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Performance Analysis of Concrete Materials for Dam Body Energy Storage Modified by Graphene Oxide

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This study primarily focuses on the modification of concrete materials by incorporating graphene oxide (GO). The dispersion of GO in concrete was characterized through Fourier transform infrared spectrometer (FTIR) and scanning electron microscopy (SEM), and the ability of concrete specimens with varying GO content to endure mechanical and climate temperature challenges were investigated. Additionally, the energy conversion relationship during uniaxial compressive failure was analyzed. The experimental results show that when the GO content is 0.05 %, the top stress, top strain, ultimate strain, and elasticity modulus increase by 29.54 %, 23.41 %, 61.72 %, and 34.93 %, respectively, relative to the reference concrete. With a GO content of 0.03 %, the GO/recycled cement-based composite material exhibits the greatest strength improvement after 7 days of hydration. At a 0.02 % GO content, the GO/recycled cement-based composite material exhibits the most notable strength enhancement after 28 days of hydration. Relative to conventional concrete, GO substantially boosts the key characteristics of uniaxial compression tests, notably diminishing the rate at which elastic strain energy is discharged, increasing the dissipation energy, decreasing the brittleness, and augmenting the malleability and toughness of concrete. However, efficient dispersion and cost-effective production methods for GO have not yet been achieved, and there are no long-term engineering applications of GO-modified concrete. Further research into GO-modified concrete technologies is recommended to promote the practical application and production of GO-incorporated concrete composites.

Keywords: graphene oxide, dam body, concrete.

1. INTRODUCTION

Concrete, as an inorganic material, has been extensively utilized in construction, bridges, marine engineering, and other areas due to its high mechanical strength, strong adaptability, and cost-effectiveness [1 – 5]. It has turned into a prevalent choice for building materials in the field of civil engineering. Despite the many advantages of concrete, as its service life increases and the demands for material performance in modern architectural structures rise, the drawbacks of typical concrete, like its weak tensile strength, poor transformation ability, and high susceptibility to cracking, have become more pronounced. These issues pose potential risks to structural safety, durability, and applicability, seriously limiting the use of concrete in engineering applications [6 – 12]. Moreover, during long-term use, concrete is also exposed to environmental temperature changes and corrosion from different acidic substances and gases, which imposes higher requirements on its performance. To address these challenges, researchers have long been working on improving concrete's toughness, freeze-thaw resistance, corrosion resistance, and other properties by incorporating various toughening materials such as fibers, epoxy resins, mineral admixtures, and nanomaterials.

Nanomaterials, as some of the most promising materials of the 21st century [13 – 18], are increasingly being applied in the modification of cement-based materials due to their unique attributes. These materials offer new possibilities for solving the brittleness problem in cement-based materials by improving the microstructure of the paste [19 – 22]. Among the various nanomaterials, graphene oxide (GO) has attracted widespread attention due to its unique structure and outstanding properties. GO not only has high tensile strength and elastic modulus but also possesses an extremely elevated specific surface area and a considerable aspect ratio due to its two-dimensional nanostructure. More importantly, GO contains abundant oxygen-containing functional groups, which, on one hand, lessen the van der Waals attractions among its atomic layers, making it hydrophilic and facilitating its dispersion in the matrix. On the other hand, these groups give GO excellent surface activity, making it more likely to interact with polymers, inorganic materials, and small molecules [23, 24]. Investigations into GO-modified cement-based materials reveal that GO can boost the performance of cement-based materials in combination with various components: Firstly,

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GO regulates cement's hydration process or the hydration products while also improving the microstructure of the paste; at the same time, the presence of GO helps strengthen the interfacial performance between fibers and the matrix. Therefore, the role of GO in altering both the micro and macro features of cement-based composites fully demonstrates its potential for application in cement-based composite materials [25, 26].

GO-modified cement-based materials have emerged as a novel class of composites that have attracted significant research attention in recent years. The incorporation of GO into cementitious matrices can markedly enhance the mechanical properties, durability, and impermeability of the materials, thereby meeting the increasingly stringent performance requirements of modern construction engineering. These composites have been widely applied in structural repair and reinforcement, waterproofing and corrosion protection, as well as in the remediation of environmental pollution. Recent studies on GO-modified concrete have explored various new aspects. In terms of mechanical performance enhancement, ultrasonic-assisted dispersion combined with polymer stabilizers (such as Polyvinyl Alcohol) has been used to achieve uniform dispersion of GO in cement matrices, producing a 40 % – 50 % enhancement in compressive strength and an increase of more than 60 % in flexural strength. By combining GO with carbon nanotubes or cellulose nanofibers to establish a three-dimensional network configuration, the toughness of the concrete is significantly improved. In terms of durability and corrosion resistance, GO fills nano-sized pores, reducing the chloride ion permeability (by up to 70 %) and extending the service life of concrete in marine engineering. GO-loaded corrosion inhibitors (such as molybdate) are released intelligently in alkaline environments, significantly inhibiting steel reinforcement corrosion. In terms of self-healing functionality, GO serves as a photothermal conversion carrier, heating up under near-infrared light to trigger the release of microcapsule repair agents, with a crack repair efficiency of up to 90 %. Recently, the application of GO-modified concrete has moved from laboratory studies to engineering pilot projects, such as the Shenzhen-Zhongshan Tunnel and the Dubai Solar Park. The core breakthroughs focus on the "high performance - multifunctionality – low carbon" system, and future research needs to address issues such as cost and long-term performance validation.

