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A Review Paper on the Developmenta Performance Evaluation of Graphene Oxide Modified Concrete

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Abstract:

Concrete is one of the most widely used construction materials because of its high compressive strength, availability and versatility. However, its brittle nature, relatively low tensile and flexural strength, crack formation and permeability-related durability problems remain important limitations. Graphene oxide (GO), a two-dimensional carbon-based nanomaterial containing oxygenated functional groups, has attracted attention as a nano-reinforcing material for cement-based composites. This review examines forty GO-specific studies published between 2013 and 2026, arranged in reverse chronological order, to trace the development of research on GO-modified cementitious materials, with emphasis on the progression from cement paste and mortar studies toward concrete, durability, targeted interfacial transition zone (ITZ) modification and low-carbon cement systems. Published studies indicate that controlled amounts of GO can improve strength and modify hydration and microstructure, while excessive addition or inadequate dispersion can reduce workability and limit performance. Recent studies have also examined sulfate and freeze-thaw exposure, abrasion, impact performance, fly-ash concrete, curing-temperature effects and low-clinker cement systems. The literature shows that GO dosage and dispersion are strongly dependent on the particular cementitious system and mixing conditions. Important research gaps remain in consistent dosage selection, large-scale dispersion, long-term field durability, cost, and validation using controlled concrete mixtures. The present review therefore provides a GO-specific basis for experimental performance evaluation of concrete.

Keywords: *Graphene Oxide, GO, Concrete, Compressive Strength, Durability, Microstructure, Dispersion, Hydration.*

1. INTRODUCTION

Concrete is the principal material used in a large proportion of civil engineering structures because it is economical, easy to cast and capable of carrying high compressive loads. Nevertheless, conventional concrete has inherent weaknesses, including brittleness, low tensile capacity, susceptibility to cracking and transport of aggressive agents through its pore network. These limitations have encouraged researchers to investigate nano-engineered cementitious materials.

Graphene oxide (GO) is a two-dimensional carbon-based nanomaterial with a large specific surface area and oxygen-containing functional groups. These characteristics allow GO to interact with water and cement hydration products and make it suitable for investigation as a nano-scale additive in cementitious materials. Early studies reported that small quantities of GO could influence hydration, strengthen the cement matrix and modify crack development. Pan et al. [38] reported that 0.05 wt% GO increased compressive strength by approximately 15–33% and flexural strength by 41–59% under the investigated conditions.

Research on GO has progressively moved from cement paste and mortar toward concrete-scale mixtures and application-oriented studies. Recent work has considered durability under sulfate attack and freeze-thaw cycles, abrasion resistance, impact performance, ITZ modification, cement-reduced fly-ash concrete, curing temperature and low-clinker cement. However, GO performance remains sensitive to dosage, dispersion technique, superplasticizer compatibility and the composition of the cementitious system. The present review therefore focuses specifically on graphene oxide and the development of GO-modified cementitious materials.

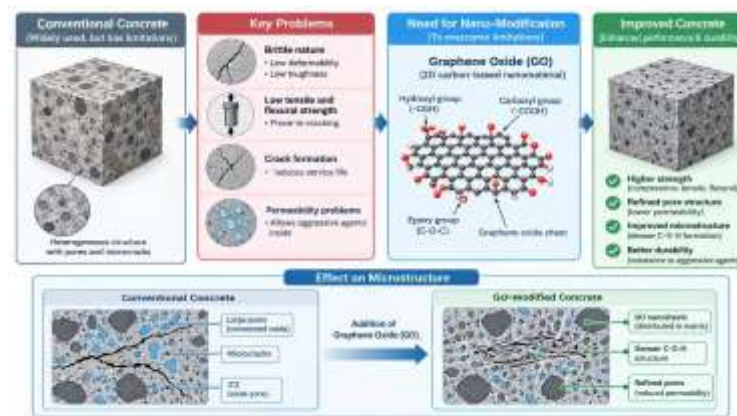


Figure 1. Conceptual representation of the limitations of conventional concrete and the role of graphene oxide in modifying cementitious materials.

2. OBJECTIVES

- To review the development of research on graphene oxide (GO)-modified cementitious materials from 2013 to 2026.
- To identify how GO research progressed from cement paste and mortar studies toward structural concrete, durability and application-oriented studies.
- To identify limitations and unresolved issues in GO dosage, dispersion, workability, durability and practical application.
- To identify research gaps and future scope specifically for GO-modified concrete in civil engineering applications.

