

INFLUENCE OF GALVANIZED IRON FIBER AND SILICA FUME ON THE MECHANICAL AND DURABILITY PROPERTIES OF HIGH PERFORMANCE CONCRETE

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ABSTRACT

In the pursuit of durable and sustainable high-performance construction materials, this study explores the effect of galvanized iron fiber (GIF) as fiber reinforcement and silica fume (SF) as an additional cementitious material in high performance concrete (HPC). HPC offers significant advantages over conventional concrete due to its high compressive strength, notable durability, and excellent ductility when reinforced with fibers. Due to its local availability and cost-effectiveness, GIF, having a 0.5 mm diameter and a length of 25 mm, was utilized as the fiber reinforcement in HPC. Nine combinations, incorporating SF at 0%, 10%, and 20% by weight, and GIF at 0%, 0.25%, and 0.5% by volume of concrete, were investigated. Mechanical properties of concrete were evaluated by performing compressive strength test on the cylindrical specimens after 28 days of curing, while the non-destructive ultrasonic pulse velocity (UPV) and surface resistivity tests were also assessed on the same specimens. Results revealed that incorporating 20% SF with 0.25% GIF resulted in the highest compressive strength of 76.4 MPa, representing a 31.27% improvement compared to the control mix. The same mix exhibited a notable surface resistivity of 42.08 kΩ-cm, which is 3.16 times that of the control sample, indicating improved resistance to chloride ion penetration. Moreover, the UPV increased by 29.39% compared to the control mix upon adding 20% SF with 0.25% GIF. These enhancements were made possible by the improved microstructure of concrete, attributed to the pozzolanic reaction of silica fume and the fiber-bridging ability of GIF. However, incorporating 0.5% GIF, combined with SF, decreased compressive strength due to reduced workability, leading to non-uniform compaction. Reduced workability can hinder proper compaction of the concrete mix, leading to increased entrapped air and voids, eventually adversely affecting compressive strength. To mitigate these problems, ACI practice guidelines recommend using GIF and SF in optimized proportions, in addition to use of high-range water-reducing admixture. Moreover, adequate consolidation techniques should be used to minimize void formation during concrete placement. Therefore, the results of compressive strength and non-destructive tests conducted demonstrate the significant potential of the synergistic effect of SF and GIF in improving both mechanical and durability properties of HPC when used in optimal proportions.

Keywords: *High performance concrete (HPC), galvanized iron fiber, silica fume, compressive strength, chloride ion penetration*

1. INTRODUCTION

Concrete is the most widely used construction material globally. Excellent mechanical and physical properties are the main reasons for its popularity (Farahani et al., 2017). Every year, 6 billion tons of concrete are produced worldwide. It is second only to water in terms of annual global consumption by volume (Randl et al., 2014). Cement is one of the primary components of concrete and serves as an inorganic binding agent. Since limestone is the primary raw material in cement production, using cement as the primary element of concrete contributes to the issue of the exhaustion of Earth's natural resources (Mohamad et al., 2022). Therefore, to address the growing problems of civilization, the incorporation of advanced materials in concrete production is inevitable. Additionally, since waste disposal is a significant concern today, incorporating by-products from various industrial processes presents a sustainable and effective solution. Hence, this initiative not only enhances the performance of concrete but also contributes to efficient waste management, promoting eco-friendly construction practices and reducing the industry's overall carbon footprint.

Several years of research have led to the fact that conventional regular-strength concrete has notable limitations in meeting the performance and durability needs of high-rise structures. Due to this, civil engineers and researchers have long been concerned about concrete's shortcomings in terms of mechanical and durability properties. Numerous studies have been conducted to enhance the strength of concrete. This has led to the development of high performance concrete (HPC), which combines high strength and durability. Besides the three basic ingredients—cement, fine aggregate, and coarse aggregate used in conventional concrete, HPC incorporates active mineral additives, such as fly ash, silica fume, and superplasticizer, to enhance workability, strength, and durability. HPC offers significant benefits over traditional concrete due to its enhanced durability and abrasion resistance (Aitcin, 2003).

