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ENHANCING THE MECHANICAL PROPERTIES AND DURABILITY OF INDUSTRIAL STEEL SLAG CONCRETE THROUGH THE INCORPORATION OF GRAPHENE OXIDE DERIVED FROM WASTE PLASTIC

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ABSTRACT

The study on graphene oxide which is recycled from plastic waste and BSRM steel slag as coarse aggregate for concrete utilization, improvement and durability. Solving the environmental issues through reusing hazardous waste plastics and industrial slag to create useful nanomaterials is the ultimate aim of this study and hence provides a green economy. In the world, approximately 400 million tons of waste plastic are generated and a significant amount of the waste is discharged into the environment. Graphene oxide is produced as a result of a controlled chemical reaction (pyrolysis) of waste produced by plastic. The waste slag from steelmaking is used to pollute land and water. Substituting natural coarse aggregates with steel slag, it minimizes pollution and makes it a green construction material, which is used as an additional material to increase the mechanical properties. The findings of this paper, which investigated the compressive strength, flexural strength, splitting tensile strength, and the effect of water absorption revealed that the addition of graphene oxide and substitution of coarse aggregate enhanced the overall mechanical characteristics of concrete. Graphene oxide was added up to 0.1% concentrations of cement with a plasticizer to disperse it. The 0.05% graphene oxide mix had the lowest water absorption 2.76%, while the control sample had the highest water absorption 3.67%. As a result, for the 0.05% graphene oxide mix, the compressive strength, flexural strength, and splitting tensile strength of the material will be approximately 35%, 45%, and 55% better than those of the control sample. The performance of concrete with the variation of graphene oxide can establish a relation that gives useful information to choose the right parameters. It helps to make construction materials more useful and improve the mechanical characteristics of concrete.

Keywords: *Green concrete, Graphene oxide, Recycling, Plastic waste, Steel slag.*

1. INTRODUCTION

The most widely used building material around the world has been concrete because of its low cost, structural and adaptive characteristics (Meyer, 2005). About 8 percent of CO_2 is emitted in globally, and about 1.6 billion tonnes per year of CO_2 is emitted from cement production (Erick Burgueño Salas, 2025; World Economic Forum, 2024). Therefore, researchers have been looking for new materials and technologies in order to improve the concrete mechanical properties while reducing its environmental impact during its preparation. One of the potential methods is partly replacement of concrete material by industrial waste like steel slag. By 2025, Bangladesh is likely to have some 40 steel mills with an annual steel production capacity of 9 million tonnes, while its steel consumption is likely to be around 8 million tonnes (Business Inspection BD, 2022). These mills produce massive amounts of steel slag, a residue that, if not handled correctly, can become an environmental problem. Nevertheless, from the perspective of chemical composition and physical properties, it may prove a viable alternative to natural concrete aggregates which is a sustainable solution to waste disposal and concrete performance. Research has also found out that steel slag might enhance the compressive and flexural strengths of concrete particularly when the slag is cured at early ages, due to an angular particle shape and higher density which represents more bonding area between aggregates and cement paste (Miah et al., 2020). Steel slag has been shown to increase the durability of concrete such as abrasive resistance and resistance to chemical attacks (Masilamani et al., 2022). By using steel slag as a coarse aggregate in concrete, sustainable development is ensured and greenhouse gas emissions during burnt clay aggregate production will be minimized (Mohammed et al., 2017). In concrete technology, the addition of graphene oxide (GO) to concrete is another potential eco-friendly technique to be developed. GO has gained much attention in the past few years for its excellent mechanical, electrical, and thermal properties. Its 2D-based structure is like carbon nanotubes (CNTs), it can also strengthen fragile cement (Chuah et al., 2014). Graphene is a well-known type of carbon (carbon family) with many excellent properties such as extremely high stiffness and large mechanical strength. It also has higher elasticity than steel (Mas-Ballesté et al., 2011). GO is very reactive to the cement hydration products because the area of surface to react is large and due to the presence of groups of oxygen components which leads to the formation of a microstructure that is refined and better bonding (Lv et al., 2013). It has been demonstrated that the incorporation of GO improves compressive, tensile, and flexural strength, decreases porosity and water permeability (Pan et al., 2015). GO nanosheets can be used to form bar-like crystals into flower-like and polyhedral crystals. In low doses of GO (less than 0.03 percent) researchers find flower-like crystals and in high doses (more than 0.03 percent) polyhedral or lamellar crystals. The flower-shaped crystals are generated in the voids and cracks of the cement paste, cross-linking with each other to form a multipoint network, which reduces the porosity and pore size, and all types of crystals will develop into dense networks (Lv et al., 2014). When mixed with concrete, the GO can make the material stronger and more flexible, while also making it last longer. It was revealed in the recent research that plastic waste can be transformed into GO with preferred structural and functional characteristics by the processes of pyrolysis and chemical oxidation (Tatrari et al., 2021a). So that two major environmental problems will be addressed simultaneously: the uncontrollable growth of plastic and the improvement of the properties of concrete. Plastic waste-derived carbon materials are in the form of paste and can be used to develop sustainable/green technology such as graphene which will become a top-most material due to its high surface area (Le, 2025). The main purpose of this study is to enhance the mechanical properties and the durability of the industrial steel slag concrete containing GO produced through the use of waste plastic. While there are many single studies on GO, steel slag in concrete is available, but few studies have been conducted to utilize them together. In theory, the addition of GO in steel slag-based concrete may have a synergistic improvement. Steel slags, on the one hand, increase mechanical interlocking and strength of aggregate skeleton; on the other hand, GO can alter the cement paste matrix and reduce the pore structure (Wang et al., 2023). A combination of these two mechanisms may lead to a higher degree of compressive strength, toughness, and long-term performance compared to manufacturing both materials separately (Hosseini et al., 2023). Besides, GO addition reduced the disadvantages of steel slag due to lower workability and increased water penetration, enhancing the resistance of concrete to environmental corrosion and chemical assaults (Sun et al., 2024). The combination is therefore a long-term sustainable material solution since it is upcycled industrial by-product steel slag and waste-derived GO, which suits green construction projects and provides better concrete performance. There is a chance that the outputs will be more robust, less expensive, and more multifunctional building resources, which would be a nice addition to our global vision of inexpensive and sustainable infrastructural projects (Kiamahalleh et al., 2024). The paper aims to offer an affordable and environmentally friendly method for addressing the performance and sustainability issues through the design of waste plastic-derived GO in steel slag concrete.

