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Mechanical Performance of Concrete with Graphene Oxide: Evaluation of Compressive and Splitting Tensile Strength

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Abstract - Concrete is currently one of the most widely used materials in the world, but its production involves the emission of significant amounts of CO_2 due to cement manufacturing. To address this global issue, various materials and methods have been explored. In this context, the incorporation of graphene oxide (GO) into concrete emerges as an innovative solution due to its remarkable physical and chemical properties. GO has been shown to enhance the mechanical properties of concrete, allowing target strength to be achieved with less cement. Therefore, this study aims to evaluate the influence of GO on the mechanical properties and workability of concrete. Four concrete mix designs were evaluated, consisting of a control group and three dosages (0.03%, 0.05%, and 0.08% GO relative to the cement weight). Tests were conducted for compressive strength, split tensile strength, and slump. Results indicate that the 0.08% dosage proved to be optimal, with a 22.71% increase in compressive strength and a 23.37% increase in split tensile strength at 28 days compared to the control mix. However, this dosage exhibited the lowest slump, measuring 139 mm. In conclusion, the incorporation of GO into concrete improves its strength, particularly at early stages, suggesting its potential for structures subjected to heavy loads from the outset.

***Keywords*:** Graphene Oxide, concrete, mechanical properties, compressive strength, splitting tensile strength, CO_2

1. Introduction

Concrete is among the most widely used construction materials globally and accounts for approximately 8% of global CO_2 emissions [1]. In Lima, cement plants significantly contribute to greenhouse gas emissions and other pollutants [2]. To mitigate this environmental impact, sustainable solutions have been investigated through supplementary cementitious materials and additives. For instance, the addition of fly ash to concrete has been studied to partially replace cement in the mix. However, higher replacement ratios tend to reduce strength [3]. Similarly, the use of incinerated solid waste and recycled plastic waste to partially replace fine aggregates and cement in concrete mixtures has been explored. It was found that replacing fine aggregates can slightly increase strength, whereas replacing cement results in reduced strength [4]. Residual glass powder has also been investigated as a partial replacement for cement, yielding slight improvements in mechanical properties [5]. Additionally, studies on the partial replacement of cement with ceramic waste powder showed a slight increase in concrete strength, though it also led to higher water absorption [6].

On the other hand, additives such as GO have demonstrated potential to enhance the mechanical properties of concrete, enabling a reduction in the required amount of cement with minimal dosages [7-14]. However, despite GO's hydrophilic properties compared to pristine graphene, there is a strong interaction between GO sheets, known as Van der Waals forces, which causes nanoparticle agglomeration. Therefore, proper dispersion is crucial to maximize its effectiveness [12]. Techniques such as dry, wet, and ultrasonic dispersion are used for this purpose, with the latter being the most effective when combined with surfactants or superplasticizers [[8], [11], [14]].

This article presents a literature review on the incorporation of GO in concrete and proposes an experimental evaluation using small GO dosages prepared through magnetic stirring, a technique less explored compared to ultrasonic dispersion [7]. This proposal focuses on the Lima region, employing GO dosages below 0.1% of the cement weight, following international practices [[12], [13]].

The research aims to evaluate the effects of GO on the mechanical strength and workability of concrete, contributing a novel approach to civil engineering in Peru and promoting solutions to reduce the environmental impact of cement production.

2. Bibliographic Review

2.1. Graphene Oxide

GO, a graphene derivative, can be described as a single-layer nanomaterial that has garnered interest for its ability to disperse in water, unlike other graphene derivatives, due to the presence of oxygen functional groups in its structure, such as carboxyl (–COOH), epoxy (–O–), hydroxyl (–OH), and carbonyl (–CO) [16] (Fig. 1).

