

Review Article

Cement-Based Graphene Oxide Composites: A Review on Their Mechanical and Microstructure Properties

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Concrete is a material made from cement that is widely used because it has a high compressive strength, is resistant to water, is easy to mold, and is cheap to make. But concrete's biggest problem is that it's easy to break because it does not resist cracking well, has low tensile strength, and cannot take a lot of stress. Researchers have been successful in enhancing the quality of cement composites by using fibers, admixtures, and other cementitious materials. When it comes to building objects, nanotechnology could open up a whole new world. Building materials have made nanosized materials that are used to make cementitious materials stronger and last longer. For example, they stop microcracks from starting and spreading. One of the most well-known graphene derivative nanomaterials is graphene oxide (GO), which has a lot of active oxygen-containing groups on its surface, outstanding mechanical properties, and thermal conductivity. Researchers have found that adding small amounts of GO in various dosages increases the flexural, tensile, and compressive strengths of cement paste and mortar. The majority of studies have looked at cement paste and mortar. There are few GO-concrete studies. One of the most characteristic graphene derivative nanomaterials, graphene oxide (GO), has a huge specific surface area, outstanding mechanical properties, thermal conductivity, and a lot of active oxygen-containing groups on its surface. Small amounts of GO at various dosages boost the flexural, tensile, and compressive strengths of cement paste and mortar, according to researchers. Most researches have examined cement paste and mortar. There are few GO-concrete studies. This article review paper will be useful for engineers and researchers investigating the impact of GO on mechanical qualities and advanced nanomaterials in cement-based materials like concrete. It will also be a point of reference for further research.

1. Introduction

Concrete and other cement-based materials are frequently used in prefabricated buildings due to their great compressive strength, water resistance, moldability, and low production costs [1]. Because of its poor tensile strength, strain capacity, and crack resistance, concrete is extremely fragile. Cement's chemical and physical properties have a major bearing on how concrete performs [1]. Portland cement concrete has a nanostructure and is a multiphase composite made up of bonded water, nano- to micrometer-sized crystals, and an amorphous phase. Calcium(C)–silicate(S)–hydrate(H) is a nanomaterial used as an adhesive in concrete. This adhesive is based on the amorphous phase [2]. The main hydration products are gels composed of calcium silicate hydrate (C–S–H) nanocrystals, which have structures on the atomic

scale [3]. There are many excellent reasons to incorporate nanomaterial technology into cement-based materials to make nanoscale modifications to their structures and also improve the materials' macroproperties.

In the realm of architecture and the materials used to make buildings, nanotechnology has the potential to usher in a brand-new age. Current advancements in nanotechnology have made it possible to use nanoscale materials to increase the mechanical strength and endurance of cementitious materials. This has been made possible as a result of recent discoveries in the field of nanotechnology. Nanoscale materials can accomplish this by preventing the initiation and spread of microcracks. Cementitious materials can also have TiO₂ and other nanoparticles that have antibacterial, antipollution, and self-cleaning properties added to them to improve their attributes [4]. As nanotechnology and

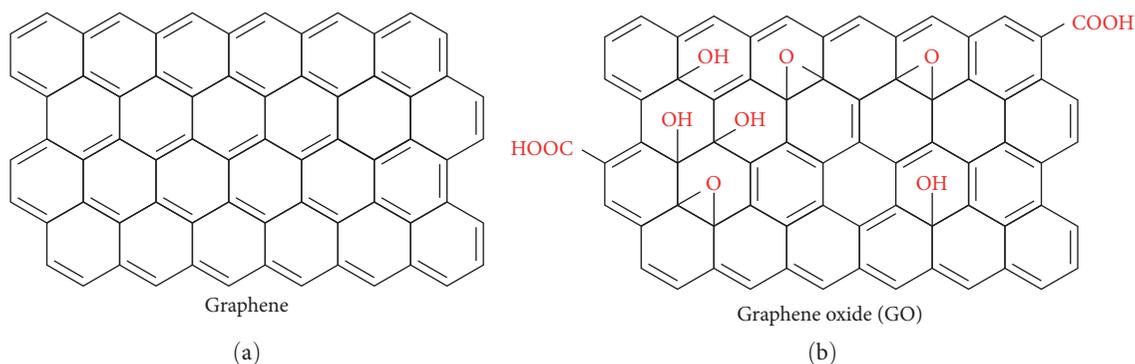


FIGURE 1: Graphene and graphene oxide expressed visually [31].

materials continue to advance, we will usher in a new era of high-performance construction materials. These materials will be of the next generation.

The development of nanomaterials has made it possible to make significant changes to the nanoscale microstructure of cement composites. Because of this, the effectiveness of these things has seen a significant boost as a result. The mechanical characteristics of cement composites have been reported to be improved by the addition of nanosilica, nanoalumina, nanocalcium carbonate, nanotitanium dioxide, nanoferric oxide, carbon nanofibers, and carbon nanotubes (CNTs), albeit to varying degrees [5–11]. The incorporation of additional nanoparticles into cement composites has the potential to further improve the material's mechanical qualities.

