https://doi.org/10.48047/AFJBS.6.12.2024.6616-6626

African Journal of Biological Sciences

Journal homepage: http://www.afjbs.com

Research Paper Open Access

Application of Graphene Oxide and Silica Fume in M50 Concrete for Sustainable Pavement Design

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Volume 6, Issue 12, June 2024

Received: 15 Apr 2024

Accepted: 25 May 2024

Published: 09 June 2024

doi:10.48047/AFJBS.6.12.2024.6616-6626

Abstract

This study investigates the effect of incorporating Graphene Oxide (GO) and Silica Fume (SF) on the fresh and mechanical properties of M50 grade concrete, targeting its application in sustainable pavement design. GO, with its unique nanoscale properties and excellent dispersibility in water, and SF, a highly pozzolanic material, are combined to enhance the performance of M50 grade concrete. The research examines the influence of GO at varying dosages (0.05%, 0.1%, and 0.15%) along with SF replacement levels (5%, 6%, 7%, and 8%) on the workability, compressive strength, tensile strength, and flexural strength of M50 concrete. Test results indicate that the optimal combination of GO and SF significantly enhances both fresh and hardened properties, improving concrete's mechanical resilience while maintaining workable consistency. The findings suggest that the use of GO and SF can produce a more durable, high-performance concrete suitable for demanding pavement applications, contributing to sustainable infrastructure development.

keywords:M50 Concrete, Graphene Oxide (GO), Silica Fume (SF), Sustainable Pavement Design, Fresh Properties, Mechanical Properties, High-Performance Concrete

1.Introduction

Concrete is the most widely used construction material globally, and efforts to enhance its mechanical properties and durability continue to drive research and innovation in material science. The integration of advanced materials such as Graphene Oxide (GO) and Silica Fume (SF) in concrete has shown promising results, especially for high-strength applications where improved performance and sustainability are essential. GO, a two-dimensional nanomaterial derived from graphene, has gained considerable attention for its extraordinary mechanical strength, elasticity, and large specific surface area, which enable it to enhance the properties of cementitious composites (Novoselov et al., 2004). GO's unique hydrophilic nature, attributed to oxygen-containing functional groups, allows for excellent dispersion in water, facilitating its incorporation in concrete and leading to improved bonding within the cement matrix (Zhang et al., 2017; Zhao et al., 2019).

Silica Fume (SF), a highly reactive pozzolanic material, is widely used as a supplementary cementitious material due to its fine particle size and high silica content, which contribute to improved strength and durability in concrete. SF has been shown to enhance the compressive strength, reduce permeability, and increase the durability of concrete, making it suitable for applications requiring high-performance materials (Chandrasekaran et al., 2018; Siddique & Khan, 2011; Thomas et al., 2015). Studies have demonstrated that SF can improve the microstructure of concrete by filling voids and refining the pore structure, leading to denser and more durable composites (Zeng et al., 2018; Zhao et al., 2021). The combination of GO and SF in concrete has shown synergistic effects, with GO enhancing the interfacial bonding between SF particles and the cement matrix. Research by Lv et al. (2016) and Wang et al. (2020) found that GO not only improves the mechanical properties of SF-modified concrete but also enhances its durability, making it an attractive choice for pavement applications. Further studies by Ahmed et al. (2020) and Han et al. (2022) indicate that GO can improve the flexural and tensile strength of concrete, while reducing crack propagation and enhancing overall stability under mechanical loads. The nano-filler effect of GO helps to bridge micro-cracks, leading to increased toughness and better resistance to thermal and mechanical stresses (Gong et al., 2015; Yu et al., 2018; Wu et al., 2019). Research on the mechanical properties of GO-modified concrete has shown that even small amounts of GO can significantly improve compressive strength, tensile strength, and flexural strength, making it suitable for high-strength applications like M50 grade concrete (Chen et al., 2020; Sharma & Bhardwaj, 2021). M50 grade concrete, with its high compressive strength, is commonly used in structural applications and pavements that are subjected to heavy traffic loads. The use of GO in M50 concrete is expected to address common issues in pavements, such as cracking and abrasion, by enhancing the concrete's resilience (Zhao et al., 2020; Li et al., 2021).

