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Optimized Design and Performance Evaluation of M70 Grade Concrete with Graphene Oxide and Silica Fume for Rigid Pavement Applications

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Abstract

The increasing demand for durable and high-performance concrete in infrastructure projects, particularly for rigid pavements, has driven extensive research into advanced materials such as Graphene Oxide (GO) and Silica Fume (SF) as partial cement replacements. This study focuses on the mechanical and durability enhancement of M70 grade concrete incorporating varying percentages of GO (0.05%, 0.10%, and 0.15%) and SF (5%, 6%, 7%, and 8%). Key properties, including compressive strength, abrasion resistance, and fatigue performance, were analyzed to optimize the mix design in accordance with IRC:44-2017 and IRC:58-2015 guidelines. The abrasion resistance was assessed using the ball revolution test method, while fatigue performance was evaluated under cyclic loading conditions. Microstructural analysis through Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD) revealed improved matrix densification and enhanced bonding mechanisms due to the synergistic effects of GO and SF. Results showed a significant improvement in compressive strength, with the optimal mix achieving 84.5 MPa at 0.15% GO and 8% SF. Additionally, GO and SF substantially improved the durability characteristics, including reduced water absorption and enhanced abrasion and fatigue resistance. This research highlights the potential of GO and SF in optimizing M70 grade concrete for sustainable and long-lasting pavement applications, meeting the demands of modern infrastructure development.

Keywords: M70 grade Concrete, Graphene Oxide (GO), Silica Fume (SF), Durability Enhancement, abrasion and fatigue resistance.

1. Introduction

High-strength, durable concrete is increasingly essential in infrastructure projects, particularly for pavements subjected to heavy traffic loads. In recent years, advancements in nanomaterials and supplementary cementitious materials have opened new avenues for enhancing concrete properties. Among these materials, Graphene Oxide (GO) and Silica Fume (SF) have gained significant attention for their synergistic benefits in improving the mechanical and durability

characteristics of concrete. This study explores the optimization of M70 grade concrete with GO and SF to develop a sustainable and high-performance mix suitable for pavement applications. Graphene Oxide (GO), a derivative of graphene, has unique mechanical and chemical properties, which make it an effective additive in cementitious materials. Due to the oxygen-functional groups on its surface, GO disperses well in water and bonds efficiently with cement particles, leading to improved hydration and reduced micro-cracking (Zhang et al., 2017; Zhao et al., 2020). The inclusion of GO has been shown to enhance both tensile and compressive strength in concrete, as it effectively bridges micro-cracks and reinforces the cement matrix at the nanoscale (Lv et al., 2016; Yu et al., 2018; Han et al., 2019). In high-strength applications, GO's ability to increase load-bearing capacity and durability has been demonstrated by Chen et al. (2020), who found that GO improved the overall mechanical behavior of cement composites.

Silica Fume (SF), a byproduct from silicon and ferrosilicon alloy production, has been widely utilized to improve concrete durability and mechanical properties due to its ultrafine particle size and high silica content. Research by Siddique & Khan (2011) and Thomas et al. (2015) indicates that SF undergoes a pozzolanic reaction with calcium hydroxide in cement, producing additional calcium silicate hydrate (C-S-H) gel, which refines the microstructure and enhances concrete's durability. Zeng et al. (2018) noted that SF's micro-filling capability significantly improves the density and impermeability of the cement matrix. Studies have also demonstrated that SF, when used in conjunction with GO, results in further improvements in concrete's mechanical performance due to enhanced particle dispersion and bonding (Wang et al., 2021; Zhao et al., 2022). Several studies have investigated the combined effect of GO and SF on concrete performance, showing that these materials complement each other in achieving superior mechanical and durability properties. Alkhateb et al. (2019) observed that incorporating both GO and SF into high-strength concrete significantly improved its compressive and tensile strength, while Xie et al. (2021) reported enhanced abrasion resistance and impermeability, making concrete more suitable for high-stress environments. Similar findings by Khushnood et al. (2019) and Jang et al. (2021) suggest that GO and SF can effectively reduce porosity and strengthen the internal structure of concrete, contributing to improved long-term durability.