Researchers have been interested in graphene, a two-dimensional nanomaterial made of a single sheet of sp^2 -linked carbon atoms, since 2004 [12] because of how well it works mechanically, thermally, and electrically. Graphene nanoplatelets (GNPs) are essentially just a few layers of graphene nanoplatelets put together. GNPs may be challenging to closely link at the interface of the GNPs and the cement matrix due to their severe hydrophobicity and chemical inertness. As a result, when the cement is stressed, the GNPs may become dislodged from the matrix and lose their beneficial properties. Because of the strong van der Waals forces between the platelets and their huge surface area, it is difficult to distribute GNPs.

In 2004, British scientists Novoselov et al. [13] and Geim and Novoselov [14] used a mechanical peeling method to successfully separate graphene from graphite. A frenzy of theoretical and applied research was triggered as a result of its unexpected presence and great properties. Since then, advancements have been made in the methods used to prepare graphene. Graphene has been successfully manufactured using the epitaxial growth technique [15], a technique of chemical vapor deposition [16], combined with the graphite oxide reduction technique [17]. Studies show graphene has outstanding characteristics Panda et al. [18], Tera-Pascal Young's modulus [19], optics [20], biology [21], conduction [22], thermodynamics [23], catalysis [24], ferromagnetism [24].

An extremely popular nanoreinforcement is graphene oxide (GO), a kind of graphene. These nanoreinforcements'

relatively high surface area, outstanding mechanical properties, as well as strong thermal conductivity can all be related to the enhanced concentrations of different active oxygen-containing groups on their surface. Graphene oxide, also known as GO, is widely recognized as one of the most extraordinary nanoreinforcements on the market today [25]. Cement pastes that incorporate GO-cement composites benefit from their high hydrophilicity, which also facilitates their mass production and dissemination. Common GO preparation procedures include the Brodie, Staudenmaier, and Hummer approaches [26–28]. Functional groups containing oxygen were used to form the hydroxyl, epoxy, and carboxyl edges of graphene [29]. These hydrophilic groups not only aid in GO's dispersion in water but also provide a vast.

As a result of the cross-linking functional oxygen groups, van der Waals forces have been reduced, and electrostatic polarization is enhanced, facilitating dispersion in water [30]. Also, active functional groups are interacting chemically or physically, which could strengthen the interfacial connection of the composites shown in Figures 1(a) and 1(b). Due to its many advantages, GO has recently gained in popularity and is currently included into a wide variety of matrix materials, including ceramic and polymer composites [30–35].

Much research has looked into how GO changes the properties of cement paste, cement mortar, and concrete. Workability, hydration process, mechanical characteristics, and microstructure are studied in relation to GO's incorporation into cement. Despite this, there is a lack of familiarity with graphene oxide in cement-based materials like concrete throughout the construction industry. This analysis has the potential to pave the way for further study into incorporating GO into cement composites as a nanotechnology-enhanced additive. Read it if you are an engineer or scientist.

2. Graphene Oxide Dispersion

It is anticipated that the ions present throughout the hydration system as well as the alkalinity of the cement pore water will influence GO's capacity to disperse throughout the cement. It was discovered that GO aggregation commenced immediately upon contact between aqueous solution and GO

powder in cement. GO must be uniformly distributed throughout cement pastes for it to be effective. Due to the impossibility of GO particle sizes approaching that of C–S–H gel, their nonuniform distribution prohibits them from enhancing the nanoscale cement matrix [36].

Under optimal conditions, an upsurge in the graphene oxide composition of cement-based composite materials will, over time, improve both their mechanical qualities and their durability [36]. Due to its large specific surface area and strong van der Waals force between layers, GO agglomerates during preparation and use [36]. Cement composite performance does not increase with GO concentration, and it may decrease. Hence, GO adoption requires good dispersion [36]. Due to its two-dimensional-layered structure, graphene is easier to distribute than CNTs. Individually or in combination, the following methods—a combination of GO, physical dispersion, and mechanical dispersion—are possible possibilities for achieving this objective.

2.1. Graphene Oxide Combination. Anyone reading this will quickly get that oxygen is just one of several functional groups found on the GO sheet. Particles can always be dissolved in water electrostatic repulsion and a strong hydrophilic attraction [37, 38]. In contrast, the presence of several metal cations (such as Ca^{2+} , K^+ , Na^+ , and so on) renders cement pore solution extremely alkaline [39]. Numerous research [40, 41] have examined this same agglomeration of GO through cement paste. The excessive alkalinity and calcium ion concentration in cement paste are the primary causes of agglomeration. Due to its limited Ca^{2+} tolerance, GO will clump together if the concentration of Ca^{2+} is increased too much [42]. This is due to the fact that GO acts as a bridge for Ca^{2+} ions, which causes this effect. Mechanical dispersion is one way to achieve this goal, while it can also be achieved through the employment of other techniques.

As indicated by several studies [43, 44], the presence of Ca^{2+} as well as OH in cement paste can be detrimental to that same stability systems in the region of GO. The aggregation of GO is caused by two main factors: Ca^{2+} complexation and the fast deoxygenation process in an alkaline environment. Looking examining GO's behavior as it was distributed in solutions of $\text{Ca}(\text{OH})_2$, CaCl_2 , and Na OH, Zhao et al. [45] were able to identify the critical parameters that affect GO dispersion. Another factor contributing to GO clumping is an alkaline atmosphere, with only 2.2 mm of calcium being adequate to rapidly destabilize the GO solution and promote rapid agglomeration. In addition to causing GO aggregation, an alkaline environment is a necessary condition for its formation. Enhancing GO dispersion inside the cementitious matrix is one way to get something out of GO's remarkable properties. Nanomaterial dispersion research has advanced greatly.

