

# **Research** Article

# **Experimental Study on Mechanism of Graphene Oxide-Modified Coral Sand Cement Mortar to Resist Sulfate Erosion**

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Coral sand particles with low strength and rich pores affect the mechanical properties and durability of their cement-based materials. This paper investigates the mechanical properties and internal pore evolution of graphene oxide-modified coral sand cement mortar under sulfate erosion environment, aiming to better understand the effect of graphene oxide on the mechanical properties of coral sand cement mortar under an erosion environment, especially in wet and dry cycles. Mechanical properties of coral sand cement mortar were tested with different amounts of graphene oxide and different erosion cycles to understand the relationship between the change of flexural and compressive strength and the content and erosion cycle. The microscopic parameters of hydration products and internal dissolution pores were analyzed by XRD and SEM. The results showed that the degree of erosion performance improvement is related to the content of GO, and the two are positively correlated at first and then negatively correlated. At 0.03 wt% content, the retardation effect is the best. There were more orderly pore arrangement with less morphological complexity, when the dissolution amount of  $Ca(OH)_2$ , porosity, total pore area, pore number, probability entropy, average form factor, and fractal dimension decreased. Coral sand cement mortar increases resistance to sulfate attack, which graphene oxide inhibits the formation of new dissolution pores and the expansion of original pores.

# 1. Introduction

In recent years, with the continuous advancement of the development of marine resources, the utilization of coral sand resources has become an important part of the construction of islands and reefs [1–3]. Because of its special marine biogenesis and pore structure characteristics, it has a great influence on mechanical strength [4], and it will break under the normal engineering stress level [5]. Water infiltration and hydraulic coupling have a greater impact on rock mechanical properties [6, 7], As the main body of the coral reef, its physical and engineering properties determine the construction of various projects. At the same time, due to the special composition and complex origin of reef limestone, the properties of the reef limestone are quite different from other common sedimentary rocks [8, 9], and the

seepage of the rock and the defects of the rock itself have a great influence on the mechanical properties [10, 11], more serious in hydration corrosive environments [12, 13]. However, the marine environment contains a large number of corrosive ions, which has a serious adverse effect on the service performance and structural safety of coral sand cementbased structures [14-17]. Weerdt et al.'s investigation of ordinary concrete in the bay for 10 years found that  $SO_4^{2-}$ , Mg<sup>2+</sup>, and other corrosive ions changed the hydration products of concrete, resulting in strength deterioration. In particular, sulfate-enriched areas were detected on concrete surfaces exposed to seawater erosion for a long time, where gelled calcium hydroxide was depleted and nongelling calcium sulfate had formed [18]. Wu et al. investigated the coral sand concrete structures built about 25 years ago on an island in the South China Sea and found that the coral

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Sieve size/mm	4.75	2.36	1.18	0.6	0.3	0.15	< 0.15
Cumulated retained percentage (by mass)/%	0	1.95	58.90	79.23	95.84	99.88	100

TABLE 1: Coral sand particle size distribution.

TABLE 2: Chemical composition of ordinary Portland cement.

Chemical composition	CaO	SiO <sub>2</sub>	$Al_2O_3$	Fe <sub>2</sub> O <sub>3</sub>	K2O	MgO	Na <sub>2</sub> O	SO3
Content/%	62.37%	22.38%	5.13%	3.31%	0.82%	2.66%	0.57%	2.16%

TABLE 3: The physical and mechanical properties of cement.

Setting times		Stability	y flexural	Compressive			
(min)		strengtl	ns (MPa)	strengths (MPa			
Initial	Final	3 days	28 days	3-days	28 days		
180	240	5.6	8.9	26.3	48.8		