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 Cement

Ordinary Portland Cement (OPC) was implemented to prepare the concrete mixes for this investigation. OPC was obtained from the local cement shops. It conforms to the Bangladesh Standard BDS EN 197-1:2023, CEM-I, 52.5 N (Which is equivalent to ASTM C150 Type-1).

2.1.2 Fine Aggregates (FA)

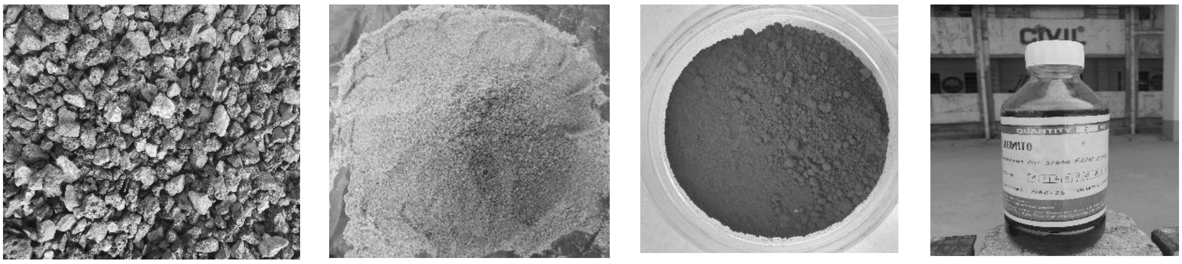
The fine aggregate here was the locally available Sylhet sand, shown in Figure 1(b). The sand was sieved to ensure that the sand passed the maximum and minimum sizes of ASTM C33 (Standard Specifications for Concrete Aggregates) and the fineness modulus (FM) of the sand sample was determined to be 2.554.

2.1.3 Coarse Aggregate (CA)

This study utilized industrial steel slag derived from the BSRM steel plant as a full substitute for the traditional coarse aggregates in concrete. In Figure 1(a) shows that steel slag was rough, angular, and had no dust or metals. It was sieved to a size range of 8-25 mm, which is appropriate for use in structural concrete (BSRM, 2020).

2.1.4 Graphene Oxide (GO)

GO was prepared from waste plastic through the pyrolysis process. GO was added at small percentages of cement, specifically 0.01%, 0.03%, 0.05%, 0.08%, and 0.10% by weight of cement in the concrete mix. In this study, GO was purchased from Rail Udyog, Howrah-711103, India. In Figure 1(c) shows, the physical appearance of GO is Grey-Black. It is solid, non-electric conductive, and easily soluble in water. The material was used as such without any additional purification. CHEMITO SIGMA FLOW 2800 was used as a plasticizing agent and complies with ASTM C494-1981 Type G standards, which helped in the dispersion of GO within the cementitious matrix. Plasticizer is normally added to reduce the water-cement ratio, but this product is a plasticizing and retarding admixture of the type based on modified polycarboxylate, providing first-rate dispersing quality that ensures homogeneous dispersion of GO in the blend.



(a) (b) (c) (d)

Figure 1: a) Steel slag, (b) Sand, (c) Graphene Oxide, (d) Plasticizer.

2.2 Preparation of Specimens

The concrete was prepared in the laboratory using the mix design, which included waste plastic-derived GO, as well as steel slag aggregate. As per the ASTM standard, specimens were cast, cured, and monitored under controlled conditions to maintain uniformity.

2.2.1 Mix Proportions

Concrete of grade M20 was designed with a mix proportion of 1:1.5:3 (cement: fine aggregate: coarse aggregate), and the water-cement ratio is considered as 0.35. GO was used in varying dosages 0%, 0.03%, 0.05%, 0.08% and 0.10% by wt. of cement on a dry mass basis respectively. The natural coarse aggregate in this study was fully replaced by BSRM steel slag also with particle size from 8 mm to 25 mm. To obtain an even dispersion of the GO and enhance workability, a plasticizer was used as a chemical additive. Detailed mix proportions and experimental parameters of all tested concrete samples are shown in Table 1.

Table 1: Mix proportions and parameters for all samples.

Mix ID	Sample ID	W/C	% of GO Wt. by Cement	% of PS Wt. by Cement
M1	SG-GO	0.35	0%	0.60%
M2	SG-GO03	0.35	0.03%	0.60%
M3	SG-GO05	0.35	0.05%	0.60%
M4	SG-GO08	0.35	0.08%	0.60%
M5	SG-GO10	0.35	0.10%	0.60%