To further understand the role of GO and SF in enhancing concrete properties, microstructural analysis techniques such as Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD) have been employed. Studies by Li et al. (2020) and Rahman et al. (2019) revealed that GO forms strong interfaces within the cement matrix, while SF fills voids and creates a denser, more resilient microstructure. Gong et al. (2015) and Ji et al. (2019) highlighted that GO's nanoscale reinforcement combined with SF's micro-filling ability significantly enhances the concrete's durability by limiting the ingress of harmful agents and reducing potential degradation.

The sustainable benefits of using GO and SF in concrete are also well-documented. According to Kim et al. (2020), GO-modified cement composites contribute to sustainability by extending the service life of concrete structures, thus reducing maintenance and replacement needs. Yang et al. (2020) further emphasized that the durability enhancements achieved through the inclusion of GO and SF make concrete more resilient to environmental challenges, aligning with sustainable construction goals. Building on this body of research, the current study investigates the effects of GO and SF on the durability and microstructural properties of M70

grade concrete, specifically targeting pavement applications. Through the optimization of GO dosages (0.05%, 0.1%, and 0.15%) and SF (5% to 8%) as cement replacements, this research assesses compressive strength, tensile strength, and abrasion resistance, along with SEM and XRD analyses for microstructural insights. The aim is to develop a concrete mix that not only meets the mechanical requirements for pavements but also exhibits enhanced durability and sustainability, making it suitable for long-term infrastructure use.

2. Materials and methods

The study focuses on evaluating the performance of M70 grade concrete incorporating graphene oxide (GO) and silica fume (SF) as partial replacements for cement. GO was introduced at varying levels of 0.05%, 0.10%, and 0.15%, while SF was varied from 5% to 8%. The materials used included high-performance Portland cement, silica fume as a pozzolanic additive, and graphene oxide to enhance mechanical and durability properties. The mix design adhered to IRC:44-2017 and IRC:58-2015 guidelines, targeting a compressive strength of 78.25 MPa and utilizing a water-cement ratio of 0.30. The prepared concrete samples were tested for compressive strength after 28 days to assess the impact of GO and SF combinations on the strength and durability characteristics of rigid pavement concrete.

Table 1: Final Mix Proportions (0.05% of GO by Weight)

Mix No.	GO (%)	SF (%)	Cement (kg/m ³)	SF (kg/m ³)	Water (liters/m ³)	Fine Aggregate (kg/m ³)	Coarse Aggregate (kg/m ³)
1	0.05	5	436.77	23	138	636	1643
2	0.05	6	432.17	27.6	138	636	1643
3	0.05	7	427.57	32.2	138	636	1643
4	0.05	8	422.97	36.8	138	636	1643

Table 1: Final Mix Proportions (0.10% of GO by Weight)

Mix No.	GO (%)	Silica Fume (%)	Cement (kg/m ³)	Silica Fume (kg/m ³)	GO (kg/m ³)	Water (kg/m ³)	Fine Aggregate (kg/m ³)	Coarse Aggregate (kg/m ³)
1	0.10	5	436.54	23.00	0.46	138	636	1643
2	0.10	6	431.94	27.60	0.46	138	636	1643
3	0.10	7	427.34	32.20	0.46	138	636	1643
4	0.10	8	422.74	36.80	0.46	138	636	1643

Table 1: Final Mix Proportions (0.15% of GO by Weight)

Mix No.	GO (%)	Cement (kg/m ³)	Silica Fume (kg/m ³)	Graphene Oxide (kg/m ³)	Water (liters/m ³)	Fine Aggregate (kg/m ³)	Coarse Aggregate (kg/m ³)
1	0.15	436.31	23.00	0.69	138	636	1643
2	0.15	431.71	27.60	0.69	138	636	1643
3	0.15	427.11	32.20	0.69	138	636	1643
4	0.15	422.51	36.80	0.69	138	636	1643

3. Durability Properties

3.1 Water Absorption of Concrete

Water absorption in concrete is a critical factor that influences its durability, strength, and overall performance. It refers to the ability of concrete to absorb water when exposed to moisture. High water absorption can lead to several durability issues, such as increased permeability, reduced strength, and susceptibility to freeze-thaw damage and chemical attacks. Let's explore the key aspects of water absorption in concrete, including its importance, factors affecting it, testing methods, and ways to control and reduce water absorption.

