Reducing carbon emissions by strengthening blended cement's functional properties with graphene oxide as a reinforcing filler

Adhit Mandal

Abstract

Cement production accounts for approximately 8% of global CO2 emissions. Cement is made from crushed limestone and aluminosilicate clay and roasted in kilns to produce calcium oxide, the desired product, and CO2. CO2 accounts for 600 grams of the byproduct per kilogram of cement produced. To some extent, the high CO2 emissions have been addressed in the past by using supplementary cementitious materials (SCMs) to replace the clinker. These are industrial (like fly ash) and agricultural wastes (like rice husk) that have already been processed and do not further release any CO2. However, such substitutions often result in a loss of strength. This can be addressed by incorporating nanoparticles to modify or re-engineer the concrete mix. One such nanomaterial is graphene oxide (GO), which is expected to reduce CO2 emissions because the same structural task can be achieved with a lesser amount of cement, since graphene oxide enhances the strength of the concrete mix. This research uses research-grade graphene oxide (instead of pristine graphene due to dispersibility issues) in small percentages (0.01% to 0.05% by weight of cement) to observe the enhancement in mechanical strength and workability of the concrete mix. While the mechanical strength increased significantly, the workability of samples infused with graphene oxide poses a problem because as we add more GO to our cement mix, the higher the slump value of the mix becomes.

Keywords: Blended cement, M40 grade concrete, supplementary cementitious materials, nanomaterials, nanoparticles, graphene, graphene oxide

Introduction

Concrete is the most widely used construction material and the second most consumed material in the world. As a composite, its main constituent is cement, production of which accounts for approximately 8% of global CO2 emissions [1]. Over the past few decades, the global demand for cement has grown exponentially, especially with the rising construction in countries like China and India, resulting in a corresponding growth in CO2 emissions.

$$CaCO_3 \text{ (Limestone)} \rightarrow CaO \text{ (Desired Product)} + CO_2 \text{ (Undesired product)}$$

Clinker (a key component of cement) is made by roasting crushed limestone (CaCO3) and aluminosilicate clay in kilns. The above reaction shows the reason for the high carbon footprint of the cement production process. We see that for every 1kg of CaCO3, 0.44kg of CO2 is released. Taking energy considerations(heat etc.) into account, 600 grams of CO2 is produced for every kilogram of cement we produce. In the past, the high CO2 emissions have been addressed to some extent by using supplementary cementitious materials (SCMs) as partial replacements of Portland cement [2]. These materials, which are industrial wastes (like fly ash from coal-fired power plants, blast furnace slag, silica fume, ferrous and non-ferrous slags) and agricultural wastes (like rice husk), have already been processed and do not further release any CO2. However, such substitutions result in a loss of mechanical strength by upto 20% [3].

This loss in mechanical strength can be addressed by incorporating nanoparticles (like graphene, nano silica, nano alumina, nano titania, carbon nano tubes) to modify or re-engineer the concrete mix. Nanoparticles fill the voids in the concrete mix and lead to lower porosity, higher mechanical strength, and durability. In this research, graphene oxide was tested further. Given its capability to enhance the mechanical strength of the concrete mix, the same structural task can be achieved with a lesser amount of cement and a higher amount of the SCM. Graphene has a single layer of carbon atoms in a hexagonal lattice. Its high tensile strength results from strong covalent bonds of carbon atoms. Its two-dimensional structure gives it a high specific surface area; hence, a very small quantity can increase the strength of concrete [4]. Hence, it is expected to reduce CO2 emissions by as much as 30% [5].

Graphene has different forms and chemical composites. Some of its derivatives include graphene nanoplatelets, graphene oxide (GO), and reduced graphene oxide, which exhibit different physical and chemical properties due to their different molecular structure. In this research, GO has been used to examine the increase in mechanical strength and workability of concrete mix across samples, as it has higher hydrophilicity than the other graphene derivatives, giving it better dispersibility [6].

GO is primarily composed of carbon, oxygen, and hydrogen. The exact ratio of these elements varies depending on the synthesis method and oxidation degree. Because GO has oxygen-containing functional groups attached to the carbon lattice, it is more suited for concrete mixes. These groups, such as hydroxyl (-OH), epoxy (-O-), and carboxyl (-COOH) groups, alter GO's properties, making it more hydrophilic and enabling it to interact with other molecules, thus enhancing its functionality during cement hydration. GO enhances the bond between the reinforcing filler and silicate hydrate (C-S-H) gel that is formed during cement hydration, increasing the concrete's durability [7].

GO can be an effective reinforcing filler in the cement composites used for repairing damaged concrete. Salami investigated the enhancement properties of multiple nanoparticles [8], mainly GO, graphene nanoplatelets, and functionalized graphene, as reinforcing fillers for cementitious composites. The composite exhibited enhanced mechanical properties and environmental benefits, including a 25-33% reduction in carbon footprint when incorporating 0.03 weight of graphene oxide into concrete. This reduction is because we do not need to use as much clinker to achieve the same mechanical strength.

Except in the initial manufacturing process, GO can also be used to recycle demolished concrete. The waste management of Construction and demolition pose an environmental challenge and existing strategies, such as converting this waste to recycled aggregates (RA), result in extreme loss of mechanical performance and durability. Adding GO to RA cement composites can increase compressive strength and lower CO2 emissions. Even a 0.2% GO addition increased the compressive strength of the mortar by 19.2% and flexural strength by 47.5%. GO improves RA cement properties by filling pores, pozzolanic reactions, and bridging cracks due to enhanced interfacial transition zones and increased hydration reactions [9]. Hence by using GO we can increase the use RA cement composites in places other than lightweight applications.

Methodology

Use of Graphene Oxide (GO)

Graphene has dispersibility issues within the cement mix; hence, we use GO. We see the oxygen-containing functional groups in GO act as nucleation sites during the hydration process, allowing for the formation of stronger crystals of other components as seen in Figure 1 [10]. Moreover, the oxidation groups can form intermolecular hydrogen bonds due to the δ(-) charge on the oxygen, allowing it to incorporate easily as seen in Figure 2.

