-bonded networks in GO act as nucleation sites due to their significant heat generation (Qureshi & Panesar, 2020). Oxygen-containing functional groups, crucial during early hydration, increase water and ion adsorption, accelerating cement hydration (Li et al., 2017; Zhu et al., 2017). This heightened water adsorption not only reduces the water-to-binder ratio but also supports curing and causes spontaneous shrinkage.

Table 1. Graphene reinforcing mechanism

Properties	Description	References
Potential nucleation sites	GO is dispersed on the surface of cement particles.	Meng et al., 2021
	GO has ultrahigh specific surface area.	Pan et al., 2015; Wu et al., 2021
	GO has more oxygen functional group which increase water adsorption and cumulative heat during hydration process.	Han et al., 2017; Li et al., 2017; Lu & Ouyang, 2017
Nanoscale size	GO fills the voids in cement matrix and reduce internal bleeding by giving a greater homogeneity.	Diagne et al., 2021; Martínez-García et al., 2022
	GO reduces pore diameter and permeability. C-S-H gel pore concentration densifies the hydrated cement matrix.	Wu et al., 2021; Zeng et al., 2021
	GO has peak value of addition; excessive usage may produce more pore.	Lu et al., 2016; Yuan et al., 2014; Zhao et al., 2020c
Interfacial bond advantages	Hydroxyl groups in GO accompany hydrogen bonds as main sources of interfacial bond by forming van der Waals interaction with C-S-H.	Bahraq et al., 2022; Chen et al., 2017; Wan & Zhang, 2020; Wang et al., 2020
	GO increases interfacial frictional resistance by performing mechanical interlocking.	Chen et al., 2017; Kai et al., 2019; Wang et al., 2020
	GO creates more crack bridging.	Belmonte et al., 2016; Ovid'ko, 2015; Ramírez et al., 2018

Furthermore, ion adsorption accelerates nucleation and enhances C-S-H gel aggregation, improving cement compactness (Han et al., 2017).

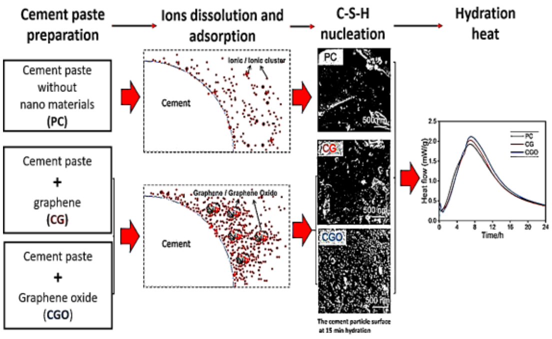

Figure 3. Graphene oxide nucleation in cement paste and its effect on hydration heat increase (Meng et al., 2021)

Filling Effect

In cementitious composites, pores of varying sizes in the hydrated cement paste matrix influence mechanical properties (Hilal, 2016; Wu et al., 2021). Graphene-based materials, with their nanoscale dimensions (Figure 4), fill these voids effectively, reducing internal bleeding (Gholampour et al., 2017; Diagne et al., 2021), enhancing aggregate paste bonding, and promoting structural uniformity (Martínez-García et al., 2022). Mercury intrusion porosimetry (MIP) measures pore size by immersing samples in mercury under pressure (Hilal, 2016). Zeng et al. (2021) report a 37.3% reduction in pore diameter and an 80.2% decrease in the permeability coefficient. This improves the microstructure, doubles C-S-H gel pores, reduces porosity, and enhances filling effects (Wu et al., 2021). However, excessive filler content can lead to issues like overlapping graphene sheets, increased composite viscosity, and larger void pores due to agglomeration, posing risks to mechanical properties (Yuan et al., 2014; Lu et al., 2016; Zhao et al., 2020b).