In this study, graphene oxide (GO) was incorporated to modify the physicochemical properties of concrete substrates and alter the microstructure of the material, thereby enhancing the physical performance of concrete as well as its resistance to freeze – thaw cycles and weathering. The goal is to provide a reliable foundation for the further development of high-performance GO-modified concrete. Currently, the application of GO in concrete is still at an early stage. Given the relatively high cost of GO, strategies for cost reduction warrant in-depth investigation. To meet the performance requirements related to strength and deformability, it is essential to fully exploit the potential of GO-based cementitious composites. Therefore, this study uses GO-modified concrete-based composite materials. By employing ultrasonic dispersion of GO, different amounts of GO are incorporated into recycled cement-based composite materials to evaluate its influence on the dispersion, strength, microstructure, and durability of the materials. The physical and chemical properties of the GO-modified concrete composite materials are examined through scanning electron microscopy (SEM), infrared spectroscopy, and material porosity analysis. Durability tests, including freeze-thaw and weathering tests, are conducted to evaluate the materials' performance. Uniaxial compression tests are performed to explore the energy dissipation patterns during the uniaxial compressive failure process of GO-modified concrete, aiming to provide references for the engineering implementation of GO-modified concrete.

2. EXPERIMENTAL

2.1. Materials

The standard sand used in the experiment complies with the technical specifications of GB/T 17671-1999. Tap water is utilized for mixing, and ordinary Portland cement (P.O. 42.5) is chosen, with its primary chemical composition detailed in Table 1. GO was acquired from Shenzhen Hongdachang Evolution Technology Co., Ltd., with its technical details provided in Table 2.

Table 1. Cement's physical attributes

Water requirement of normal consistency, %	28.5	
Specific surface area, $m^2.kg^{-1}$	386	
Density, $g.cm^{-3}$	3.13	
Setting time, min	Initial	136
	Final	224
Flexural strength, MPa	3 days	5.1
	28 days	6.3
Compression strength, MPa	3 days	25.6
	28 days	43.4

Table 2. Attributes of GO

Purity, %	Lamellar diameter, μm	Thickness, nm	Carbon, %	Oxygen, %	Sulphur, %
>95	10 – 50	～1	<50	>42	<4

2.2. Experimental equipment

The equipment used in the experiment is shown in Table 3.

Table 3. Experimental equipment

Equipment	Equipment Model
Electronic balance	JJ600K
Electric constant temperature blast drying oven	DCTG-9140A
Scanning electron microscope	Axia ChemiSEM
UV curing box	RAY-400
Laser particle size analyzer	N5
Contact angle measuring instrument	DAS100
UV-visible spectrophotometer	UV756C
Thermogravimetric analyzer	Q6000
In Situ solid phase infrared detection instrument	Thermolysis/RSFTIR

2.3. Preparation of GO/recycled cement-based composite materials

Cement mortar was prepared by mixing water, cement, sand, and GO in specific proportions. The coarse and fine aggregates used in this study, including crushed stone and natural sand, were supplied by Guangxi Kefeng Building Materials Co., Ltd. The particle size of the sand ranged from 0.3 to 2.36 mm, while the crushed stone was graded into two size ranges: 5 – 10 mm and 10 – 20 mm. The mortar had a water-to-cement ratio of 0.35, and a cement-to-sand ratio of 1:3. Table 4 displays the specific mix ratio. The preparation process followed GB/T 8077-2012 "Test Methods for Homogeneity of Concrete Admixtures." The specific preparation steps for the mortar specimens are as follows:

1. First, prepare the dispersion suspension of GO by adding a fixed amount of water, and use ultrasonic dispersion at 120 W power and 20 °C water bath for 30 minutes.
2. Then, mix the mortar paste using a JJ-5 mortar mixer, weighing the cement and sand according to the mix ratio, and adding them to the mixing bowl. Dry mix at low-speed for 2 minutes, then add water and GO dispersion liquid, mixing at low-speed for 2 minutes, and conclude with high-speed mixing for another 2 minutes. Scrape the paste from the bowl wall to the center of the mixture using a spatula.
3. Afterward, pour the mixture into a 40 mm × 40 mm × 20 mm (length × width × height) block mold and a 50 mm × 50 mm (diameter × height) cylindrical mold. Vibrate for 1 minute and then leave to set.
4. Once the specimens are formed, remove them from the molds and place them in a curing box for standard curing.