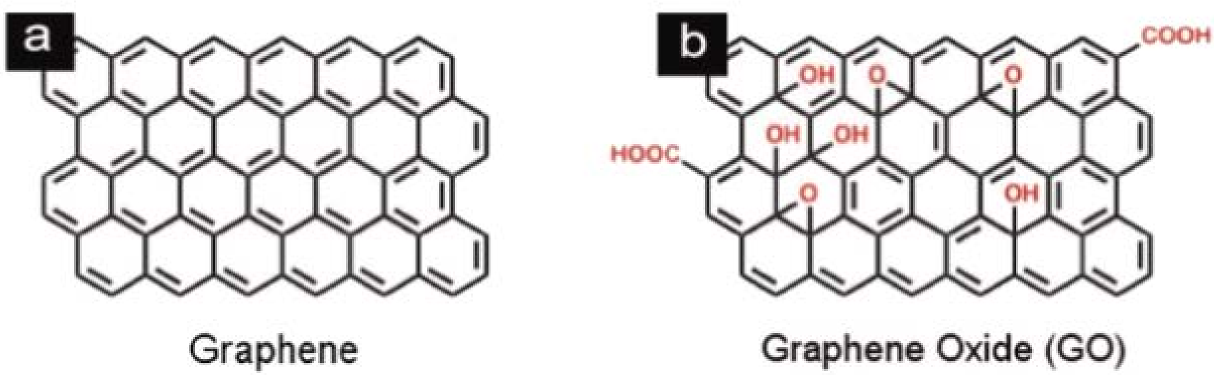

Fig. 1: Representation of (a)Graphene (b)GO

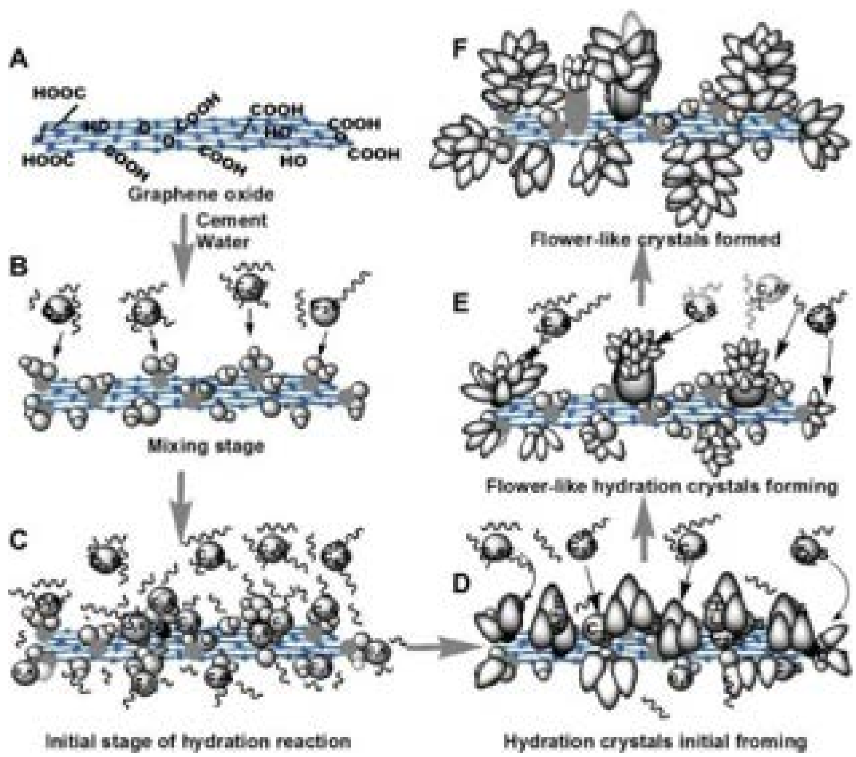

Fig. 2: Shows hydration process based on data from Liu, C.; Huang, X.; Wu, Y.-Y.; Deng, X.; Liu, J.; Zheng, Z.; Hui, D. Review on the research progress of cement-based and geopolymer materials modified by graphene and graphene oxide. Nanotechnology Reviews 2020, 9 (1), 155–169. https://doi.org/10.1515/ntrev-2020-0014.

Preparation of concrete mix samples

For the experiments, concrete mixes made of GO, cement, fine aggregates, and coarse aggregates were prepared. Commercially available research-grade GO was procured. The cement grade chosen was 53-grade fly-ash blended cement. The fly ash constituent as an SCM in this blended cement was 35% by mass of the cement. The term “53-grade” signifies that the cement attains a minimum compressive strength of 53 megapascals (MPa) after a 28-day curing period. River sand was used as fine aggregate, with its most common ingredient being silica (SiO2), which has a notable chemical inertness. It was surface-dried before use. Coarse aggregates comprise gravel and crushed stone (maximum nominal size of 12.5mm), and are used to provide strength, durability, and volume to the concrete mix.

Concrete samples were created using the mix ratio M40 grade as it is the industry standard. M40 grade concrete has a characteristic compressive strength of 40 MPa. This grade was chosen due to its varied applications, such as high-rise buildings, commercial structures, bridges, high load-bearing columns, and heavy-duty pavements. The materials used in the concrete mix – cement, coarse aggregate, fine aggregate - were taken in the ratio of is 4: 2: 1. Water is essential for the strength of the concrete. The quantity of water was fixed at 40% of the weight of the concrete block, to ensure that it remains fully hydrated. The samples were prepared to ensure a consistent density of 2400 kg/m3. Table 1 summarizes the mix of the M40 concrete samples.

Table 1: Specifications for preparation of concrete samples for testing

Features of M40 concrete mix	
Ratio of cement: coarse aggregates: fine aggregates	4:2:1
Density of concrete block (kg/m3)	2400
Weight of Cement (kg)	4.6
Weight of sand or fine aggregates (kg)	1.2
Weight of course aggregates (kg)	2.3
Weight per sample of concrete being tested (kg)	8.1
Weight of water (kg)	3.24

A total of six concrete mix samples were prepared. The ingredients were mixed thoroughly at room temperature, keeping the cement, fine aggregates, and coarse aggregates ratios constant, to create homogenous mixtures. First, the dry mix was prepared, then GO was added to five of the six samples with varying percentage content by weight of cement from 0 to 0.05%, with an increment of 0.01%. Water was added thereafter and mixed thoroughly as seen in Figure 3 and Figure 4.