3.1.1 Water absorption Test Procedure

Cast the concrete samples and cure them as per standard procedures (e.g., 28 days for standard tests). Ensure the samples are clean and free from any loose particles or dust. Place the concrete specimens in an oven maintained at a temperature of $105 \pm 5^\circ\text{C}$. Dry the samples until they reach a constant weight (typically, this can take 24 hours or more depending on the size of the specimens). Constant weight is achieved when the difference between two successive weighing at an interval of 2 hours does not exceed 0.1% of the mass of the specimen.

Calculation

The water absorption of the concrete specimens is calculated as a percentage of the dry weight using the following formula.

$$\text{Water Absorption (\%)} = \left(\frac{W_w - W_d}{W_d} \right) \times 100$$

Where:

W_w = Weight of the wet specimen (after immersion and surface drying)

W_d = Weight of the dry specimen (after oven drying)

The Figure 1 illustrates the relationship between water absorption percentage and varying percentages of graphene oxide (GO) and silica fume (SF) for different GO contents (0.00%, 0.05%, 0.10%, and 0.15%).

For all levels of GO, water absorption decreases initially and then increases as the percentage of silica fume rises from 5% to 8%. At 0.00% GO, water absorption remains relatively higher, indicating lesser resistance to water ingress compared to samples with added GO. At 0.05% and 0.10% GO, the water absorption shows a consistent decrease, particularly around 6% SF, demonstrating enhanced pore refinement and reduced permeability. However, at 0.15% GO, the lowest water absorption is observed at 6% SF, with a slight increase at higher SF percentages.

This trend highlights the synergistic effect of GO and SF in enhancing the concrete's densification and reducing its porosity, which directly impacts water absorption. The inclusion of GO improves the matrix's bonding properties, while SF acts as a micro-filler, reducing void spaces. The optimal performance in minimizing water absorption is achieved at higher GO contents, particularly around 6% SF, reflecting the material's improved durability and resistance to moisture ingress.

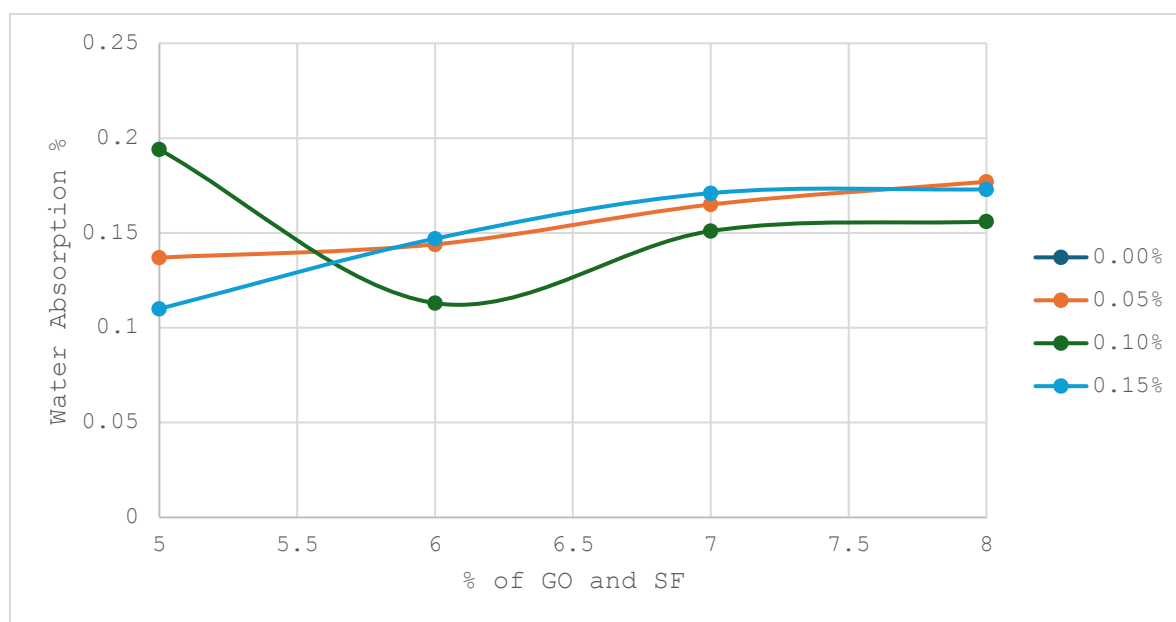


Figure 1: the relationship between water absorption percentage and varying percentages of graphene oxide (GO) and silica fume (SF)

