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A review of Research on the Modification of Mechanical Properties and Durability of Cement-based Materials by Graphene Oxide

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ABSTRACT
Graphene oxide (GO) can significantly improve the mechanical and durability properties of cement-based materials due to its high specific surface area, rich oxygen-containing functional groups, and excellent mechanical properties. This article systematically reviews the modification effects of GO on compressive/flexural strength (improved by 15%~90%), as well as impermeability, chloride ion resistance, sulfate resistance, and freeze-thaw resistance. The enhancement mechanism can be attributed to the synergistic effect of nucleation, nanofilling, and interface bridging.The poor dispersibility of GO in high alkaline environments of cement is the core bottleneck, and existing dispersion strategies such as physical, chemical, and hybrid have their own advantages and disadvantages. Currently it face challenges such as complex dispersion processes, high costs, and shallow mechanisms. In the future, it is necessary to develop new dispersion technologies, deepen microscopic mechanism research, and promote multifunctional engineering applications.

KEYWORDS
Graphene oxide; Cement-based materials; Mechanical properties; Durability; Dispersibility; Microscopic mechanism

1 Introduction

As the main material of modern infrastructure, cement-based materials have been widely used in the field of civil engineering due to their mature preparation process, good plasticity, and economy. However, traditional cement-based materials have inherent defects such as high brittleness, easy cracking, low tensile strength, and insufficient durability, which have long constrained the service life and safety of engineering structures[1-2]. With the development of the construction industry towards high strength, functionality, and intelligence, the development of new high-performance cement-based composite materials has become an urgent need.

In recent years, graphene and its derivatives (graphene oxide (GO), reduced graphene oxide (rGO), graphene nanosheet (GNPs)) have been recognized as ideal nano reinforcement phases for cement-based materials due to their excellent mechanical properties (tensile strength 130 GPa, Young's modulus 1 TPa), ultra-large specific surface area (2630 m^2/g), and excellent thermal and electrical conductivity[1-2]. Research has shown that uniformly dispersed graphene can significantly improve the mechanical properties and durability of cement-based materials by regulating cement hydration reactions, optimizing pore structure, and enhancing interfacial bonding mechanisms[1-2].

However, the application of graphene in cement-based materials faces a key bottleneck - poor dispersibility.The strong van der Waals forces between graphene layers make it highly prone to agglomeration; Although GO has good dispersibility in water due to its oxygen-containing functional groups, once it comes into contact with cement pore solutions (high pH, rich in Ca^{2+}), the carboxyl groups and other functional groups on its surface will undergo cross-linking reactions with Ca^{2+}, leading to rapid aggregation and sedimentation. This not only fails to enhance the effect, but also introduces microscopic defects[1-2]. Therefore, achieving uniform and stable dispersion of graphene in cement matrix is a prerequisite for exerting its modification effect.

In response to this challenge, researchers have developed various dispersal strategies.Physical dispersion (ultrasound, ball milling, shearing) is easy to operate but difficult to maintain long-term stability; Non-covalent chemical dispersion (surfactants, polycarboxylate superplasticizers) improves dispersibility through electrostatic repulsion and steric hindrance; Covalent chemical dispersion (grafting polymers onto GO surfaces) can fundamentally improve dispersibility and compensate for fluidity loss; In addition, new methods such as hybrid dispersion, coating dispersion, and in-situ growth have also demonstrated promising application prospects[1-2].

Numerous studies have shown that the moderate addition of uniformly dispersed graphene can significantly improve the compressive strength (15%~77%) and flexural strength (20%~90%) of cement-based materials, while also improving durability properties such as resistance to chloride ion penetration, carbonation, and freeze-thaw resistance[1-2]. The enhancement mechanism can be summarized as: providing nucleation sites to promote the regular growth of hydration products, filling nanopores to refine pore size, deflecting/bridging microcracks, and forming chemical bonds between surface functional groups and Ca^{2+} to construct a three-dimensional network structure[1-2].