Fig. 3: Concrete mix sample being created for testing

During the preparation of the samples, water was added slowly to avoid the creation of any lumps, and special care was taken to ensure the absence of any kind of foreign materials.

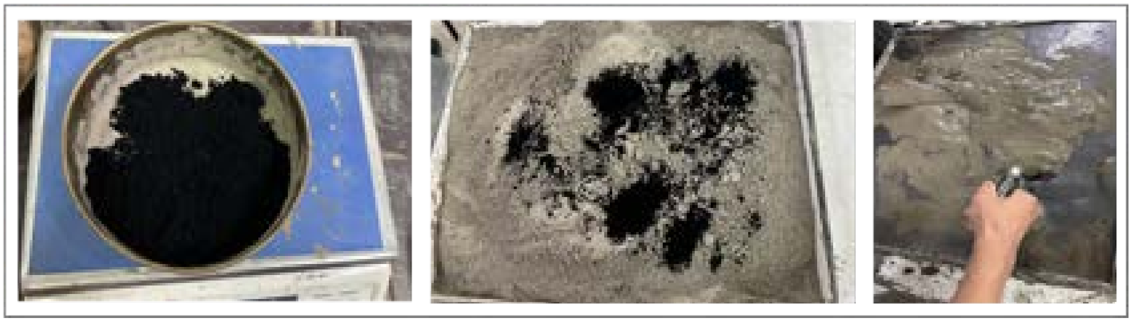

Fig. 4: GO being weighed for use in a concrete sample

The mix proportions and weights of graphene are summarized in Table 2.

Table 2: Proportions and weight of graphene by weight of cement in samples

% GO added	GO amount (grams)
Sample 1 – 0%	0
Sample 2 - 0.01%	0.46
Sample 3 - 0.02%	0.93
Sample 4 - 0.03%	1.39
Sample 5 - 0.04%	1.85
Sample 6 - 0.05%	2.31

Compression strength test of concrete samples

For each of the six samples of concrete mix, three cube molds per sample were prepared (dimensions 15X15X15 cm), to test for compressive strength at 7 days, 28 days, and 56 days, respectively. A total of eighteen cube molds were created for the compression strength test. The upper surface of each mold was levelled with a trowel and was covered with a wet jute bag. Then it was left to set for 24 hours.

Fig. 5: Concrete samples being prepared for compression test

After 24 hours, the concrete cubes were removed from the molds and submerged in water to promote hydration. The concrete samples were taken up for testing compressive strength using a compression testing machine (CTM) having a capacity of 2000 KN. The six samples were taken at 7 days, 28 days, and 56 days of curing. The CTM is designed to apply a compressive load to the sample until it breaks. The apparatus comprises a piston that applies the load to the sample by moving up and down inside a cylinder.

Fig. 6: Compression Testing Machine with a capacity of 2000 KN

The CTM was prepared by ensuring the platens (plates that apply the load) were clean and properly aligned. Each cured concrete sample was separately placed between the plates of the CTM. Until the sample's resistance to the growing load failed and no higher load could be sustained, the load was applied without shock and increased steadily at a rate of about 140 kg/sq cm/min. This test was conducted using the ASTM C349 test method [13].

Fig. 7: Breaking point of concrete block on CTM

The maximum load (in kilo-Newtons) applied to each sample was then recorded. Each of the six samples underwent this process.

Split tensile strength test of concrete samples

The split tensile strength of concrete refers to the ability to resist pulling or stretching forces. It is typically less than its compressive strength, ranging from 10-15% of compressive strength. It plays a crucial role in determining the bending resistance and preventing the crack propagation of concrete structures, particularly in large-scale bridge structures. For the split tensile strength test the ASTM C496 [14] standard test was used, where three cylindrical molds (length 30 cm, diameter 15 cm) per sample were prepared to test for compressive strength at 7 days, 28 days, and 56 days, respectively. A total of eighteen cylindrical molds were created for the test. The split tensile strength was calculated using the formula, $f_{st} = \frac{2F_{max}}{\pi DL}$ where f_{st} is the split tensile strength, F_{max} is the ultimate tensile strength, D is the diameter of the cylinder, and L is the length of the cylinder [15]. We can also define a relationship between the compressive strength and the split tensile strength of the same material according to ACI 318 [16] using the formula $f_{st} = 0.56 . \lambda . \sqrt{F'}$ for S.I. units, where λ is the lightweight aggregate factor, and F' is the compressive strength.

Fig. 8: Tensile strength test of cylindrical concrete block

Slump test of concrete samples for workability

Workability in concrete refers to its ability to be easily mixed, handled, and placed in its intended form, with a minimum loss of homogeneity. A workable concrete mix is crucial for achieving the desired strength, quality, and appearance of the final concrete structure. Poor workability can lead to issues like honeycombing, poor compaction, or difficulty in achieving a smooth finish. The most common test for this is the slump test, which measures the concrete's consistency by observing how much it settles after it is poured in a standard cone and when the cone is removed.

Metal cones with specific dimensions (10 cm top diameter, 20 cm bottom diameter, and 30 cm height) were filled with each concrete sample in layers and then compacted with a tamping rod. The cones were carefully lifted vertically, allowing the concrete to slump. The height of each coned concrete was measured to record the slump value (or the vertical settlement) for the six samples, which is an indicator of the influence of GO on the fluidity of the concrete mix.

Fig. 9: Preparation for slump test

Results and discussion

Results of mechanical strength tests

Compressive strength: The compressive strength of the concrete cubes was calculated by dividing the maximum load applied to each cube during the tests (in kN) by the cross-sectional area of the cube (225 cm^2) and expressed to the nearest MPa or N/mm^2. The results of the compressive strength tests of the six specimens of concrete indicate that all the concrete mixes with GO showcased better compressive strength than the concrete mix without GO. The results of the strength test are summarized in Table 3.