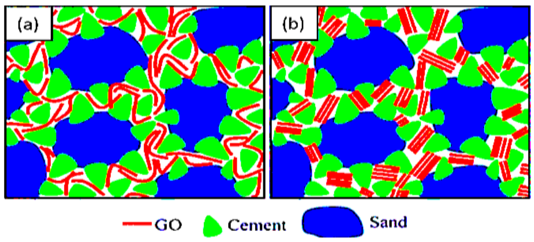

Figure 4. Visualization of (a) uniformly dispersed GO and (b) aggregated/overlapping GO sheets in cement mortar (Gholampour et al., 2017)

Toughening Effect

Graphene oxide (GO) contains oxygen functional groups that can create robust interfacial bonds with calcium hydroxide or C-S-H gel in cement (Bahraq et al., 2022; Chen et al., 2017; Wang et al., 2020). These connections are commonly formed through the ionic interaction of calcium in C-S-H with the oxygen-functional groups on GO sheets and the hydrogen bonds between water molecules in C-S-H and the hydroxyl groups of GO (Chen et al., 2017;

Wan & Zhang, 2020). Molecular dynamics (MD) simulations have shown that hydroxyl groups exhibit stronger interactions with C-S-H compared to carboxyl groups due to more stable chemical interactions at the COOH/C-S-H interface (Hou et al., 2015). The interaction between C-S-H and GO flakes is illustrated in Figure 5 (Babak et al., 2014). Additionally, the presence of hydroxyl groups roughens the GO surface and initiates mechanical interlocking, enhancing interfacial frictional resistance (Wang et al., 2020).

Pull-out simulations indicate that mechanical interlocking plays a pivotal role in the shear strength between GO and the C-S-H matrix (Kai et al., 2019). Moreover, the interfacial resistance is influenced by disproportionate adhesion forces near the crack surface (Chen et al., 2017). This research also reveals that GO's interfacial shear strength can reach hundreds of MPa, up to nine times higher than that of GNP, due to van der Waals interactions with C-S-H. Consequently, GO's strong interfacial bonding enhances the mechanical properties of cementitious composites (Wan & Zhang, 2020).

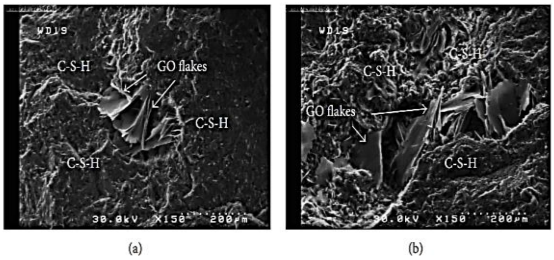

Figure 5. Nucleation formation of C-S-H by the GO flakes (Babak et al., 2014)

GO not only reinforces but also enhances the durability of composites by controlling cracks. Typically, cracks branch and deflect. However, adding GO disrupts the bamboo-like fracture pattern observed in pure epoxy resin (Wang et al., 2013). In graphene-reinforced cementitious composites, the increased occurrence of crack-bridging demonstrates strong interfacial bonding, aided by the smaller size of GO (Ramírez et al., 2018; Belmonte et al., 2016).

Graphene's character as an impermeable nanomaterial with complex shapes makes it difficult to pull out, further contributing to crack-bridging (Ovid'ko, 2015) This crack-bridging effect absorbs more energy, effectively increasing crack path length, which delays crack initiation and impedes propagation, thereby enhancing toughness, as shown in Figure 6 (Wang et al., 2021; Rehman et al., 2017). The toughening effect is also influenced by interfacial sliding, observable in pull-out failures under SEM (Liu et al., 2020).

Working Performance

Introducing graphene oxide (GO) as a nanomaterial modifier increases cement viscosity and reduces workability significantly (Devi & Khan, 2020a; Lv et al., 2013). This viscosity rise can hinder the final mechanical properties of the composite matrix, making it challenging to work with fresh cement composites, particularly when their fluidity is insufficient (Pan et al., 2015).

