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A COMPREHENSIVE REVIEW OF GRAPHENE OXIDE MODIFIED CONCRETE FOR ENHANCED MECHANICAL AND DURABILITY PERFORMANCE

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ABSTRACT

Graphene oxide (GO) has become an attractive nanomaterial in modifying cementitious composites owing to its high specific surface area, two-dimensional configuration, and functional groups containing oxygen atoms. The addition of GO into concrete has become an interesting field of research due to the capability of GO in improving the mechanical properties of cementitious composites, altering the microstructure of cement paste and enhancing durability against the effect of deteriorative environments. This paper gives an extensive review of the published literature on GO modified concrete especially focusing on its mechanical and durability performances. The review covers the features and application of GO in concrete, GO dispersion method, its interaction with hydration products of cement, and impact of GO on pore structure and interfacial transition zone. The literature survey indicates that well-added GO increases compressive, tensile, and flexural strengths through the promotion of hydration reaction, modification of pore structure, strengthening of cementitious matrix and restriction of cracking. Regarding durability performance, the inclusion of GO has shown the reduction in water absorption and permeability, enhancement of durability against the effects of chlorides, carbonation and other forms of deterioration. Nevertheless, the performance of GO-modified concrete is highly sensitive to the amount of GO, dispersion method of GO, composition of concrete, water-to-cement ratio, mixing and curing processes.

Keywords: *Graphene oxide; modified concrete; nanomaterials; mechanical properties; durability; cementitious materials; microstructure; pore refinement.*

1. INTRODUCTION

Increased demands in terms of the strength and durability of concrete have led to research efforts in the field of nanotechnology-related modifications of cement-based materials [1]. The use of conventional additives and supplementary cementitious materials allows one to enhance certain properties of concrete; however, the efficiency of such additions can depend on the material composition, dosing and environment-related factors [2]. Nanomaterials constitute a separate source of potential for the development of materials because of their extremely small particle size and high surface activity that can be used to interact with cement hydration products on a micro- and nano-scale [3]. In this connection, graphene-related materials, namely GO, have become an increasingly popular topic in relation to improvement of several properties of cement-based composite [4].

The behaviour of GO in concrete depends on its physical and chemical properties [5]. Oxygen-containing functional groups present on the GO surface can provide the interaction of the material with cement particles and hydration products; furthermore, its two-dimensional structure can serve as a basis for the modification of the internal matrix [6]. These effects can be reflected in the changes in terms of hydration and pore structure and thus influence the development of strength and the protection from water and other aggressive agents [7]. However, the performance of GO-added concrete reported in the existing literature varies significantly because of the differences in terms of the characteristics of GO, dosing, dispersion methods, concrete composition, curing regime and other factors [8].

In this connection, some experimental studies have been aimed at the analysis of the link between GO addition and mechanical and durability-related characteristics of the material [9]. Although individual studies report some positive results concerning the increase of strength, crack resistance, permeability and durability of the material, it is necessary to analyze the findings jointly in order to obtain an idea about the properties of GO-added concrete [10]. A review of the existing literature can allow establishing the general effect of GO, identifying the key mechanisms behind performance enhancement and obtaining an idea of the potential of GO as a modifier for cement-based construction materials [11].

In light of the above, the present review is aimed at the consideration of the use of GO in concrete in terms of its effect on the mechanical and durability characteristics of the material. This review analyzes the influence of the characteristics of GO, its dosage and dispersion as well as the hydration behaviour and microstructure of the material.

1.1 Graphene Oxide Modified Concrete: Background and Research Context

Concrete is one of the most popular construction materials owing to its high mechanical properties, versatility, availability and economical cost [12]. Nevertheless, the existing conventional concrete features such limitations as low tensile strength, brittle behavior, susceptibility to cracking, high permeability, deterioration in aggressive environments and others [13]. In order to overcome the mentioned drawbacks, there are developed new cementitious materials reinforced by nanomaterials. GO is regarded as a prospective nano-additive owing to its high specific surface area, nanometer size, mechanical properties and oxygen-containing functional groups [14].

The addition of GO to concrete affects processes of cement hydration, pores formation, interfacial bonding and cracks formation [15]. The GO sheets may be considered as the sites of the formation of hydration products and refinement of pores in the cementitious matrix, which can positively affect such parameters of the material as compressive, tensile and flexural strength, its permeability and the resistance to degradation [16].

The behavior of the modified concrete using GO highly depends on some parameters, such as dose of GO, its good dispersion, water-cement ratio, mixing method, chemical composition of cement and others [17]. Good dispersion of GO sheets is rather important since the agglomeration of GO sheets negatively affects its performance. Therefore, the review of the literature is rather important in order to evaluate the influence of GO on the properties of concrete.