The use of fiber is increasingly emphasized in HPC mixing because of its natural tensile properties, which help address brittleness and enhance ductility and toughness (Gupta et al., 2020). Among many fibers, steel fiber is the most popular and widely used. It also shows excellent performance when integrated with concrete. A study by Abbas et al. (2015) showed that compressive strength increased by 3%, 9%, and 13% for mixtures with 1%, 3%, and 6% of 8 mm (0.31 in) steel fibers, respectively, compared to mixtures without steel fibers. However, since steel fiber is costly and not readily available in Bangladesh, fibers prepared from galvanized wire can provide an adequate, low-cost substitute for steel fibers. GI wires are mild steel wires with a thin coating of zinc, which are locally produced and are available at a relatively low price in the market (Emon et al., 2017). Since concrete is weak in tension, it is prone to cracking owing to plastic and drying shrinkage; thus, introducing these short, discrete fibers into the concrete can prevent the propagation of cracks (Afroughsabet et al., 2016). Another material that enhances the strength of concrete is silica fume (SF); a pozzolanic by-product produced during the manufacture of silicon metal and ferrosilicon alloys, is commonly used in concrete production. It can be used as a partial cement replacement or as an additive. Adding SF to concrete reduces the permeability of concrete (Lee et al., 2017). Moreover, it also improves concrete's mechanical properties, bond strength, and abrasion resistance. Mazloom et al. (2004) investigated the influence of silica fume on the compressive strength of concrete over a period of 400 days. The percentages of silica fume used as a partial replacement for cement were 0%, 6%, 10%, and 15%. It was found that the compressive strength of concrete increased as the percentage of silica fume increased.

It is observed from the study of past literature that SF is very efficient in enhancing the mechanical properties of HPC when used in proper percentages (Smarzewski, 2019). But further research is needed to determine the optimal dose of these fibers to achieve desirable results. Although numerous studies confirm the benefits of SF and steel fibers in HPC, limited research has focused on the use of locally available galvanized iron fibers (GIF) as a cost-effective alternative. This study aims to mitigate the research gap and explore the effect of GIF as fiber reinforcement and SF as an additional cementitious material in high performance concrete (HPC) to evaluate its mechanical and durability properties.

2. METHODOLOGY

2.1 Material Properties

2.1.1 Cement

For this study, ordinary Portland cement, as per BDS EN 197-1:2010, CEM 1, 52.5 N, is used to make the concrete mix. Cement was collected from local manufacturers. Afterwards, it was tested in the laboratory, following ASTM standards, to determine its physical and mechanical properties. Table 1 presents the properties of the cement used in this study.

Table 1: Properties of Cement

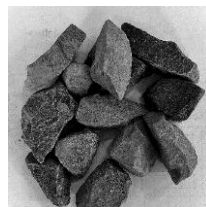
Test Name	Standard Requirement (OPC)	Obtained Result	ASTM Standard
Specific Gravity	-	3.17	ASTM C188 (2014)
Normal Consistency	-	26%	ASTM C187 (2011)
Initial Setting Time	Not less than 45 min ASTM C150 (2021)	81 min	ASTM C191 (2013)
Final Setting Time	Not more than 375 min ASTM C150 (2021)	205 min	

2.1.2 Aggregate

Locally sourced natural crushed stone (NCA) is utilized as coarse aggregate (CA) in the concrete mix for this study. Aggregates larger than 19 mm and smaller than 4.75 mm were excluded by sieving to achieve a uniform mixture. Aggregates sized 19 mm, 12.5 mm, 9.5 mm, and 4.75 mm were used in the concrete mix. For this study, Sylhet Sand has been used as fine aggregate (FA). Table 2 presents the properties of the fine and coarse aggregates used in this study. Figure 1 (a) and (b) show coarse and fine aggregate, respectively.

Table 2: Properties of aggregate

Test Name	Properties (CA)	Properties (FA)	ASTM Standard
Specific Gravity (Oven Dry)	2.79	2.57	ASTM C127 (2015)
Specific Gravity (Saturated Surface dry)	2.80	2.60	
Apparent Specific Gravity	2.83	2.65	
Absorption [%]	0.56	1.10	
Unit Weight (Loose) [kg/m ³]	1540	1486	ASTM C29 (2009)
Unit Weight (Compact) [kg/m ³]	1605	1531	



19 mm



12.5 mm



9.5 mm



4.75 mm

Figure 1 (a): NCA



Figure 1 (b): Sylhet Sand

2.1.3 Galvanized iron fiber (GIF)

The GIF used in this study is locally sourced. The bundle of GIF of diameter 0.5 mm is manually chopped to the desired length of 25 mm and used in this study. Table 3 shows the mechanical and physical properties of the GIF used. Figure 2 shows the GIF used in the study.

Table 3: Properties of GIF

Properties	Value
Length (mm)	25
Diameter (mm)	0.5
Maximum stress (MPa)	458
Maximum elongation (%)	23.28
Elastic modulus (GPa)	50

2.1.4 Silica fume (SF)

For this study, Elkem Microsilica Grade 920 was used as a partial replacement for cement. The physical and chemical properties of SF were tested in the laboratory following ASTM standards. The specific gravity of SF used was 2.32, which is less than that of the cement used in this study. Figure 3 illustrates the SF used in the study.