3. LITERATURE REVIEW

3.1 Saravanan et al. (2026)

Saravanan and co-workers examined how the dispersion state of graphene oxide governs hydration and carbonation in low-clinker cement, a binder class that is becoming central to carbon-reduction strategies in the cement industry. Because clinker substitution usually slows early hydration and can increase vulnerability to carbonation, the study explored whether well-dispersed GO could offset these drawbacks by acting as a nucleation platform for hydration products. Different dispersion conditions were compared, and hydration development was assessed together with carbonation behaviour. The work showed that the benefit of GO in such systems depends strongly on how uniformly the nanosheets are distributed, since agglomerated GO cannot provide effective nucleation sites. This study represents one of the most recent directions in GO research, linking nano-modification directly with the development of lower-carbon cementitious binders.

3.2 Djenaoucine et al. (2026)

Djenaoucine and co-workers studied the influence of very small GO additions, namely 0.0005%, 0.005% and 0.05% by weight of cement, on hydration products, microstructure and the mechanical performance of cement paste and mortar with a water–cement ratio of 0.5. Thermogravimetric analysis, X-ray diffraction and SEM/EDS were combined with compressive and flexural tests up to 90 days. At early ages, GO slightly reduced C–S–H and portlandite contents and lowered compressive strength, but by 28 and 90 days the GO mixes showed higher C–S–H contents and smaller calcium hydroxide crystals than the reference. At 90 days, compressive strength increased by about 9.3–9.5% and flexural strength by up to 16.7%. The authors explained the gains through GO acting as a water reservoir and nucleation site, demonstrating that even extremely low GO dosages can refine the long-term microstructure.

3.3 Ganesh et al. (2026)

Ganesh and co-workers addressed a practical question that is rarely considered in GO research, namely whether the age of stored GO affects its performance in cement mortar. Commercial GO and laboratory-synthesised GO were aged from 4 to 35 weeks and added at 0.03% by weight of Portland pozzolana cement. Spectroscopic characterisation showed that the carbon-to-oxygen ratio and structural disorder of the GO increased with storage time, indicating gradual chemical change. Freshly aged GO improved splitting tensile strength by more than 50%, but the laboratory GO lost its benefit after about 15 weeks and eventually reduced compressive strength below the control. The authors recommended using GO within roughly 13 weeks of production. This study highlights shelf life and quality control of GO as important, previously overlooked factors for reliable field application.

3.4 Gao et al. (2025)

Gao and co-workers investigated the durability of C30 graphene oxide concrete exposed to a combined sodium sulfate and sodium chloride environment, which represents conditions found in coastal and saline soils. GO was added at 0.03–0.09% of cement weight, and specimens were subjected either to wet–dry cycling for up to 120 days or to continuous immersion for up to 240 days. At 0.07% GO, the 7-day and 28-day compressive strengths increased by about 13.1% and 27.7%, effectively raising the concrete from C30 to C40 grade. Under long-term immersion, GO markedly reduced strength loss and mass loss, with 0.07% again giving the best performance, although its effect under wet–dry cycling was smaller. SEM observations showed denser and better-connected hydration products, which the authors associated with slower ingress of aggressive ions.

3.5 Ginigaddara et al. (2025)

Ginigaddara and co-workers carried out a comprehensive macro-scale evaluation of GO-enhanced high-strength concrete designed for 65 MPa with a water–binder ratio of 0.30, using GO produced from vein graphite. GO was added at 0.03% and 0.05% by binder weight, and fresh properties, strength, elastic modulus and drying shrinkage were measured together with SEM, FTIR, TGA and NMR analysis. At 28 days, the 0.05% mix showed about 25% higher compressive strength and 16% higher split tensile strength than the control. A notable finding was improved slump retention, with the 0.05% mix keeping 84% of its initial slump after 60 minutes compared with 53% for the control. The study demonstrated that GO can contribute to low-carbon concrete by enabling higher performance per unit of cement while maintaining workability.