1.2 Objectives of the Study

The objectives of this review are to:

- Examine the existing literature on graphene oxide incorporation into concrete and cementitious materials.
- Review the influence of graphene oxide on the mechanical properties of concrete.
- Evaluate the influence of graphene oxide on the durability characteristics of concrete.
- Summarise the mechanisms through which graphene oxide modifies the microstructure and overall performance of concrete.

2. GRAPHENE OXIDE IN CEMENTITIOUS MATERIALS

Graphene oxide (GO), which stands out with its unique nanostructure and oxygen-containing functional groups, has become widely popular for the modification of cement-based systems due to its high specific surface area. Its application in such systems has been extensively studied in order to improve the interaction between cement particles and hydration products as well as modification of the cement matrix [18]. Research works in the field have considered the effect of GO on the hydration process, pore structure, interfacial bonding, mechanical properties and durability of cement-based materials including cement paste, mortar, and concrete.

The efficiency of GO as a concrete nano-additive depends on a number of interdependent factors. Namely, the properties and surface chemistry of GO determine its ability to interact with the components of cement-based systems. The way of the incorporation and dispersion of GO in the system affects its spatial distribution in the matrix, after which GO may take part in the hydration process, participate in pore refinement and increase the cohesiveness of the cement matrix. Moreover, the quantity of incorporated GO matters since the insufficient or excess amounts of the additive might affect the dispersion and performance of the composite material differently.

2.1 Properties and Characteristics of Graphene Oxide

GO is a two-dimensional nanomaterial made up of carbon atoms. GO is obtained through the process of oxidation of graphite. GO contains a large specific surface area, nano-level thickness, and various types of oxygenated functional groups such as hydroxyl groups, epoxy groups, carbonyl groups, and carboxyl groups. These features make GO to have high surface activity and interactions with the cement particles and hydration products. The 2-D structure of GO

makes GO to be able to interact with the cement matrix on the nano-level, hence being used in the modification of properties of cementitious materials.

2.2 Incorporation of Graphene Oxide into Cementitious Materials

GO has been used in various cementitious systems, such as cement paste, mortar, normal concrete, and high-performance concrete. The studies related to GO have mainly used rather limited amounts of GO due to its huge specific surface area and strong reaction with cementitious compounds. Inclusion of GO may affect hydration process, density of matrix, porosity, strength formation and durability properties. The performance of GO depends on various factors, which include the amount of GO, w/c ratio, composition of cement, mixing and curing methods. Thus, proper proportioning of GO is critical to gain the improvement in concrete performance. Several review papers have reviewed the inclusion of GO in various cement-based systems.

Figure 1: Concrete mixing and placement during the preparation of cementitious specimens.

2.3 Dispersion of Graphene Oxide in Cement Matrix

The uniform dispersion of GO is considered one of the main aspects that affects the effectiveness of the use of GO-modified concrete [19]. This is because of the large specific surface area and a high level of interaction between single sheets; GO has the potential to form aggregates when dispersed without proper dispersion. The formation of aggregates may lead to uneven distribution of GO and the formation of weaker zones in the cement matrix. Several methods have been used in order to improve dispersion such as ultrasonication, mechanical mixing, chemical dispersants, and a combination of several of these methods. Good dispersion will help GO sheets to be dispersed in an even manner and increase interaction with cement and its hydration products.

2.4 Influence of Graphene Oxide on Cement Hydration

GO has the potential to impact the hydration process of cement through the creation of new surfaces to aid in the nucleation and growth of hydration products. In addition, GO has the potential to have an impact on the nucleation and growth of C-S-H gel, which is one of the major phases for strength gain in cementitious systems. The interaction between GO and hydration products will aid in better development and bonding of the cement matrix. Moreover, the oxygen functional groups on GO will help to enhance the interaction of GO with cement hydration products and thereby create a strong bond with the cementitious phases around it.

2.5 Microstructural Modification and Pore Structure Refinement

The inclusion of GO could alter the microstructure of cement-based composite materials by controlling pore generation, pore distribution, and matrix densification. A good dispersion of GO could lead to the development of refined pores and better densification of the cement matrix, leading to the formation of a refined microstructure. The

refining of the pore structure would limit the permeation of water and aggressive agents into the concrete. Hence, it could be seen that the refining of the microstructure is directly linked to improved performance in terms of enhanced strength and improved durability.

2.6 Interfacial Bonding and Effect of GO Dosage

The reaction of GO with the hydration products can result in enhanced cohesiveness of the cement paste. The functional groups of the GO enable interactions with the surrounding hydration products, contributing to enhanced interfacial bonding and stress transfer. Such interactions are important regarding the ability of the cement paste to resist microcracks formation. Nevertheless, the efficiency of GO depends significantly on the dosage of the additive. At low or moderate levels, GO results in positive effects in the form of enhanced hydration, pore refinement, and interactions with the interfacial phase, while too high dosages might lead to agglomeration and higher water requirements.