sand concrete protective layer had a large area of pulverization, exposed aggregates, and other deterioration phenomena; also, with the increase of concrete surface depth, the erosion effect of SO42- is gradually stronger than that of Mg<sup>2+</sup> [15]. The damage of sulfate to cement-based materials cannot be ignored, especially in the environment of islands and reefs. Sulfate not only damages cement-based materials but also forms a pore system that intensifies the penetration of Cl-, which in turn causes electrochemical corrosion of internal steel bars, posing a serious threat to the service performance of structures [19]. At present, many achievements have been made in improving the mechanical properties and durability of coral sand cement-based materials by adding modifiers or mineral admixtures, but the performance improvement is relatively simple and the dosage is large [20-22]. However, with the development of science and technology, nanomaterials have shown good application prospects in many fields. Such as graphene oxide, an oxidation product of graphene, it has a large number of active groups, large specific surface area, super mechanical properties, and flexibility. It has shown obvious enhancement and toughening effects in cement-based materials [23, 24]. The compressive performance of graphene oxide for cementbased materials is improved by 12%-45%, and the flexural strength is improved by 16%-70% [25, 26]. Coral sand cement-based materials would be degraded by the erosion of sulfate ions under the attack of seawater. In addition, the engineering mechanical properties of coral sand are significantly different from those of terrigenous sand due to the large difference in particle structure and the richness of internal pores [27, 28]. The research on the effect of graphene oxide on the inhibition of sulfate erosion of coral sand mortar and the mechanism of action is still unclear. The main objectives of this study are to investigate the mechanical properties under sulfate attack and to determine the optimal content of graphene oxide to improve coral sand mortar properties considerably. Furthermore, through XRD and SEM tests, the effects of graphene oxide on the appearance, hydration products, and pore structure of coral sand mortar under sulfate erosion conditions were analyzed.

It has certain practical significance for the construction of islands and reefs.

# 2. Materials and Test Program

2.1. Materials. Coral sand is taken from a certain island reef in the South China Sea which is in loose form; the mud content is less than 1.3% after washing and drying. The particle gradation is shown in Table 1. P·O 42.5 cement was used as a cementitious material. The chemical compositions and mechanical properties are summarized in Tables 2 and 3. Graphene oxide adopts brown-black SE3522 GO dispersion produced by Changzhou Sixth Element Materials Technology Co., Ltd. (as shown in Figure 1): pH  $\approx$  1.8, D50 particle size < 4  $\mu$ m, GO solid content 1.07%, and sample monolayer rate > 90%.

2.2. Specimen Fabrication. To obtain the effect of graphene oxide content on the inhibition of sulfate corrosion of coral sand mortar, the water-cement ratio and sand-cement ratio of all specimens were uniformly set at 0.5. The graphene oxide dispersion was diluted with water and dispersed by ultrasonic wave for 30 min, and the solid mass was 0.00%, 0.01%, 0.02%, 0.03%, 0.04%, and 0.05% of the cement mass (to ensure a constant water-cement ratio, the design proportions have deducted the moisture content of the graphene oxide dispersion). In accordance with the requirements of ≪test method of cement mortar strength (ISO method) ≫ GB/T 17671-2020 [29], firstly, add the mixing water and cement and stir at low speed for 30 s, then add the sand evenly, then stir at high speed for 30 s, stop mixing for 90 s, scrape the mortar on the pot wall and blades into the pot within 15 s, and then stir at high speed for 60 s. Three samples of  $40 \text{ mm} \times 40 \text{ mm} \times 160 \text{ mm}$  in each group were made according to different graphene oxide dosages.

2.3. Testing Methods. To simulate the most unfavorable environmental conditions of islands and reefs, this experiment adopts the dry-wet cycle sulfate erosion process (a dry and wet cycle is 24 h). The specimens were placed in a constant temperature and humidity box with a temperature of  $20^{\circ}$ C and a humidity of 95% for 28 days, taken out, and put into an oven for drying at  $80^{\circ}$ C for 48 hours. After cooling, the quality test was performed. Then, the specimens are placed in a dry-wet cycle sulfate attack equipment. And then 15 d, 30 d, 45 d, 60 d, 75 d, and 90 d dry-wet cycle sulfate erosion test was executed. When the corresponding age is reached, we take it out and continue to dry for 48 hours to test the

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FIGURE 1: Dispersions of SE3522 GO.