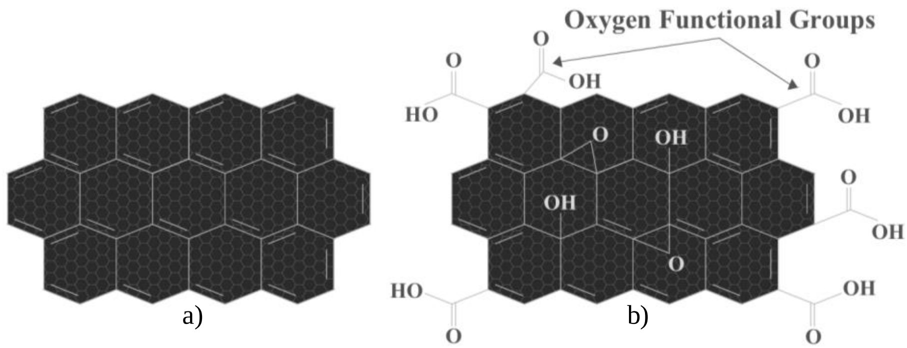


Fig. 1: Chemical structure of (a) Graphene and (b) GO.

The oxygen groups in GO reduce the Van der Waals forces between its layers, increasing electronic repulsion and promoting the dispersion and reactivity of GO within the cementitious matrix [15]. GO has gained popularity as a nanomaterial in recent literature due to its remarkable properties, including a high elastic modulus ranging from 210 to 470 GPa, a specific surface area of 700 to 1500 m^2/g, and a tensile strength of 130 GPa [7].

On the other hand, GO has prominent applications in environmental fields, such as air and water purification, toxic gas removal, and CO2 conversion. In the medical and biological domains, it is used in the development of biosensors and the treatment of genetic disorders. Additionally, it can enhance high-temperature-resistant materials and Portland cement (OPC) by reducing its porosity and increasing its strength, which is particularly relevant to our research [16].

2.2. Reaction of GO in Concrete

According to the reviewed literature, GO can increase the strength of concrete due to two fundamental aspects: its chemical interaction and physical interaction. Regarding the chemical interaction, the incorporation of GO into concrete directly affects the cement hydration process. This process is essential for the development of its mechanical properties and durability, as hydration is responsible for the formation of products such as calcium hydroxide (CH) and calcium silicate hydrate (C-S-H), which are critical for the material's cohesion and strength [17].

In detail, GO's functional groups, such as carboxyl, accelerate the dissolution of cement particles like Ca^{2+} and other ionic species in the mix, promoting faster hydration. This process leads to increased formation of CH and C-S-H crystals, which are directly responsible for the mechanical strength of concrete [18]. Furthermore, due to the hydrophilic nature of epoxy and hydroxyl functional groups and GO's high specific surface area, an additional surface is provided for the nucleation of these hydration products. This promotes more uniform and dense crystal growth, thereby enhancing the strength of the concrete [19].

In terms of physical interaction, GO can fill pores and microcracks within the concrete matrix, which are weak points where cracks initiate and propagate under mechanical loads or adverse conditions [17]. These cracks allow the ingress of corrosive agents, such as chlorides and sulfates, which damage steel reinforcement and other components, compromising structural durability and integrity [22]. Additionally, by occupying these voids, GO increases the density of the concrete, thereby improving its mechanical strength and contributing to more durable and resilient structures capable of withstanding external factors [19].

2.3. Influence of GO on concrete strength

Previous research demonstrates that GO significantly enhances the mechanical properties of concrete. Regarding compressive strength, Table 1 highlights increases ranging from 14% to 61% at 28 days, depending on the dosage used. However, variability in results and optimal dosages is evident, possibly due to testing conditions, the concrete mix preparation method, or the characteristics of the GO used. Despite this dispersion in results, a general trend is identified: higher GO dosages lead to higher concrete strength. For instance, some studies show increases of 14% and 30% respectively with an addition of 0.06% GO [[11], [14]]. On the other hand, using a dosage of 0.08%, more significant increases ranging from 34% to 49% have been recorded [[21], [8]]. Nevertheless, exceptions exist where increases reached only 16% and 21%, respectively, with the same dosage [[10], [12]]. Finally, notable cases include a 0.15% GO addition resulting in a 61% increase [9], and a 0.12% dosage reporting a 33% increase [13].

Regarding splitting tensile strength, comparable trends are observed. Increases range from 12% to 38% at 28 days. For example, a 25% increase has been reported with a 0.03% GO dose [21]. Conversely, a more notable 33% increase was recorded with 0.06%, while a maximum increase of 38% was achieved with 0.08% [8]. However, exceptions also exist; for instance, a 0.12% dosage resulted in a 24% increase [13], and a 0.15% dosage led to a 31% increase [9]. In another study, an 0.08% dosage yielded only a 12% increase [12].