2.1.5 Admixture

Admixtures are additives that modify or change specific characteristics of concrete after it is mixed and before it sets. These are chemicals used either to improve the workability of the concrete during placement and finishing or to enhance its performance after it is cured and in use. This study utilized MasterGlenium SKY 8632, a high-performance polycarboxylic ether (PCE)-based superplasticizer specifically designed for high-durability and performance applications in concrete. This admixture is chlorine-free and congruent with all cement types. Figure 4 shows the admixture used for this study.



Figure 2: GIF



Figure 3: SF



Figure 4: Admixture

2.2 Mix design

This study investigated nine different concrete mix designs for cylinders. A water-cement ratio (w/c) of 0.3 was kept constant throughout all the mixes. Other variations were conducted at different percentages of SF and GIF used. SF was used as a partial replacement of cement at 0%, 10%, and 20% of the cement's weight. Fiber content of 0%, 0.25%, and 0.5% of the volume of the concrete was incorporated in the concrete mix. Table 4 shows the proportion of different materials used in the concrete mix.

Table 4: Mix proportion for 1 m³ of concrete

Designation	Cement (kg)	SF	NCA	GIF	Sand	Water	Admixture
	kg	kg	kg	kg	kg	kg	ml
C100SF0G0	586	0	1003	0	673	176	5860
C90SF10G0	532	59	1011	0	657	177	5860
C80SF20G0	477	119	1019	0	642	179	5860
C100SF0G25	586	0	1004	19.4	673	176	5860
C90SF10G25	531	59	1012	19.4	657	177	5860
C80SF20G25	476	119	1020	19.4	642	179	5860
C100SF0G50	586	0	1004	38.85	673	176	5860
C90SF10G50	531	59	1012	38.85	657	177	5860
C80SF20G50	476	119	1020	38.85	642	179	5860

Note: CxSFyGz, where, C = Cement Content, x = % of Cement used in the total volume of concrete. SF = SF content, y = % of SF of the total weight of cement. G = GIF content and z = % of GI fiber of total cement volume. G25= 0.25% GIF of total concrete volume. G50= 0.50% GIF of total concrete volume.

2.3 Sample preparation

A total of 144 concrete cylinders from nine combinations (16 cylinders per combination) with a formwork diameter of 100 mm and a height of 200 mm were cast and demolded the next day after casting and cured for 28 days in accordance with ASTM C192 (2015). Figure 5 illustrates the entire workflow for sample preparation and testing, in compliance with the required standards.

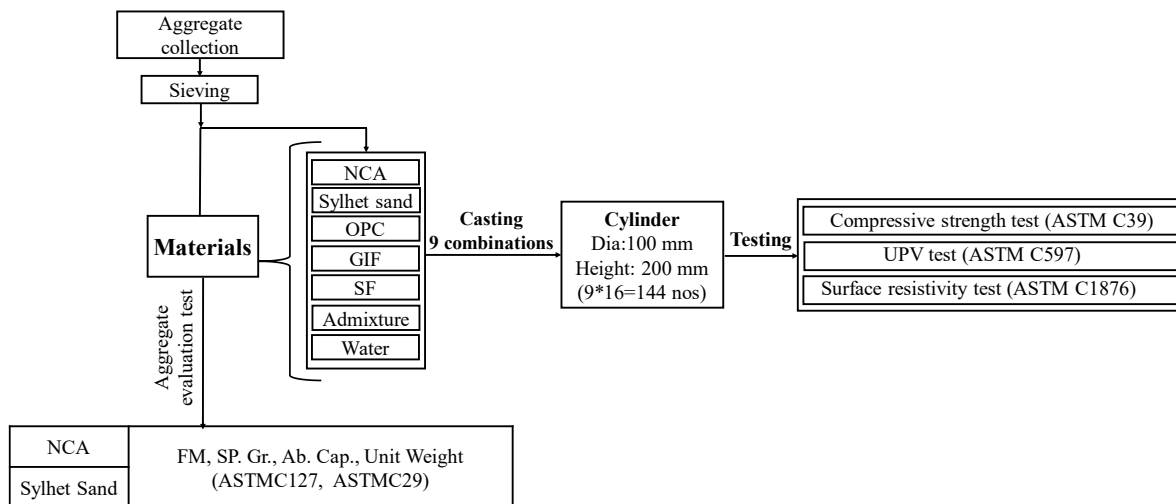


Figure 5: Flow chart showing workflow

3. RESULTS AND DISCUSSION

The test results of mechanical and non-destructive tests conducted on the cast specimens are illustrated in Table 4. The results from the compressive strength test conducted on concrete cylinders at 28 days of curing show that the mix containing 20% SF and 0.25% GIF (C80SF20G25) demonstrated the highest compressive strength, 76.4 MPa, showing a 31.2% increase compared to the control sample (C100SF0G0). Results show that, keeping the SF content constant, increasing the fiber content results in an improvement in compressive strength at a 0.25% fiber addition. However, upon the addition of 0.50% fiber, the strength begins to decline. If the fiber content is kept constant, the addition of 10% SF