Because the aggregate structure can hold some of the combined water, the apparent volume is lowered. Another contributor to a higher internal friction is an increase in the number of agglomerated particle concentration inside the cement paste. The paste loses a lot of its workability as a

result of the reaction between these two ingredients [45]. Wang et al. [46] note that adding GO to cement paste makes it less malleable. The formation of GO agglomerates is the result of the chemical cross-linking of GO nanosheets by calcium cations.

2.2. Method of Physical Dispersion. It is common practice to use high shear milling, ball milling, or ultrasonication as the means to achieve the objective of physically dispersing particles [45]. It is generally accepted that the release of mechanical energy occurs either through high-velocity shear or ultrasonic waves as the mechanism underlying the phenomenon known as physical dispersion. When energy is supplied, it has the potential to disturb the chemical interactions that are taking place between nanomaterials. This can make the van der Waals force weaker and spread the materials out more [45, 46]. The researchers' methods and the functionality of their tools both contribute to the physical spread. Truth of this has been demonstrated by Liu et al. [47] that if the ultrasonic intensity is already too low, increasing the ultrasonic time will not improve the dispersion impact of GO. The lamellar structure of GO, however, is susceptible to damage if an excessive amount of ultrasonic power is used, which renders the technique ineffective for dissemination. Lu et al. [42] came at the same conclusions, which were in line with previous research. It is important to remember that the physical dispersion method has severe limitations and is unable to assist in the dispersion of GO in any medium other than water. It is notably obvious in alkaline cement paste that GO reaggregates after the physical action has finished. This is due to the fact that GO cannot operate endlessly and must eventually stop. As a result of this, it is occasionally necessary to combine the method of chemical modification with the method of physical dispersion.

2.3. Method of Chemical Modification. As a result of the flexibility of the chemical modification process, GO can be tailored both to its structural makeup and the specifics of a certain application [48]. As a means of surface activation, surfactants are commonly used in chemical dispersion techniques [49]. Some examples of high-range water reducers include polycarboxylate-based high-range water reducer and naphthalene-based high-range water reducer. During the chemical modification process, surfactants are often applied to the surface of GO in order to adsorb the material, reduce the surface energy of the material, and make its dispersion easier through electrostatic repulsion. Meanwhile, in order to enhance the hydrophilicity of the GO, numerous functional groups have always been bonded or integrated into the surface of the material. In addition, physical and chemical dispersion assist nanomaterial dispersion. GO is more difficult to disperse than nanoparticles because of its larger specific surface area. Physical diffusion of GO is improved in water, although it can still be recombined by Ca^{2+} , as reported by Li et al. [49]. Extensive research shows that chemical modification enhances GO dispersion in cement matrix [50].

If the first method works or not depends on how well the surfactant and cement get along with each other. For their GO dispersions, Zhao et al. [49] and Long et al. [50]

employed amino sulfonic acid, aliphatic, naphthalene, and polycarboxylate superplasticizers. When added to cement-based products, each superplasticizer improved GO dispersion. When it came to alkaline dispersion and cement compatibility, polycarboxylate superplasticizer was the clear winner.

Instead of using a powder to mix the nanomaterials, try using a liquid [51]. Ultrasonication, high-shear mixing, electromagnetic stirring, surfactants, and chemical surface modification can also produce a homogeneous aqueous nanomaterial suspension. Alternative methods [52] are covalent bonding or functionalization. Ultrasonication is a useful tool for assisting in the dissolution of nanoparticles in liquids [49]. Because of the chemical interaction that takes place between the carboxyl groups of GO and Ca^{2+} [49, 51], GO can only be distributed in water through the use of physical methods. Chemical modification of the GO makes it more useful by adding functional groups to the surface of the GO or by building covalent bonds with dispersants. When substances go through a chemical change, they invariably introduce new chemical agents into the hydration system. This might lead to incompatibility if the two systems are not compatible with one another. The process of modifying anything chemically is one that is time-consuming and expensive [51, 53].

The majority of studies combined the GO aqueous dispersion with solid objects by mechanically stirring the mixture or by using ultrasonication. Calcium ions react with the deprotonated carboxyl groups of GO when they are introduced into the cement pore solution. As a result, the sheets are unable to disperse throughout the solution. Agglomerated GO is said to be broken up into shards of 100 nm via shear mixing, which is a size much larger than the 1 nm GO sheets, as stated by Lijun et al. [54]. According to these reports, the performance of cement composites is affected not by loosely dispersed GO sheets but rather by GO agglomerates. When substances go through a chemical change, they invariably introduce new chemical agents into the hydration system. This might lead to incompatibility if the two systems are not compatible with one another. The process of modifying anything chemically is one that is time-consuming and expensive [51, 53].

3. GO-Modified Cement Performance

Construction has used ordinary Portland cement since its 19th-century inception. “Faster, higher, and stronger” building has raised cement-based material expectations. Cement makes concrete and mortar. Brittle material has strong compressive strength but low tensile and flexural strength. Cracks easily occur in usage, reducing performance and lifespan [53, 54]. Cement-based products increase energy and pollutants [52, 55].