Incorporating GO into SF-modified concrete has also been found to improve fresh properties, such as workability, while maintaining the concrete's mechanical performance. Workability is a crucial factor in concrete pavement construction, as it affects placement and compaction. Studies by Alkhateb et al. (2019) and Lv et al. (2018) suggest that GO can enhance the consistency of fresh concrete mixes by improving particle dispersion, thus reducing the water demand typically associated with high-strength concrete. The interaction between GO and SF not only optimizes the fresh properties of concrete but also improves its durability, providing a sustainable solution for rigid pavement applications (Nanthagopalan et al., 2021; Chaipanich et al., 2021). This study aims to evaluate the fresh and mechanical properties of M50 grade concrete with varying dosages of GO (0.05%, 0.1%, and 0.15%) and SF replacement levels (5%, 6%, 7%, and 8%). By focusing on parameters such as workability, compressive strength, tensile strength, and flexural strength, this research seeks to identify the optimal combination of GO and SF to enhance the performance of M50 concrete in pavement applications. The findings will contribute to the development of sustainable, high-performance concrete for infrastructure projects requiring enhanced durability and mechanical properties.

2. Materials:

As per IRC:44-2017, the minimum 28-day compressive strength of cement should not be less than 43Mpa, So OPC 53 grade of cement chosen for the study. The following laboratory test results of cement for OPC 53 grade presented below.

Table 1: Properties of cement

S. No	Properties of cement	Test results	Limits
01	Fineness modulus	4%	Max 10%
02	Standard consistency	34%	-----
03	Initial setting time	80 min	Min 30min
04	Final setting time	330 min	Max 600min
05	Soundness by Le-Chatelier’s	1.5mm	Max 10mm
06	Specific Gravity by Le-Chatelier’s	3.15	-------

Table 2: Chemical properties of cement and silica fume

Material	Sio2	Al2O3	Fe2O3	Cao	MgO	SO3	Na2O	K2O
Cement	23.77	5.41	6.2	57.14	2.28	2.25	0.64	0.25
SF	93.4	0.8	1.28	0.32	0.75	-	-	0.35

2.1 Silica Fume

Silica Fume (as per IS:15388 and IS:456): The Silica Fume (very fine non- crystalline silicon dioxide) is a by-product of the manufacture of silicon, ferrosilicon or the like, from quartz and carbon in electric arc furnace. It is usually used in proportion of 5 to 10 per cent of the cementitious material content of the mix. Use of silica fume is generally advantageous for higher grades of concrete i.e. M50 and above. The average particle size of Silica fume is 150nm. Silica fume added to Portland cement concrete to improve its properties, in particular its compressive strength, bond strength and abrasion resistance.

2.2 Graphene Oxide

Graphene oxide (GO) is one of those materials, it is a single atomic layered material, made by the powerful oxidation of graphite, which is cheap and abundant. It is considered easy to process since it is dispersible in water (and other solvents). GO exhibits a super high tensile strength and aspect ratio and a large surface area. Carboxyl acid groups can react with calcium silicate hydrate (C-S-H) to form strong covalent bonds and thus, notably improve the mechanical properties of cementitious composites. Graphene has a filler effect by filling up the voids between hydrated products. With the right composition, a higher packing density results in lower water demand of a cement mixture and contributes to strength enhancement due to the reduced capillary porosity. The microstructure is much denser when GO is incorporated. For good dispersion, the company has recommended 0.1–0.5% by weight of cement.