2.2.2 Mixing Procedure

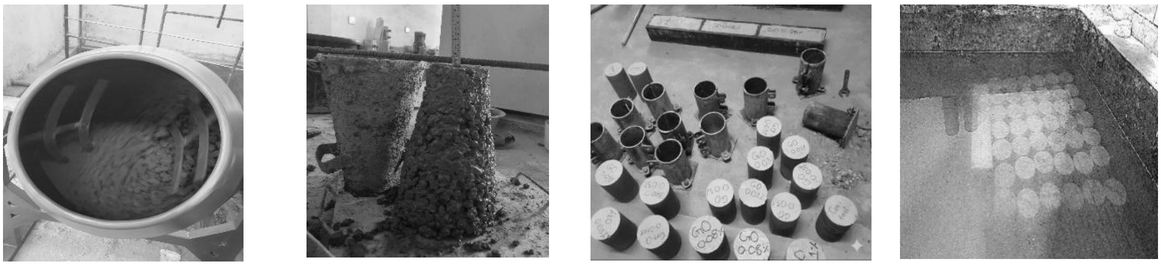
The materials used for the concrete mix were prepared and weighed accurately as per their mix design. The process was made by following a sequence for each constituent, BSRM steel slag as coarse aggregate, Sylhet sand as fine aggregate, Cement and GO. The dry mix was homogeneously mixed and the added water requirement was adjusted to achieve consistency. As it is difficult to disperse GO sufficiently in water, a plasticizer named CHEMITO SIGMA FLOW 2800, from Figure 1(d) was added with the water to improve the dispersion of GO and keep the workability of the mixed cement. The remaining water was added in portions, with mixing continuing until the desired consistency and uniformity were achieved. Figure 2(a) shows the mixing of materials, which ensured a homogeneous and workable mix for casting the concrete specimens.

2.2.3 Sampling

The metal molds had an inner diameter of 100 mm x 200 mm depth in which the cylindrical concrete blocks were cast, while for the plain beam specimens, wooden molds having dimensions of 100mm depth x 100mm width x 350mm length were used. Both the metal and wooden molds were cleaned, greased, and tightened to avoid loss of water during compaction. The first layer of concrete was placed into the mold and compacted in three layers using a mechanical vibrator for each layer, 15 seconds of vibration to obtain full compaction of the concrete and avoid segregation. The top layer was moderately overfilled and then properly spread using a straight edge. Five different concrete mixes were prepared with seven cylindrical specimens and two beam specimens for each mix prepared. All samples were cured for 28 days before testing. The sampling of specimens is shown in Figure 2(c).

2.2.4 Curing

After the casting, the concrete specimens were placed in a controlled laboratory environment maintained at 25 ± 2 °C and covered with plastic sheets to prevent premature moisture loss and ensure uniform setting conditions. The specimens were left undisturbed for 24 hours to allow initial hardening. Subsequently, the mold screws were loosened, and the specimens were carefully demolded to avoid any surface damage. Each specimen was assigned a unique identification code based on its respective mix proportion. Following demolding, the specimens were immediately immersed in a water-curing tank shown in Figure 2(d) and cured under standard conditions for a period of 28 days to facilitate proper hydration and strength development.

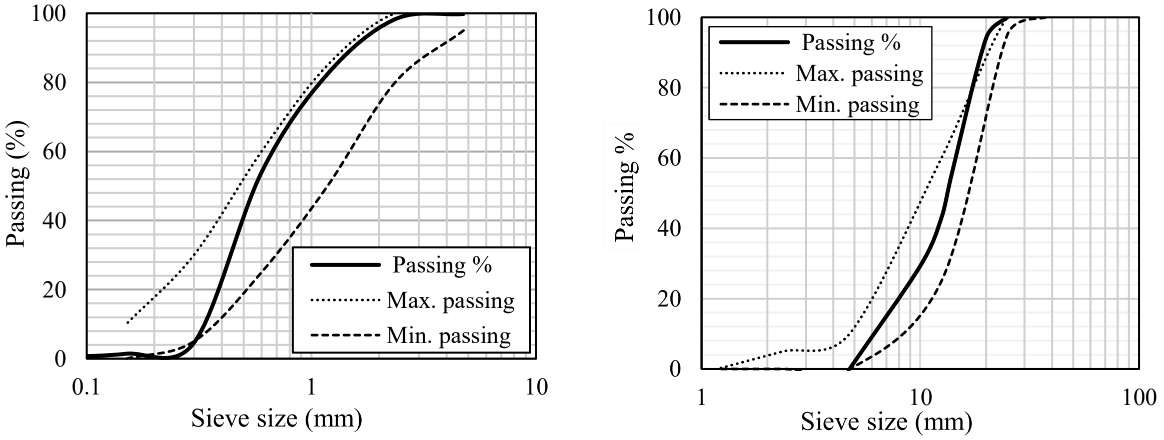


(a) (b) (c) (d)

Figure 2: (a) Mixing of Materials, (b) Slump Test, (c) Sampling, and (d) Curing.

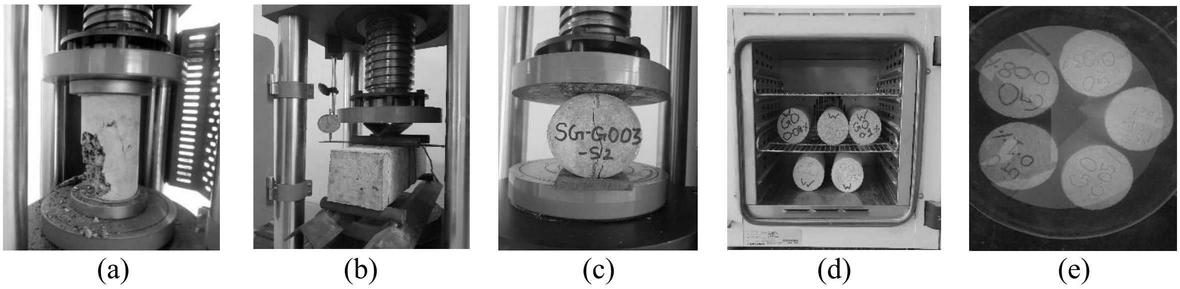
2.2.5 Evaluation of Concrete Properties

The properties of the cylinder and beam specimens were tested through various tests. The tests that were done were, the Compressive Strength Test, Flexural Strength Test, Splitting Tensile Strength Test, and Water Absorption Test, which were shown in Figure 4. All the tests were conducted using the standardized manner of testing concrete. The sieve analysis of fine and coarse aggregate was done according to ASTM C136, shown in Figure 3. The Compressive Strength Test and Flexural Strength Test were conducted according to ASTM C39 and ASTM C78, respectively. The Splitting Tensile Test was conducted following ASTM C496, while the Water Absorption Test was conducted following ASTM C642. The results shown in this paper are results of the means of 2 specimens.