3.6 Cabello-Mendez et al. (2025)

Cabello-Mendez and co-workers deliberately examined poor-quality concrete with a high water–cement ratio of 0.7 to determine whether GO can improve durability where it is most needed. GO suspensions were added at 0.03%, 0.06% and 0.09% by weight of cement, and the concrete was assessed using an integrated set of non-destructive and durability tests, including electrical resistivity, ultrasonic pulse velocity, capillary absorption and rapid chloride permeability. Electrical resistivity and compressive strength increased with GO content, but total porosity remained around 21% and chloride permeability and capillary absorption did not improve. Microscopy revealed GO agglomerates, which the authors attributed to the absence of a dispersing agent. This study provides an important counterpoint to positive reports by showing that GO cannot compensate for a poor mix design or inadequate dispersion.

3.7 Benavente et al. (2025)

Benavente and co-workers presented a quantitative analysis of the mechanical and microstructural behaviour of concrete designed for 280 kg/cm² strength, with GO added at 0.05–0.20% of cement weight after ultrasonic dispersion with a plasticizer. Compressive, indirect tensile and flexural strength and modulus of elasticity were measured following ASTM procedures, and the microstructure was studied using TGA/DSC, FTIR, SEM–EDS and XRD. The optimum dosage of 0.05% increased compressive strength by about 14.6%, tensile strength by about 12.3% and elastic modulus by about 27%, while SEM showed fewer and smaller pores and cracks. -Higher dosages progressively reduced the benefit, and 0.20% GO lowered flexural strength below the reference. The study confirms that GO behaves as an effective modifier only within a narrow dosage window, beyond which agglomeration dominates.

3.8 Dominguez-Santos et al. (2025)

Dominguez-Santos and co-workers evaluated whether GO-reinforced concrete can make reduced-cement mixtures technically and economically viable, linking material performance with carbon emissions. The study combined mechanical and microstructural testing of concrete with lower cement content against a techno-economic and environmental assessment of the GO addition. The underlying idea is that if GO restores the strength lost by cutting cement, the overall cost and CO₂ footprint of the concrete could be reduced even though GO itself is an expensive additive. This work is significant because it moves GO research beyond laboratory strength gains toward questions of feasibility, cost and sustainability, which ultimately determine whether the material can be adopted in construction practice. It also provides a framework for judging GO concrete on performance per unit of embodied carbon.

3.9 Dai et al. (2025)

Dai and co-workers studied how curing temperature changes the effect of GO on the hydration of cement-based materials, an issue of direct relevance to concreting in hot and cold climates. GO dosage, hydration kinetics and pore structure were examined at different curing temperatures. The results showed that the influence of GO on hydration and pore refinement is not fixed but varies with the thermal conditions during curing, so that a dosage found to be effective at standard temperature may not perform equally well under other conditions. This finding is important because most GO studies are carried out under controlled laboratory curing, while real structures experience wide temperature variations. The study therefore emphasises that curing conditions must be considered alongside dosage and dispersion when designing GO-modified concrete for field use.

3.10 Chen and Du (2025)

Chen and Du proposed a targeted strategy in which GO is used specifically to strengthen the interfacial transition zone (ITZ) between aggregate and cement paste, rather than being dispersed uniformly throughout the mix. The ITZ is generally the weakest and most porous region of concrete and is the main pathway for cracking and the ingress of aggressive agents. By concentrating GO in this zone, the authors aimed to achieve greater improvement for a given quantity of nanomaterial. The results showed a denser ITZ microstructure and improved resistance of the concrete to environmental deterioration. This represents a shift from bulk modification toward precision nano-engineering of concrete, and suggests a way to use expensive GO more efficiently by placing it where it has the greatest effect on strength and durability.

3.11 Kumar et al. (2024)

Kumar and co-workers investigated GO in fly ash concrete using response surface methodology (RSM) to optimise the combined effect of both materials. Class F fly ash replaced 5–15% of cement, and GO was added at 0.05–0.08% by cement weight in an M45-type concrete with a water–cement ratio of 0.36. Compressive, tensile and flexural strength, modulus of elasticity and drying shrinkage were measured. The best mix, containing 10% fly ash and 0.05% GO, reached 62 MPa compressive strength at 28 days, about 17% above the control, with similar improvement in tensile strength. Drying shrinkage of all GO–fly ash mixes was lower than that of the control. The RSM models fitted the data with very high accuracy, showing that statistical optimisation is a useful tool for selecting GO and supplementary material dosages together.