Table 1: Bibliographic summary.

Reference	GO (%)	Maximum increase in strength at 28 days (%)	
		Compression	Splitting traction
(Reddy & Prasad, 2022)	0.15	61	31
(Fonseka, Mohotti, Wijesooriya, Lee & Mendis, 2024)	0.12	33	24
(Fonseka, Mohotti, Wijesooriya, Lee & Mendis, 2023)	0.08	21	12
(Mohotti, Mendis, Wijesooriya, Fonseka, Weerasinghe & Lee, 2022)	0.08	16	-
(Devi & Khan, 2020)	0.08	49	38
(Ren, Bai, Luo, T. Wang, & Z. Wang, 2024)	0.06	30	33
(Susan Ja, Mathew & George, 2023)	0.06	14	-
(Walunjkar & Bajad, 2023)	0.08	34	-
	0.03	-	25

3. Materials

The materials used in this study include Type I Portland cement, in accordance with ASTM C-150; coarse and fine aggregates, meeting the specifications of ASTM C-33; and a superplasticizer additive based on lignosulfonates and organic polymers, compliant with ASTM C-494. The chemical composition of the cement is presented in Table 2, while the characteristics and gradation curve of the aggregates are shown in Table 3 and Fig. 2, respectively.

Table 2: Chemical composition of cement.

Chemical composition	MgO	SO_3	Loss on ignition	Insoluble residue
Content (%)	2.9	2.8	2.2	0.9

Table 3: Characteristics of aggregates.

Characteristics	Fine aggregate	Coarse aggregate
Compacted unit weight (kg/m^3)	1721.26	1611.78
Specific weight (kg/m^3)	2676.87	2751.08
Fineness modulus	2.74	8.73
Size number (ASTM C33)	-	5 (1 in. to #4)
Absorption percentage (%)	1.18	0.43

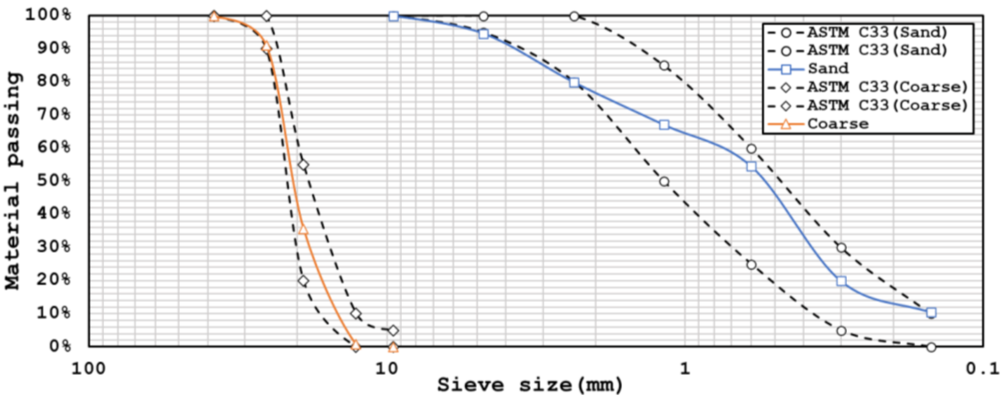


Fig. 2: Granulometric curve of the aggregates.

The graphene oxide utilized in this study was sourced from Xi'an Lyphar Biotech Co., Ltd., located in China. This product is industrial-grade, and its technical parameters are presented in Table 4.

Table 4: Technical parameters of GO.

Appearance	Purity (%)	Number of layers	Laminar diameter (μm)
Black powder	≥ 95	Monolayer	10 ~ 50

3.1. Preparation of the solution with Graphene Oxide

Initially, water and superplasticizer additive were mixed in a magnetic stirrer. Then, the GO powder was gradually and gently added to the mixture while progressively increasing the speed until reaching 1500 rpm for 30 minutes. Finally, this solution was incorporated into the concrete mix along with the remaining design water. The mixture of the solution can be observed in Fig. 3.