(a) (b)

Figure 3: Sieve Analysis Curves (a) Fine aggregates, and (b) Coarse aggregates.



(a) (b) (c) (d) (e)

Figure 4: (a) Compressive Strength Test, (b) Flexural Strength Test, (c) Splitting Tensile Strength Test, (d) Oven Dry of samples, and (e) Immersion of Samples.

3. RESULTS AND DISCUSSION

3.1 Slump Values

The slump test was performed according to ASTM C143/C143M and the observed slump values were given to the nearest 5 mm as per standard practice shown in Figure 2(b). This test is used to determine the consistency or workability of fresh concrete. All the compositions of concrete mixtures are tested for slump stayed together, showed no segregation or bleeding when observed by visual inspection. From Table 2, it can be seen that all the mixtures exhibit true slumps, which ranged from 10 to 20 mm, respectively, indicating the low workability of the concrete mix. True slump concrete was used to maintain steady fresh state behavior and to allow an accurate comparison of workability between mixes with different dosages of graphene oxide. Initially, the SG-GO mix has a 10 mm slump value, showing lower workability and a stiffer mix. An increase in the GO increases its slump value too, with SG-GO03 and SG-GO05 both having a slump value of 20 mm. This demonstrates that by adding more GO into the mix, the resulting concrete becomes harder, but there is less workability in the material. The SG-GO08 mix displays a slump value of 15 mm that is just a little higher than being on the right path. SG-GO10 follows close behind, with a slump value of 10 mm. This confirms again that, compared to the previous two mixes, it only marginally improved workability and is still less workable. This shows that GO can improve specific properties of the concrete, but the impact on workability is minimal.

Table 2: Slump Values for Different Mixes.

Mix ID	Description	Slump Value (mm)
M1	SG-GO	10
M2	SG-GO03	20
M3	SG-GO05	20
M4	SG-GO08	15
M5	SG-GO10	10

3.2 Water Absorption

Figure 5 shows that the tested water absorption rates among the concrete samples were significantly different and each demonstrated specific patterns based on the material mixing method. Control mix (SG-GO-WA) had the highest absorption rate at 3.67%, implying that this mix was the most porous or had the least hydrophobic properties out of all used. Similarly, sample SG-GO05-WA had the lowest absorption rate of 2.76%, indicating that it was the least permeable by water among all the concrete mixes. The other water absorption rate samples comprised SG-GO03-WA, SG-GO08-WA, and SG-GO10-WA at 2.95%, 3.45%, and 2.78%, respectively. The observed results imply that incorporating GO and steel slag in modifying the concrete mix will result in concrete resistant to water.

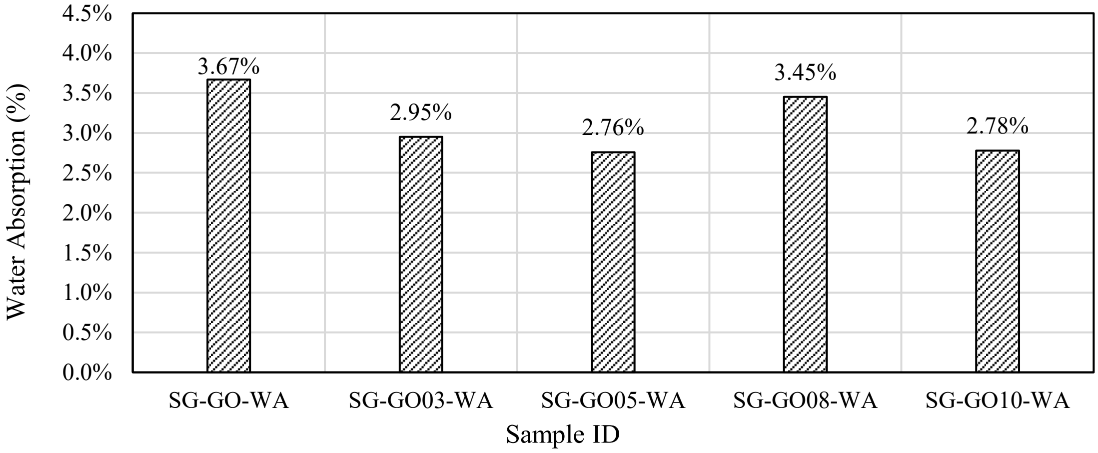


Figure 5: Percentage of Water Absorption for Different Concrete Mixes.

3.3 Compressive Strength

From Figure 6 and Figure 7**Error! Reference source not found.**, it can be observed that there is a variation in compressive strength and percentage improvement for different concrete mixes incorporating GO. The control mix without GO gained a compressive strength of 40.65 MPa. The addition of 0.03% GO resulted in 20.52% increased strength compared to the control specimen. The most significant improvement was observed in SG-GO05, the mix contained 0.05% GO, which is 54.87 MPa, representing a 34.96% improvement over the control sample. The percentage of GO effectively accelerates the hydration process. when the GO content was further increased beyond this optimal level, the compressive strength slightly decreased 0.08% of GO showed a compressive strength of 41.39 MPa, which is only 1.82% improved than the control. This result indicates that the excessive GO content has an adverse effect. The mix with 0.10% GO achieved a compressive strength of 45.04 MPa. For this mix a moderate level of improvement is noticed, which is 10.79%. These results indicate that the addition of a small dose of GO does not contribute proportionally to strength gains; rather, it can lead to a degradation in performance. The current study obtained a higher initial compressive strength of 40.65 MPa than the previous study, which obtained a baseline compressive strength of 28 MPa with an increment of 25 to 42.86% under 0.1 to 1.5% Graphene sheets using natural coarse aggregate reported by (Tatrari et al., 2021b). It is noteworthy that similar strength improvement up to 34.96% was achieved at 0.05% GO, which has a much lower GO content, showing better effectiveness and higher material performance.