FIGURE 2: Quality changes of coral sand mortar.

quality, the flexural test was performed on the specimen at a loading rate of 50 N/S, the compression test was performed at a loading rate of 2.4 kN/S, and samples were taken from the fractured section of the specimen. The cross-section samples were dried and crushed into powders and passed through an 80  $\mu$ m sieve, and then the main hydration products at different curing ages were studied by using the ultimate V-type X-ray polycrystalline powder diffractometer; small pieces with relatively flat bottom surface were selected, and the microstructure changes were observed by JSM-6490LV scanning electron microscope after metal spraying process.

# 3. Results and Discussion

3.1. Varying Regularity in Quality of GO-Modified Coral Sand Mortar under Different Erosion Cycles. Quality changes of coral mortars modified with different dosages of graphene oxide with erosion cycles are shown in Figure 2. After 90 days of the dry-wet cycle, the specimens were loose, and the lumps were seriously dropped. It turned into powder when twisted with fingers, and the quality test was invalid.



FIGURE 3: Quality changes of coral sand mortar.



FIGURE 4: Quality changes of coral sand mortar.

The quality of the five groups of coral sand mortar specimens increased in different degrees after being eroded by sulfate in different cycles. It is obvious that the quality of the specimens without adding graphene oxide increases rapidly. After 15 d dry-wet cycles of sulfate attack, the quality increased by 11.58 g, accounting for about one-third of the quality increase in the whole cycle. The quality of the specimens doped with graphene oxide increases slowly. The dosage is 0.01%-0.05%, and the quality increase is between 5.19 g and 7.36 g after 15 dry and wet cycles of sulfate erosion. Compared with the undoped graphene oxide group,



FIGURE 5: SEM image of 28 d coral sand mortar with 0.00% and 0.03% GO magnified at 5000 times. (a) the dosage of GO is 0.00%. (b) The dosage of GO is 0.03%.



FIGURE 6: Phase analysis by XRD.

the quality growth rate decreased by about 49%. The chemical reaction between sulfate and cement mortar produces a large amount of crystalline salt. The crystalline salt produced in the initial stage quickly fills the pores on the surface of coral sand, and the mass increase is relatively rapid [30]. Since the surface of the coral sand mortar without doped graphene oxide is loose and porous, the coral sand contains a large number of internal pores [31]. However, the pores on the surface of coral sand mortar become denser with the addition of graphene oxide, which has a certain resistance effect on the filling of crystalline salt in the pores on the surface of the specimens. With the gradual increase of the content of graphene oxide, the impedance effect shows a trend of increasing first and then decreasing. When the content of graphene oxide is 0.03%, an inflection point appears, and the content of graphene oxide is gradually increased between 0.01% and 0.03%. The ability of graphene oxide to regulate hydration products, the template effect, and the filling effect of coral sand mortar pores is gradually enhanced [32, 33], showing that the increase in mass decreases with the increase in the amount of graphene oxide. However, excessive graphene oxide will cause agglomeration in cement-based materials, which will weaken the impedance

effect [34]. Therefore, when the content of graphene oxide increases between 0.03% and 0.05%, the mass increase increases slightly. In summary, graphene oxide is more sensitive to the quality of coral sand mortar under sulfate erosion, and the effect is most significant at 0.03% dosage.

# 3.2. Variation Rule of GO-Modified Coral Sand Mortar Strength under Different Erosion Cycles

3.2.1. Variation of Compressive Strength. The variation trend of the compressive strength of coral sand mortar with the content of graphene oxide and the period of sulfate erosion is shown in Figure 3. The compressive strength of coral sand mortar increases first and then decreases under the conditions of 0-90 d dry-wet cycles of sulfate erosion, which is consistent with the conclusion of ordinary cement-based materials [35, 36]. After 15 drywet cycles of sulfate attack, the strength of all specimens increased to varying degrees. Since sulfate invades to form gypsum, ettringite, and sodium sulfate crystalline salt, the pores of coral sand mortar are filled to a certain extent. And the inner and outer pores of coral sand mortar provide a larger reaction space for the formation of ettringite, gypsum, and sodium sulfate crystalline salt, making the coral sand mortar denser. According to analysis, the filling effect of the crystalline product has a greater influence on the compressive strength than the deterioration of the cement matrix by the sulfate. Therefore, the strength of coral sand mortar in this period is enhanced to varying degrees. Comparing the strength increase of the doped graphene oxide and the undoped group, the dosage is from 0.00% to 0.05%. The increases after 15 dry-wet cycles of sulfate erosion were 6%, 3.5%, 3.2%, 2.3%, 0.9%, and 0.16%, respectively. It illustrates that the addition of graphene oxide increases the compactness of the coral mortar slurry structure to a certain extent, which hinders the intrusion of sulfate into the coral sand mortar. However, the structure of the slurry without adding graphene oxide is more porous and loose, and the sulfate crystallization and reaction products fill the pores more obviously, which makes the strength increases larger. During the dry-wet cycle sulfate attack, the strength degradation process of the graphene oxide specimens showed a certain stage. In the 0-15 d dry-wet cycle sulfate attack stage, the strength