Table 4. Mix proportion

Specimen	Cement, g	Gravel, g	Sand, g	Water, g	GO, g	Superplasticizer, g
GOC-0	100	220	300	35	0	0.5
GOC-0.3	100	220	300	35	0.03	0.5
GOC-0.5	100	220	300	35	0.05	0.5

2.4. Performance testing

The curing and strength tests of the recycled cement-based composite materials were executed in accordance with GB/T 17671-1999. Freeze-thaw tests were executed in accordance with GB/T 50476-2008, and weathering tests were conducted using a ZN-P type UV aging test chamber (Shanghai Maijie Experimental Equipment Co., Ltd.).

2.4.1. Characterization of composite materials performance

The infrared spectrum of GO was analyzed to identify the corresponding oxygen-containing functional groups. The tests were conducted using an AVATAR 360 Fourier Transform Infrared Spectrometer (FTIR) (Thermo Fisher Scientific), with a spectral range from 4000 to 400 cm^{-1}. The resolution is better than 12.5 px^{-1} and the wave number accuracy is better than 0.25 px^{-1}.

The hydration products' morphology was examined through SEM. The SEM instrument (QUANTA250, FEI Co.) had an energy dispersive spectroscopy (EDS) system installed. Prior to testing, samples were selected for their flat surfaces and appropriate size, gold-coated using a vacuum sputtering device to improve conductivity and ensure better imaging quality.

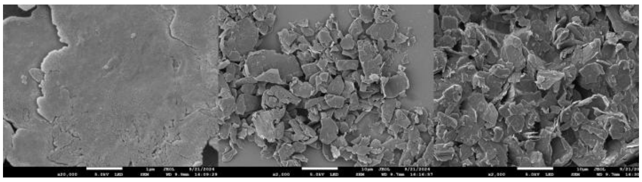
2.4.2 Uniaxial compression test

The uniaxial compression test followed the provisions of GB/T 50081-2019 "Test Methods for Physical and Mechanical Properties of Concrete" [18]. The experiment utilized a WAW-2000D electro-hydraulic servo universal testing machine with a loading speed of 0.01 mm/s. The DTS-530 high-speed static data acquisition system was used for automatic data collection during the test.

3. RESULTS AND ANALYSIS

3.1. SEM characterization

Fig. 1 a shows the microstructure of hardened ordinary concrete, which contains numerous dense, needle-like ettringite crystals and $Ca(OH)_2$ formation. It is also evident that the cracks and pore distribution in the ordinary cement paste are quite prominent. When an appropriate proportion of GO is added, the XRD diffraction peaks around 18° and 37°, corresponding to portlandite and ettringite respectively, are significantly enhanced. This indicates that the incorporation of GO accelerates the hydration process of cement mortar and promotes the formation of well-defined crystalline structures [32]. Fig. 1 b illustrates that adding 0.03 % GO leads to a reduction and shrinkage of cracks and pores in the cement paste. Additionally, because the amount of GO is relatively low and its distribution is uniform, there are no significant signs of aggregation or particle formation, and the structure shows a large number of stacked plate-like structures. As depicted in Fig. 1 c, when the GO content hits 0.05 %, there is a reduction in harmful pores, leading to a more compact texture. This also indicates that at higher GO content, agglomeration occurs due to the excessive amount of GO in the cement paste. Furthermore, the number of crystalline compounds increases as the GO content increases.



a b c

Fig. 1. SEM images of GO-modified concrete: a – GOC-0; b – GOC-0.03; c – GOC-0.05

3.2. Infrared spectra of GO-modified concrete materials

Fig. 2 presents the infrared spectra of cement-based grout materials modified with GO. From Fig. 2, it can be seen that all samples exhibit an O-H stretching vibration peak at 3642 cm^{-1}, indicating the existence of $Ca(OH)_2$. The diffraction peak intensity of the grout material without GO is the weakest. The inclusion of GO leads to a notable increase in the intensity of the modified cement-based grout material, with sharper peaks, suggesting that GO enhances CH production. From Fig. 2, it can also be observed that all samples show a diffraction peak at 1639 cm^{-1}, which is the absorption peak of chemically bound water (H–O–H). The diffraction peak intensity of the grout material without GO is again the weakest. After the addition of GO, a diffraction peak appears at 2350 cm^{-1} in the modified cement-based grout, which corresponds to the asymmetric stretching vibration peak of CO_3^{2-}. This is because GO has a large specific surface area and adsorbs more H–O–H in the cement-based grout. Additionally, a stretching vibration peak of Si-O bonds in calcium silicate hydrate (C–S–H) gel appears at 1088 cm^{-1}, and carbonate absorption peaks in the cement-based grout are observed in the range of 1381 – 1491 cm^{-1}, indicating that partial carbonation has occurred in the grout material.