Table 3: Compressive strength test results of concrete samples

GO by % weight of cement	GO weight (grams)	Compressive strength test result 7 days (MPa)	Compressive strength test result 28 days (MPa)	Compressive strength test result 56 days (MPa)
Sample 1 - 0%	0	22.6	26.6	27.4
Sample 2 - 0.01%	0.46	23.7	29.9	31.8
Sample 3 - 0.02%	0.93	24.6	30.2	33.1
Sample 4 - 0.03%	1.39	25.5	33.3	36.4

Sample 5 - 0.04%	1.85	26.2	34.8	37.0
Sample 6 - 0.05%	2.31	26.0	31.3	36.1

GO infusion of 0.01% by weight of cement or 0.46 grams in Sample 1, resulted in the compressive strength going up by 5% in 7 days, 13% in 28 days, and 16% in 56 days. Significant increases were seen in the compressive strength as the dosages were increased by 0.01% in subsequent samples. The maximum increase in compressive strength came for Sample 5, having 0.04% of GO (1.39 grams) in the concrete mix. The increase in compressive strength was 16%, 31%, 35% for curing ages of 7 days, 28 days, and 56 days, respectively, as compared to the original sample without GO.

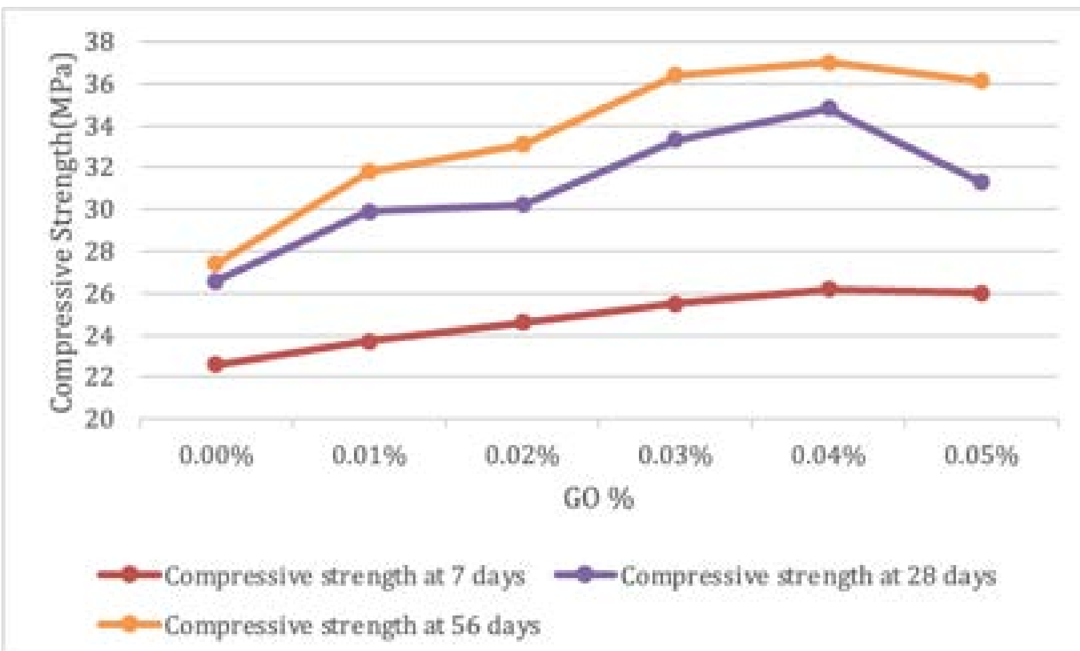

Fig 10: Comparative Analysis of Compressive Strength

However, an excessive dosage of GO adversely affects the mechanical characteristics of the concrete samples, as evident from a decline in compressive strength of Sample 6, having 0.05% of GO (2.31 grams) in the concrete mix. This is largely because GO begins to agglomerate and form clumps because of the van der Waals force, which causes floating, precipitation, and uneven dispersion[11]. As more of GO is added, this agglomeration disrupts the hydration process of the cement and leads to flaws in the end composite.

Results of split tensile strength tests

The results of the split tensile strength tests at 7, 28, and 56 days for the six specimens of concrete indicate that all the concrete mixes with GO exhibited better tensile strength than the concrete mix without GO. The results of the strength test are summarized in Table 4.

Table 4: Tensile strength test results of concrete samples – curing period of 7, 28, 56 days

GO by % weight of cement	GO weight (grams)	Split tensile strength test result 7 days (MPa)	Split tensile strength test result 28 days (MPa)	Split tensile strength test result 56 days (MPa)
Sample 1 - 0%	0	2.49	2.92	3.15
Sample 2 - 0.01%	0.46	2.73	3.44	3.78
Sample 3 - 0.02%	0.93	3.25	3.93	4.24
Sample 4 - 0.03%	1.39	3.29	4.17	4.55
Sample 5 - 0.04%	1.85	3.20	4.00	4.40
Sample 6 - 0.05%	2.31	3.14	3.95	4.34

The findings indicate that when the GO dosage is increased from 0.0% to 0.03%, the split tensile strength of the concrete samples increases. However, when the GO dosage is increased from 0.04% onward, the strength gradually decreases. The concrete Sample 3, having a GO dosage of 0.03% shows the greatest enhancement, indicating that 0.03% is the optimum value of GO dosage for improving the split tensile strength of the concrete mix prepared as per the M40 specifications.