Despite fruitful achievements, graphene cement-based composite materials still face problems such as complex dispersion processes, high costs, insufficient mechanism research, and lack of engineering standards[1-2]. Based on the

above two reviews, this article discusses the dispersion methods, mechanical and durability modification effects of graphene and its derivatives in cement-based materials, and elucidates their mechanisms of action at the micro and nano scales. Finally, the engineering application prospects in this field are discussed.

2 Overview of Graphene Materials

Graphene is a two-dimensional nanomaterial with a single atomic layer thickness formed by sp^2 hybridization of carbon atoms. The carbon atoms are arranged in a honeycomb hexagonal lattice [3-5]. Since the first independent monolayer graphene was obtained through mechanical exfoliation in 2004, its outstanding mechanical, electrical, and thermal properties have sparked widespread research and industrial interest [3-4].

Single layer graphene has extremely high Young's modulus (about 1 TPa) and tensile strength (about 130 GPa), making it one of the strongest materials currently known [5]. The theoretical specific surface area is approximately 2630 m^2/g [3,5]. Meanwhile, the absorption rate of visible light by single-layer graphene is only 2.3%, almost transparent [4]. These characteristics make graphene an ideal mechanical reinforcement filler for various composite materials.

However, the preparation cost of pure single-layer graphene is high, and its derivatives are more commonly used in practical engineering applications. According to the naming conventions recommended by the international academic community (Bianco et al.), graphene materials are classified based on the number of layers, carbon to oxygen ratio, and lateral dimensions [3,5]. The main categories include:

Graphene nanosheets (GNPs): Composed of multiple layers of graphene (usually greater than 10 layers) stacked together, with a thickness ranging from 0.34 to 100 nm, and lateral dimensions ranging from submicron to tens of micrometers [3,5]. GNPs have lower production costs and are currently the graphene product with the highest market share (about 52%).

Graphene oxide (GO): It is produced by oxidizing graphite with a strong oxidant and then peeling it off, and its surface contains oxygen-containing functional groups such as hydroxyl, carboxyl, and epoxy groups [4-5]. GO has good water dispersibility and solution processability, but its mechanical properties decrease due to an increase in sp ^ 3 hybridization defects (Young's modulus of about 200-250 GPa), and it exhibits electrical insulation [4-5].

Reduced graphene oxide (rGO): GO is reduced by chemical, thermal, or electrochemical methods, partially restoring the sp ^ 2 conjugated network. The carbon oxygen ratio can be increased to 10:1 or above, and its conductivity and mechanical properties are superior to GO, but some structural defects still remain [4-5].

The dispersion uniformity of graphene in the matrix is the key factor determining the modification effect.GO is easily dispersed due to its good hydrophilicity;GNPs and pristine graphene are prone to aggregation and often require surface functionalization or dispersants [4-5].

In terms of mechanical property modification, graphene and its derivatives mainly enhance matrix materials through the following mechanisms [4-5]:

Filling effect: Nanoflakes fill the micro and nano pores in the matrix, improving compactness;

Crack deflection and bridging: Two dimensional layers span the crack surface, hindering crack propagation and dissipating fracture energy;

Interface bonding: The oxygen-containing functional groups on the GO surface form hydrogen bonds or covalent bonds with the polar matrix, enhancing stress transfer efficiency.

In summary, graphene and its derivatives provide a new approach for improving the performance of cement-based materials due to their unique two-dimensional structure, high specific surface area, and excellent mechanical properties.

3 Modification Effect of Graphene Oxide on Compressive and Flexural Strength of Cement-based Materials

Graphene oxide (GO) has been widely used to enhance the mechanical properties of cement-based materials due to its extremely high specific surface area, abundant oxygen-containing functional groups, and excellent mechanical properties.Research has shown that the moderate addition of GO can significantly improve the compressive strength and flexural strength of cement-based materials, but its enhancement effect is influenced by multiple factors such as GO dosage, size, dispersibility, blending strategy, and curing conditions.