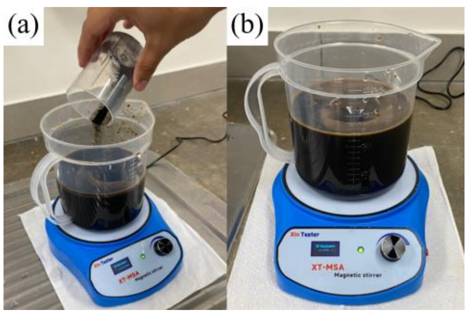


Fig. 3: (a) Incorporation of GO into the moving solution and (b) Magnetic stirring of the GO solution.

3.2. Preparation of concrete samples

To study the influence of GO on concrete, different percentages of GO addition relative to the cement weight were evaluated: 0.03% (PGO-03), 0.05% (PGO-05), and 0.08% (PGO-08). Additionally, concrete without GO addition (PGO-00) was used as a control sample. The proportions for each dosage are presented in Table 5.

Table 5: Concrete mix proportions (kg/m^3).

Specimen	Cement	Water	Additive	Coarse	Sand	GO
PGO-00	323	210	4.56	809.5	999.6	-
PGO-03	323	210	4.56	809.5	999.6	0.097
PGO-05	323	210	4.56	809.5	999.6	0.162
PGO-08	323	210	4.56	809.5	999.6	0.258

4. Methods

Regarding the slump test, it was performed using the Abrams cone, in accordance with ASTM C143. The slump values were recorded for both the reference mix and the samples containing GO. On the other hand, for the compressive strength and splitting tensile strength tests, cylindrical specimens with a diameter of 150 mm and a height of 300 mm were used, manufactured and tested following ASTM C39 (for compression) and ASTM C496 (for splitting tension). Additionally, the samples were evaluated at 7, 14, and 28 days of curing. Fig. 4 shows the execution of the slump and strength tests.

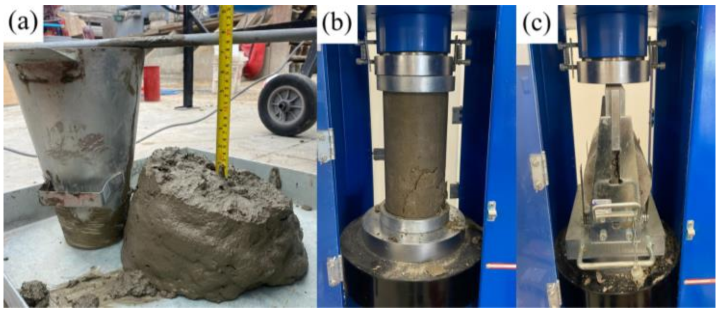


Fig. 4: (a) Slump test, (b) Compressive strength test and (c) Splitting tensile test.

5. Results and discussion

5.1. Workability

In Fig. 5, the slump results for the reference concrete and each GO dosage are presented. It was observed that the slump decreases as the GO dosage increases, dropping from 185 mm in PGO-00 to 139 mm in PGO-08. This suggests that GO reduces the workability of the concrete, likely due to its interaction with the cementitious matrix. A possible explanation lies in the high specific surface area of GO [19], which causes it to absorb a greater amount of water molecules upon contact with the mix [8]. This interaction may affect the lubrication of the aggregates, increasing friction and resulting in a less fluid mixture.

This behavior aligns with previous studies, such as those by Devi & Khan [8] and Mohotti, Mendis, Wijesooriya, Fonseka, Weerasinghe & Lee [10], which evaluated the influence of GO on concrete workability and found that increasing the GO dosage reduced slump. Similarly, this can also be corroborated by the study of Reddy & Prasad [9], which reported a decrease in slump when GO was incorporated into the mix.