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FIGURE 7: Pore characteristics of samples with different GO contents under 30 dry-wet cycles of sulfate erosion. (a, b) The dosage of GO is 0.00%. (c, d) The dosage of GO is 0.03%.



FIGURE 8: Coral sand particles and coral sand mortar erosion interface: (a) sand particles and (b) mortar erosion interface.

is in a stable stage, 15-60 d in a slow decline stage, and after 60 d in a rapid decline stage. The strength stabilization stage is mainly due to the fact that graphene oxide makes the coral sand mortar form a relatively dense structure, and the penetration channel is blocked during the intrusion of sulfate into the interior of the mortar. And the template effect of graphene oxide makes the arrangement of hydration products more orderly, which weakens the erosion effect of sulfate to a certain extent. In the stage of slow strength reduction, sulfate has initially formed a permeation path, eroded the cementitious substances, and gradually produced gypsum, ettringite, and other expansive crystalline substances that accumulated inside. Simultaneously, the dry-wet cycle promotes the continuous crystallization and precipitation of sodium sulfate crystals in the internal pore structure, and the expansion pressure of the erosion product has a gradually increasing negative effect on the cementation stress between the internal materials. During the rapid strength drop stage, microcracks occurred on the surface and inside of the specimens, and the expansion pressure of the erosion product made the local bonding force in the specimen fail [37] and provided a new erosion channel for the invasion of sulfate ions, and the strength decrease rate increased.

3.2.2. Variation of Flexural Strength. The variation trend of the flexural strength of coral sand mortar with the content of graphene oxide and the period of sulfate erosion is shown in Figure 4. The flexural strength of coral sand mortar continues to decrease under the conditions of 0-90 d dry-wet cycle sulfate erosion. After 15 d dry-wet cycle sulfate erosion, the flexural strength of the specimens without graphene oxide decreased by about 17%, and the flexural strength of the graphene oxide group decreased by about 1%-7%. In comparison, it was found that the addition of graphene oxide slowed down the decrease in the strength of the coral sand mortar specimens. During the period of 15-60 d dry-wet cycle sulfate attack, the flexural strength decreased most significantly. With the infiltration of sulfate, the dissolution pores inside the specimen gradually formed, and with the increase of the number of drying and wetting cycles, the dissolution pores gradually developed into seepage channels, and gel substances such as Ca(OH)<sub>2</sub> were gradually lost with the erosion of sulfate ions [38]. The addition of graphene oxide makes the flexural strength of the specimen better than that of the undoped group to a certain extent by comparison. During the 60-90 d sulfate dry-wet cycle erosion process, the decrease in flexural strength has slowed down because a relatively complete

 TABLE 4: Pore structure parameter values.

Cycle-dosage\pore parameters	0 d-0.00 wt%	0 d-0.03 wt%	30 d-0.00 wt%	30 d-0.03 wt%	75 d-0.00 wt%	75 d-0.03 wt%
Total pore area	56754.432	41545.762	70974.069	49830.265	81978.889	66275.596
Pore number	137	99	211	157	310	237
Porosity	4.59%	3.36%	5.74%	4.03%	6.63%	5.36%
Maximum pore area	6434	5980	13907	6884	23644	13536
Average pore area	414.66	419.65	336.37	317.39	264.45	297.64
Average perimeter	96.58	81.54	153.46	130.49	197.04	178.95
Average form factor	0.4368	0.3843	0.4306	0.4507	0.4546	0.5561
Probability entropy	0.9839	0.9868	0.9491	0.7997	0.959	0.9427
Fractal dimension	1.1459	1.2041	1.3057	1.4154	1.2923	1.2716

sulfate ion intrusion channel has been formed in the specimens during the previous dry-wet cycle process. And the reduction of the gel material reduces the corrosion reaction of sulfate in the later stage. It is observed that powder sand particles have appeared on the surface of the specimens, and the cohesive force between the sand particles is close to failure. The powder is formed when the pieces are crushed lightly with fingers.