3.1 Improvement Effect of Compressive Strength

Fonseka et al. systematically studied the effect of GO combined with fly ash (FA) on the compressive strength of concrete [6]. The results indicate that the addition of 0.12% GO (based on the mass of cementitious material) alone can

increase the compressive strength of concrete by 33% after 28 days. When using 30% FA instead of cement and combining 0.12% GO, the compressive strength at 28 days increased by 6% compared to ordinary concrete, while the control group with only FA decreased by 13%, indicating that GO effectively compensated for the strength loss caused by FA.Lu et al. used GO pre saturation or pre-coated sand method, and only 0.03%~0.05% GO (by cement mass) can increase the compressive strength by 32%~40% after 28 days, which is significantly better than the effect of directly adding GO (0.05% GO directly added only increases by 11%), highlighting the advantages of targeted reinforcement of the interface transition zone (ITZ) [7]. Yang et al. added 0.03% GO to cement mortar, and after 180 days of sulfate attack, the compressive strength increased by 26.65% compared to ordinary mortar, and the corrosion coefficient improved by 12.34%, confirming that GO not only enhances strength, but also improves the durability against erosion [8]. Han et al. found through regulating the oxygen-containing functional group density of reduced graphene oxide (rGO) that when the rGO content was 0.4%, the moderate reduction degree of rGO (reduced by 5 times the reducing agent for 6 hours) increased the compressive strength of cement mortar by about 12.4% after 28 days compared to ordinary mortar, and the pressure sensitivity and compactness were synchronously enhanced [9]. Fan et al. combined GO with multi walled carbon nanotubes (MWCNTs) and found that the synergistic effect of 0.05% GO and 0.125% MWCNTs resulted in a 103.38% increase in 28 day compressive strength compared to the GO doped group, demonstrating a significant "positive mixing effect" [10].

3.2 Improvement Effect of Flexural Strength

In terms of flexural strength, GO also exhibits excellent reinforcement effect. Fonseka et al. reported that 0.12% GO increased the flexural strength of concrete by 25% after 28 days, while still maintaining a 3% increase when compounded with 30% FA [6]. Lu et al. improved the 28 day flexural strength by about 30% with only 0.05% GO pre-coated sand, and the flowability loss was only 6.8%, proving that this method achieves efficient enhancement while ensuring workability [7]. Fan et al.'s research is more prominent: after compounding 0.05% GO with 0.125% MWCNTs, the 28 day flexural strength reached 10.13 MPa, an increase of 34.70% compared to the single doped MWCNTs group [10]. Molecular dynamics simulations show that the GO layer enhances the interlayer shear stress between CNTs and C-S-H matrix, improving the load transfer efficiency at the interface.Yang et al. found that the flexural strength of 0.03% GO modified mortar increased by 47.89% compared to ordinary mortar after 180 days in a sulfate attack environment, indicating that GO has a particularly significant improvement on long-term flexural performance [8].

3.3 Analysis of Influencing Factors

3.3.1 GO Dosage and Dispersibility

Most studies suggest that the optimal dosage of GO is between 0.01% and 0.05%. Fonseka et al. achieved significant enhancement using 0.12% GO, while Yang et al. pointed out that 0.03% GO had the best overall effect, and after exceeding 0.05%, the strength decreased due to aggregation [6, 8]. Han et al. found that a high density of oxygen-containing functional groups in rGO can weaken conductivity and interface bonding, while a low density can lead to aggregation, indicating an optimal degree of reduction [9].

3.3.2 GO Size and Functional Groups

Yang et al. found that GO with moderate size (average diameter of about 1.2 μ m) has a better effect on improving the flexural strength of mortar than GO with too large or too small size [8].Lu et al. used GO coating on the surface of sand, effectively avoiding the agglomeration of GO in cement pore solution, allowing GO to directly act on ITZ, greatly improving the reinforcement efficiency [7].