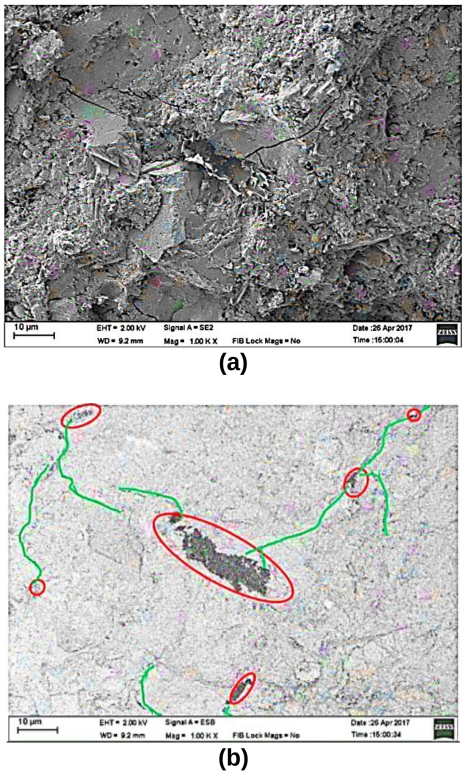

Figure 6. Graphene crack bridging (a) and graphene crack propagation (b), where green lines indicate the longitudinal growth of cracks, and red circles indicate the presence of graphene (Rehman et al., 2017)

GO incorporation consistently decreases fluidity, with a clear inverse relationship between GO concentration and paste fluidity. GO's 2D structure and hydrophilic functional groups demand more water to wet the surface and reduce available free water for mixing (Suo et al., 2020; Li et al., 2018). This decrease in workability impedes cement hydration reactions and can result in GO sheet re-agglomeration, especially at higher GO concentrations (Birenboim et al., 2019).

Direct GO addition to cement paste leads to flocculation and reduced fluidity. The dispersion of GO in the cement matrix correlates with fluidity and compressive strength, influenced by GO concentration and water-to-cement ratio. Adjusting the w/c value can balance fluidity and compressive strength, aided by superplasticizers like polycarboxylate ethers (PCEs), which enhance fluidity efficiently, as shown in Figure 7 (Lv et al., 2015; Suo et al., 2020) by dispersing cement grains and releasing trapped water (Stephens et al., 2016), making PCE a practical solution making PCE a practical solution (Guo et al., 2019).

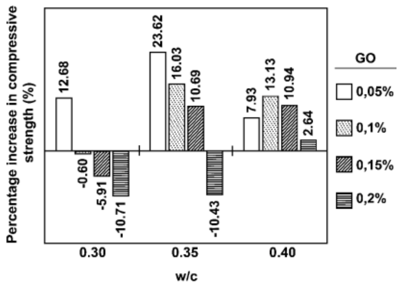

Figure 7. Graph of w/c Relation to Compressive Strength (adapted from Suo et al., 2020)

Mechanical Properties

The addition of GO offers several benefits to the mechanical properties of cement-based materials (Liu et al., 2020, 2021; Murali et al., 2022; Suo et al., 2022; Zhao et al., 2020a). GO, when combined with a compatible surfactant in cement slurry, stabilizes its dispersion and enhances flexural strength (Chuah et al., 2018). Studies have consistently shown that the strategic addition of GO to cementitious composites can influence the structure of hydration products, resulting in improved mechanical properties (Lv et al., 2015). The abundance of nucleation sites in GO accelerates the hydration process, leading to the refinement and increased cementation of CH crystals with other hydration products like C-S-H gel, contributing to enhanced strength (Yang et al., 2017).