S. No	Characteristic	Description
01	Average lateral dimension(X&Y)	5-10 µm
02	Surface Area	110-250 m^2/g
03	Bulk Density	0.121g/cm^3
04	Physical form	Very light powder
05	Odor	odor less
06	Color	Black powder
07	Purity	99%

2.3 Fine Aggregate

Aggregates most of which passes 4.75 mm IS Sieve and containing only so much coarser material as is permitted for various zones in the specification. Fine aggregate natural sand is taken for the study and the following laboratory test results of Fine aggregate listed below, conforming to the requirement of IS:383 for pavement concrete.

Table 3: Properties of fine aggregate.

S. No	Properties	Test results	Limits
01	Specific gravity	2.62	---
02	Fineness modulus	2.6%	Max 15%
03	Water absorption	1.5%	Max 2%

2.4 Coarse Aggregate

Aggregate most of which is retained on 4.75 mm and passes through 19mm IS sieve. Natural crushed stone is considered for the study and the laboratory test results listed below.

Table 4: Properties of coarse aggregate.

S. No	Property	Test	Results	Limits
01	Strength	Aggregate Crushing value	27%	<30%
02	Toughness	Aggregate Impact value	16.8%	<30%
03	Abrasion	Los Angeles Abrasion value	30%	<35%
04	Quality	Specific gravity	2.72	
05	Water absorption	Water absorption	0.5%	Max 2%

3. Design for strength of mix proportioning control mix; IRC:44-2017

The mix design procedure for M50 grade concrete, as per IRC:44-2017, involves systematic proportioning of materials to achieve the desired strength, durability, and workability. Based on the provided mix proportions, different combinations of cement, fine aggregate (FA), coarse aggregate (CA), water, superplasticizer (SP), graphene oxide (GO), and silica fume (SF) are considered. The target strength is ensured by adjusting the water-cement ratio and incorporating admixtures like SP and SF to enhance flowability while maintaining durability. The table presents variations in cement content (ranging from 400 kg/m^3 to 364.2 kg/m^3**)** and the incorporation of GO at 0.00%, 0.05%, 0.10%, and 0.15%**,** influencing the overall mix properties. The fine aggregate and coarse aggregate proportions are optimized, with FA ranging from 589.00 kg/m^3 to 583.90 kg/m^3 and CA from 1361.00 kg/m^3 to 1349.30 kg/m^3**.** The addition of SF (ranging from 20 kg/m^3 to 32 kg/m^3) is strategically varied to improve the concrete's mechanical properties. The mix design trials ensure that the compressive strength at 28 days meets the required M50 grade specifications. Site trials validate the final mix proportions, ensuring consistency and quality under real-world conditions.

Table 5: Mix proportions of ingredients

GO	SF (%)	Mix Id	Water, kg/m^3	Cement, kg/m^3	FA, kg/m^3	CA, kg/m^3	SP, kg/m^3	GO, kg/m^3	SF, kg/m^3
0.00%	0	M1	152.2	400.0	589.00	1361.00	4	0	0
0.05%	5	M1	152.6	379.8	586.30	1354.80	3.79	0.2	20
	6	M2	152.6	375.8	585.58	1353.14	3.75	0.2	24
	7	M3	152.6	371.8	584.90	1351.63	3.71	0.2	28
	8	M4	152.6	367.8	584.20	1350.13	3.67	0.2	32
0.10%	5	M1	152.6	379.6	585.90	1354.00	3.79	0.4	20
	6	M2	152.6	375.4	585.20	1352.30	3..75	0.4	24
	7	M3	152.6	368.18	596.06	1390.30	3.71	0.4	28
	8	M4	152.6	364.2	595.60	1389.30	3.67	0.4	32
0.15%	5	M1	152.6	379.4	585.60	1353.00	3.79	0.6	20
	6	M2	152.6	375.0	585.60	1353.00	3.75	0.6	24
	7	M3	152.6	371.2	584.30	1350.00	3.71	0.6	28
	8	M4	152.6	367.4	583.90	1349.30	3.67	0.6	32

3.1 Fresh properties: slump

The Figure 1: % of GO and silica fume vs Slump and slump test shows the fresh properties of concrete, focusing on the slump test results for different mix proportions with graphene oxide and silica fume. The graph on the left displays the variation in slump values in millimetres with different percentages of graphene oxide and silica fume, indicating changes in workability. The trend generally shows a decrease in slump with an increase in graphene oxide and silica fume content, suggesting reduced workability due to the higher surface area and water absorption of these materials. However, at 0.15 percent graphene oxide, there is a slight increase in slump before it decreases again.