3.3.3 Collaborative Blending Strategy

The combination of GO and FA can compensate for the low early strength of FA by promoting the secondary hydration reaction of FA and achieving later strength rebound [6]. The combination of GO and MWCNTs can form a three-dimensional network structure, significantly improving the flexural strength [10]. In addition, the synergistic use of PC water reducer and GO can optimize the dispersion of GO and further enhance its mechanical properties [6].

3.3.4 Maintenance and Erosion Environment

Yang et al.'s study showed that under sulfate attack environment, the strength attenuation rate of GO modified mortar is significantly lower than that of ordinary mortar, and it still maintains high compressive and flexural strength after 180 days, indicating that GO also has a positive contribution to durability [8].

In summary, GO can significantly improve the compressive and flexural strength of cement-based materials, with the optimal dosage generally ranging from 0.03% to 0.12%. The effect can be further enhanced by adding mineral admixtures, nanomaterials, or using pre-coating strategies.Future research should further optimize the dispersion process

and compound design to achieve efficient application of GO in cement-based materials.

3.4 Impact of Graphene Oxide on the Durability of Cementitious Materials

When cement-based materials are used in marine environments, salt lake environments, and extremely cold regions, their durability often faces multiple threats such as chloride ion erosion, sulfate erosion, and freeze-thaw cycles.Graphene oxide (GO), with its nano filling effect, hydration control effect, and optimization effect on microstructure, can significantly improve the impermeability, ion erosion resistance, and frost resistance of cement-based materials, thereby effectively extending the service life of the structure [11-13].

3.4.1 Resistance to Water Penetration and Chloride Ion Penetration Performance

The addition of GO can significantly refine the pore structure of cement-based materials, reduce the proportion of harmful pores, and thus improve their resistance to water and chloride ion penetration. Zhan Genrui found through the water infiltration height method and RCM method that after adding 0.06% GO (based on the mass of the cementitious material), the water infiltration depth of marine high-performance concrete at 28 days of age decreased by 48.4%, and the chloride ion infiltration depth decreased by 50% [11]. When the GO dosage increased to 0.08%, the improvement effect slightly declined, indicating the existence of an optimal dosage (0.06%).The mercury intrusion test (MIP) further revealed that GO significantly reduced the proportion of harmful pores larger than 100 nm in concrete, while the proportion of gel pores (5-10 nm) increased, and the pore structure was significantly refined [11]. Lu Fenglei also confirmed in his research on graphene oxide reinforced cement-based gradient materials that as the thickness of the toughening layer with GO added increases, the diffusion coefficient of chloride ions gradually decreases [12]. When the thickness of the toughening layer is 16 mm and the GO content is 0.1%, the chloride ion diffusion coefficient decreases by 39.74% compared to the benchmark group, and the toughening layer plays an effective "protective layer" role. Liu Chunyan pointed out in the literature review that previous studies have shown that GO can improve the water permeability resistance, chloride ion diffusion coefficient, and chloride ion migration coefficient of cement mortar by 64%, 70%, and 31%, respectively, and significantly increase the tortuosity of erosion channels [13].

3.4.2 Resistance to Sulfate Corrosion Performance

Sulfate corrosion is one of the important causes of concrete deterioration in marine environments. Zhan Genrui [11] found through a wet-dry cycle test (5% Na_2SO_4 solution) that after 45 wet-dry cycles, the corrosion resistance coefficient of concrete specimens without GO decreased to 0.86, while the corrosion resistance coefficient of specimens with 0.06% GO remained at 0.92.The addition of GO effectively reduces the quality loss rate during the wet-dry cycle, suppresses the excessive generation of expansion products such as ettringite and gypsum, which is attributed to GO's promotion of cement hydration and refinement of pore structure, reducing the permeation channels of sulfate ions [11].