3.12 Djenaoucine et al. (2024)

Djenaoucine and co-workers examined the mechanical properties and durability of cement mortar containing three GO dosages at water–cement ratios of 0.35, with a polycarboxylate superplasticizer, and 0.50 without it. Hydration was characterised using thermogravimetric analysis and ^{29}Si MAS-NMR, which showed that GO increased C–S–H content, degree of hydration and the mean silicate chain length at 28 days. Compressive strength increased by about 9% and flexural strength by more than 20% for the GO–superplasticizer mix. Durability indicators improved substantially: electrical resistivity increased by over 21%, oxygen permeability decreased by up to about 93%, and chloride diffusion was lower in GO mortars. This study is valuable because it connects GO-induced changes in silicate structure at the molecular level with measurable improvements in transport-related durability.

3.13 Wang et al. (2024)

Wang and co-workers investigated the effect of monolayer graphene oxide on the impact mechanical properties of concrete, extending GO research from static loading to dynamic and impact conditions. Concrete specimens with different GO contents were subjected to impact loading, and the strengthening mechanism was analysed using fractal theory applied to pore structure and crack patterns. The results indicated that GO improved impact resistance by refining the pore structure, restricting crack initiation and promoting more distributed cracking that dissipates energy more effectively. The fractal analysis provided a quantitative way to relate microstructural changes to macroscopic impact performance. This work is relevant to structures exposed to impact, such as pavements, industrial floors and protective structures, and shows that GO benefits extend beyond conventional compressive and flexural strength.

3.14 Fonseca et al. (2024)

Fonseca and co-workers systematically investigated how the properties of GO, the type of superplasticizer and the dispersion technique together control the mechanical performance of GO-added concrete. Rather than treating GO content as the only variable, the study compared GO with different characteristics and evaluated several dispersion procedures and admixture types. The results demonstrated that the same nominal GO dosage can give very different strength outcomes depending on how it is dispersed and which superplasticizer is used, because these factors determine whether GO remains as individual sheets or forms agglomerates in the alkaline cement environment. The study provides practical guidance for producing consistent GO concrete and explains much of the scatter in published results. It strongly supports specifying the dispersion method as an essential part of any GO concrete mix design.

3.15 Udumulla et al. (2024)

Udumulla and co-workers presented a focused review of the effect of graphene oxide nanomaterials on the durability of concrete, covering mechanisms, testing provisions, challenges and future prospects. The review discussed how GO can reduce permeability, refine pores and slow the transport of water, chlorides and sulfates, thereby improving resistance to deterioration processes such as reinforcement corrosion, sulfate attack and freeze–thaw damage. It also identified inconsistencies between studies arising from differences in GO quality, dosage, dispersion and test methods. The authors highlighted the shortage of long-term and field-exposure data and called for standardised durability testing of GO concrete. This review is important because durability, rather than short-term strength alone, ultimately determines the service life and economic value of GO-modified concrete structures.

3.16 Walunjkar and Bajad (2024)

Walunjkar and Bajad reviewed the effect of graphene oxide reinforcement on the properties of cement concrete, collecting results reported for different concrete grades, GO contents and testing ages. The review found that most studies reported improvements in compressive, split tensile and flexural strength at low GO contents, typically well below 0.1% by weight of cement, while higher dosages often reduced workability and strength because of agglomeration. The authors emphasised that the optimum GO content is not universal but depends on the concrete mixture, the characteristics of the GO used and the dispersion method adopted. The review is useful for practitioners in India because it summarises dosage ranges and performance trends in a form that can guide the design of experimental programmes on GO concrete.

3.17 Wang et al. (2023)

Wang and co-workers studied the mechanical and fatigue behaviour of GO concrete subjected to sulfate corrosion, combining two damage mechanisms that act together in many real structures. GO was added at 0.02–0.08% of cement mass, and specimens were exposed to up to 120 wetting–drying cycles in a 10% sodium sulfate solution before static and fatigue testing at different stress levels. After 120 cycles, GO concrete lost about 3.1–4.0% of its mass compared with 4.8% for plain concrete, and the largest strength improvement occurred at 0.05% GO. Fatigue life decreased with higher stress levels and longer sulfate exposure, and was modelled using Weibull distributions. SEM showed that GO densified the microstructure, while excessive dosage caused agglomeration and additional pores, again confirming the existence of an optimum dosage.