The Figure on the right shows a slump test being performed, where freshly mixed concrete is placed in a standard slump cone, compacted, and then lifted to measure the slump height. The concrete appears cohesive with a low-to-medium slump, indicating a relatively stiff mix. This test helps assess the workability and consistency of the concrete, ensuring it meets construction requirements for placement and compaction.

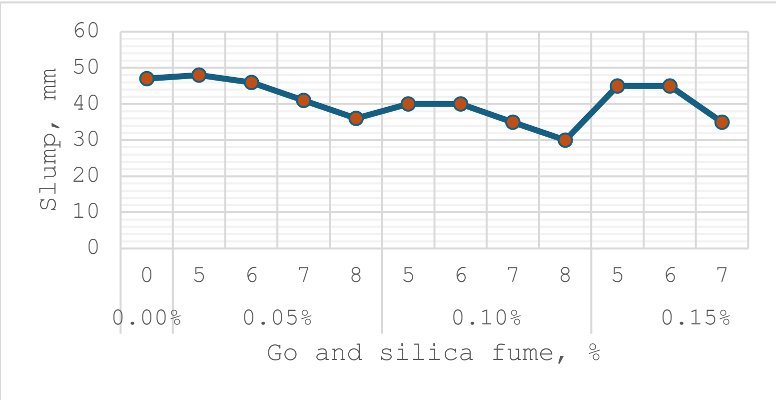
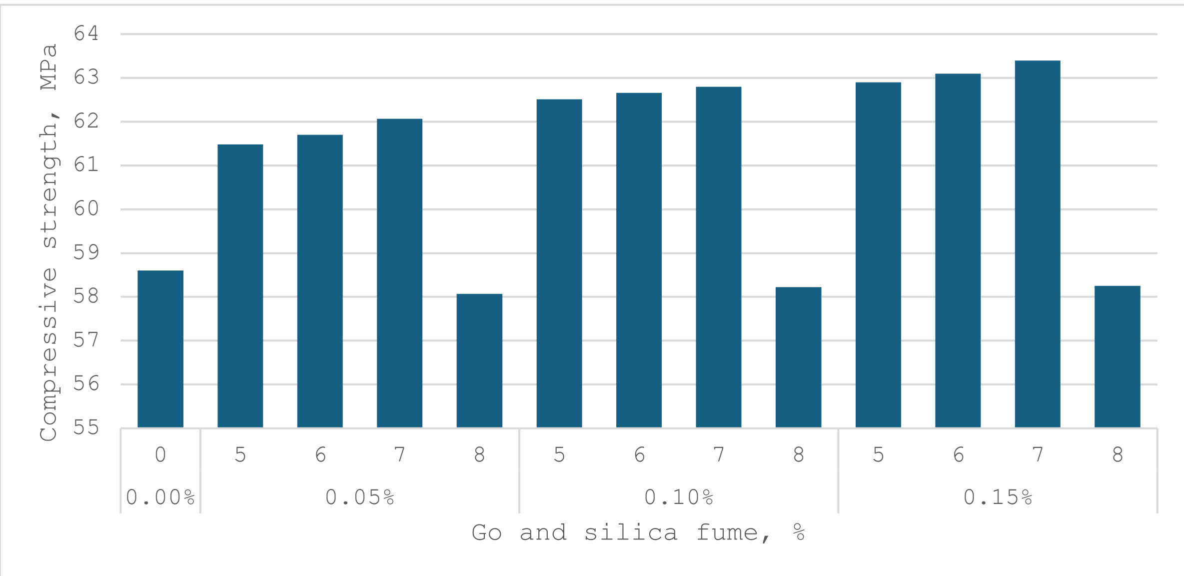