#### 3.3. Evolution Discipline of Microscopic Pores in GO-Modified Coral Sand Mortar Resisting Sulfate

3.3.1. The Effect of GO on the Hydration Reaction. As shown in Figure 5, the SEM images of 28 d coral mortar without GO and 0.03% GO are magnified by 5000 times for comparison: the hydration products such as ettringite with needlelike, rod-like, and lamellar crystals in the mortar mixed with 0.03% GO were significantly more than those without GO. The results are similar to the XRD results shown in Figure 6. And the polyhedral hydration products grow along with the surface pores of coral sand particles, filling and covering most of the surface pores. It indicates that GO played a template role in cement hydration products and promotes the cement hydration reaction process [33], forms more hydration products, and makes the mortar structure denser. Simultaneously, the porous coral sand particles have a larger specific surface area, which provides more attachment sites for GO to exert the bridging effect [39]. It can not only form a good filling effect on the cavities of sand particles but also facilitate the occurrence of hydration reaction, form a certain control effect on cement hydration products, and further improve the microstructural properties of coral sand mortar. As shown in Figure 6, the phase analysis of coral sand mortar was carried out under the conditions of dry and wet cycle sulfate erosion for 0 d, 30 d, and 75 d, under the condition of zero incorporation of GO and under the condition of 0.03% incorporation of GO, and it was observed that When the erosion period is 0 d, the diffraction peak of the hydration product Ca(OH)<sub>2</sub> of the doped graphene oxide specimens is significantly higher than that of the undoped specimens. Graphene oxide promotes the production of hydration products, which increases the gel content inside the specimen and improves the mechanical strength of coral sand mortar. In the process of sulfate erosion, the H<sup>+</sup> ions and

 $SO_4^{2-}$  ions dissociated from sulfate are combined with the OH- and Ca<sup>2+</sup> of Ca(OH)<sub>2</sub> in the cement stone to form water and calcium salts, respectively, as shown in (1).

$$Ca^{2+} + 2H^{+} + 2SO_4^{-} + 2OH^{-} = CaSO_4 \cdot 2H_2O.$$
 (1)

When the erosion period was 30 d, the diffraction peak of Ca(OH)<sub>2</sub> in the doped graphene oxide group was stronger than the undoped group, indicating that the incorporation of graphene oxide blocked the effect of sulfate on the hydration product Ca(OH)<sub>2</sub>. During the corrosion process, the loss of gel material is slowed down, making the strength decrease slower. Comparing the CS + GO(0.00%) + 0 d group and the CS + GO(0.03%) + 30 dgroup, the diffraction peaks of Ca(OH)<sub>2</sub> are roughly the same. After adding graphene oxide, the coral sand mortar still maintains roughly the same amount of  $Ca(OH)_2$  as the noneroded and undoped graphene oxide group after 30 dry-wetting cycles, and the mechanical strength is also roughly the same. The addition of graphene oxide significantly improves the service life of coral sand mortar which is consistent with the results shown in Figures 2 and 3 for mechanical properties. When the erosion period is 75 d, the diffraction peak of Ca(OH)<sub>2</sub> is extremely weak, and the Ca(OH)<sub>2</sub> in the coral sand mortar is completely consumed. It is observed that the surface of the specimen mixed with graphene oxide is relatively complete, and the water chestnut appears pulverized. However, the surface of the specimen without adding graphene oxide was powdered and had no cementitious properties, showing a loose state, and the cement hydration product lost its cohesive force and slag appeared. In summary, the addition of graphene oxide to coral sand mortar can promote the production of internal hydration product  $Ca(OH)_2$ . Under the condition of sulfate erosion, graphene oxide plays a certain role in the loss process of Ca(OH)<sub>2</sub>. The blocking effect is maintained, and the strength is maintained to a certain extent, which improves the service life of the coral sand mortar.