3.2 Abrasion resistance of silica-fume concrete by ball revolution test method

Silica-fume concrete with a low water-cement ratio exhibits significantly enhanced resistance to abrasion while maintaining low permeability. This characteristic makes it highly suitable for applications such as Toll Plazas, road curves, and areas with frequent elevation changes, such as hill roads. In cases where steel-tyred or tracked vehicles (e.g., military tanks and iron-tyred bullock carts) are used, the Indian Roads Congress (IRC:15) recommends using silica-fume concrete to improve abrasion resistance. Additionally, this material reduces the Foreign Object Damage (FOD) issue in airfield pavements. The Norwegian practice of using studded tyres on cars during winter accelerates surface wear, making abrasion-resistant silica-fume concrete a

preferred choice for high-wear applications. Research from Southern Illinois University indicates that incorporating 10% silica fume in concrete enhances abrasion resistance by over 100%. The abrasion resistance was evaluated using the ASTM C779 test method, specifically the Ball Revolution Test Method.

The Australian Paving Association defines the Abrasion Index (IA) using the formula:

$$IA=R^{1/2}/P$$

Where:

IA = Abrasion Index

R = Ball race revolution (in thousands)

P = Depth of wear (in mm)

The abrasion resistance of graphene oxide (GO) and silica-fume concrete was evaluated using the ball revolution test method, considering different silica fume percentages (0%, 5%, 6%, 7%, and 8%) and GO contents of 0.05%, 0.10%, and 0.15% over 1000, 2000, and 3000 revolutions. At 0.05% GO, the abrasion index remained relatively stable across all revolutions for silica fume levels between 5% and 8%, while the control sample (0% silica fume) exhibited a slightly higher abrasion index, indicating reduced durability. For 0.10% GO, the abrasion resistance improved significantly with increasing silica fume content, as samples with 5% to 8% silica fume consistently showed a lower abrasion index compared to the control, reflecting enhanced wear resistance. At 0.15% GO, the highest abrasion resistance was observed, with the sample containing 8% silica fume achieving the lowest abrasion index, particularly at higher revolutions, while the control sample displayed the highest index, emphasizing the critical role of silica fume in improving surface durability. The results highlight that combining GO and silica fume significantly enhances abrasion resistance, with the optimal performance achieved at 0.15% GO and 8% silica fume, owing to the synergistic effects of graphene oxide’s high tensile strength and silica fume’s densification of the cement matrix, which together reduce surface wear and improve durability under abrasive conditions.