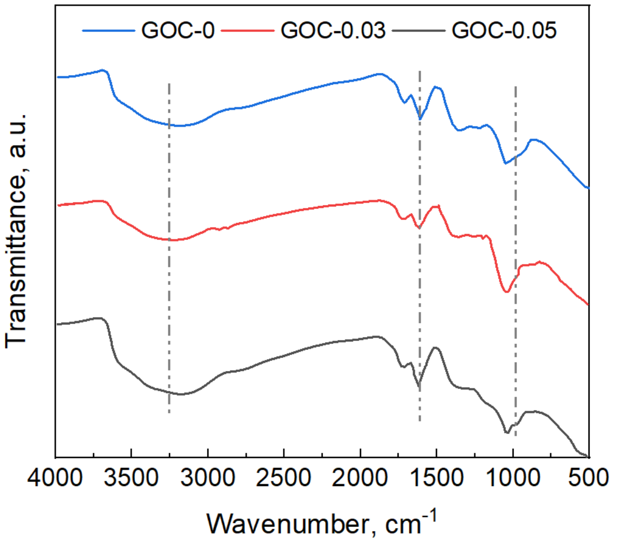


Fig. 2. Infrared spectra of GO-modified concrete materials

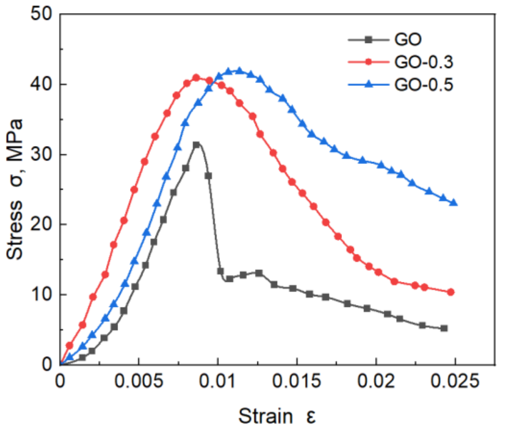
3.3. Uniaxial compression test

The uniaxial compressive strength-strain curves and energy curves are shown in Fig. 3. As shown in Table 5, the peak stress, peak strain, ultimate strain, and elastic modulus of the GO-modified concrete specimens are all greater than those of the reference concrete.

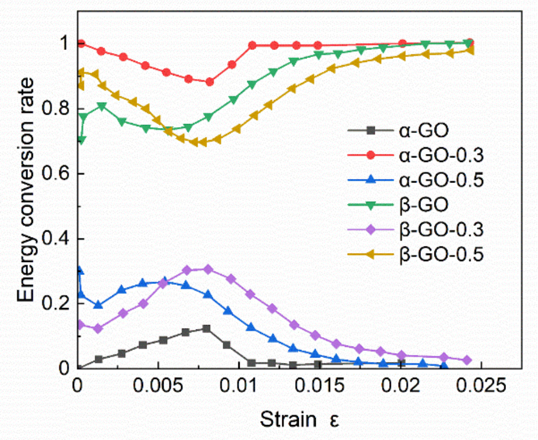
Table 5. Characteristic parameters of uniaxial compression test

Sample	Peak stress, MPa	Peak strain	Ultimate strain	Elastic modulus, MPa	Brittleness index	Ductility index
GOC-0	33.5	0.00896	0.00920	28523	0.732	0.521
GOC-0.3	41.8	0.00087	0.01224	36145	0.635	0.682
GOC-0.5	42.5	0.01205	0.01523	38432	0.723	0.621

When the GO content is 0.05 %, the peak stress, peak strain, ultimate strain, and elastic modulus are improved by 29.54 %, 23.41 %, 61.72 %, and 34.93 %, respectively, relative to the reference concrete. This implies that GO markedly enhances the strength of the concrete, improving the stiffness of the concrete matrix. This improvement is mainly due to two factors: firstly, GO smooths the surface of the concrete, promoting cement hydration reactions and reducing the number and size of internal pores; secondly, GO promotes the formation of a large number of sheet-like crystals, which significantly reduces the free hydration products in the concrete, thereby increasing the overall density of the concrete and the adhesion between the coarse aggregate and the cement matrix.