It is possible for the material’s microscopic pores to communicate with one another and expand after being loaded. This results in a reduction in the material’s tensile strength and capacity for deformation. Cement-based composites are porous and heterogeneous. Cement hydration products quickly deteriorate as a consequence of high pore density, which leads to poor durability and high costs associated with maintenance [56, 57]. Cement hydration products are prone

to rapid deterioration because of the high concentration of pores. Fortifying items created with cement with cementitious composites, chemical and mineral admixtures, or decreasing the water-to-binder ratio is one way to increase the durability of cement-based products [58]. Nanomaterials have been shown to increase the mechanical properties of materials that are based on cement, in addition to increasing their longevity.

Nanoparticles and macromaterials differ in mechanical, chemical, thermal, and magnetic characteristics. They are able to find solutions to issues that cannot be resolved using conventional methods [59]. Nanomaterials have the power to manage nanoscale fissures in cement-based materials, transforming them into microcracks [60, 61]. This is possible due to the fact that the majority of hydration products and gel pores have a size of nanometers. The properties of bulk materials can be altered as a result of processes occurring at the nanoscale [62–64]. Graphene has emerged as a topic of significant interest as of late. Recent developments in graphene-based nanomaterials have given the scientific community reason to be optimistic. The application of graphene in goods made with cement has recently garnered a lot of attention.

3.1. The Effect of GO-Blended Cement-Based Composites—Workability. If the combination works well, it may have desirable properties such as low resistance to deformation after molding, high strength as well as stability, and protection against engineering disasters approximating collapses and fissures. New studies on GO cement materials confirm that GO decreases cement slurry fluidity.

Wang et al. [65] found that GO enhances cement hydration and decreases cement slurry-free water. Li et al. [43] observed that chemically cross-linking GO microflakes with calcium ions promotes water retention in GO aggregates. GO reduces concrete slump and cement slurries [66]. Naphthalene, polycarboxylic acid, or silica fume can restore cement-based composites’ workability [67–69].

According to Wang et al. [65], GO helps the hydration process of cement, and at the same time, the amount of free water in the cement slurry is reduced, which makes the cement less fluid. Table 1 demonstrates that GO has a negative impact on workability. Because GO has such a large surface area and functional groups that are hydrophilic, it may be able to absorb water. As a consequence of this, the cement grains have a reduced need for water as a lubricant, but there is an increased resistance to sliding [70]. Because well-dispersed GO has a higher specific surface area, more free water needs to be bound to GO sheets before the fresh cement composites that are produced may be worked with [70]. It has been hypothesized that the presence of GO particles in cement composites makes the mixture less workable [43].

3.2. The Effect of GO-Blended Cement-Based Composites—Mechanical. The mechanical properties of cement composites are essential in various contexts. The mechanical properties of cement composites have a direct effect on the efficiency and durability of engineering applications. Evidence suggests that the addition of GO can greatly improve the mechanical

TABLE 1: Fresh cement composites and the impact of GO on their workability.

Composition	W/C	% of GO	Test method	Fluidity variation	Refs.
Paste	0.5	0.03	Slump test (mini)	34.6% lesser diameter	[70]
Paste	0.5	0.05	Slump test (mini)	41.7% lesser diameter	
Mortar	0.37	0.05	Digital rotary viscosity method	15.2% less fluidity	[43]
Paste	0.4	0.08	Slump test (mini)	GO decreased diameter and increased yield stress and viscosity.	[71]
Paste	0.29	0.05	Rotary viscometer	Fluidity dropped 54.4%.	[72]
Paste	0.35	0.05	Brook field RST-Cc rheometer	70.3% less fluidity.	[61]
Paste	0.4	0.03	Slump test (mini)	21% lower slump flow diameter	[73]
Mortar	0.5	0.1	Slump test (mini)	Drop in flow of 27.8%.	[74]
Mortar	0.66	0.2	Slump test (mini)	18.8% lower workability	[72]
Concrete	0.2	0.03	Slump test and slump flow test	Slump flow decreased 8.3% and slump decreased 15.6%.	[75]

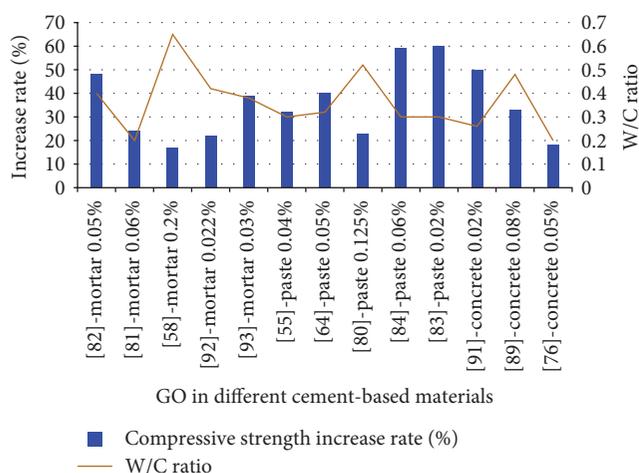


FIGURE 2: Enhanced compressive strength in cement composite specimens reinforced with graphene oxide [1].

qualities of cement-based materials when employed within the acceptable dosage range. Compressive, flexural, and tensile strengths of cement-based materials are illustrated in Figures 2–4 [61, 71–76], respectively. Adding even a modest amount of GO to a material has been shown to significantly improve its mechanical qualities. Several research have reached different conclusions about the optimal starting doses and maximum increases. Although a “ideal” level of GO content has not been determined, studies have shown that concentrations between 0.02% and 0.06% are acceptable [36].