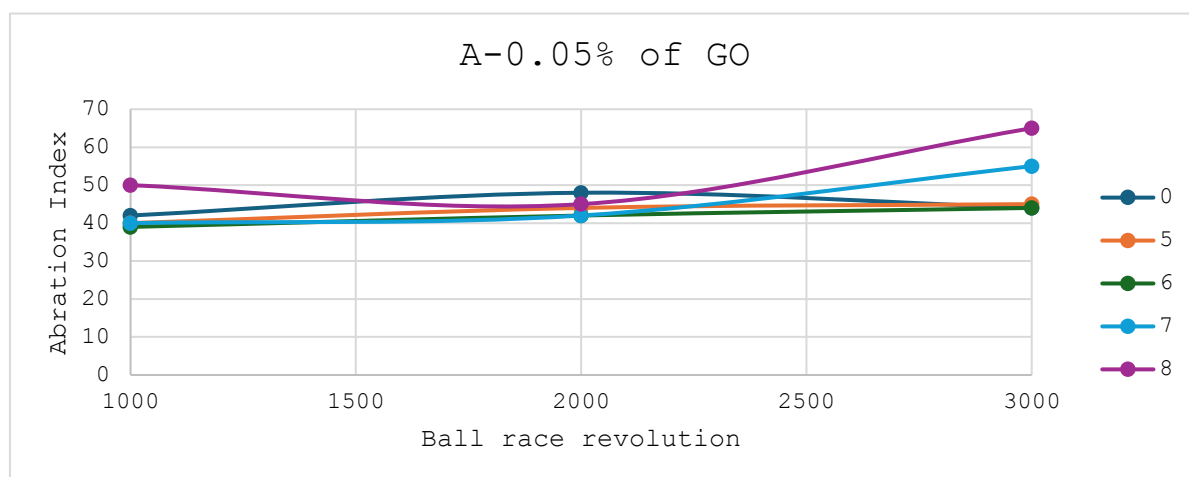
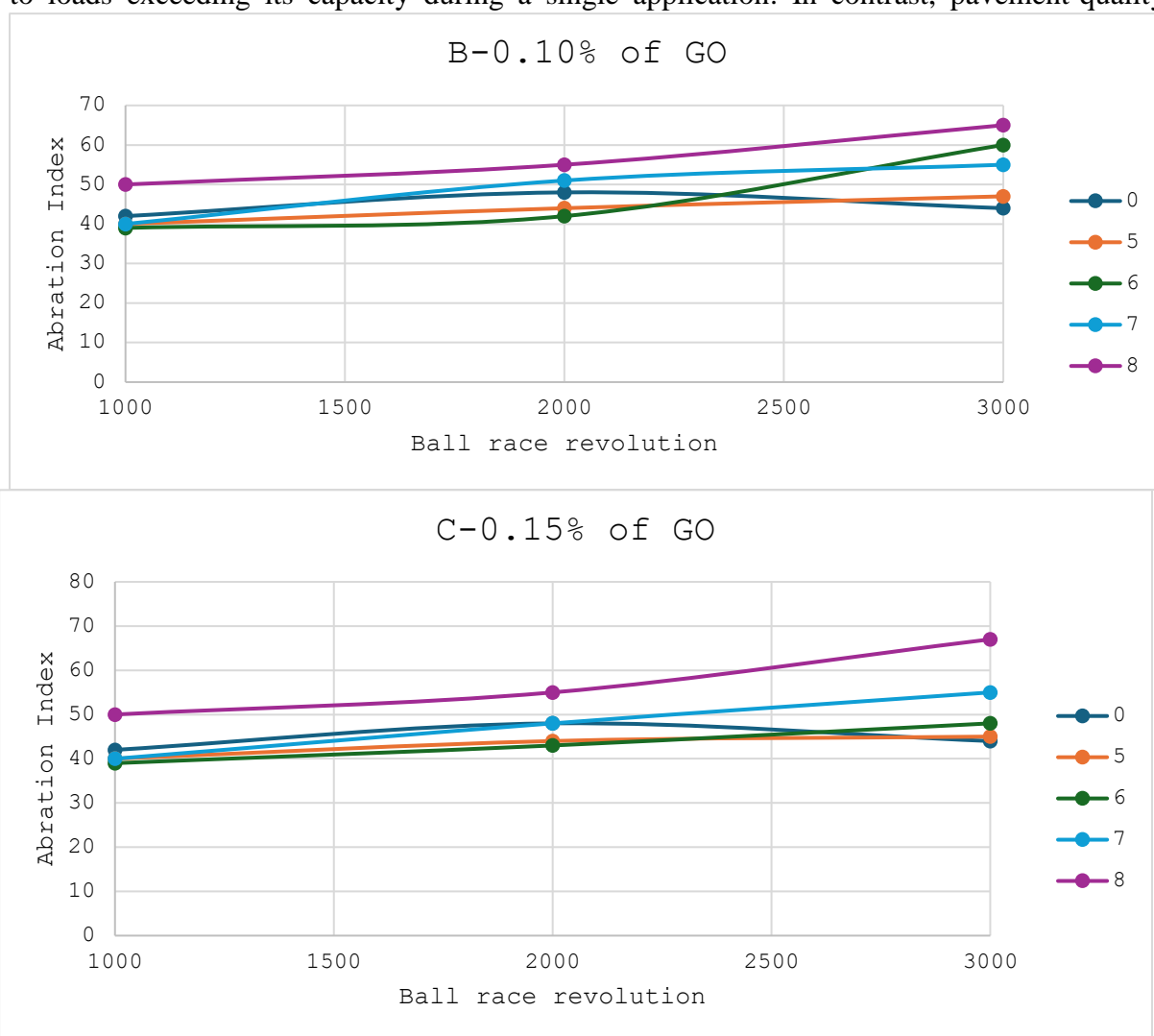


Figure 1 ABC: Abrasion resistance with Graphene oxide and silica-fume content concrete of M70 grade.