3.4.3 Frost Resistance

The improvement of frost resistance of cement-based materials by GO has been confirmed by multiple studies. The freeze-thaw cycle test (200 times) conducted by Zhan Genrui [11] showed that the quality loss rate of marine high-performance concrete with 0.06% GO added was reduced by 0.55% compared to the untreated group, and the relative dynamic elastic modulus was increased by 6.5%. Analysis suggests that GO refines the pore structure, making it difficult for water to freeze in the fine pores;On the other hand, GO suppresses the propagation of nanoscale microcracks through bridging, thereby slowing down the accumulation of freeze-thaw damage.Liu Chunyan [13] also pointed out that graphene oxide can optimize the pore structure of cement-based materials at the microscale, improve matrix density, which is the fundamental reason for its improved frost resistance.

3.4.4 Self Shrinking Characteristics

It is worth noting that while GO improves durability, it also increases the autogenous shrinkage of cement-based materials.According to the test data of Zhan Genrui [11], the larger the content of GO, the greater the autogenous shrinkage of concrete, and the impact on early (1d) autogenous shrinkage is more significant (growth rate of 10%~35%), and the growth rate drops to 1.1%~7.9% in the later stage (60d).This is mainly due to GO's promotion of cement hydration and the formation of more C - S - H gel. The absorption of water by gel pores leads to the reduction of free water, which intensifies the self drying shrinkage.

In summary, GO significantly improves the durability of cement-based materials such as impermeability, chloride ion resistance, sulfate resistance, and frost resistance through multiple mechanisms such as refining pores, optimizing interface transition zones, and bridging microcracks. However, attention should also be paid to its adverse effects on early autogenous shrinkage. Reasonable control of GO content and mineral admixtures can ensure durability while also considering volume stability [11-13].

3.5 Microscopic Mechanism and Interface Interaction of Graphene Oxide Reinforced Cementitious Materials

The improvement of mechanical properties of cement-based materials by GO is not due to changes in the types of hydration products, but is achieved through multiple micro mechanisms such as regulating the hydration process, optimizing the microstructure, and strengthening the interface transition zone[14-16]. Based on existing research, its mechanism of action can be attributed to the synergistic contributions of nucleation effect, nanofilling effect, and interface bridging effect.

3.5.1 Nucleation Effect and Hydration Regulation

GO, due to its extremely high specific surface area (up to 1500m^2/g) and abundant oxygen-containing functional groups on the surface (such as carboxyl and hydroxyl groups), can serve as an effective nucleation site for cement hydration products. Peng Yuzhe[14] found that after adding 0.02% GO (10~50 Ωμ m diameter), the content of chemically bound water in ultra-high performance concrete (UHPC) increased by 22.3%, and the content of calcium hydroxide (CH) increased by 23.3%. The results of solid-state nuclear magnetic resonance (^{29}Si NMR) showed that the degree of polymerization and average chain length of C - S - H gel significantly increased, which proved that GO effectively promoted the early and late hydration of cement. Yu Lingbo[15] also pointed out that GO induces more C-S-H generation through nucleation effect, reducing the porosity of the matrix, especially improving the pore structure in the transition zone between steel fiber and matrix interface.

3.5.2 Nano Filling and Optimization of Pore Structure

The two-dimensional layered structure of GO can effectively fill the nanoscale pores in the cement matrix and optimize the pore size distribution. Peng Yuzhe[14] found through mercury intrusion porosimetry (MIP) testing that after adding 0.02% GO, the proportion of pores below 50nm in UHPC increased from 3.16% to 25.14%, and the total porosity decreased by about 5.94% in the later stage. The connectivity of harmful pores was significantly weakened. Yu Lingbo further confirmed through multifractal analysis that GO and nanoSiO_2 can significantly reduce the proportion of harmful pores larger than 200nm in mortar, with the critical pore size decreasing from 836nm to 349nm and the pore distribution becoming more uniform[15]. Du Yuhang also observed in the GO/carbon nanotube (CNT) composite system that the optimal composite ratio (GO: CNTs=3:2) can reduce the porosity of cement paste and refine capillary pores[16].