We observed that even a small amount of GO significantly increased the compressive, flexural, and tensile strengths of cement composites. The following procedures have been proposed in the literature as reinforcements: Because of its exceptional mechanical properties, GO can be investigated for use as a reinforcing material in cement composites. As a result of chemical interaction at the GO/matrix interface, load transfer efficiency can be increased [77], cement hydration can be sped it up [78–80], and GO can decrease porosity, density, and fracture propagation at the initiation stage [51, 81–83].

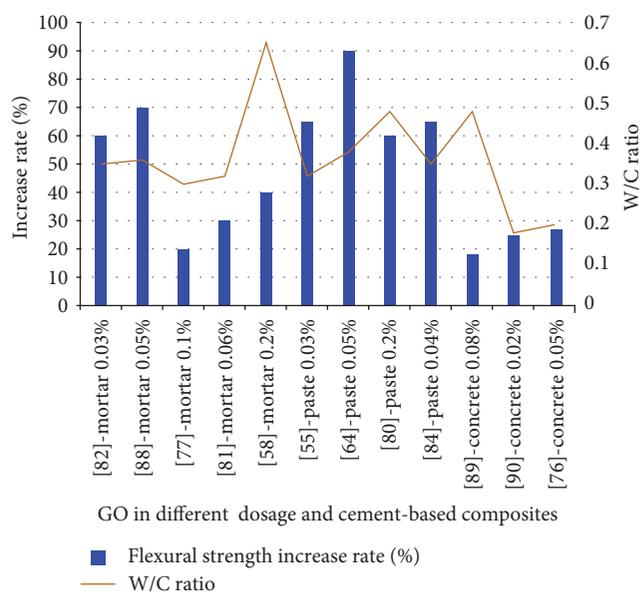


FIGURE 3: Flexural strength of GO cement-based products at various doses [1].

There have been many investigations into the impact of GO content on mechanical properties, and the general law depicted in Figure 5 summarizes these findings. If enough GO is added to cement mortar, the mortar’s mechanical characteristics will improve. However, even when the W/C ratio and GO dosage are identical, the increase in mechanical strength is not. Variations in outcome may have origins in variables like GO dispersion, cement type, production process, and curing conditions.

Gholampour et al. [84] conducted an experiment where they mixed GO into cement mortar at eight different weight percents and discovered that adding 0.1 wt% of GO raised the mortar’s compressive and tensile strengths by 77% and 37.5%, respectively, after 28 days. The rate of increase in strength drastically decreased around 0.01 wt%. Compressive strength is maximized at 0.05 wt% GO, while tensile and flexural strengths are maximized at 0.03 wt% GO (78.6% and 70.0%),

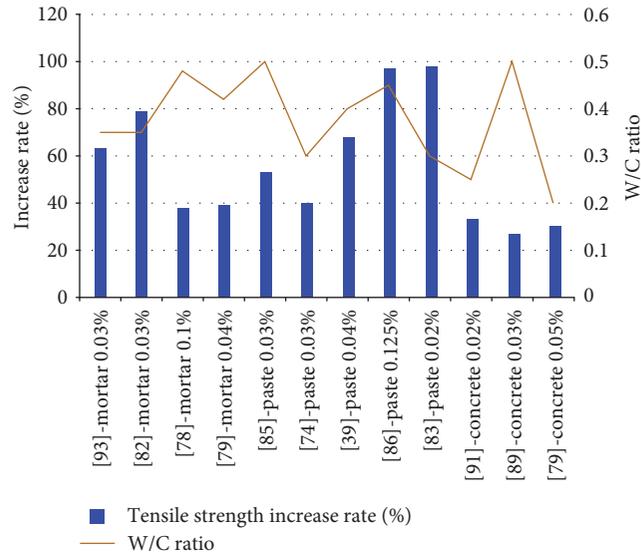


FIGURE 4: GO-reinforced cement composite tensile strength [36].