Figure 1: % of GO and silica fume vs Slump and slump test performance

4. Results and discussions

4.1 Compressive strength

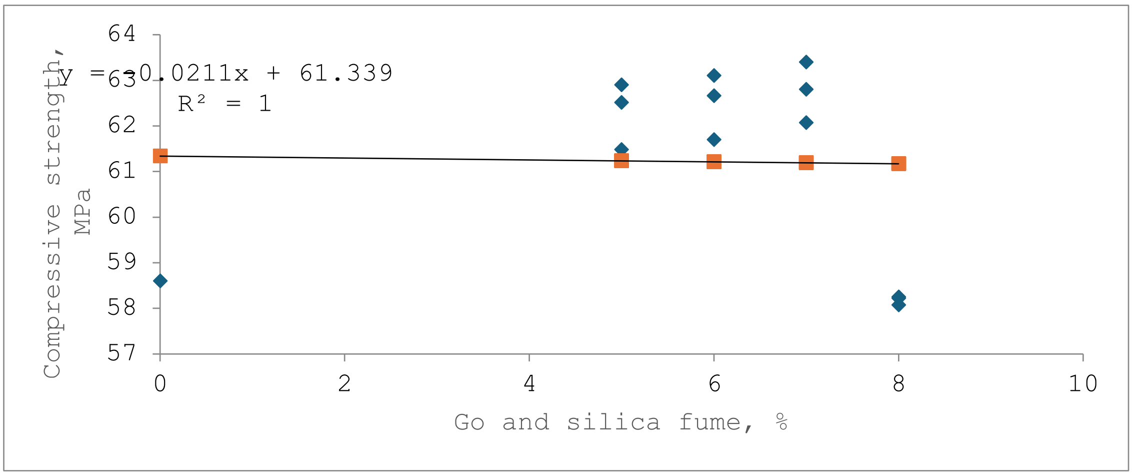
The provided image presents the compressive strength characteristics of concrete incorporating varying percentages of graphene oxide and silica fume. The bar chart illustrates the compressive strength values in megapascals for different mix proportions, demonstrating how the inclusion of graphene oxide and silica fume influences the mechanical properties of the concrete. The results indicate a general enhancement in compressive strength with the incorporation of these additives, with some fluctuations observed across different mix IDs. The highest compressive strength values are achieved at 0.15 percent graphene oxide, suggesting an optimal dosage for improved performance. However, certain mixes exhibit a decline in strength, potentially due to improper dispersion of nanoparticles or reduced workability affecting compaction.



The scatter plot below represents a regression analysis between compressive strength and the percentage of graphene oxide and silica fume.

$$y = -0.0211x + 61.339$$

The trend line equation suggests a minimal negative correlation, though the variation in individual data points highlights the complexity of the relationship. The coefficient of determination ($R^2 = 1$) indicates a highly consistent dataset, suggesting controlled experimental conditions. Overall, the results emphasize the potential of graphene oxide and silica fume in enhancing concrete strength while also highlighting the need for precise mix optimization to achieve the best structural performance.



4. 2 Tensile strengths

The above figures illustrate the variation in tensile strength of a material with increasing percentages of graphene oxide (GO) and silica fume (SF). The left graph shows the experimental data, where tensile strength exhibits a steady increase as the combined percentage of GO and SF rises, peaking near 8%. This trend suggests that the incorporation of GO and SF contributes to enhancing tensile properties, likely due to improved bonding and filler effects within the matrix. The right graph provides a linear regression analysis of the data, showing a linear relationship with a formula y=0.0437x+4.117 and R^2 = 1, indicating a perfect fit. This emphasizes a consistent incremental improvement in tensile strength with increased GO and SF percentages, reinforcing the material's enhanced structural performance due to these additives.