3.5.3 Interface Transition Zone Strengthening and Bridging Toughening

The strengthening of the interface transition zone by GO is the key to improving fracture performance. Yu Lingbo found through backscattered electron imaging (BSE) and energy dispersive spectroscopy (EDS) line scanning that GO nanoSiO_2 can significantly reduce the porosity of the aggregate matrix ITZ, weaken CH enrichment, promote C-S-H generation, and increase the micro fracture toughness of ITZ by about 24.9%[15]. In the steel fiber UHPC system, GO adsorbs on the fiber surface and covalently bonds with hydration products, increasing the average interfacial bonding strength of straight steel fibers by about 28.9%. Du Yuhang[16] proposed that GO and CNTs form a nanoscale three-dimensional network structure through π - π stacking and covalent bonding, which not only bridges microcracks, but also forms O - Ca - O covalent bonds with C - S - H gel, significantly improving the load transfer efficiency. Scanning electron microscopy (SEM) also confirmed that GO/CNTs exhibit three-dimensional cross-linking distribution in cracks, playing a bridging and filling role.

In summary, the micro reinforcement mechanism of GO and its composite system on cement-based materials can be summarized as follows: nucleation effect promotes hydration, nano filling refines pores, and interface strengthening and bridging toughening synergistically enhance crack resistance. The combined effect of three aspects makes the material denser and more homogeneous at the micro level, and exhibits higher strength and fracture toughness at the macro level[14-16].

4 Conclusion

(1) Graphene oxide (GO) can significantly enhance the compressive strength (15%~77%) and flexural strength (20%~90%) of cement-based materials, with the optimal dosage generally ranging from 0.03% to 0.12%. Excessive dosage (> 0.05%) can lead to GO agglomeration and actually reduce mechanical properties. The size, density of oxygen-containing functional groups, and dispersion state of GO are key factors affecting the enhancement efficiency.

(2) The co-Cudoping of GO with fly ash (FA), nano calcium carbonate (NC), carbon nanotubes (CNTs) and other materials can produce a synergistic enhancement effect. The combination of GO and FA can compensate for the low early strength of FA and promote secondary hydration reactions; The combination of GO and CNTs can form a three-dimensional network structure, significantly improving the flexural strength (34.70% higher than the single doping

group);The strategy of GO pre-coated sand can target and enhance the interfacial transition zone (ITZ), resulting in a 32% to 40% increase in compressive strength at 28 days, with a flowability loss of only 6.8%.

(3) GO significantly improves the impermeability of cement-based materials by refining pores (reducing the proportion of harmful pores, increasing the number of harmless and less harmful pores), optimizing interface transition zones, bridging microcracks, and other multiple mechanisms (reducing water penetration depth by 48.4%), resisting chloride ion erosion (reducing chloride ion penetration depth by 50%), resisting sulfate erosion (increasing the corrosion coefficient from 0.86 to 0.92 after 45 dry-wet cycles), and improving freeze-thaw resistance (reducing mass loss rate by 0.55% after 200 freeze-thaw cycles and increasing relative dynamic elastic modulus by 6.5%). However, it is also necessary to pay attention to the adverse effects of GO on early autogenous contraction (1d growth rate of 10%~35%).

(4) The micro reinforcement mechanism of GO on cement-based materials can be summarized as three synergistic contributions: nucleation effect (promoting the generation of hydration products, increasing chemical binding water content by 22.3%, and increasing C-S-H polymerization degree), nano filling effect (refining pore size, increasing the proportion of pores below 50 nm from 3.16% to 25.14%), and interface bridging effect (forming O-Ca-O covalent bonds between GO and C-S-H, increasing interface fracture toughness by 24.9%). The three-dimensional network structure formed by π - π stacking and covalent bonding between GO and CNTs can effectively bridge microcracks and significantly improve load transfer efficiency.

(5) The current research still faces challenges such as complex dispersion processes, high costs, insufficient in-depth mechanism research, and lack of engineering standards. In the future, emphasis should be placed on developing new dispersion technologies (such as in-situ growth and power ultrasound assistance), conducting in-depth research on interfacial mechanisms at the nanoscale, promoting the engineering application of GO modified cement-based materials in marine engineering, cold regions, and intelligent structures, and achieving collaborative design of mechanical enhancement, self sensing, self-healing, and other functional characteristics.