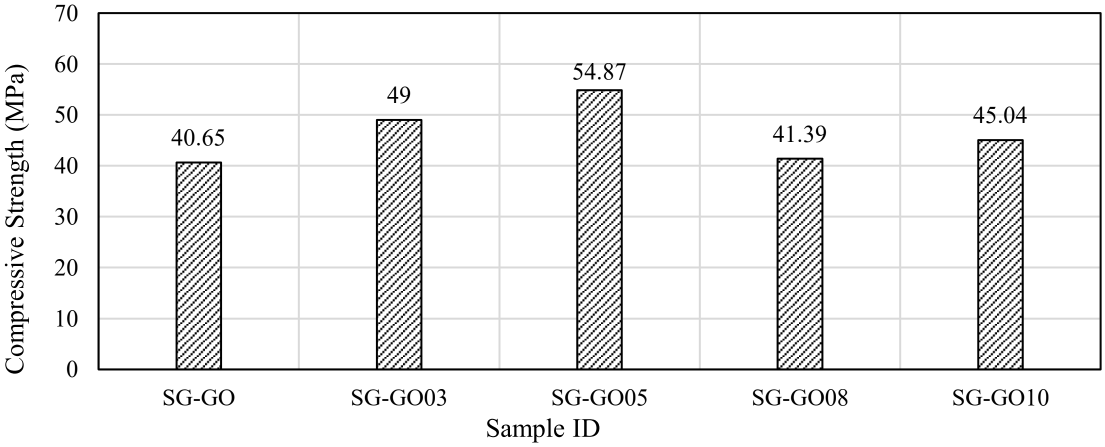


Figure 6: Compressive Strength for different doses of GO.

These agglomerates act as weak spots and hinder the hydration process. The result of the figure clearly suggests that the integration of GO can significantly enhance the compressive strength of concrete, but only up to a certain concentration.

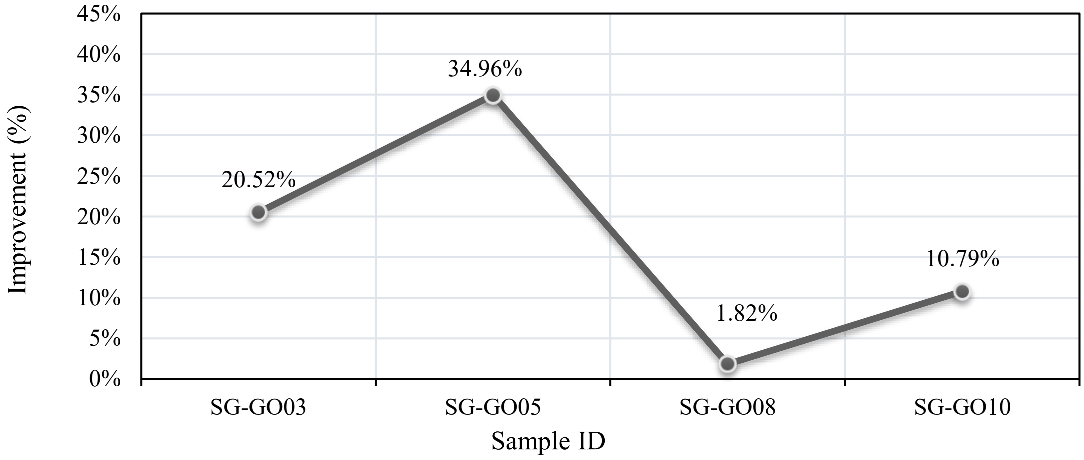


Figure 7: Percent Increase in Compressive Strength over Control (SG-GO) for different doses of GO.

3.4 Flexural Strength

From Figure 8 and Figure 9, shows the flexural strength and percent improvement for different doses of GO in the concrete mix. The control (SG-GO), the absence of GO, had a flexural strength of 4.38 MPa. As the GO was added, a sharp increase in strength was noted for some dosages. The flexural strength in sample SG–GO03 was 5.97 Mpa, which was an increase of 36.33% relative to the control mix. Sample SG-GO05 achieved the greatest flexural strength of 6.35 Mpa, which was 44.84% higher than the control. It is possible to note that the flexural strength has been improved due to the homogeneous dispersion of the GO throughout the cementitious matrix. This dispersal improved interfacial bonding of the matrix and the aggregates to facilitate crack bridging and strengthening load transfer capacity that led to a ductile, and stronger composite structure. The slight decrease in flexural strength was noted beyond the optimum dosage. Samples SG-GO08 and SG-GO10 had flexural strengths of 6.04 MPa and 5.97 MPa, respectively. The cause of this reduction in strength can be linked to the concentration of the excess GO particles that can cause weak areas and the creation of micro-cracks hence lowering the overall strength. As such it can be deduced that the ideal percentage content of GO to be used to improve the flexural performance of steel slag concrete is 0.05% by cement weight; otherwise, there is no additional enhancement in the flexural performance of the material and a slight decline in the strength is noticed.