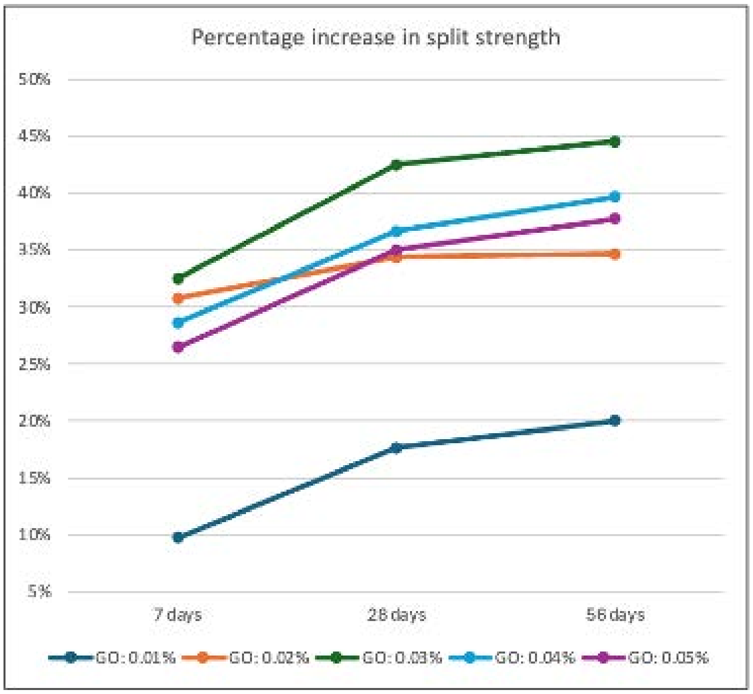

Fig 11: Percentage increase in split strength for the GO-infused samples

Results of slump tests

The slump tests revealed that the concrete mix sample 6, having the highest graphene infusion, was observed to have the lowest slump at 60 mm, and significantly lower (~38% lower) than the ideal slump of the concrete mix without graphene, at 98 mm. The slump of the GO-reinforced concrete samples is seen to reduce with an increase in GO percentage content. A 0.01% infusion of GO reduced slump by 7%, a 0.02% infusion reduced slump by 12%, a 0.03% reduced slump by 19%, and a 0.04% infusion led to 29% lower slump. Thus, the incorporation of GO in the concrete mixes reduces the workability.

Table 5: Results of the slump test

GO by % weight of cement	GO weight (grams)	Slump Value (mm)
Sample 1 - 0%	0	98
Sample 2 - 0.01%	0.46	91
Sample 3 - 0.02%	0.93	86
Sample 4 - 0.03%	1.39	79
Sample 5 - 0.04%	1.85	70
Sample 6 - 0.05%	2.31	60

This is because the high specific area of GO (the theoretical surface area of a single-layer graphene sheet is around 2630 m^2/g) adsorbs water from the fresh mix into the GO nano sheets.8 The hydrophilic oxygenated functionalities attached to the GO nano sheets absorb the water molecules and keep them entrapped. This is because of flocculation and agglomeration formation. The trapped water is unavailable for lubrication and thus reduces the fluidity of the concrete, which decreases the slump. Hence, with increases in GO content in the concrete mixes, their slump value decreases linearly, indicating diminished workability.

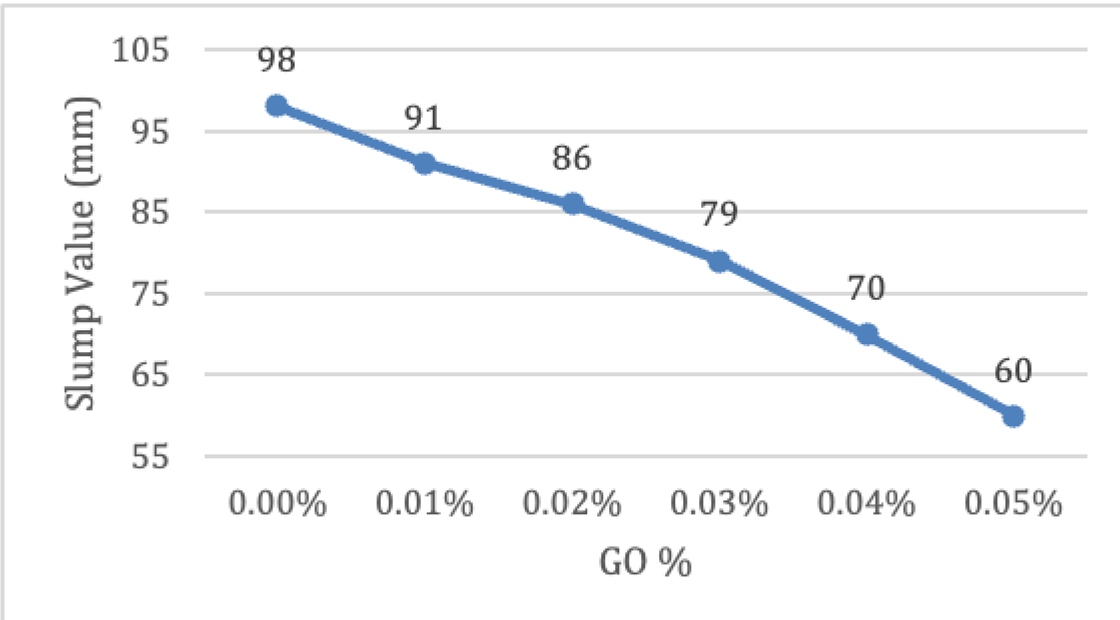

Fig. 12: Slump value of concrete mix samples

The issue of agglomeration needs to be addressed so that the GO is thoroughly dissolved in water, and its inclusion enhances the performance of the concrete mix. This can be managed through dry dispersion techniques or mechanical scattering techniques such as high-shear mixing, ultrasonication, and electromagnetic stirring, using a high-speed shear mixer or an electric concrete mixer [11]. These techniques help to disintegrate stacked GO sheets by weakening the van der Waals forces, exposing more functional groups for improved interactions in aqueous environments. Chemical surface modifications can be undertaken, which will enhance the dispersion efficiency, chemical retention, and stability of GO in highly alkaline environments. These modifications include the use of surfactants such as polycarboxylate ethers, sodium dodecylbenzene sulfonates, lignosulfonates, and anionic agents, which introduce electrostatic repulsion and steric hindrance, thus improving dispersibility [12].

Economic Analysis

The properties of graphene oxide that enhance the cement mix have already been discussed but its real-world application with respect to its economic viability needs to be touched upon. Cement is categorized into multiple grades with different mix ratios. Table 6 shows a detailed list of all the mix ratios.