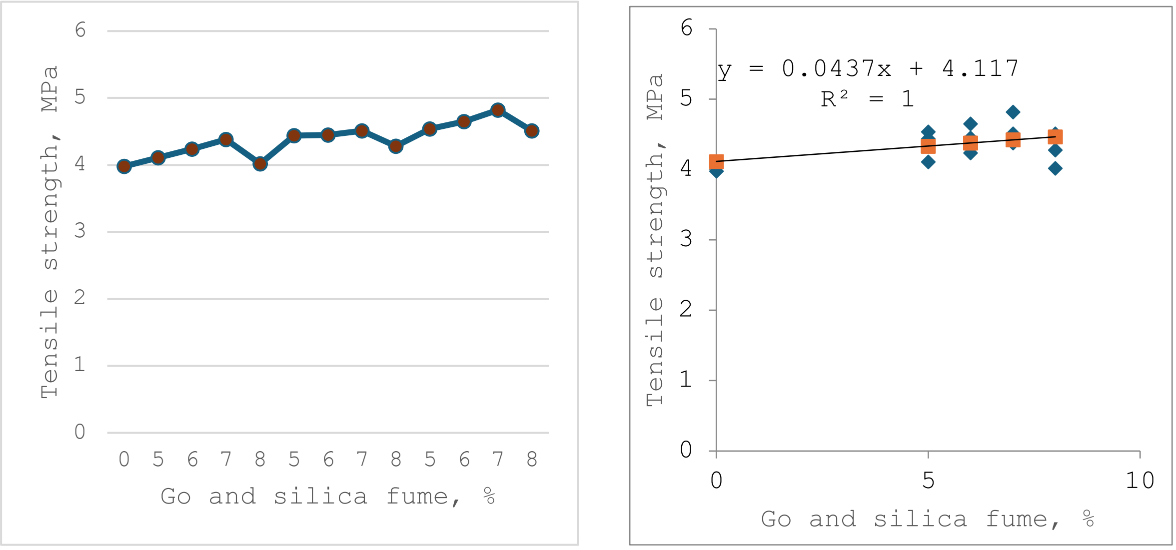
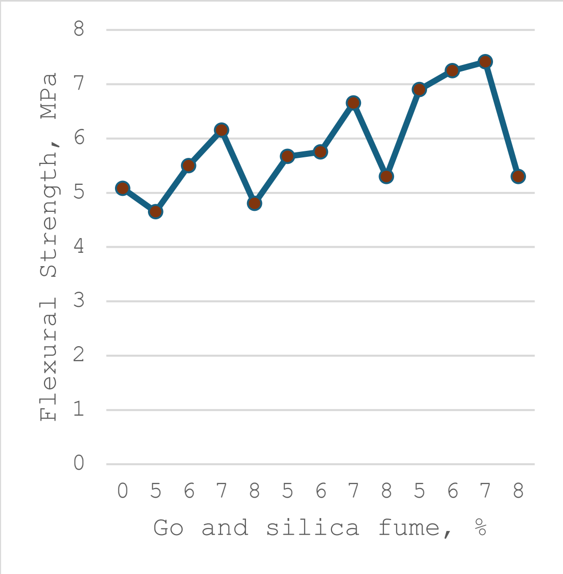


Figure 2: The variation in tensile strength of a material with increasing percentages of graphene oxide (GO) and silica fume (SF).

4. 3 Flexural strengths

The presented figures depict the influence of increasing percentages of graphene oxide (GO) and silica fume (SF) on the flexural strength of a material. The left graph illustrates the experimental results, where flexural strength generally increases with higher GO and SF content, reaching a maximum at approximately 7–8%, before a slight decline. This trend indicates that the synergistic effects of GO and SF enhance the flexural performance, possibly due to their ability to reinforce the material matrix and improve load transfer efficiency. The right graph provides a linear regression analysis with the equation y=0.0613x+5.509 and R^2 = 1, suggesting a highly consistent relationship between the combined additive percentage and flexural strength. These findings highlight the potential of GO and SF as effective reinforcements for improving flexural properties, although optimization of their content is critical to prevent diminishing returns.