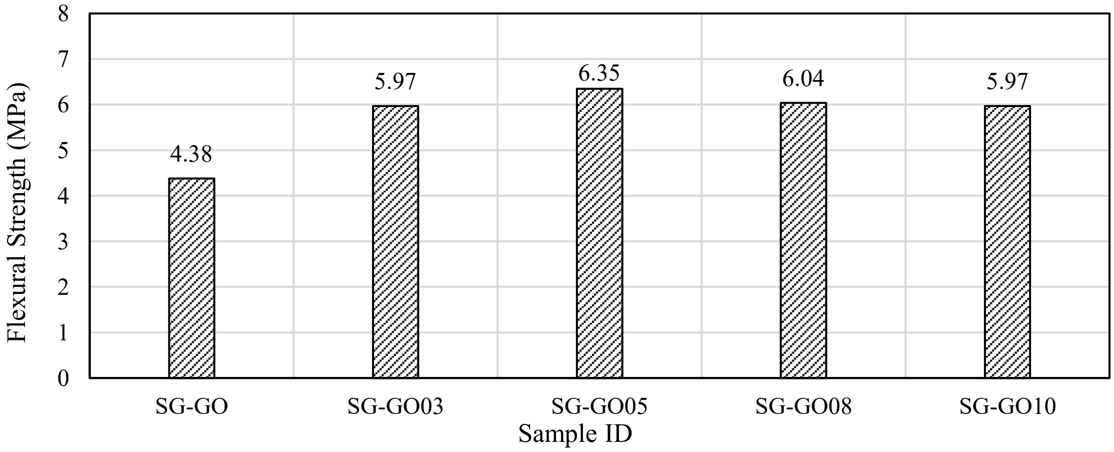


Figure 8: Flexural Strength for different doses of GO.

(Hong et al., 2022) presented flexural strength of 5.45 MPa of specimens for 0% GO content using shale ceramsite as a coarse aggregate, with the highest percentage of increase 15% at 0.08% GO content, which varies from 0 to 0.08%. Conversely, in the current research, the initial flexural strength stood at 4.38 MPa at 0% GO and increased up to 44.84% at 0.05% GO content, which varies from 0.03 to 0.1%, showing a significantly greater strengthening efficiency with a lower GO dosage.

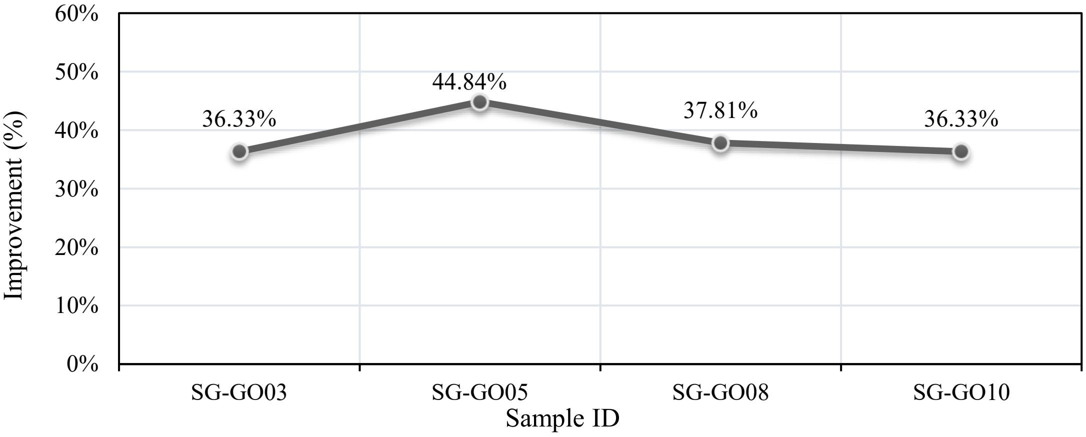


Figure 9: Percent Increase in Flexural Strength over Control (SG-GO) for different doses of GO.

3.5 Split-Tensile Strength

The findings of the experiment in Figure 10, demonstrate a significant increase in the tensile strength of the concrete mixes compared to the splitting strength of the control mix (SG-GO). All the mixes, SG-GO03, SG-GO05, SG-GO08, and SG-GO10, had significant improvements, with SG-GO05 recording the highest percentage change of 55% is shown in Figure 11. This drastic increase in strength indicates that the addition of certain materials or alterations in SG-GO05 had a beneficial impact on the resistance of tensile forces on the concrete, which is a significant property to consider in defining the qualities of concrete structures in terms of durability and strength. when compared to the existing literature, it is much higher than several that are reported. (Tatrari et al., 2021b) achieved tensile strength of up to 30% improvement to waste plastic-based graphene sheets using graphene contents of 0.1 to 1.5%, with the best enhancement recorded at 0.5% graphene using natural coarse aggregate. Conversely, the current work attained significantly better tensile strength improvement of up to 55% at a significantly lower additive concentration of 0.05% GO, which shows better reinforcement efficiency and transfers the load well with a lower dosage of additive.

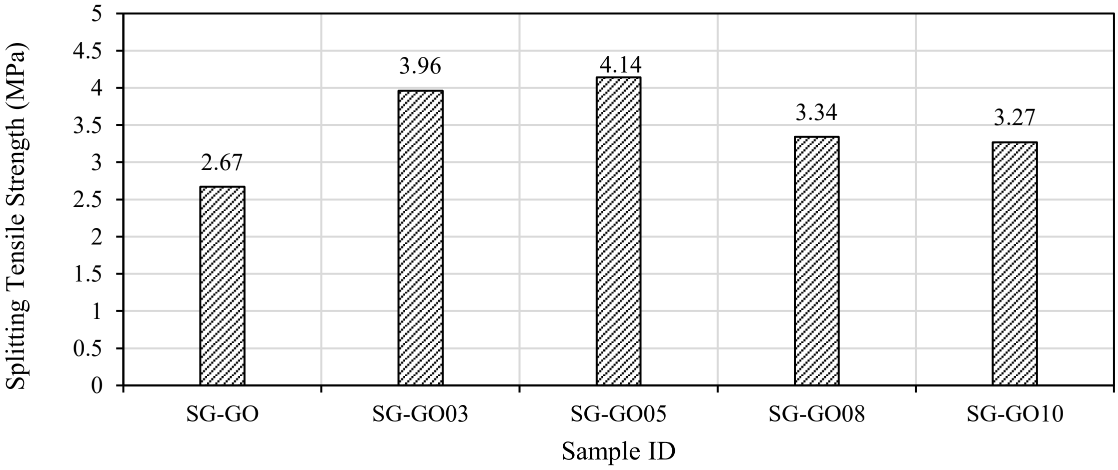


Figure 10: Splitting Tensile Strength for different doses of GO.