a



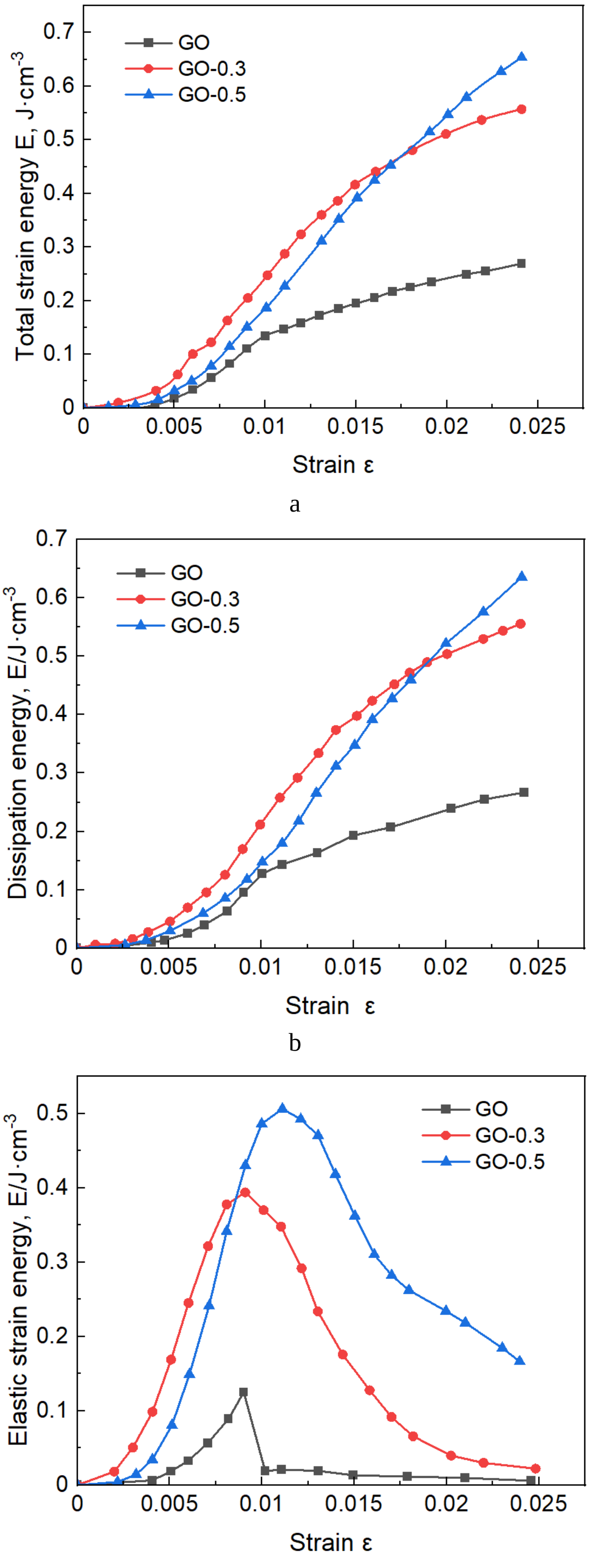
b

Fig. 3. Performance curves of GO-modified concrete: a – uniaxial stress-strain curve; b – energy transformation curve

The brittleness index and ductility index calculated for each specimen in Table 5 show that as GO levels go up, the brittleness index of the concrete significantly decreases, and the ductility index increases. When the GO content reaches 0.05 %, the brittleness index decreases by 7.02 % and the ductility index increases by 6.56 % compared to the reference concrete. In comparison with the GO-modified concrete, the reference concrete exhibits more pronounced brittle failure. This indicates that GO effectively reduces the brittleness of concrete during compression failure, increasing its ductile failure characteristics.

The energy transformation rate during uniaxial compression of GO-modified concrete is shown in Fig. 3 b. As can be seen from Fig. 3 b, the addition of GO to the concrete effectively reduces the elastic strain energy transformation rate, increasing the dissipation energy transformation rate.

Fig. 4 illustrates the variations in total strain energy, dissipation energy, and elastic strain energy during the uniaxial compression failure of GO-modified concrete. Fig. 4 a and b reveal that the total strain energy and dissipation energy are elevated in GO-modified concrete relative to the reference concrete. This suggests that GO significantly increases both the total strain energy and dissipation energy of the concrete.



a

b

c

Fig. 4. Energy variation curves of GO-modified concrete: a – dissipation energy; b – elastic strain energy; c – changes during uniaxial compression failure of concrete

As observed in Fig. 4 c, before the elastic strain energy peaks, GO's impact on elastic strain energy during concrete compression failure aligns with the trend of total strain energy and dissipation.After the peak of elastic strain energy, the reference concrete experiences a sharp decline in elastic strain energy, while the GO-modified concrete shows a more gradual decrease, enhancing the concrete's toughness and its ductile failure characteristics.

Fig. 5 illustrates the variation in flexural strength of GO/recycled cement-based composites at curing ages of 7 and 28 days. It can be observed that the presence of GO led to varying degrees of strength improvement at both curing ages. At 7 days, the flexural strength of GO-modified concrete exhibited a linear increase as the GO content rose from 0.03 % to 0.05 %, with the maximum strength achieved at a GO content of 0.05 %, representing a 16 % increase. At 28 days, a significant improvement in flexural strength was observed when the GO content was 0.03 %. However, as the GO dosage increased from 0.03% to 0.05 %, a slight decrease in flexural strength was noted. Dong Jianmiao et al. [37] employed molecular dynamics simulation to construct a molecular model of graphene oxide and further optimized the GO/calcium hydroxide (GO/CH) interfacial structure. Their simulation revealed a nucleation effect of GO during the hydration process. Experimental results indicated that graphene oxide effectively reduces internal porosity within cement-based materials and enhances their mechanical performance.