3.3.2. Effect of GO on Pore Characteristics during Sulfate Erosion. As shown in Figure 7, the dry-wet cycle sulfate erosion for 30 d, GO zero-incorporation, and GO-incorporated 0.03% coral sand mortar was magnified 100 times by SEM.

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FIGURE 9: Pore parameters: (a) total pore area, (b) pore number, (c) porosity, (d) maximum pore area, (e) average pore area, and (f) average perimeter.

The figure shows that under the zero incorporation of GO, the coral mortar has obvious dissolution pores, and there are micropores with the widest diameter of about 200  $\mu$ m. Affected by the pores, the interface strength is weakened, and the mortar strength is reduced. With the addition of 0.03% GO, the coral mortar has no obvious large-diameter dissolution pores. Affected by the GO template and the promotion of hydration reaction, the interface quality of the coral mortar is improved, the occlusal effect between the cement slurry and the sand particles is strengthened, and

the slurry is denser, which has a good blocking effect on the invasion of sulfate ions.

3.3.3. Quantitative Analysis of Pore Evolution. As shown in Figure 8, the surface of coral sand is rough and porous and rich in internal pores due to biological origin, and the gradual formation of new pores during sulfate ion erosion has a great impact on the strength of coral sand mortar. After adding GO, it has a good blocking effect on the formation of coral sand mortar erosion pores, to quantify the effect of



FIGURE 10: Pore parameters: (a) probability entropy, (b) average form factor, and (c) fractal dimension.

GO on the evolution of pore parameters, the SEM images of coral mortar specimens magnified 100 times were binarized, and the microscopic pore parameters were calculated by Particles (Pores) and Cracks Analysis System (PCAS) [40–42] and 3 SEMs from each sample. In the complex environment of sulfate erosion, the pore area, pore number, porosity, and other parameters are insufficient to fully characterize the pore evolution law. In order to fully characterize the pore morphology, probability entropy, average form factor, and fractal dimension are used as additional parameters. To describe the two-dimensional directionality of pores, roundness, roughness, and irregularity of pore edges [43], the statistical results are shown in Table 4.

(1) Variation in the Number and Area of Pores. As shown in Figures 9(a)-9(c), with the extension of the sulfate erosion period, the pore area, number, and porosity all increased to different degrees. Comparing the samples with graphene oxide content of 0.00 wt% and 0.03 wt%, it is found that the retardation effect of graphene oxide on the pore area, number, and porosity of coral sand mortar increased by 26.8%, 27.7%, and 26.8%, respectively, compared with the undoped group at the 0 d erosion period. When the erosion period is 30 d, it increases by 29.8%, 25.6%, and 29.8%, and

when the erosion period is 70 d, it increases by 23.4%, 23.5%, and 19.2%, respectively. It can be inferred that without the addition of graphene oxide specimens, sulfate ions can easily penetrate into the interior of the mortar through the internal pores of the coral mortar and participate in the reaction to generate nongelling substances such as ettringite and dihydrate gypsum. The eroded pores are formed gradually under the dissolution. The addition of graphene oxide has a promotion and template effect on the formation of cement hydration crystal products, which can promote the formation of neat and regular flower-like nanoscale microcrystals in cement hydration products, so that sulfate ions are hindered in the infiltration process, thereby achieving a high resistance: the effect of stagnant pore development. As shown in Figure 9(d), comparing the maximum pore area of the two, without adding graphene oxide, the maximum pore area of coral sand mortar pores increases significantly more than the graphene oxide-doped group under the passage of the erosion cycle. It shows that the addition of graphene oxide has a retarding effect on the expansion of the eroded pore edge. As shown in Figure 9(e), the change of the average pore area and the erosion cycle shows a slowly decreasing trend. The analysis shows that when the total pore area increases with the

erosion cycle, the decrease of the average pore area indicates that the newly formed pore area is larger than the original pore expansion area. It makes the average pore area show a slowly decreasing trend. The average pore area was slightly higher or the same in comparison with the nonparticipating group with graphene oxide added. It can be seen that the addition of graphene oxide has a good blocking effect on the formation of new pores during the sulfate erosion process. This is highly consistent with the dissolution of Ca(OH)<sub>2</sub> in the XRD analysis.