GO's crack-bridging mechanism inhibits microcrack expansion due to its interlocking with C-S-H (Murali et al., 2022). SEM observations confirm that cracks, typically straight, cannot penetrate graphene sheets (Pan et al., 2015). For instance, adding 0.05 wt% GO yields a strong interfacial bond between GO and the cement matrix, resulting in a 33% increase in compressive strength and a 59% increase in flexural strength of cement sandstone after 28 days. Low GO content (0.03 wt%) gradually improves flexural and tensile strength by up to 60.7% and 78.6%, respectively, within 28 days, reaching a peak in compressive strength (47.9% improvement within 28 days).The peak in compressive strength is attributed to the flocculation of hydrated cement crystals around GO, while a decline is linked to GO agglomeration, reducing its surface area and matrix aggregation (Gholampour et al., 2017; Lu et al., 2019). Controlled growth of cement hydration products and aggregation contributes to the increased mechanical strength of cement mortar (Lv et al., 2013). Therefore, it's important to consider key aspects when using GO, as summarized in Table 2. While most research has focused on cement paste and mortar (Zhao et al., 2020a), similar patterns have been observed in concrete, where an optimal amount of GO addition leads to strength improvements, as shown in Figure 8. GO's filling effect reduces pore volume, inversely affecting porosity, microstructure density, and the compressive-to-indirect tensile strength ratio in cement-based materials (Wang et al., 2015; Chen et al., 2013). A 0.05% GO mass addition results in a maximum increase of 57% in compressive strength and 48% in flexural strength, with reduced porosity (Ullah et al., 2021).

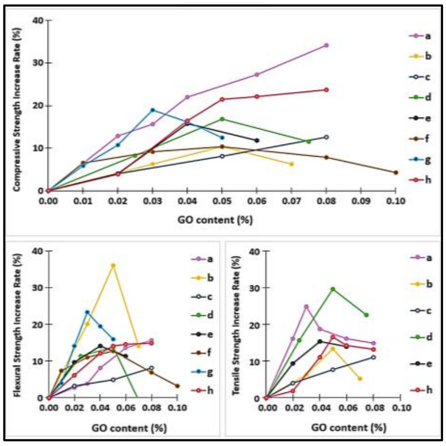

Figure 8. Mechanical Properties Enhancement of Concrete (a) Wu et al. (2019; (b) Jyothimol et al. (2020); (c) Chen et al. (2020); (d) Chu et al. (2020); (e) Yeke & Yu (2021); (f) Lu & Ouyang (2017); (g) Ellala (2022); (h) Hong et al. (2022).

Blocking Transport Channels in Concrete

Transport channels in concrete, including gel pores, capillary pores, interfaces, and cracks, are responsible for the penetration of corrosive agents such as CO_2, chloride ions, alkalis, and acids. Graphene oxide (GO), due to its hydrophobic nature, can be applied to concrete either by mixing it into the matrix or coating cement products, serving as a protective barrier against these corrosive substances.

Application of GO by Mixing

When added to cement composites at 0.03%, GO reduces water absorption by 14.5%, but at 0.04%, water sorptivity increases due to GO nanosheet agglomeration (Indukuri & Nerella, 2021). Larger amounts of GO, like 0.06 wt%, can reduce the relative permeability of cement mortar by up to 80.6% (Zeng et al., 2021).

Table 2. Utilization Consideration of Graphene Oxide

Properties	Description	References
GO addition reduces workability	GO increases viscosity significantly which caused by hydrophilic functional groups	Devi & Khan, 2020a; Li et al., 2018; Lv et al., 2013; Suo et al., 2020
	Low fluidity may cause entrapped air spaces	Pan et al., 2015
	Low workability prevents cement hydration reaction and cause GO re-agglomeration	Birenboim et al., 2019
	Workability can be improved by adding superplasticizers	Lv et al., 2015; Stephens et al., 2016; Wang et al., 2015; Zhao et al., 2020a
Peak addition ratio	GO improves compressive, flexural, and tensile strength of concrete, however, excessive addition of GO reduces mechanical performance	Chen et al., 2020; Chu et al., 2020; Hong et al., 2022; Jyothimol et al., 2020; Lu & Ouyang, 2017; Wu et al., 2019; Yeke & Yu, 2021
	Mechanical performance decreased due to GO agglomeration and aggregation	Gholampour et al., 2017; Indukuri & Nerella, 2021; Lu et al., 2019; Yuan et al., 2014
Capitalizing GO unique properties	Mixing GO into cement matrix reduces corrosive substance intrusion	Guo et al., 2019; Indukuri & Nerella, 2021; Korucu et al., 2019; Muthu et al., 2021b; Zhao et al., 2020b
	Covering concrete surface using GO reduces capillary adsorption and permeability	Korayem et al., 2020
	GO composite emulsion provides better waterproofing performance	Chen et al., 2021; Moshiri et al., 2020; Shi et al., 2022; Yu et al., 2019