3.18 Esmaeili et al. (2023)

Esmaeili and co-workers investigated ultra-high-performance concrete (UHPC) modified with economical graphene oxide nanosheets, addressing the high cost that limits GO use in practice. Different GO contents were incorporated, and mechanical properties, elastic modulus, durability indicators and microstructure were evaluated. The results showed that a suitable amount of low-cost GO improved strength, stiffness and durability-related properties of UHPC and produced a denser microstructure. Since UHPC already has a very compact matrix, these improvements show that GO can still contribute to further refinement of high-performance systems. The use of economical GO gives the study practical relevance, suggesting that cost-effective production routes for GO could make nano-modified high-performance concretes more attractive for demanding applications such as bridges and thin structural elements.

3.19 Qian et al. (2023)

Qian and co-workers investigated the degradation of mechanical properties of GO concrete under sulfate attack and freeze–thaw cycles, two common causes of deterioration in cold regions and sulfate-bearing soils. GO-modified and plain concrete specimens were exposed to these environments and their strength and damage development were monitored over the exposure period. The results indicated that an appropriate GO content slowed the loss of mechanical properties compared with plain concrete, which was attributed to a more compact pore structure that limits the penetration of sulfate solution and the internal stresses caused by freezing water. This research is significant because it extends GO studies from short-term strength to performance under realistic environmental actions, which is essential for estimating the service life of GO concrete structures.

3.20 Fonseka et al. (2023)

Fonseka and co-workers studied the influence of graphene oxide on the abrasion resistance and strength of concrete, a property of particular importance for pavements, industrial floors and hydraulic structures. GO was added to concrete with suitable superplasticizer and dispersion arrangements, and abrasion resistance was measured together with mechanical properties and pore structure. The results indicated that GO improved both strength and resistance to surface wear, and the improvement was linked to a refined pore structure and a denser surface layer. The study also showed that the benefit depends on achieving good GO dispersion, since poorly dispersed GO cannot uniformly strengthen the cement matrix. This work broadened GO research to surface durability and laid the groundwork for the authors' later systematic investigation of dispersion and admixture effects.

3.21 Reddy and Prasad (2022)

Reddy and Prasad investigated the effect of graphene oxide on the microstructure and mechanical behaviour of concrete with a water–cement ratio of 0.5, using GO contents of 0, 0.025, 0.05, 0.075 and 0.1% by weight of cement. Compressive, split tensile and flexural strengths were measured at 7 and 28 days, and microstructural studies were carried out to explain the observed behaviour. The study reported that a small GO addition significantly improved the microstructure and enhanced the static mechanical properties of concrete. The authors attributed the improvement to the formation of denser and more uniform hydration products around the GO sheets. Being carried out on ordinary-strength concrete with locally available materials and Indian Standard procedures, the study is directly relevant to the practical evaluation of GO concrete in Indian conditions.

3.22 Bagheri et al. (2022)

Bagheri and co-workers carried out a thorough experimental investigation of GO-incorporated cementitious composites, evaluating a broad range of physical, mechanical and durability-related properties instead of a single strength parameter. Specimens with different GO contents were tested for strength development, water absorption and related properties, and microstructural changes were examined to explain the results. The study found that GO influenced several properties simultaneously, generally improving strength and reducing water transport at suitable dosages. By assessing many properties together, the work provided a more balanced picture of GO performance, showing that improvements in one property should be checked against possible changes in others such as workability. This multi-property approach is particularly useful for designing comprehensive testing programmes for GO-modified concrete.

3.23 Suo et al. (2022)

Suo and co-workers reviewed graphene oxide/cement composites with a focus on performance, functionality, mechanisms and future prospects. The review summarised how well-dispersed GO can modify hydration, refine pore structure and improve mechanical and durability properties, and it also discussed functional properties such as electrical conductivity and self-sensing that may be enabled by GO-based materials. Proposed reinforcing mechanisms, including the template effect, nucleation effect and crack-bridging, were critically discussed. The authors identified long-term behaviour, the stability of GO dispersion in the highly alkaline cement environment and practical implementation as major unresolved issues. This review is valuable because it organises a rapidly growing literature into clear mechanisms and points researchers toward the questions that must be answered before large-scale application.