(2) Pore Distribution and Morphology. The probability entropy is used to describe the 2D directionality (i.e., degree of alignment) of pores. The value of the probability entropy is between 0 (all pores are aligned in the same orientation) and 1 (pores have random orientations). The pore directions become more chaotic with increasing probability entropy [44]. As shown in Figure 10(a), before the specimen was not etched by sulfate, the probability entropy of the graphene oxide group and the nonadded group was 0.9839 and 0.9746, respectively, approaching 1, and graphene oxide had little effect on the probability entropy. When sulfate attacked for 30 days, the influence of graphene oxide on the probability entropy was gradually significant, and the probability entropy decreased by about 15.7%. When sulfate attacked for 75 days, the roundness and the roughness of pore edges are also important indicators of pore evolution, and the average form factor is used to describe the characteristic shape of pores. The complexity of the pore boundary increases as the average form factor decreases [45]. As shown in Figure 10(b), the average form factor of the undoped graphene oxide group showed a decreasing trend with the increase of the erosion cycle, the roughness of the pore boundary increased, and the roundness decreased. Compared with the unetched specimens, the influence of graphene oxide on the average form factor is small, and the increase is about 3.4%. When the erosion cycle is 30 d and 75 d, the influence of graphene oxide on the average form factor is more obvious, and the increase is about 32.1% and 44.6%. The addition of graphene oxide improves the interface roughness and roundness of the dissolution pores, reduces the complexity of the pores, and tends to develop circular pores. Fractal dimension is a measure of the irregularity of complex features [46]. As shown in Figure 10(c), the fractal dimension of the unadded graphene oxide component varies from 1.2 to 1.79, indicating that the complexity of the pore edge is wide, the complexity of the pores increases with the increase of the sulfate erosion cycle, while the fractal dimension of the added graphene oxide component changes between 1.2 and 1.37, and the range of pore edge complexity is narrow. In conclusion, with coral sand mortar dissolution pores under sulfate erosion, these pores usually have a more complex pore shape due to a lower average form factor and higher fractal dimension. The addition of graphene oxide affects the pore size and pore shape, reducing the porosity, pore area, pore edge roughness, etc., so that the interior of the specimen maintains better integrity, thereby extending the service life of coral mortar.

# 4. Conclusion

This paper experimentally studied the mechanical strength and pore change laws of GO-modified coral sand mortar under the conditions of dry-wet cycle sulfate erosion aiming to better understand the effect of GO on the service life of coral sand mortar. The following conclusions can be drawn based on this study:

- (1) Under the conditions of dry-wet cycle sulfate erosion, the quality loss of GO-modified coral sand mortar is reduced, and the degradation of flexural and compressive strength is slowed down. The best effect is when the dosage is 0.03%
- (2) Through the analysis of the obtained X-ray diffraction pattern and scanning electron microscope results, it was found that GO can promote the process of cement hydration reaction but will not generate new hydration products; GO blocks the effect of sulfate on the hydration product Ca(OH)  $_2$  of the corrosion process. The loss of gel mass is slowed, resulting in a slower decrease in strength
- (3) The addition of graphene oxide has a good blocking effect on the formation of pores during the sulfate erosion process. During the 0 d, 30 d, and 75 d erosion cycles, the pore area, number, and porosity decreased by 23.4%-29.8%, 23.5%-27.7%, and 19.2%-26.8%, respectively
- (4) In coral sand mortar dissolution pores under sulfate erosion, these pores usually have more complex pore shapes due to lower average form factor and higher fractal dimension. Graphene oxide improves the interface roughness and roundness of the dissolution pores, reduces the complexity of the pores, and tends to develop circular pores

## **Data Availability**

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

## **Conflicts of Interest**

The authors declare that they have no conflicts of interest.

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