Increased incorporation of GO decreases capillary action, reduces sorptivity, and enhances resistance to water penetration. This is attributed to GO clustering, which disrupts the cement matrix microstructure and depends on the water-cement ratio and GO size (Devi & Khan, 2020a). GO's resistance to carbon dioxide, linked to improved microstructure and reduced porosity, slows down carbonation (Mohammed et al., 2018). Thermogravimetric analysis (TG) showed how GO stabilizes C-S-H during early carbonization (Long et al., 2018). GO significantly decreases carbonation depth by 60% to 81.3% over 6 to 18 months (Devi & Khan, 2020b). GO also enhances resistance to chloride ingress. For example, 0.11 wt% GO reduces the average chloride transport depth by 28.6% (Zhao et al., 2020c). In a 28-day concrete sample, 0.03% GO results in a chloride penetration depth of 11.83 mm and minimal weight loss in corrosive environments (Indukuri & Nerella, 2021). GO similarly improves resistance to acid attack, reducing mass loss and sectional area in the presence of nitric acid, hydrochloric acid, and sulfuric acid (Muthu et al., 2021a; 2021b; Korucu et al., 2019).

Application of GO by Coating

In addition to being mixed in the concrete matrix, GO has been tested as a coating emulsion. GO coatings reduce capillary adsorption and permeability (Korayem et al., 2020). GO/silane composite emulsions exhibit stable waterproofing, especially for cracked concrete (Chen et al., 2021) forming a hydrophobic layer through silane hydrolysis and producing a C-S-H gel. Silane also undergoes condensation reactions with hydroxyl groups in ettringite, reducing pore size and porosity (Moshiri et al., 2020; Shi et al., 2022). Thicker coatings have better penetration resistance, and an increased percentage of epoxy strengthens the connection between GO and epoxy molecules (Yu et al., 2019).

Current challenges

Graphene and its derivative, graphene oxide (GO), encounter obstacles to broader adoption. Market constraints, awareness, and evolving technology are among the key challenges (Meister et al., 2017). Carbon nanotubes (CNTs) pose stiff competition as alternatives to graphene, with upcoming technologies poised to surpass existing ones. Quality and cost are significant concerns in the construction industry, with graphene's price being a limiting factor, at approximately $85-100 per metric ton of concrete, even with modest usage. Internal factors, including quality control, processing, and the supply chain, along with product proficiency and cost-effectiveness, contribute to the challenge. The diverse graphene production methods and a lack of standards make ensuring product quality and addressing long-term health and environmental issues difficult (Santhiran et al., 2021; Arvidsson et al., 2022; Murali et al., 2022; Pryce et al., 2022). Uncertainty about graphene characterization and application procedures obscures its cost-benefit ratio (Zhao et al., 2020a). While GO offers numerous advantages, its price must be competitive, and more efficient processing methods need development (Lowe & Zhong, 2016). Concerns about the health risks of graphene exposure persist, necessitating further research (Ansari et al., 2019; Lin et al., 2020).

Conclusions

The increasing interest in graphene oxide (GO), a prevalent graphene derivative, has provided valuable insights into its potential. While the quest for an efficient method for large-scale production continues, GO's role in enhancing cement-based materials has been extensively explored. GO's nanoscale features reduce porosity and pore size, while its substantial surface area expedites hydration and fosters strong interconnections between C-S-Hs and GO in composites, hindering crack propagation and enhancing density. The precise GO dosage for optimal mechanical properties remains to be determined, but generally, an addition of 0.05 wt% of GO demonstrates significant strength improvements. Furthermore, GO's utility extends to addressing transport-related issues, such as improving resistance to corrosive environments. Nonetheless, the widespread use of GO in construction faces challenges tied to cost, quality, and promotion. Industrial-scale production necessitates improved quality control, and awareness campaigns are essential to highlight GO's merits and stimulate further exploration and application in the construction sector.

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