Table 6: Mix ratios for different grades of cement

Grade of Cement	Ratio (Cement: Fine Aggregate: Coarse Aggregate)
M15	1 : 2 : 4
M20	1 : 1.5 : 3
M25	1 : 1 : 2
M30	1 : 0.75 : 1.5
M35	1 : 0.5 : 1.5
M40	1 : 0.25 : 0.5

Using these ratios, we can calculate price of production using certain standardized values mentioned in Table 7.

Table 7: Standardized Price for each component of the cement mix [17]

Component	Price (Rupees/kg)
OPC Cement	8.6
53-Grade Fly Ash Blended Cement	6.8
Graphene Oxide	40000
Sand (Fine Aggregate)	3
Coarse Aggregate	1

Figure 13 shows how the price of each component to produce 1 kilogram of an Ordinary Portland Cement(OPC) Mix varies across the grades. It clearly shows how with a higher grade the cost of production is also higher as the amount of cement we use is much more.

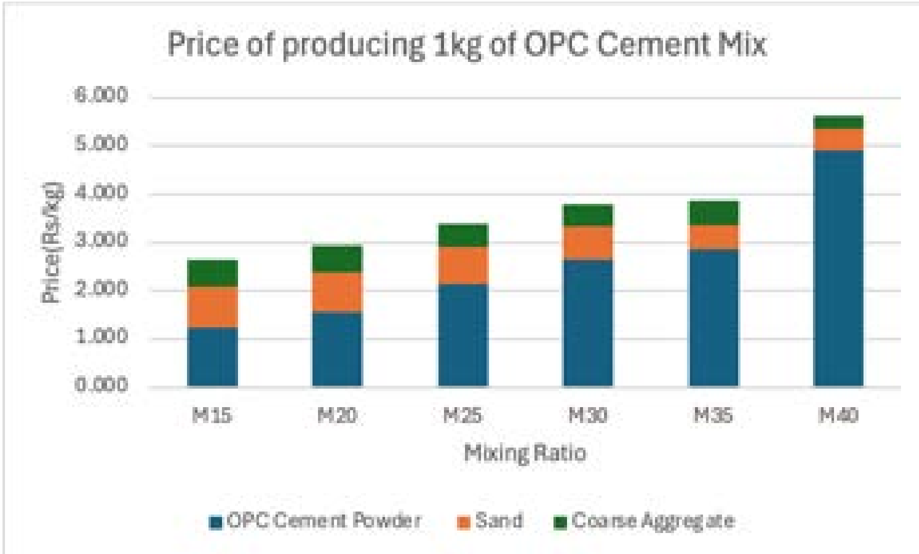

Fig. 13: Price of producing 1kg of a specific grade of OPC cement

Figure 14 compares the production cost of Ordinary Portland Cement to the cost of Portland Pozzolana Cement (PPC), specifically 53 grade fly ash blended cement, the SCM integrated cement used in this study.

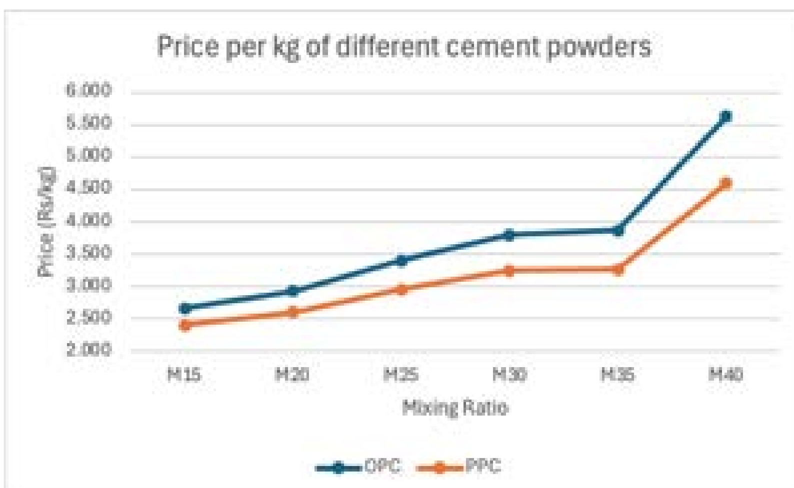

Fig. 14: Comparison of OPC vs. PPC

Figure 14 clearly indicates that despite the grade the production of PPC cement(made with fly ash) is cheaper than OPC cement. However, PPC cement produces a weaker concrete than OPC cement hence in this study we have enhanced it using Graphene Oxide.

Table 8 shows the increasing production costs of 1kg of cement as we increase the GO% in the cement mix. All calculations have been done with respect to M40 grade of cement. We see a steep linear increase in price due to Graphene Oxide being extremely costly. Hence, we should explore other nanoparticles.

Table 8: Price of 1kg of PPC with graphene oxide

GO %	Total price of 1kg M40 PPC Mix (Rs.)
0.00%	4.6
0.01%	8.6
0.02%	12.6
0.03%	16.6
0.04%	20.6
0.05%	24.6

Table 9 has a list of all the other nanoparticles that have been considered and the price for 1kg of that nanoparticle.

Table 9: Price of 1kg of a specific nanoparticle

Type of Nanoparticle	Price for 1kg (Rs/kg)
Carbon Nanotubes (Multi-walled)	28000
Graphene	6400
Nano-silica	5600
Nano titanium dioxide	50000

Figure 15 shows a cost comparison between nano particles, since we observe some are cheaper than others, future work could involve researching and testing concrete samples with different nano particles.

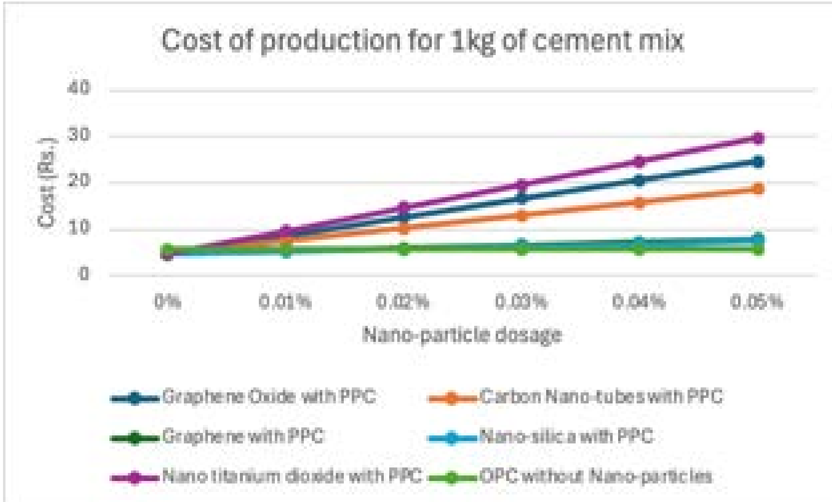

Fig. 15: Cost comparison with varying nanoparticle dosages.