The remarkably high gain in the study could be explained by the fact that the use of BSRM slag as the additional cementitious component along with the optimal dosage of GO was used. Slag promotes hydration and densification of the matrix and GO promotes microstructure refinement, is a crack-bridging agent and enhances bonding at the nanoscale. The outcome is a smoother and more permanent concrete matrix that is transferred into a higher splitting tensile strength.

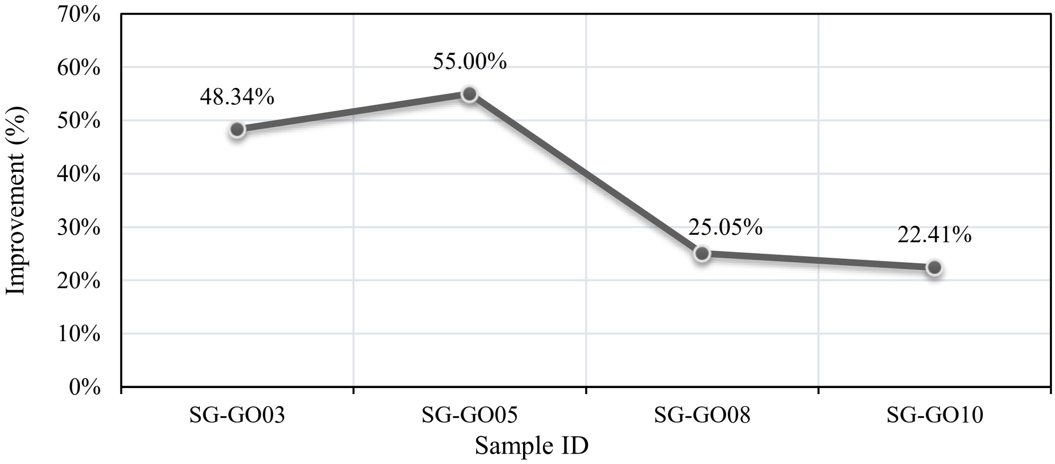


Figure 11: Percent Increase in Splitting Tensile Strength Over Control Mix (SG-GO) for different doses of GO.

4. CONCLUSIONS

In this study, an elaborate work on improving the mechanical and durability properties of an industrial steel slag concrete through the addition of GO obtained from waste plastic has been presented. The research will concentrate on developing an optimum mix design for better strength and durability in addition to developing an environmentally friendly construction industry through recycling of resources and minimizing waste. The findings are summarized as follows:

- It was concluded that 0.05% GO (SG-GO05) by cement weight was the optimal dosage on steel slag concrete, which is the same as stone chips concrete. It reduced water absorption, increasing compressive strength by 34.96%, and flexural strength by 44.84%. Another outstanding result in the SG-GO05 mix was 55% improvement in split tensile strength.
- GO improved the interfacial bonding of aggregates with the cement matrix, which positively affected the crack-bridging and transfer of loads, which increased the strength of the microstructure of concrete.
- Increasing the GO content (0.08% or SG-GO08 and 0.10% or SG-GO10) in the concrete mix resulted in a reduction due to various reasons as given below: The slower hydration of the slag with increasing percentage of GO, due to dilution effect on cement paste, leads to a decrease in early strength development. Moreover, more GO reduces workability and compactibility, which implies a larger porosity and poorer particle packing.
- The sharp decrease in compressive strength at 0.08% GO is primarily because of the poor dispersion and agglomeration of GO nanosheets to form weak points and cause local porosity, thereby adversely impacting the transfer of loads during the compressive load. The compressive strength increased at 0.10% GO compared to 0.08% GO, because of giving some nucleation and filler effects, which partially countered these defects, and the end result was a moderate strength recovery. The compressive strength is more sensitive to the matrix uniformity, where split tensile and flexural strengths are controlled by crack-bridging interfacial bonding, and are functional even with some GO agglomeration; hence, they did not conform to the same sudden tendency as the compressive strength.

- The main challenge is that the production of GO from waste plastics remains expensive and graphene is relatively new for concrete reinforcement, still lacking comprehensive research in many environments and compositions.
- GO and steel slag are good substitutes for traditional materials because they can be integrated with concrete to provide a sustainable and high-performance option. The dense structure in steel slag increases its strength and durability, whereas GO also promotes further bonding, microstructure, and load-bearing capacity.

As we keep researching the mix optimization and cost-effective production of GO, steel slag concrete has a great potential of being used in the future in the construction of high-strength as well as green construction.

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DECLARATION OF USE OF AI

The authors state that Grammarly was applied only to grammar and language enhancement of the paper. ChatGPT was applied to summarization and clarity enhancement of the text. Plagiarism and AI-generated content were uniquely checked with Turnitin to make sure the originality. The research design, data analysis, results interpretation, figure, and table preparation did not involve any AI tools.