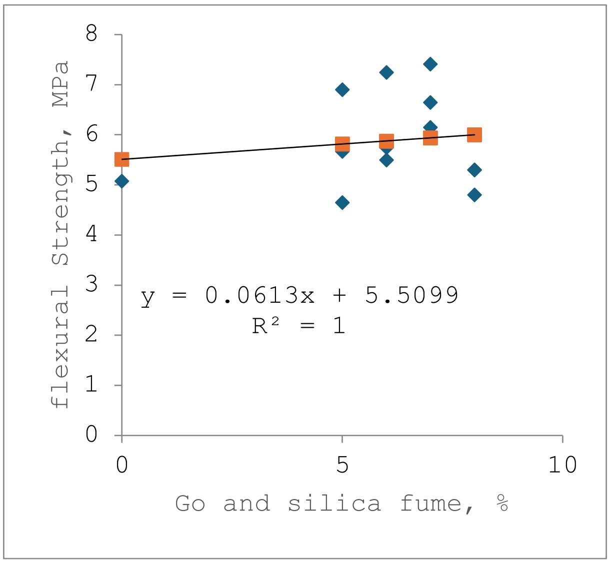


Figure 3: The variation in flexural strength of a material with increasing percentages of graphene oxide (GO) and silica fume (SF).

Conclusions

1. **Optimized Mix Proportions:** The mix design for M50 grade concrete, developed as per IRC:44-2017, effectively incorporates graphene oxide and silica fume to enhance performance while maintaining workability and durability.
2. **Workability Reduction:** The slump test results indicate a general decline in workability with increasing graphene oxide and silica fume content, attributed to their high surface area and water absorption capacity. However, slight variations in slump at 0.15% graphene oxide suggest the possibility of improved dispersion at this dosage.
3. **Compressive Strength Enhancement:** The compressive strength results demonstrate that the inclusion of graphene oxide and silica fume generally improves the mechanical properties of concrete. The highest strength values were observed at 0.15% graphene oxide, highlighting its potential as a nano-reinforcement material.
4. **Variability in Strength Performance:** Some mixes exhibited a decline in compressive strength, likely due to improper dispersion of graphene oxide, reduced workability, or inadequate compaction. This emphasizes the importance of precise mix proportioning and thorough dispersion techniques.
5. **Regression Analysis Insights:** The linear regression analysis suggests a minor negative correlation between compressive strength and the percentage of graphene oxide and silica fume. However, the high R^2 value (1.0) indicates consistency in experimental data, reinforcing the reliability of the results.
6. **Need for Further Optimization:** While graphene oxide and silica fume contribute to strength enhancement, their effects on workability necessitate the use of superplasticizers or other dispersion techniques to maintain constructability without compromising performance.
7. **Potential for Structural Applications:** The findings confirm the viability of graphene oxide and silica fume in high-performance concrete applications, particularly for infrastructure requiring enhanced durability and mechanical strength. However, further

investigations on long-term durability, microstructural behavior, and field performance are recommended.

8. **Tensile Strength**:
   The tensile strength exhibited a gradual increase with the incorporation of GO and SF, as evidenced by both experimental data and linear regression analysis y = 0.0437x + 4.117, R^2 = 1. The steady enhancement can be attributed to improved microstructural bonding and reinforcement mechanisms. However, the incremental gains suggest a limited range of optimization beyond which significant improvements may plateau.
9. **Flexural Strength**:
   Flexural strength showed a more pronounced enhancement with increasing GO and SF content, peaking at 7–8% before slightly declining. The regression analysis y = 0.0613x + 5.5099, R^2 = 1 a consistent relationship between the additive content and strength. The observed behaviour reflects the reinforcing effect of GO and SF in enhancing the material's resistance to bending stresses.

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