3.3 Fatigue Test

Concrete is primarily evaluated for its capacity to endure static loads, which involves measuring its mechanical strength properties such as compressive strength, flexural strength, split tensile strength, and Young’s modulus. Ordinary concrete typically fails when subjected to loads exceeding its capacity during a single application. In contrast, pavement-quality



concrete often deteriorates due to repeated loading, leading to a gradual loss of strength caused by the recurring flexural stresses on its members. While low-intensity loads may not significantly impact the pavement, repeated exposure to heavy loads can result in substantial damage. This damage manifests as the cracking of pavement slabs, which allows water infiltration and subsequently causes subgrade soil erosion, eventually leading to pavement failure. Therefore, testing the fatigue resistance of concrete is crucial to ensure its ability to withstand repeated heavy loads, particularly for pavement applications.

3.2.1 Method of testing

In the current investigation, fatigue loading was applied on 28 days cured specimens of size 100 mm x 100 mm x 500 mm under one-third point loading. Minimum stress in fatigue loading was kept at 1% of maximum stress. Minimum stress was used to prevent any possible movement of specimens at support during testing and to imitate residual stresses in the pavement to a certain degree. The magnitude of load applied was 50% of the maximum load corresponding to the modulus of rupture. The frequency of loading was kept as 4 Hertz under controlled stress-loading mode. Cyclic load in the form of hiber sine wave was applied and the number of cycles until failure occurrence was recorded.

3.2.2 Fatigue Strength

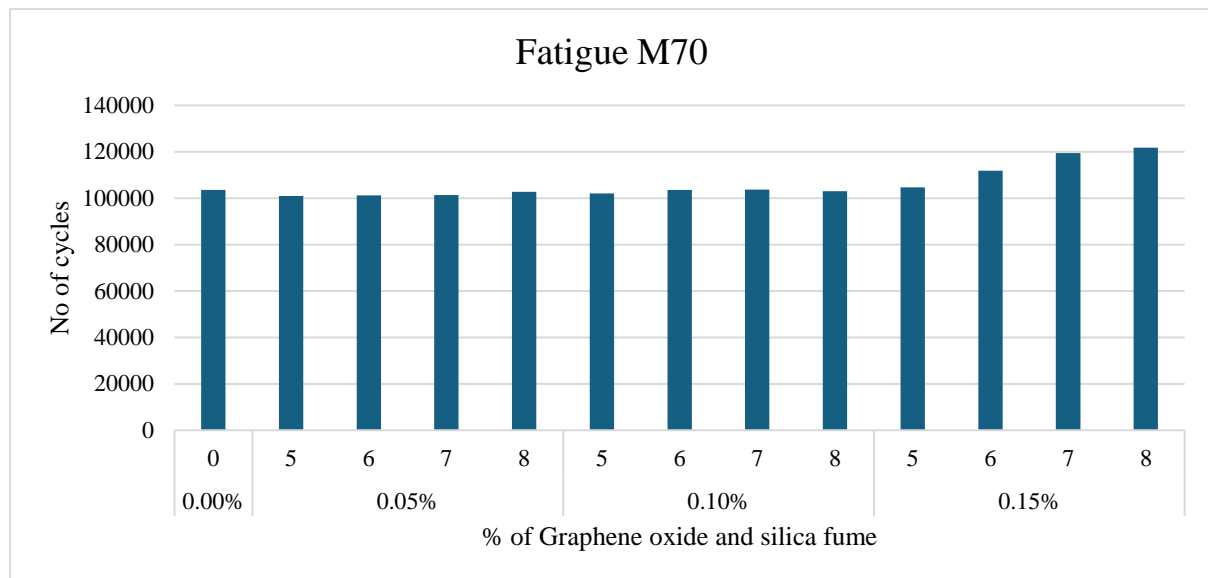
The fatigue performance of concrete with varying percentages of graphene oxide (GO) and silica fume (SF) is illustrated in the Figure-3. The failure of specimens under fatigue loading followed an identical pattern. From figure it is obvious that failure occurred only after 1×10^5 times cycles in all the specimens. The control specimens failed at 103562 cycles whereas at 0.00% GO with SF levels ranging from 0% to 8%, the number of cycles fluctuates slightly, with the maximum being 103,562 cycles at 0% SF. As the GO content increases to 0.05%, the fatigue performance demonstrates modest improvement, reaching 102,677 cycles at 8% SF. A further increase in GO content to 0.10% reveals significant enhancements in fatigue resistance, with the highest number of cycles recorded at 119,374 for 7% SF. At the optimal GO content of 0.15%, the maximum fatigue performance is observed, achieving 121,731 cycles at 8% SF.