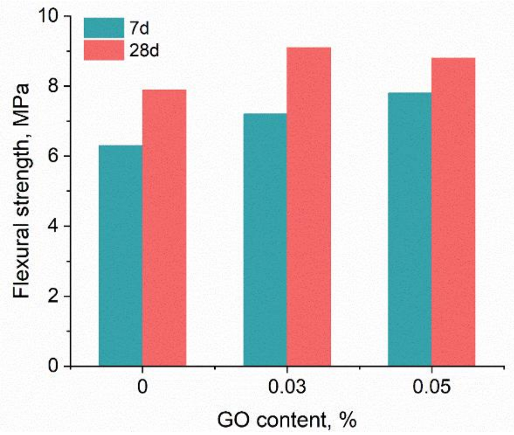


Fig. 5. Flexural strength results

3.4. Pore size distribution

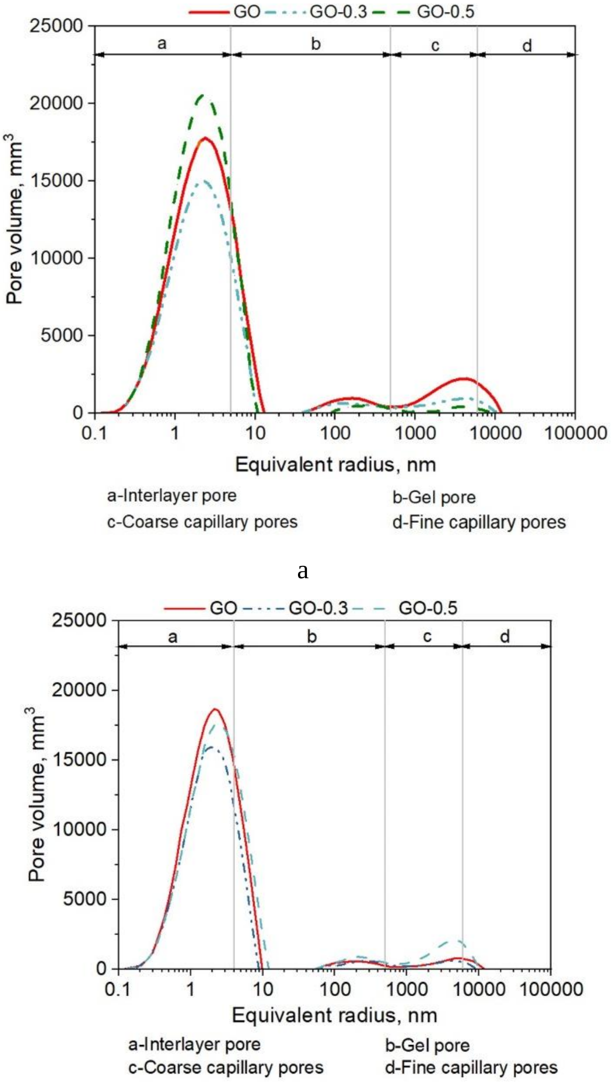
According to diffusion theory, assuming the pores are cylindrical and ignoring edge effects, the relationship between transverse relaxation time *T* and equivalent radius *r* is given by Eq. 1:

$$r = 2\rho_2 T_2, \tag{1}$$

where *r* is the equivalent pore radius, in nm; ρ_2 is the transverse relaxation coefficient; *T* is the transverse relaxation time, in seconds.

The transverse relaxation time *T* is proportional to the equivalent radius *r*. The transverse relaxation coefficient ρ_2 for white cement mortar is taken as 1.69 nm/ms. Using the equivalent radius as a grading parameter for different types of pores, the pores are classified into four levels: inter-layer pores ($r \leq 5$ nm); gel pores ($5 < r \leq 500$ nm); fine capillary pores ($500 < r \leq 5000$ nm); coarse capillary pores ($r > 5000$ nm).

The pores in the mortar are mainly distributed in three pore size ranges: 0.3 – 7 nm, 100 – 500 nm, and 2000 – 8000 nm, with inter-layer pores occupying the majority of the total pore volume. Fig. 6 a indicates that at 7 days of curing, the volume of inter-layer pores in the mortar first reduces and then grows with increasing GO content.



a

b

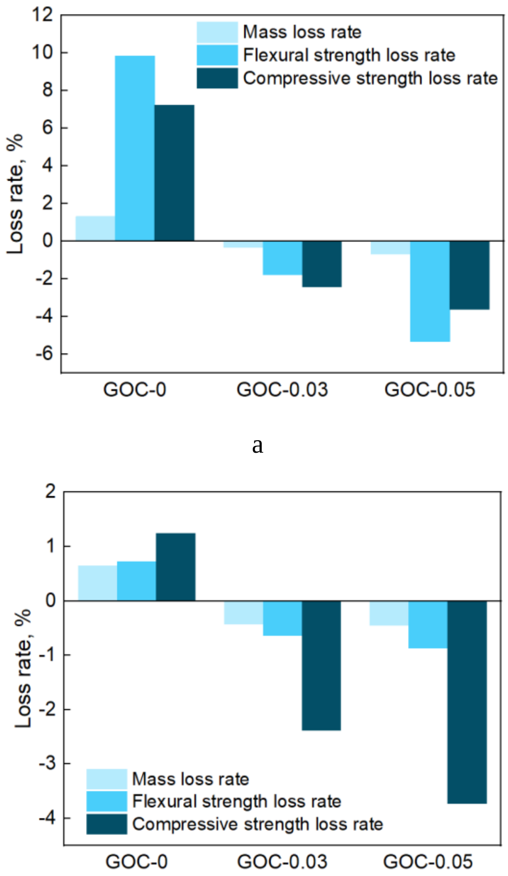
Fig. 6. Real pore volume distribution of mortar at 7 d and 28 d curing age: a – standard curing 7 days; b – standard curing 28 days