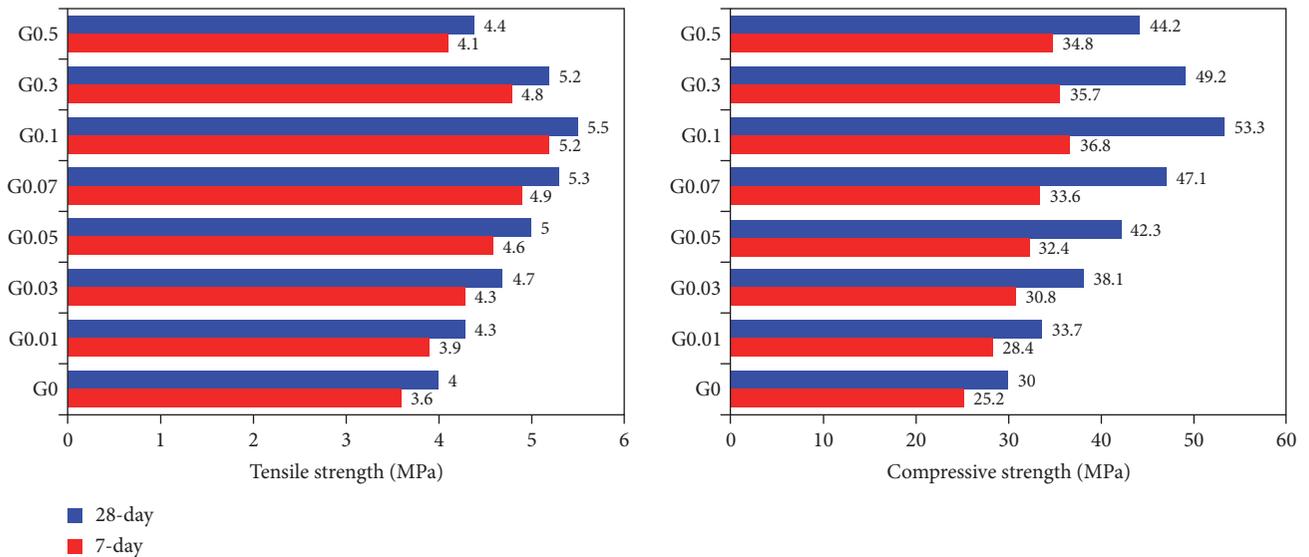


FIGURE 5: The tensile and compressive strength of GO-cement mortar after 7 and 28 days with different amounts of GO [84].

according to research by Lv [85] (47.9%). In addition, the data suggested that the 3-day strength increased at a higher pace than the 28-day strength, which indicated that the impact of GO on early strength was more substantial. Comparable tendencies were also discovered [86], which shows that this is a common occurrence.

According to the findings of Jyothimol et al. [87], the optimal level of compressive strength, split strength, flexural strength, modulus of elasticity, and impact resistance is achieved with an rGO substitution of 0.5% by weight of the cement. It was discovered that the characteristics were lessened as a result of a 0.7% decrease in the rGO content. According to the findings of Wang et al. [88], the highest strength of all the specimens increased by 40.36% after 3 days

when the GO content was 0.01%. This was in comparison to the control cement specimens. After 28 days, the tensile strength of mortars containing 0.03% GO rose by 53.77% when compared to control cement specimens. This was determined by comparing the two types of mortars to each other, shown in Figure 6.

Research into GO's effect on cement composites is ongoing in the building sector. In 2021, a construction firm called Nationwide Engineering will finish laying the first slab of graphene concrete intended for widespread commercial use anywhere in the globe. In addition to boosting concrete strength by 30%, this concept can cut carbon emissions by 2%. The construction industry is one of the most common applications for nanoparticles.

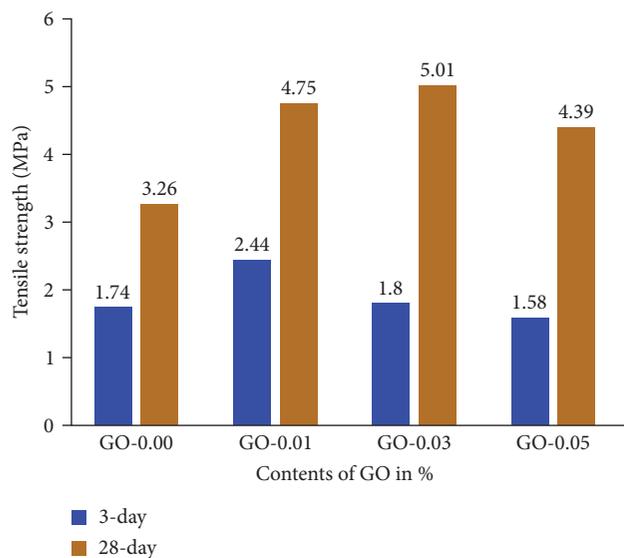


FIGURE 6: Effects of different amounts GO to tensile strength of cement mortar [88].

There are sufficient data to suggest that the incorporation of GO into cement composites can improve their mechanical properties. However, the majority of recent research has been on GO's usefulness in cement paste or mortar with a high water-to-cement ratio. This is because these applications are the most common ones. Only a small portion of the available research literature has investigated how the effects of GO on the reinforcing characteristics of concrete with a low water-to-cement ratio. Nevertheless, structural applications of GO have received scant consideration up to this point. Further in-depth research on the reinforcing capability of GO in concrete with extremely low water-to-cement ratios or on a big scale is required before it can be integrated into building practice. This is because the ratio of water to cement in the concrete must be exceedingly low.

3.3. GO-Modified Cement Composite Microstructure. Numerous studies have revealed that GO-induced microstructure changes in cement-based materials increase macro-performance. Cement-based materials have three basic microstructures: pore characteristics, hydration product microstructure, and interface transition zone microstructure. Most research shows that GO can reduce cement matrix porosity, optimize pore distribution, and compact the matrix microstructure, boosting mechanical strength and durability.

Gong et al. [81] found that adding 0.03 wt% GO to cement composites brought the porosity down by 13.5%. When compared to blank samples, GO-modified samples had 27.7% fewer capillary pores with diameters of 10 nm or less but 10 μm or larger, 36.7% more gel pores, and 36.7% smaller average pore diameters. GO has the ability to minimize the total pore area, median pore diameter, average pore diameter, and porosity of cured cement paste while

also uniformizing the pore diameter of the cement paste [69] (with median pore diameter close to the average diameter). According to Sharma and Kothiyal's [82] research, smaller GO is more effective at reducing porosity. It was discovered by Wang et al. [68] that hardening increased the impact of GO. The early stiffness of gel pores can be affected by GO. GO has an effect on both the tiny and the large pores as people age.