References

[1] Kong X Q, Ban T Y, Zhang X M, et al. (2025)A review on the dispersion of graphene in cementitious composites and its mechanisms for performance enhancement[J/OL].New Carbon Materials.

[2] Liang J F, Guo J Q, Li Y, et al. (2021) Review on Mechanism of Graphene in Cement-Based Materials[J]. BULLETIN OF THE CHINESE CERAMIC SOCIETY, 40(3): 704-713.

[3] Elsayed M H, Alakbari F S, Abd El-Haleem L E, et al. (2026) Graphene materials at scale: Synthesis routes, market and techno-economic landscape, and net-zero applications[J]. (preprint/under review, 2026).

[4] Liu J, Zhao Q, Huang J, et al. (2026) Graphene and its derivatives in biopolymer-based food packaging: Structures, physical properties, applications, migration properties and safety issues[J]. (preprint/under review, 2026).

[5] Papageorgiou D G, Kinloch I A, Young R J. (2017) Mechanical properties of graphene and graphene-based nanocomposites[J]. Progress in Materials Science, 90: 75-127.

[6] Fonseka I, Mohotti D, Wijesooriya D K, et al.(2025) Evaluating the performance of cement-reduced concrete using graphene oxide: Synergistic effects on mechanical properties[J]. Results in Engineering, 25: 104742.

[7] Lu D, Qu F, Zhao H, et al.(2024) A targeted approach of using graphene oxide in cement composites[J]. Construction and Building Materials, 456: 139339.

[8] Yang J, Ye C, Wen L, et al.(2023) Study on the microscale structure and sulfate attack resistance of cement mortars containing graphene oxide nanoplatelets[J]. Journal of Building Engineering, 78: 107727.

[9] Han L, Wang X, Geng S, et al. (2025) Effect of rGO oxygen-containing functional group density on pressure sensitivity and compactness of cement composites[J]. Construction and Building Materials, 469: 140486.

[10] Fan L, Zheng J, Wang H, et al.(2025) Graphene oxide/carbon nanotubes harmonize to enhance the initial hydration products and mechanical properties of cement mortar[J]. Construction and Building Materials, 469: 140486.

[11] Zhan G R. (2021). Experimental Study on Mechanical Properties and Durability of Graphene Oxide-Based High-Performance Concrete for Offshore Applications (Master's Thesis, Foshan University of Science and Technology).

[12] Lu F L. (2021) .Research on the Performance Enhancement of Cement-Based Gradient Materials Reinforced with Graphene Oxide (Master's Thesis, Taiyuan University of Technology).

[13] Liu C Y. (2017).Research on the Properties and Applications of Graphene Oxide Cement-Based Materials (PhD Dissertation, Xi'an University of Architecture and Technology). Doctoral Degreehttps://kns.cnki.net/kcms2/article/abstract?v=OazRilB95d2paKzCpdN3thfilERaFFOdxoRmim3RTFA2HlBja6V9Nyfp7i7vparNQWHwPr9GlWwDM4PXBgy_tlqmHcaFdGM0nMKKgpAP65lfRCl90nLk5j0hwU9B_X-EeyFVtT2s74f1exPWDWb_Iez3Zla1Fu3tZZAGOVoDqGcL4hJ958iBfMr5KbtS5f_u&uniplatform=NZKPT&language=CHS.

[14] Peng Y G.(2025).Research on the Reinforcement Mechanism of Graphene Oxide in Ultra-High Performance Concrete (Master's Thesis, Three Gorges University).

[15] Yv L B. (2023). Research on the Fractural Properties and Mechanisms of Graphene Oxide-Enhanced Cement-Based Materials (PhD Dissertation, Harbin Institute of Technology).

[16] Du Y H. (2021)Study on the Co-Enhancement Effect of Graphene Oxide/Carbon Nanotubes on Cement-Based Composites and Its Mechanisms (PhD Dissertation, Shanghai Jiao Tong University).