Specifically, when the GO content is 0.05 %, the volume of inter-layer pores decreases by 15.00 % compared to the blank specimen, indicating that an appropriate amount of GO can effectively fill and bridge the inter-layer pores during the early to middle stage of curing. Similarly, when examining the capillary pore level, the pore volume of the blank specimen (GO content 0 %) is consistently the highest, showing that the addition of GO also promotes the bridging of capillary pores. Fig. 6 b demonstrates that at 28 days of curing, the volume of pores smaller than 10 nm in the GO-modified specimens decreases compared to the blank specimen, indicating that GO addition can optimize the inter-layer pore microstructure of the mortar at 28 days of curing. Notably, when the GO content is 0.02 %, the inter-layer pore volume decreases the most by 17.72 % compared to the blank specimen. In summary, introducing a small portion of GO to cement mortar substantially reduces its porosity while improving and optimizing the microstructure of the small pores, filling and bridging the internal inter-layer pores and micro-cracks. When the GO content exceeds 0.05 %, the enhancement effect is weakened, primarily for two reasons:

1. Due to the limitations of dispersion methods, nanomaterials tend to aggregate and cluster, causing performance release to be restricted despite higher GO content.
2. Excessive GO content deteriorates the mortar's fluidity and decreases the effective water-to-cement ratio, partially delaying the hydration process.

3.5. Freeze-thaw and weather resistance of modified materials

Cement-based materials, as key building materials, also have performance indicators influenced by their freeze-thaw and weather resistance. Fig. 7 shows the freeze-thaw and weather resistance performance of GO/recycled cement-based composites. It can be observed that during the 50-cycle freeze-thaw test, mass loss and strength loss are primarily caused by the detachment of fine particles from the mortar surface and the internal pore stress-strain of the material. Increasing GO content accelerates the cement hydration process, enhances the bond between aggregate and cement, and improves capillary pore size, thereby reducing porosity. When the GO content is 0.02 %, after 50 freeze-thaw cycles, the flexural strength and compressive strength of the GO/recycled cement-based composite increase by 4.9 % and 2.9 %, respectively (Fig. 7 a). For the GO/recycled cement-based composites cured for 28 days and subjected to ultraviolet weathering tests for one week, their mass and strength changes are within 5 % (Fig. 7 b). When the GO content is between 0.01 % and 0.03 %, the mass, flexural strength, and compressive strength of the recycled mortar all improve. This is because GO acts as a catalyst in the recycled mortar during the experiment, absorbing more water and promoting secondary hydration of the cement. The outcomes reveal that the freeze-thaw and weathering resistance of the GO/recycled cement-based composite meet the standards, and the addition of GO can markedly boost the freeze-thaw and weathering resistance of recycled cement-based materials, positively affecting their performance. Wang et al. [33] prepared GO-CF hybrid fibers via electrophoretic deposition and investigated the frost resistance of cement-based composites incorporating GO, carbon fibers (CF), and GO-CF hybrids. Experimental results showed that the addition of GO significantly improved the frost resistance of cement mortar specimens, with the optimal performance observed at a GO content of 0.07 %. Although compressive strength decreased under freeze–thaw cycles, the strength loss rate of GO-CF cement mortar specimens was notably lower than that of CF-reinforced specimens. Lei et al. [34] studied the effect of GO content on the frost resistance of recycled concrete. Their findings indicated that frost resistance initially decreased and then increased with rising GO dosage, reaching the best performance at a GO content of 0.06 %. In addition, the incorporation of GO was found to reduce the permeability of concrete and enhance its overall durability.



a

b

Fig. 7. Freeze-thaw and weather resistance of GO/recycled cement-based composites: a – freeze-thaw resistance test; b – weather resistance test

3.6. Discussion

The beneficial effects of GO on the mechanical properties, durability, and pore structure of concrete have been widely reported in the literature [27 – 31]. Our findings are consistent with these previous studies, and further contribute to the understanding of optimal GO dosages for different curing ages.