3.24 Chougan et al. (2021)

Chougan and co-workers studied an extra-low GO dosage of only 0.01% by weight of cement in a commercial premixed mortar, using a nano- to macroscale approach to link GO characteristics with mortar performance. The GO was characterised in detail by XPS, FTIR, AFM, XRD and Raman spectroscopy, and was ultrasonically dispersed in the mixing water before use. Fresh properties, density, strength and permeability indicators, including surface absorption, permeable voids and chloride penetration, were evaluated. At 28 days, the GO mortar showed about 29% higher compressive strength, 13% higher flexural strength and lower permeability than the control. The authors linked the reduced permeability to refinement of the pore network. The study is important because it demonstrates measurable benefits at a very low and therefore more economical GO content.

3.25 Wang et al. (2021)

Wang and co-workers reviewed research progress on the effect of graphene oxide on the properties of cement-based composites, with emphasis on the interaction between GO surface chemistry, cement hydration and microstructure. The review described how the oxygen-containing functional groups of GO interact with calcium ions and water, influencing nucleation and the growth of hydration products. It examined the effects of GO on workability, setting, mechanical properties and durability, and compared the different dispersion approaches reported in the literature. The authors concluded that the performance of GO-modified cementitious materials depends on several interconnected parameters, such as GO size, oxidation degree, dosage, dispersion and mix composition, rather than on GO content alone. This conclusion has guided later research toward more controlled and systematic experimental designs.

3.26 Naresh Kumar et al. (2021)

Naresh Kumar and co-workers reviewed the influence of graphene oxide on the strength properties of cementitious materials, compiling results on compressive, flexural and tensile strength from a range of experimental studies. The reviewed literature generally reported strength improvements at low GO contents, with the greatest relative gains often observed in flexural and tensile strength, which are the most important weaknesses of plain concrete. At higher contents, however, agglomeration of GO sheets reduced the effectiveness of the additive and could even lower strength. The review emphasised the need for further investigation of the relationship between GO dosage, dispersion and strength development. It provided a concise reference for selecting starting dosage ranges in experimental studies and highlighted the gap between paste-level and concrete-level investigations.

3.27 Liu et al. (2021)

Liu and co-workers investigated the effect of graphene oxide on the mechanical properties, impermeability and corrosion resistance of cement mortar containing mineral admixtures, reflecting the composition of modern blended-cement concretes. Mortars combining GO with mineral admixtures were tested for strength, resistance to water penetration and protection of embedded steel against corrosion. The study also examined ultrasonic dispersion conditions, showing that the dispersion procedure strongly affects the final performance. The results indicated that GO, when properly dispersed, can improve both mechanical properties and impermeability in blended systems, which in turn supports better corrosion protection of reinforcement. This work is important because it demonstrates that GO can work together with supplementary cementitious materials, which are now widely used to reduce the carbon footprint of concrete.

3.28 Chu et al. (2020)

Chu and co-workers investigated GO as a remedy for the reduced performance of ultra-high-performance concrete prepared with recycled sand instead of natural river sand. GO was incorporated into the recycled-sand UHPC, and porosity, compressive, flexural and splitting tensile strength, elastic modulus and durability against chloride penetration and freeze-thaw cycles were evaluated. GO reduced porosity by about 4.5–11.4% and increased compressive strength by about 8–17%, flexural strength by about 11–27% and splitting tensile strength by about 16–30%. Chloride resistance and freeze-thaw resistance also improved, and an optimum dosage of 0.05% was identified. The study is significant for sustainable construction because it shows that GO can help recycled materials reach performance levels suitable for demanding applications, supporting resource conservation.

3.29 Wu et al. (2020)

Wu and co-workers examined GO nanosheets in ultra-high-performance concrete containing a high volume of supplementary cementitious materials, including silica fume, fly ash and slag, with a water–binder ratio of only 0.16. GO was added at up to 0.05% by weight of cement, and workability and strength were measured under both standard and steam curing. Slump flow decreased by up to about 16% as GO content increased. Under standard curing, the optimum of 0.02% GO raised 28-day compressive strength to about 122 MPa, a gain of roughly 29%, and flexural strength by about 25%. Under steam curing, the optimum shifted to 0.04% GO. Higher dosages reduced strength because of poor dispersion, showing that the optimum GO content depends on the curing regime as well as on the mix.