Hence from an industrial perspective,based on the analysis conducted in this work, 0.01% dosage of graphene oxide would be recommended to maintain costs while also enhancing the properties of the cement. However, the performance of other nanoparticles additives should be investigated further in future works.

Emissions Analysis

During the production of cement, there is a crucial step known as calcination which provides us with the necessary clinker to produce our cement powder. 60% of the calcium carbonate that is calcinated is converted to carbon dioxide in the chemical step only the other 40% of the calcium oxide is used to make clinker. The energy requirements for this chemical reaction to take place result in 0.9 kg of carbon dioxide for every 1 kg Ordinary Portland Cement (OPC) produced.

Certain assumptions taken in this analysis were that calculations do not include carbon dioxide emissions caused by transporting the cement, carbon footprint in procuring our fine and coarse aggregate was 0, the nanoparticle Graphene Oxide is being used in extremely small quantities, so its carbon footprint is considered negligible, fly ash is the waste product of another industrial process hence its carbon footprint is considered 0.

Under all these assumptions, we can calculate how much lower is the carbon footprint of SCM integrated cement versus Ordinary Portland Cement. Since 53 Grade Fly Ash Blended cement replaces 20% of the clinker with fly ash. We can conclude that 53 Grade Fly Ash Blended cement decreases the carbon footprint by 20%. Hence for every kilogram of 53 Grade Fly Ash Blended cement that is produced 0.72 kg of carbon dioxide is produced as compared to the 0.9 kg OPC was producing.

Applying the average global carbon tax of $50/ton we see that the price of 53 Grade Fly Ash Blended Cement does not exhibit as high an increase in price as OPC as shown in Figure

16. We also see from the x-intercepts that by dosing PPC with approximately 0.003% GO we maintain the same price as OPC without taking into account carbon tax. But if carbon tax is accounted for the dosage that we can add to PPC to ensure it remains the same price as OPC is increased to 0.004%.

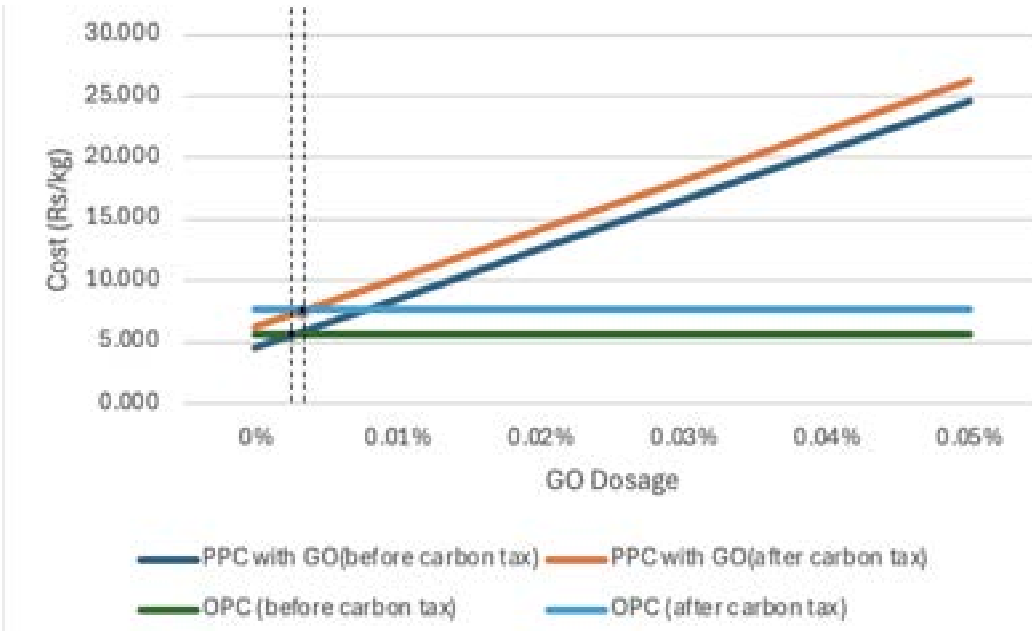

Fig. 16: Shows the cost to produce 1kg of cement mix after application of carbon tax.

Conclusion

In recent years, there has been a strong focus on reducing the carbon emissions from cement production by mixing SCMs, especially industrial waste materials, to minimize the cement quantity used. Recent advances in material sciences have resulted in nanomaterials becoming a promising area to be used as an additive in cement composites to increase mechanical strength and durability. The inclusion of different percentages of weight of GO significantly enhances the strength of the concrete mix made from SCM-based cement at the nano level and enhances the hydration reaction. However, the mechanical strength is adversely impacted when the dose of GO exceeds a certain threshold. This occurs due to the agglomeration of GO resulting from the limitations of the dispersion procedures. Strong van der Waals forces cause large concentrations of GO to aggregate, even though the oxygen-containing functional groups linked enhanced GO's dispersion in water. These aggregates lead to cement matrix imperfections and considerably weaken the mechanical characteristics of the concrete mix.

In the experiments conducted on concrete mixes based on M40 grade parameters, the GO infusion of 0.04% by weight of cement showed the most optimum compressive strength – an increase in strength of 8.5% at 7 days curing, 31% at 28 days curing, and 33% at 56 days curing. The most optimum split strength was at the GO infusion of 0.03% by weight of cement – an increase in strength of 33% at 7 days curing, 43% at 28 days curing, and 45% at 56 days curing.