Both domestic and international researchers have conducted studies on the performance of graphene oxide concrete (GOC). The dispersion of graphene oxide (GO) within concrete is a critical factor influencing its overall properties. Currently, ultrasonic treatment is widely used to preprocess GO to enhance its dispersion [27, 28]. Lv et al. [29] investigated the effects of GO with different sizes and concentrations on cement hydration crystal morphology and paste strength. Their findings indicated that GO promotes the formation of rod-like and polyhedral crystal structures, leading to a denser cement paste. This aligns with our SEM observations (Fig. 1), where GO-modified concrete exhibited a more compact microstructure with reduced porosity. Similarly, Zhao et al. [30] reported that incorporating 0.022 % GO improved early compressive and flexural strength by more than 30 %. Moreover, compared to conventional concrete, the inclusion of 0.06 % GO in cement-based composites resulted in a 10 % increase in compressive strength at 28 days [31]. Our results show even greater improvements in compressive strength (up to 29.54 % at 0.05 % GO), likely due to the specific mix design and optimized dispersion technique employed in our study.

Building on these prior studies, the present research explores the effects of GO incorporation on concrete strength, durability, and porosity, aiming to further optimize its performance. Experimental results demonstrate that the addition of GO significantly enhances the mechanical properties of concrete, achieving the anticipated research objectives. The observed modifications in the microstructure align with previous studies, confirming the beneficial role of GO in refining concrete performance. However, our work goes beyond simple confirmation by systematically investigating the energy dissipation characteristics during uniaxial compression. The observed increase in dissipation energy and reduction in elastic strain energy release rate (Fig. 3 b and Fig. 4) provide new insights into the toughening mechanisms of GO in concrete. This is a significant contribution, as it helps explain the improved ductility and reduced brittleness observed in GO-modified concrete.

Additionally, our findings further substantiate that the oxygen-containing functional groups on the nanolayers of GO can form hydrogen bonds with water molecules, facilitating uniform dispersion in the aqueous phase. This process contributes to the refinement of initially irregular and large hydration products, leading to a more homogeneous distribution and arrangement. Consequently, the hardened cementitious matrix exhibits increased density, thereby enhancing the overall strength of the cement-based material. Unlike conventional dispersion methods, this study employed a modified approach in which a portion of the concrete materials was pre-mixed before introducing the GO dispersion solution. This alternative dispersion technique resulted in slight variations in concrete performance, underscoring the importance of optimizing dispersion strategies to maximize the reinforcing effects of GO. While our dispersion method showed promising results, further research is needed to determine the optimal approach for various GO concentrations and concrete mix designs.

4. CONCLUSIONS

1. The incorporation of a certain proportion of GO significantly influences the mechanical properties of concrete composites. Traditional concrete materials often suffer from cracking, poor toughness, and low strength. The addition of GO can significantly improve these deficiencies. Adding 0.05 % GO to concrete significantly enhances the peak stress, peak strain, ultimate strain, and elastic modulus, increasing by 29.54 %, 23.41 %, 61.72 %, and 34.93 %, respectively. The introduction of GO can effectively promote the dense bonding of cement particles, filling micro-pores and cracks, thereby enhancing the overall strength and durability of cement-based materials.
2. Due to the excellent thermal conductivity and electrical conductivity of GO-modified concrete materials, they can effectively reduce temperature differences and

stress concentrations, reducing the risk of damage under extreme conditions. Their excellent wear and corrosion resistance also contribute to their freeze-thaw and weather resistance. The addition of GO in the range of 0.02 – 0.03 % significantly increases the strength of the concrete composite at 7 and 28 days of hydration.

3. When the GO content is between 0.01 % and 0.05 %, it effectively reduces the porosity of the mortar. Particularly, when the GO content is 0.05 %, the porosity at 7 d and 28 d curing ages is reduced to 5.13 % and 5.04 %, respectively. At the same time, a small amount of GO can optimize the internal structure of the inter-layer pores of the mortar through its filling and bridging actions.
4. This research has advanced the scientific understanding of GO-modified concrete by demonstrating the significant improvements in mechanical properties, durability, and pore structure achievable through optimized GO incorporation. Specifically, the detailed analysis of energy dissipation during uniaxial compression provides new insights into the toughening mechanisms of GO, highlighting its ability to increase dissipation energy and reduce the rate of elastic strain energy release. This contributes to a more comprehensive understanding of how GO enhances the ductility and reduces the brittleness of concrete.
5. Current research has not yet achieved efficient dispersion of GO. More refined research on dispersion methods is needed to achieve efficient, large-scale, and high-quality GO dispersion. This will drive the application and production of GO-cement-based composites in real-world applications. Despite the significant improvements GO brings to concrete material performance, the cost is still 30 % – 50 % higher than that of ordinary concrete. It is expected that by 2030, with scaled production and technological breakthroughs, the cost will decrease to within 1.2 times that of ordinary concrete, making it an ideal material for high-value-added projects (e.g., hydraulic dams, marine engineering). There are few practical engineering cases for GO-modified concrete with service lives exceeding 10 years, and the lack of real engineering application data makes the long-term performance (such as creep, shrinkage, etc.) of concrete an important factor that must be considered in practical engineering. It is recommended that future research focus on the impact of GO on the long-term performance of concrete.

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