3.30 Wang, Yang and Ouyang (2019)

Wang, Yang and Ouyang studied the effect of GO dosage, GO sheet size and water–binder ratio on the mechanical properties of cement mortar and investigated the underlying strengthening mechanism. GO in three size ranges, from 0.5 μm to over 50 μm , was added at 0.01–0.05% of cement weight with water–binder ratios of 0.2 to 0.4. At the optimum of 0.03%, the 28-day compressive, flexural and tensile strengths increased by about 21%, 40% and 54%, respectively. Larger GO sheets and lower water–binder ratios gave greater improvements. Interestingly, thermogravimetric and porosity measurements showed little change in hydration, leading the authors to conclude that GO mainly strengthens mortar by acting as a barrier that hinders microcrack propagation rather than by accelerating hydration, which added an important perspective to the debate on GO mechanisms.

3.31 Wu et al. (2019)

Wu and co-workers investigated the physical and mechanical properties of normal concrete containing GO nanosheets at 0.02–0.08% by weight of cement with a water–cement ratio of 0.5. Slump and compressive, flexural and split tensile strengths were measured at 7, 14 and 28 days. Slump decreased steadily as GO content increased, confirming the adverse effect of GO on workability. At 28 days, compressive strength increased by about 13–34% over the control across the dosage range, while flexural strength improved by about 3–16%. Split tensile strength reached its maximum at 0.03% GO, about 25% higher than the control. This study was one of the early investigations to move GO research from paste and mortar to full concrete with coarse aggregates, demonstrating that the benefits of GO persist at the concrete scale.

3.32 Xu et al. (2018)

Xu and co-workers presented a holistic review of cement composites reinforced with graphene oxide, bringing together evidence on GO synthesis, dispersion, hydration effects, mechanical performance and durability. The review highlighted the relationship between GO addition, microstructural modification and macroscopic properties, and discussed the reasons for the wide variation in reported optimum dosages. Dispersion and dosage were identified as the critical factors controlling GO effectiveness, and the interaction of GO with calcium ions in the pore solution was noted as a cause of agglomeration. The review also considered transport properties and potential durability benefits. This period marked a transition from isolated laboratory observations toward a more organised GO research field, and the review served as an important reference for subsequent experimental studies on GO concrete.

3.33 Li et al. (2018)

Li and co-workers investigated the actual dispersion state of GO in cement paste using X-ray computed tomography and X-ray photoelectron spectroscopy, together with measurements of electrical resistivity and flexural strength. The study revealed that GO nanosheets largely

existed as agglomerated, platelet-like phases within the hardened paste rather than as uniformly distributed individual sheets. These agglomerates affected both electrical and mechanical behaviour, explaining why the expected reinforcing effect was not always achieved. This finding challenged the common assumption that GO added to the mixing water is automatically well dispersed in cement, since calcium ions in the pore solution can cause the sheets to cluster. The study established dispersion quality as a major experimental variable and stimulated subsequent research on admixtures and dispersion techniques.

3.34 Lu and Ouyang (2017)

Lu and Ouyang investigated GO nanosheets in both cement mortar and ultra-high-strength concrete (UHSC), helping to bridge the gap between paste-level research and concrete applications. In UHSC, GO contents between 0 and 0.03% were examined, and 0.01% GO produced a reported increase of about 7.8% in 28-day compressive strength. Flexural strength and deformation capacity were also improved, indicating better resistance to cracking. However, the fluidity of the mixtures decreased as GO content increased, which demonstrates the practical trade-off between mechanical gains and workability. The study showed that GO can still provide improvement in very dense, high-strength matrices, and highlighted the need to balance GO dosage with superplasticizer content to maintain workable mixes in practical concrete production.

3.35 Li et al. (2017)

Li and co-workers studied the effect of GO on the early-age hydration, electrical resistivity and strength development of Portland cement paste. Hydration was monitored during the first days of curing, and electrical resistivity was used as a non-destructive indicator of microstructural densification. The results indicated that an appropriate GO content accelerated early hydration and produced a denser internal structure, reflected in higher resistivity and strength. However, the benefit did not increase indefinitely with GO content, because excessive addition led to agglomeration and reduced effectiveness. This study strengthened the argument that the optimum GO dosage must be determined experimentally for each cement system, and it demonstrated the usefulness of electrical resistivity as a simple tool for tracking the development of GO-modified cementitious materials.