Also, the impact of GO on workability needs to be addressed, as the slump of the concrete mix reduced linearly with the increasing infusion of GO in our samples, thus restricting its practical applications. Advancing mixing techniques that weaken van der Waals forces and disintegrate stacked GO sheets, thereby exposing more functional groups for improved interactions in aqueous environments, is beneficial. Chemical surface modifications can be undertaken, which will enhance the dispersion efficiency, chemical retention, and stability of GO in highly alkaline environments. Use of compatible surfactants for chemical surface modifications and improvement in dispersion efficiency will make GO a more popular candidate for enhance of concrete properties. Exploring the ideal dispersion procedures by using surfactants to distribute high dosages of GO in cement composites evenly can be a likely extension of the scope of this research.

Though the initial industrial recommendation was a GO dosage of 0.01% with the application of carbon tax a GO dosage of 0.02% can be used while maintaining costs. However if we want to increase the dosage without increasing price we can use other nanoparticles such as nano-silica.

Acknowledgement

I would like to thank Sushant University, Gurgaon, for supporting this Research Project and allowing me to use the concrete testing facilities at the Civil Engineering Department. I would also like to thank them for their guidance on handling the testing-related equipment. Last but not least, I would like to thank Dr. L.P. Singh, Director General, National Council for Cement and Building Materials, Ministry of Commerce and Industry, Government of India, for his valuable inputs on the materials being used in this project.

References

[1] Cement: The Most Destructive Material in the World or a Driver of Progress? 17 Jan. 2022, www.renewablematter.eu/en/cement-the-most-destructive-material-in-the-world-or-a-driver-of-progress.https://drawdown.org/solutions/alternative-cement

[2] "Supplementary Cementitious Materials: New Sources, Characterization, and Performance Insights." Cement and Concrete Research, vol. 122, May 2019, pp. 257-73. https://doi.org/10.1016/j.cemconres.2019.05.008.

[3] University of Manchester. "Secret Sauce: How Graphene Lowers Building Costs and CO_2." Secret Sauce: How Graphene Lowers Building Costs and CO_2, 13 Oct. 2021,

www.manchester.ac.uk/about/news/roller-disco-vs-climate-change--how-graphene-is-transforming-the-construction-industry.https://doi.org/10.1126/SCIENCE.1102896/SUPPL_FILE/NOVOSELOV.SOM.PDF

[4] Huseien, Ghasan Fahim, et al. "Sustainability of Nanomaterials Based Self-healing Concrete: An All-inclusive Insight." Journal of Building Engineering, vol. 23, Jan. 2019, pp. 155-71. https://doi.org/10.1016/j.jobe.2019.01.032.

[5] Salami, Babatunde Abiodun, et al. "Graphene-based Concrete: Synthesis Strategies and Reinforcement Mechanisms in Graphene-based Cementitious Composites (Part 1)." Construction and Building Materials, vol. 396, July 2023, p. 132296. https://doi.org/10.1016/j.conbuildmat.2023.132296.

[6] S. Chuah, W. Li, S.J. Chen, J.G. Sanjayan, W.H. Duan, Investigation on dispersion of graphene oxide in cement composite using different surfactant treatments, Constr. Build. Mater. 161 (2018) 519–527, https://doi.org/10.1016/j.

[7] Salami, B. A., a; Mukhtar, F.; Ganiyu, S. A.; Adekunle, S.; Saleh, T. A., d. Graphene-based Concrete: Synthesis Strategies and Reinforcement Mechanisms in Graphene-based Cementitious Composites (Part 1); 2023; Vol. 396, p 132296. https://doi.org/10.1016/j.conbuildmat.2023.132296.

[8] Alvi, I. H.; Li, Q.; Hou, Y. L.; Onyekwena, C. C.; Zhang, M.; Ghaffar, A. A Critical Review of Cement Composites Containing Recycled Aggregates with Graphene Oxide Nanomaterials. Journal of building engineering 2023, 69, 105989. https://doi.org/10.1016/j.jobe.2023.105989.

[9] Li, W.; Qu, F.; Dong, W.; Geetika Mishra; Surendra P. Shah. A comprehensive review on self-sensing graphene/cementitious composites: A pathway toward next-generation smart concrete. Construction and Building Materials 2022, 331, 127284.

[10] Pasadi Devapura, Thusitha Ginigaddara, Danula Udumulla, Priyan Mendis, Michael Booy, Nilupa Herath, Effect of graphene oxide on interfacial transition zone and strength enhancement of recycled aggregate concrete. https://doi.org/10.1016/j.jobe.2025.112570

[11] Liu, B.; Wang, L.; Pan, G.; Li, D. Dispersion of graphene oxide modified polycarboxylate superplasticizer in cement alkali solution for improving cement composites. Journal of Building Engineering 2022, 57, 104860. https://doi.org/10.1016/j.jobe.2022.104860.

[12] Liu, C.; Huang, X.; Wu, Y.-Y.; Deng, X.; Liu, J.; Zheng, Z.; Hui, D. Review on the research progress of cement-based and geopolymer materials modified by graphene and graphene oxide. Nanotechnology Reviews 2020, 9 (1), 155–169. https://doi.org/10.1515/ntrev-2020-0014.

[13] Standard test method for compressive strength of hydraulic cement mortars (Using 2-in. or [50-mm] cube specimens). https://store.astm.org/c0109_c0109m-20.html.

[14] Jsimpson. Simple guide to ASTM C496: Splitting tensile strength of cylindrical concrete specimens. Forney Online. https://forneyonline.com/simple-guide-astm-c496/.

[15] RD-E: 4702 Splitting Tensile Test (Brazilian Test). (C) Copyright 2025. https://help.altair.com/hwsolvers/rad/topics/solvers/rad/concrete_validation_example_splitting_tensile_test_r.htm.

[16] Edge, E.; Llc, E. E. Concrete splitting tensile Strength test equations and calculator. https://www.engineersedge.com/calculators/concrete_splitting_tensile_16050.htm.

[17] Mahajan, B. All Cement Price List Today 2025: Cement Rate Per Bag & Kg. Civiconcepts. https://civiconcepts.com/blog/cement-price-list-today-per-kg.