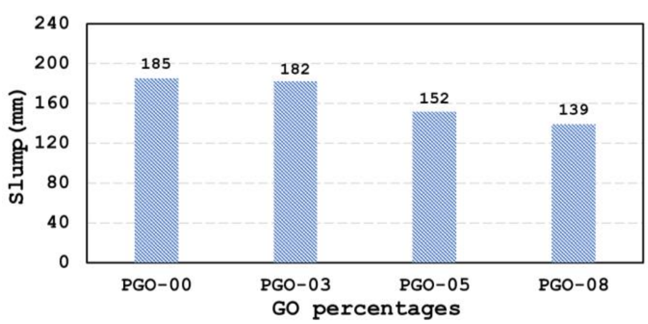


Fig. 5: Comparison of the slump of standard concrete and concrete mixes with GO.

5.2. Compressive strength

In Fig. 6, the results and percentage variations from the compressive strength of cylindrical concrete specimens test for 7, 14, and 28 days of curing are shown. It was found that incorporating 0.08% GO (PGO-08), relative to the cement weight, was the optimal dosage. At 7 days, this dosage showed the highest percentage increase in strength compared to the other GO dosages and the control sample. Then, at 14 days, an upward trend in strength continued for all dosages, culminating at 28 days.

The results revealed that the strength increase at 7 days was higher than that observed at 14 days. This behavior can be attributed to the ability of GO to act as a nucleation agent, promoting the formation of cement hydration products at an early stage, which accelerates strength development at 7 days [17]. At 28 days, the strength of the concrete continued to increase with higher GO dosages, and the maximum percentage increases compared to the control mix were observed at this curing age.

Reviewing the literature, some studies reported similar results, with an optimal dosage of 0.08% and maximum strength increases of 16% [10] and 21% [12] at 28 days, comparable to the 22.71% recorded in the present study. This consistency among investigations supports the validity of the obtained results. However, as highlighted in the literature review, the results exhibit variability. For example, some studies report strength increases of 49% [8] and 34.08% [21] for the same dosage and curing age. On the other hand, an increase of 5% has also been observed with a 0.03% dosage at 28 days [10], a value relatively close to the 8.39% increase obtained in this study for the same dosage.

Additionally, Fig. 6 shows that the results obtained in this study are close to those reported in the literature, particularly from sources using GO dosages similar to those applied in the experimental plan. Nevertheless, the figure also highlights the variability in results for similar GO dosages, confirming the earlier observations regarding the inconsistency in recent studies' outcomes.

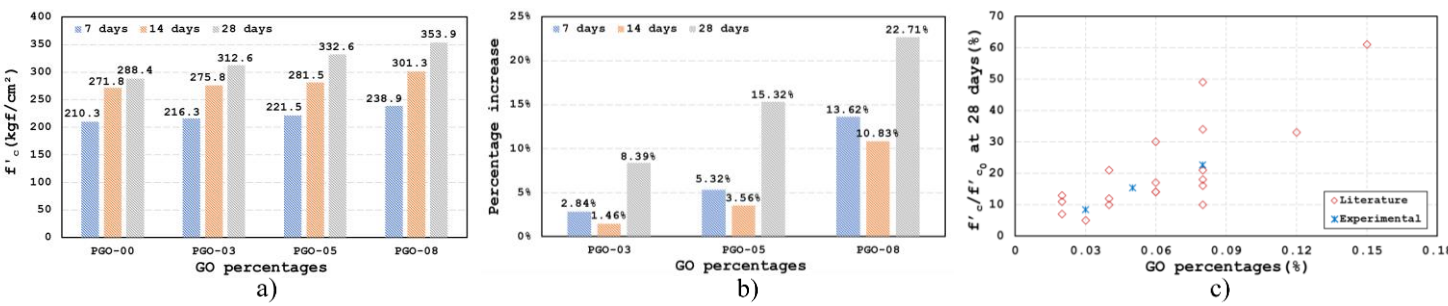


Fig. 6: (a) Compression results, their (b) Percentage variation and (c) Comparison of the results with the bibliography.