In a significant number of studies, researchers have made extensive use of scanning electron microscopy in order to explore the impacts of hydration on product microstructure (scanning electron microscope (SEM)). Figure 7 [85] is a collection of micrographs taken with an SEM of cement paste that had been fortified with varying amounts of graphene oxide (GO). In the absence of GO (G00), needle- and rod-shaped, disordered layered hydration crystals can be observed to form (Figure 7(a)). After adding 0.01–0.03 wt% GO, the crystals began to thicken and entangle, taking on the appearance of flowers (Figure 7(b)–7(d)). When 0.04–0.05 wt% GO is added to the hydration products, those products begin to crystallize into the shape of regular polyhedrons (Figures 7(e) and 7(f)), and the overall structure begins to become more compact. Because the hydration products of polyhedron crystals have a stronger compressive strength than those of flower-like crystals, cement mortar with a high concentration of GO has a greater tensile strength than mortar with a lower level of GO. This is because the GO level in the lower level of mortar.

Examining how GO concentration changes the microstructure of cement mortar over time, Lv et al. (Figure 8). The results showed that the rod-like crystals almost completely disappeared with age, but the density of the hydration products increased with age in older specimens with a low GO concentration (0.01–0.04 wt%). The hydration products of high-concentration GO samples (0.05–0.06 wt%) accumulated densely after 7 days of curing, and bigger polyhedral crystals with an interconnected structure emerged after 28 days of curing. Compressive strength appears to be affected by both the GO concentration and curing time in cement-based materials, as indicated by this research.

Addition of GO to cement-based materials has been shown to improve their microstructure by lowering matrix porosity, refining pore structure, increasing the density of hydration products, and strengthening the interfacial transition zone. Graphene oxide-treated cement-based materials exhibit enhanced macroscopic properties (mechanical strength and durability).

Overall, GO enhances the hydration process of cement, which in turn improves its mechanical properties [76] by shortening the latent hydration time of the cement, increasing the development of the C3S phase, improving the formation of the CH, and generating intermixture multiphase. It has been found that the improved mechanical properties can be attributed to the microscopic optimization that causes the GO to generate high interfacial adhesion with the negative calcium divalent ions in the C–S–H gel.

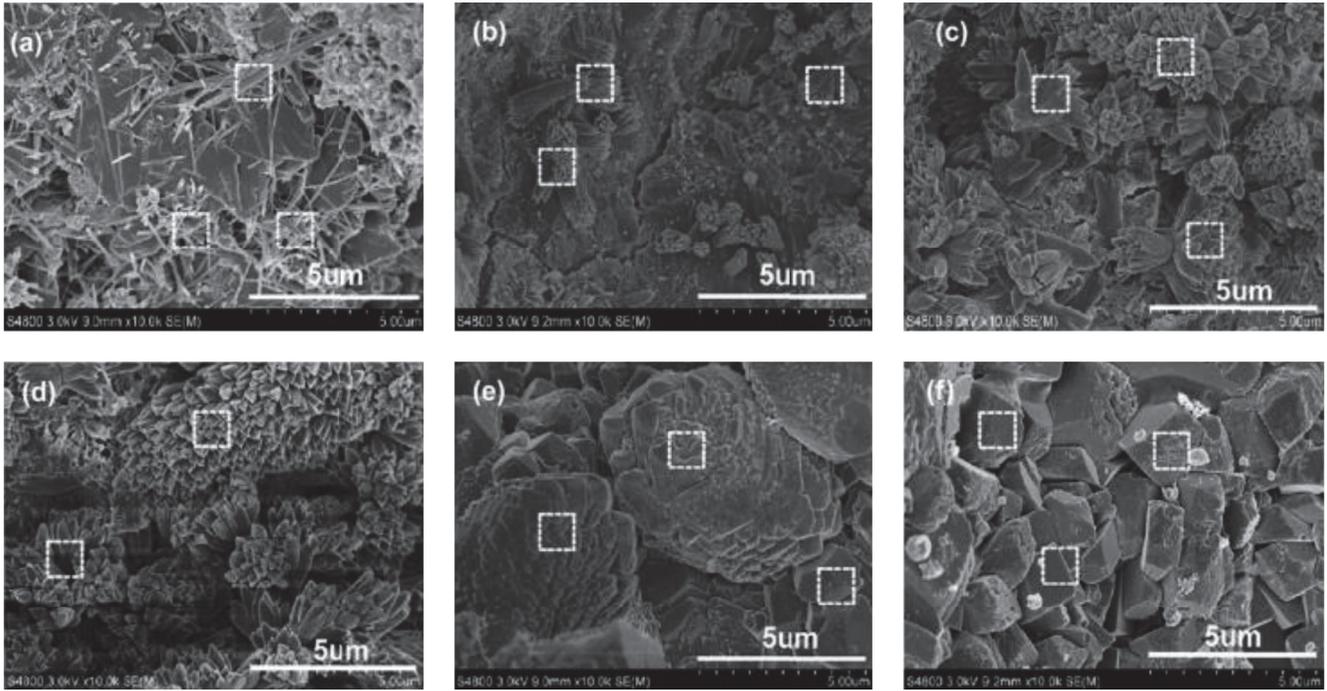


FIGURE 7: (a) GO-0%, (b) GO-0.01%, (c) GO-0.02%, (d) GO-0.03%, (e) GO-0.04%, and (f) GO-0.05% of 28-day-old cement composite SEM images [85].