REFERENCES

BSRM. (2020, August 8). *BSRM Slag for Green, Environment-Friendly Construction*. 1–4. https://bsrm.com/wp-content/uploads/2022/08/08.-BSRM-Slag.pdf

Business Inspection BD. (2022). *Top 10 Steel Mill Companies in Bangladesh - Business Inspection BD*. https://businessinspection.com.bd/top-steel-mill-companies-in-bangladesh/

Chuah, S., Pan, Z., Sanjayan, J. G., Wang, C. M., & Duan, W. H. (2014). Nano reinforced cement and concrete composites and new perspective from graphene oxide. *Construction and Building Materials*, *73*, 113–124. https://doi.org/10.1016/J.CONBUILDMAT.2014.09.040

Erick Burgueño Salas. (2025, August). *Global CO₂ emissions from cement manufacturing 1960-2023*. https://www.statista.com/statistics/1299532/carbon-dioxide-emissions-worldwide-cement-manufacturing/

Hong, X., Lee, J. C., & Qian, B. (2022). Mechanical properties and microstructure of high-strength lightweight concrete incorporating graphene oxide. *Nanomaterials*, *12*(5), 833. https://doi.org/10.3390/nano12050833

Hosseini, K., Atrian, M. A., Mirvalad, S., Korayem, A. H., & Ebrahimi, M. (2023). Influence of ground granulated blast furnace slag on mechanical properties and durability of graphene oxide-reinforced cementitious mortars. *Structural Concrete*, *24*(5), 6270–6282. https://doi.org/10.1002/SUCO.202200888

Kiamahalleh, M. V., Gholampour, A., Tang, Y., & Ngo, T. D. (2024). Incorporation of reduced graphene oxide in waste-based concrete including lead smelter slag and recycled coarse aggregate. *Journal of Building Engineering*, *88*, 109221. https://doi.org/10.1016/J.JOBE.2024.109221

Le, P. A. (2025). A review of commercial plastic waste recycling into graphene materials. *RSC Advances*, *15*(25), 20239–20267. https://doi.org/10.1039/d5ra00288e

Lv, S., Liu, J., Sun, T., Ma, Y., & Zhou, Q. (2014). Effect of GO nanosheets on shapes of cement hydration crystals and their formation process. *Construction and Building Materials*, *64*, 231–239. https://doi.org/10.1016/j.conbuildmat.2014.04.061

Lv, S., Ma, Y., Qiu, C., Sun, T., Liu, J., & Zhou, Q. (2013). Effect of graphene oxide nanosheets of microstructure and mechanical properties of cement composites. *Construction and Building Materials*, *49*, 121–127. https://doi.org/10.1016/J.CONBUILDMAT.2013.08.022

Mas-Ballesté, R., Gómez-Navarro, C., Gómez-Herrero, J., & Zamora, F. (2011). 2D materials: to graphene and beyond. *Nanoscale*, *3*(1), 20–30. https://doi.org/10.1039/C0NR00323A

Masilamani, A., Ramalingam, M., Kathirvel, P., Murali, G., & Vatin, N. I. (2022). Mechanical, physico-chemical and morphological characterization of energy optimised furnace steel slag as coarse aggregate in concrete. *Materials*, *15*(9), 3079. https://doi.org/10.3390/MA15093079

Meyer, C. (2005). Concrete as a Green Building Material. *Proceedings of the Third Int. Conference on Construction Materials*, 10.

Miah, M. J., Hossain Patoary, M. M., Paul, S. C., Babafemi, A. J., & Panda, B. (2020). Enhancement of mechanical properties and porosity of concrete using steel slag coarse aggregate. *Materials*, *13*(12), 2865. https://doi.org/10.3390/MA13122865

Mohammed, T. U., Noor, M. A., Apurbo, S. M., Ahmed, M., Arhab, A., & Mazumder, M. H. (2017). Utilization of Induction Furnace Slag in Concrete as Coarse Aggregate. *Proceedings of the 1st International Conference on Engineering Research and Practice*, 6.

Pan, Z., He, L., Qiu, L., Korayem, A. H., Li, G., Zhu, J. W., Collins, F., Li, D., Duan, W. H., & Wang, M. C. (2015). Mechanical properties and microstructure of a graphene oxide-cement composite. *Cement and Concrete Composites*, *58*, 140–147. https://doi.org/10.1016/j.cemconcomp.2015.02.001

Sun, J., Hou, S., Guo, Y., Cao, X., & Zhang, D. (2024). Feasibility of preparing steel slag–ground granulated blast furnace slag cementitious materials: synergistic hydration, fresh, and hardened properties. *Buildings*, *14*(3), 614. https://doi.org/10.3390/BUILDINGS14030614

Tatrari, G., Tewari, C., Bohra, B. S., Pandey, S., Karakoti, M., Kumar, S., Tiwari, H., Dhali, S., & Sahoo, N. G. (2021a). Waste plastic derived graphene sheets as nanofillers to enhance mechanical strength of concrete mixture: An inventive approach to deal with universal plastic waste. *Cleaner Engineering and Technology*, *5*, 100275. https://doi.org/10.1016/J.CLET.2021.100275

Tatrari, G., Tewari, C., Bohra, B. S., Pandey, S., Karakoti, M., Kumar, S., Tiwari, H., Dhali, S., & Sahoo, N. G. (2021b). Waste plastic derived graphene sheets as nanofillers to enhance mechanical strength of concrete mixture: An inventive approach to deal with universal plastic waste. *Cleaner Engineering and Technology*, *5*. https://doi.org/10.1016/j.clet.2021.100275

Wang, Q., Wang, X., & Liu, H. (2023). Reaction kinetics, mechanical characteristics, and microstructure of steel slag-cement binder modified with graphene oxide. *RSC Advances*, *13*(20), 13991–14000. https://doi.org/10.1039/D3RA00257H

World Economic Forum. (2024, September 13). *Cement is a big problem for the environment. Here's how to make it more sustainable*. https://www.weforum.org/stories/2024/09/cement-production-sustainable-concrete-co2-emissions/