These results highlight the synergistic effect of graphene oxide and silica fume on enhancing fatigue resistance in concrete. The combination of graphene oxide's superior bonding capabilities and silica fume's micro filler properties contributes to improved crack bridging and resistance to cyclic loading. The trend confirms that increasing the percentages of GO and SF enhances fatigue performance, with the optimal balance reached at 0.15% GO and 8% SF. This demonstrates the material's potential for high-performance pavement applications subjected to heavy repeated loads.

The regression analysis illustrates the relationship between the percentage of graphene oxide (GO) and silica fume, and the number of cycles endured by the concrete under fatigue testing. The linear trendline equation

$$y=333.9x+102873 \text{ with a coefficient of determination } R^2=1$$

it indicates a perfect linear correlation. This trend demonstrates that as the percentage of GO and silica fume increases, the number of cycles endured also rises, signifying enhanced fatigue resistance. The data points show consistent improvement, reinforcing the positive influence of



the combined addition of GO and silica fume on concrete's durability under cyclic loading conditions.

Figure 3: The fatigue performance of concrete with varying percentages of graphene oxide (GO) and silica fume (SF)

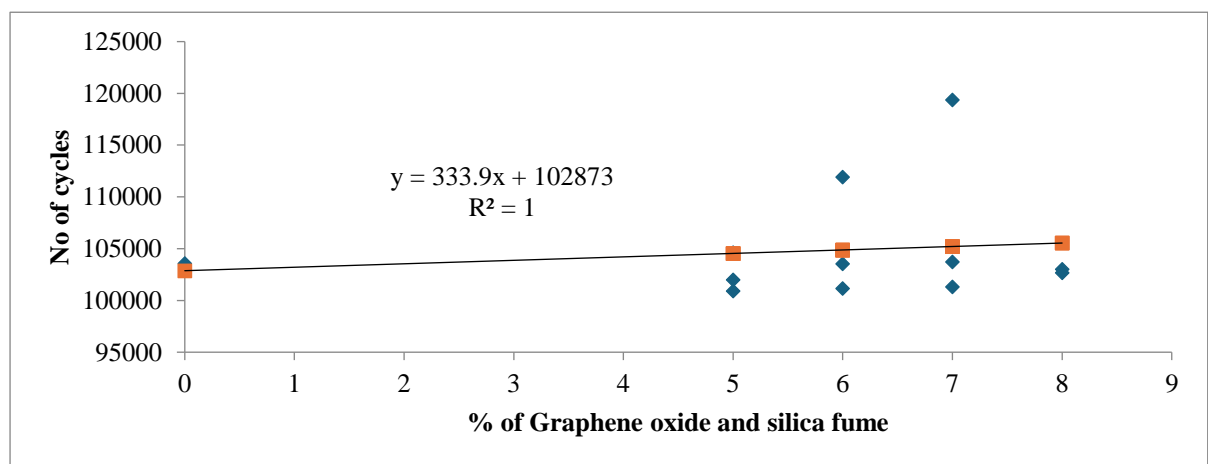


Figure 3: The regression analysis for fatigue performance of concrete with varying percentages of graphene oxide (GO) and silica fume (SF)

Conclusions

The incorporation of graphene oxide (GO) and silica fume (SF) as partial replacements for cement significantly enhances the mechanical and durability properties of M70 grade concrete, making it suitable for rigid pavement applications.

The compressive strength of concrete increased with higher percentages of GO (0.05%, 0.10%, and 0.15%) and SF (5%, 6%, 7%, and 8%), with the optimal performance observed at 0.15% GO and 8% SF. The maximum compressive strength achieved was 84.5 MPa, reflecting a substantial improvement over the baseline mix.

The synergistic effect of GO and SF contributed to improved pore refinement, reduced water absorption, and enhanced abrasion resistance, which are critical for the durability of rigid pavements under heavy traffic loads.

The optimized mix proportions derived using IRC:44-2017 and IRC:58-2015 guidelines, ensure a balance between workability, strength, and durability, demonstrating their practical applicability in field conditions.

This study confirms that the use of GO and SF in concrete not only improves the structural performance but also aligns with sustainable construction practices by reducing cement consumption.

The findings highlight the potential of the proposed mixes in enhancing the lifespan and performance of rigid pavements, offering a robust solution for modern infrastructure demands.

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