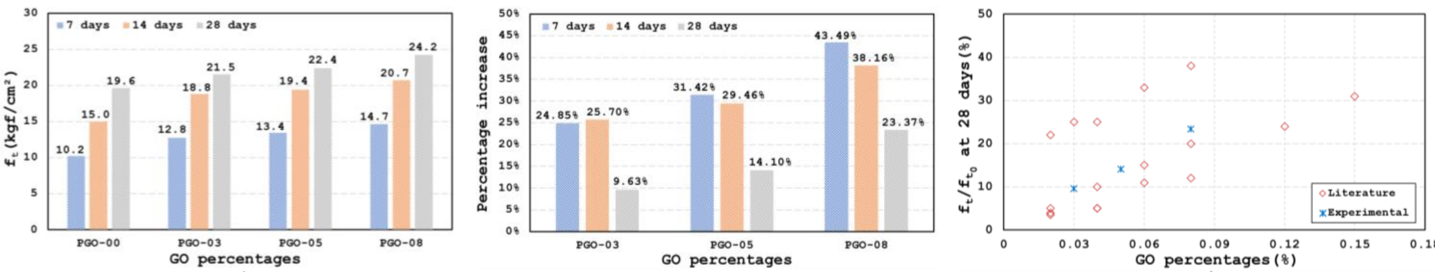
5.3. Splitting tensile strength

In Fig. 7, the results and percentage variations from the splitting tensile strength of cylindrical concrete specimens test for 7, 14, and 28 days of curing are shown.

The results indicate a decrease in the rate of strength gain as the curing period lengthened. For instance, from 7 to 14 days, the rate of strength gain decreased slightly, with this trend becoming more pronounced at 28 days. This trend supports the earlier observation that: GO promotes strength gains at early ages due to its influence on concrete hydration. Additionally, it is noteworthy that the strength increments observed in this test exceeded those recorded in the compressive strength test at 7 and 14 days of curing. However, by 28 days, the strength increments were comparable between both tests. This could be because GO initially has a greater impact on the tensile strength of concrete by improving cohesion and reducing microcracks in the concrete matrix [19].

When comparing the results with the reviewed literature, the tensile strength increases for a 0.08% dosage at 28 days range between 12% and 38% [[12], [8]]. In this context, the 23.37% increase observed in this study aligns with these findings. Furthermore, when comparing the 0.03% and 0.05% dosages with similar studies using close dosages (0.02%, 0.04%, and 0.06% GO), expected ranges of percentage increase can be established. For the 0.05% dosage, the expected range is between 5% and 15%, with this study achieving a 14.10% increase. For the 0.03% dosage, the expected range is 3.5% to 10%, and we obtained 9.63%. Although some studies, such as Walunjkar & Bajad [21], report higher increases (24.81%), our results are consistent with the literature, validating the data obtained and confirming the observed trend.

On the other hand, Fig. 7 shows that the results obtained in this study align closely with some of those reported in the literature. However, the variability in the results is also evident, as there are data significantly higher than those obtained in this research for similar dosages. Furthermore, unlike compressive strength, there is a noticeable trend of linear increase in tensile strength as the GO dosage increases in the reviewed studies.



a) b) c)

Fig. 7: (a) Splitting traction results, their (b) Percentage variation and (c) Comparison of the results with the bibliography.

6. Conclusion

This study evaluated the influence of GO on the mechanical and workability properties of concrete through a literature review and experimental tests. The findings indicate that the use of GO improves mechanical strength, with increases ranging from 14% to 61% in compressive strength and from 12% to 38% in splitting tensile strength, with optimal dosages between 0.03% and 0.08%. Although dosages above 0.10% are less common, some studies reported improvements with dosages as high as 0.15%.

Experimental results confirmed that GO reduces concrete workability due to its high specific surface area, which promotes water absorption and reduces aggregate lubrication. For reference, a 0.08% dosage reduced workability by 24.86% compared to the control mix.

Regarding strength tests, the 0.08% dosage showed the best results at 28 days of curing, with increases of 22.71% and 23.37% in compressive and splitting tensile strength, respectively. Finally, it was confirmed that GO enhances concrete hydration, accelerating strength development at early ages.

Finally, the incorporation of GO into concrete establishes itself as a technically viable solution to reduce the demand and production of cement. Moreover, by enhancing the strength and durability of concrete, it helps decrease the frequency of reconstructions and demolitions, as it extends the service life of structures. Thus, incorporating GO into concrete represents a promising advancement toward more sustainable construction practices, contributing to a reduction in environmental impact.

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