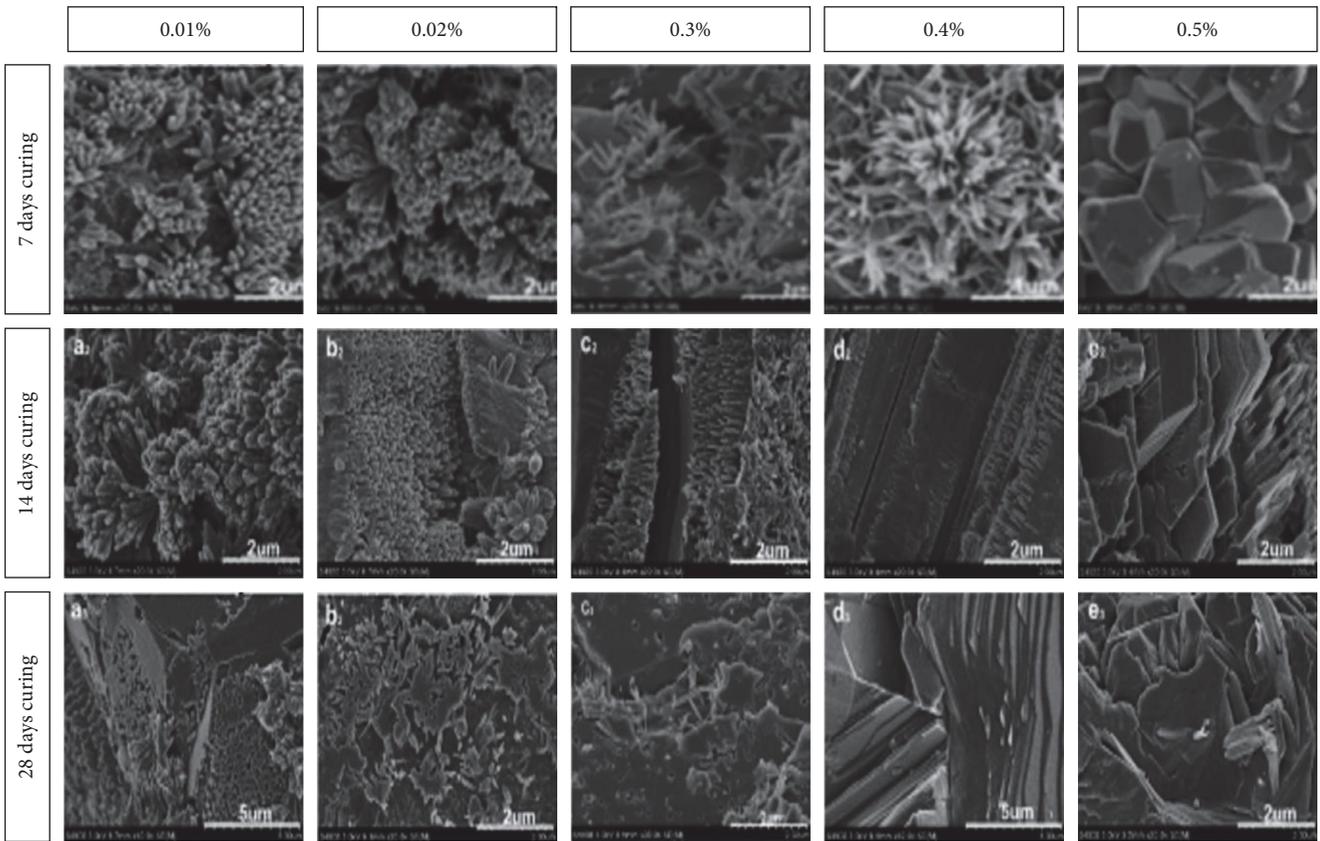


FIGURE 8: Surface SEM image of cured and hardened cement pastes containing GO [79, Figure 8].

4. Conclusion

This paper reviews recent cement-based GO applications. Research suggests the following:

- (1) Alkaline cement paste and high Ca^{2+} content cause GO to agglomerate. GO dispersion can be physical or chemical. Mechanical stirring and ultrasonic dispersion are unstable. GO dispersion is good after chemical modification but expensive.
- (2) The best dispersion effects can be obtained with polycarboxylate superplasticizer and ultrasonic dispersion; therefore, these methods have been extensively investigated.
- (3) GO's high specific surface area and robust van der Waals contact between layers make cement-based products less effective. Polycarboxylate ether's electrostatic repulsion and steric hindrance diminish GO's productivity losses.
- (4) The compressive, tensile, flexural, elastic modulus, and fracture performance of cement-based materials are all improved by the addition of a little quantity of GO.
- (5) The main characteristic of GO's effects on cement-based composite microstructures is as follows:
 - (a) Reduction in porosity as well as improvement in pore structure.
 - (b) Controlling hydration product morphology for homogeneous and complex microstructure.
 - (c) The interface transition zone reinforces paste-aggregate connections. Cement composites have undetermined GO reinforcement.
- (6) Reduce the amount of money spent on maintenance.

Data Availability

All the data associated with this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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