3.36 Lin, Wei and Hu (2016)

Lin, Wei and Hu investigated the catalytic behaviour of graphene oxide during the cement hydration process using characterisation techniques such as XRD and FTIR. The study focused on the role of the oxygen-containing functional groups on GO, including hydroxyl, epoxy and carboxyl groups, and their interaction with water and cement phases. The results indicated that these groups can promote the dissolution of cement components and act as active sites for the formation of hydration products, effectively catalysing hydration. The contribution of this research was mainly mechanistic: rather than simply reporting percentage improvements in strength, it attempted to explain why GO alters the cement matrix. This understanding of GO surface chemistry has since informed studies on GO oxidation degree, functionalisation and compatibility with chemical admixtures.

3.37 Mohammed et al. (2015)

Mohammed and co-workers examined the effect of incorporating graphene oxide on the transport properties of cement composites, which govern durability more directly than strength. Cement composites with and without GO were tested for properties related to the movement of water and aggressive ions, such as chloride penetration and water sorptivity. The results indicated that GO refined the pore structure and made the transport paths more

tortuous, thereby reducing the penetration of water and chloride ions into the matrix. This was one of the early studies to show that GO could improve the durability-related performance of cementitious materials, not only their mechanical properties. It therefore opened an important line of research on GO for protecting reinforced concrete against chloride-induced corrosion and other transport-controlled deterioration mechanisms.

3.38 Pan et al. (2015)

Pan and co-workers investigated the mechanical properties and microstructure of ordinary Portland cement paste modified with graphene oxide used as a nano-scale reinforcement. A small amount of GO, about 0.05% by weight of cement, significantly improved the mechanical performance, with reported increases of approximately 15–33% in compressive strength and 41–59% in flexural strength under the investigated conditions. The improvement was associated with the ability of GO to influence cement hydration and to refine the internal microstructure. Microscopic observations showed a denser cement matrix and more tortuous crack paths, which made crack propagation more difficult. The study demonstrated that GO can act not only as a filler but as an active nano-reinforcing material in cement composites, and it became one of the most widely cited references in the field.

3.39 Fakhim Babak et al. (2014)

Fakhim Babak and co-workers prepared GO–cement nanocomposites using a polycarboxylate superplasticizer to assist the dispersion of GO in the mixing water. GO contents ranging from 0.1% to 2% by weight of cement were investigated, which is considerably higher than the dosages used in most later studies. The tensile strength of the composites increased with GO content up to the optimum investigated, with an improvement of about 48% at 1.5% GO. FE-SEM observations showed good bonding between the GO sheets and the surrounding cement matrix, while XRD indicated increased formation of C–S–H. The main significance of this study is that it demonstrated the importance of combining GO addition with an appropriate admixture system, an idea that has remained central to the practical production of GO-modified cementitious materials.

3.40 Lv et al. (2013)

Lv and co-workers carried out one of the pioneering studies on graphene oxide nanosheets in cement composites, focusing on microstructure and mechanical behaviour. GO was prepared by chemical oxidation of graphite followed by ultrasonic dispersion, and was incorporated into cement composites at small dosages. The study reported that a GO content of about 0.03% produced large increases in tensile, flexural and compressive strength. Microscopic examination showed that GO regulated the formation of hydration crystals, producing flower-like and polyhedral crystal structures, and the authors proposed a template effect of GO in controlling hydration-crystal morphology. This study was important because it moved graphene research toward cement-based materials and demonstrated a direct relationship between nanoscale GO addition and the internal structure of cement composites, laying the foundation for later research.

4. CONCLUSION

After studying the above review, we concluded that graphene oxide has developed from an emerging nano-scale additive for cement paste into a broad research area covering mortar, concrete, durability, targeted ITZ modification, impact performance, cement-reduced mixtures and low-clinker cement systems. Early studies established that small, controlled amounts of

GO (generally in the range of about 0.01–0.10% by weight of cement) can accelerate hydration, refine the pore structure and improve compressive, tensile and flexural strength. Later studies showed that GO dosage, dispersion technique, superplasticizer compatibility, curing conditions and concrete composition strongly affect the final performance.

We also concluded that recent research has increasingly addressed durability, sustainable concrete and practical dispersion, while also exposing limitations: excessive GO reduces workability, agglomerated GO loses its benefit, and long-term field data, cost and large-scale quality control are still limited. The literature does not support one fixed GO content or one universal mixing procedure for every concrete. Therefore, controlled experimental validation under a specific concrete mix is required, and this provides the basis for the present project to evaluate concrete modified only with graphene oxide using a clearly defined control mix, selected GO dosages and a consistent testing programme, with conclusions drawn from measured performance.

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