Table 1. Summary of Reviewed Studies on Graphene Oxide Modified Cementitious Materials

Author and Year	Topic Covered	Title of the Study
Wang et al. (2020) [20]	Graphene and GO modified cementitious materials, including their properties, modification mechanisms, effects on cement hydration, microstructure, mechanical performance, and potential applications	*Advances of Graphene- and Graphene Oxide-Modified Cementitious Materials*
Hu et al. (2025) [21]	Influence of GO on cement composites, with emphasis on GO characteristics, interaction with cement hydration products, microstructural changes, and resulting performance of cement-based materials	*A Review of the Impact of Graphene Oxide on Cement Composites*
Xu et al. (2018) [22]	Comprehensive assessment of GO reinforced cement composites, covering GO incorporation, dispersion, mechanical properties, microstructure, and strengthening mechanisms	*A Holistic Review of Cement Composites Reinforced with Graphene Oxide*
Udumulla et al. (2024) [23]	Durability of GO-modified concrete, including mechanisms of durability enhancement, permeability, resistance to aggressive agents, practical considerations, and challenges associated with GO incorporation	*Effect of Graphene Oxide Nanomaterials on the Durability of Concrete: A Review on Mechanisms, Provisions, Challenges, and Future Prospects*
Mukherjee et al. (2023) [24]	Fresh properties, mechanical performance, and durability characteristics of graphene-based cement composites, with emphasis on the influence of graphene-based nanomaterials on cementitious performance	*A Review on the Fresh Properties, Mechanical and Durability Performance of Graphene-Based Cement Composites*

3. MECHANICAL PERFORMANCE OF GRAPHENE OXIDE MODIFIED CONCRETE

A significant portion of the existing literature has examined the influence of GO on the mechanical properties of concrete [25,26]. The principal findings can be summarised as follows:

- **Compressive strength:** Many studies have reported an increase in compressive strength following the incorporation of appropriate quantities of GO, primarily due to improved hydration and matrix densification.
- **Tensile strength:** GO can improve tensile and splitting tensile strength by strengthening the cementitious matrix and restricting the development of microcracks.
- **Flexural strength:** Improvements in flexural performance have been associated with enhanced bonding and the ability of GO-modified matrices to resist crack initiation and propagation.

- **Crack resistance:** The nanoscale structure of GO can contribute to crack control by restricting the growth of microcracks within the cement paste.
- **Microstructural contribution:** The mechanical enhancement is closely related to pore refinement, improved hydration, and stronger interaction between GO and cement hydration products.
- **Influence of GO dosage:** Strength improvement is generally dependent on the amount of GO used, with excessive dosages potentially causing particle agglomeration and reducing the expected benefits.
- **Influence of dispersion:** Uniform GO dispersion is an important factor governing mechanical performance because poorly dispersed GO can create local defects rather than strengthening the matrix.

4. DURABILITY PERFORMANCE OF GRAPHENE OXIDE MODIFIED CONCRETE

The durability-related literature indicates that GO can contribute to improved resistance against several forms of concrete deterioration [27,28]. The major observations include:

- **Water absorption:** GO incorporation can reduce water absorption by refining the pore structure and reducing the connectivity of capillary pores.
- **Permeability:** The denser microstructure produced by GO can restrict the movement of water and other harmful substances through the concrete matrix.
- **Chloride penetration:** Several studies have reported improved resistance to chloride ion ingress, which is particularly relevant to the protection of embedded reinforcement against corrosion.
- **Carbonation:** The refinement of the pore network may influence the penetration of carbon dioxide and consequently affect the carbonation behaviour of concrete.
- **Chemical resistance:** GO-modified cementitious materials have demonstrated potential for improved resistance to aggressive chemical environments through reduced permeability and improved matrix compactness.
- **Freeze–thaw resistance:** Improvements in matrix density and reduced water penetration may contribute to better resistance against freeze–thaw deterioration.
- **Microstructural influence:** Most durability improvements are associated with pore refinement, reduced permeability, improved hydration, and greater compactness of the cementitious matrix.
- **Overall performance:** The durability benefits of GO are closely linked to its dosage, dispersion, cement composition, curing conditions, and the specific exposure environment [29,30].

5. CONCLUSION

The research confirms the ability of GO to be considered as an effective nano-additive for improving the mechanical performance and durability of concrete by affecting its hydration, porosity, interface bonding, and cracking. Proper inclusion and distribution of GO have typically led to better compressive, tensile, and flexural strength as well as lower water absorption and permeability and higher resistance to chlorides, carbonation, and chemical attack. Nevertheless, the effectiveness of GO-based concrete has greatly depended on some parameters including dosage of GO, dispersibility, water-to-cement ratio, composition of concrete mixture, mixing process, and curing method. While proper distribution and appropriate amounts of GO have helped obtain denser, tougher, and better-bonded cement matrix, the high content and improper dispersion of GO could result in agglomeration and have negative impacts on the workability and performance of the concrete mixture. All in all, the literature provides convincing evidence of the ability of GO to be used as an advanced nano-material for obtaining durable and tough concrete.

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