results in a strength increment, whereas the addition of 20% SF shows a decline in strength. But when 20% SF is combined with 0.25% GIF, improvement is observed, which indicates a synergistic effect of the pozzolanic reaction of SF and the confinement effect provided by fibers.

Table 4: Test results of the mechanical, non-destructive test properties of concrete

Designation	Slump value	Compressive strength	UPV	Surface resistivity
	mm	MPa	km/s	k Ω -cm
C100SF0G0	220	58.2	3.3	13.73
C90SF10G0	200	67.3	2.76	52.38
C80SF20G0	85	61.9	3.26	102.72
C100SF0G25	215	60.4	4.33	10.13
C90SF10G25	155	74	3.23	29.08
C80SF20G25	25	76.4	4.27	42.08
C100SF0G50	180	59.2	4.21	5.84
C90SF10G50	110	56.7	3.01	12.71
C80SF20G50	22	50.3	4.19	29.72

These results can be attributed to the workability of the concrete mix. The slump test results show that with the incorporation of SF and GIF workability reduces noticeably. This reduction can be attributed to the dense, interwoven network of fibers within the concrete matrix, which forms a three-dimensional scaffolding structure that restricts the flow of the fresh mix, resulting in a significant reduction in workability (Emon et al., 2017). Higher SF content increases water demand and reduces the lubricating effect of the mix, which occurs due to the lower specific gravity of SF compared to OPC. SF refines the pores of the concrete mix, making the mix less workable. This reduction in workability disrupts the continuity of the cementitious matrix, hindering effective load transfer and ultimately leading to a decrease in strength. The addition of 20% SF and 0.50% (C80SF20G50) GIF resulted in a 15.7% reduction in strength compared to the control sample. Therefore, moderate fiber dosage of 0.25% effectively enhances compressive performance when paired with a 20% SF. The reduction of workability attributed to the addition of GIF and SF has been addressed in ACI 234R (2009), ACI 544.3R (2008), and ACI 309R (2006). ACI 214R (2011) recognizes the increased internal voids, entrapped air, and lack of uniformity in concrete placed in formwork due to reduced workability eventually reduces the compressive strength. These guidelines suggest maintaining workability through optimized fiber and SF dosage alongside the use of high-range water-reducing admixture.

A higher UPV value indicates that the concrete has fewer pores and a more uniform distribution of constituents. Here, the control sample (C100SF0G0), with a UPV of 3.3 km/s, indicates moderate-quality concrete. Keeping the fiber content, the same, incorporating 10% SF did not lead to an improvement; however, the addition of 20% SF showed an increment in UPV value. It is observed that incorporating GIF alone, without SF change, showed a significant improvement as a combination; C100SF0G25 exhibits a 31.21% increase in UPV value compared to the control sample. In combination with 0% and 10% SF, up to 0.25% addition of GIF showed improvement, but 0.50% GIF reduces UPV due to fiber clustering and poor dispersion. Here, in combination with C80SF20G25, which has 0.25% GIF when paired with 20%, a good improvement of 29.39% UPV was observed compared to the control sample.

Better resistance to ion penetration (such as chloride) is indicated by higher surface resistivity (SR) values, which makes the concrete less permeable and more resilient. Here, keeping the fiber content constant, increasing the SF content increased the SR value, with a significant improvement of 7.48 times that of the control sample, achieved with only 20% SF. This suggests that the microstructural changes caused by silica fume are due to densification. When 0.25% GIF was incorporated with 20% SF content, the SR value became 3.16 times that of the control sample. Results show that, in contrast to 0.25% fiber content, 0.5% fiber content exhibited low SR values. Here, with the increment of fiber content, the surface resistivity decreased due to the formation of conductive bridges within the cement matrix, which facilitated the charge transport within the concrete (Cleven et al., 2022). Because of this, by

keeping the SF content constant increment of GIF shows less resistance. Figure 6 illustrates the fiber bridging effect of GIF in concrete.

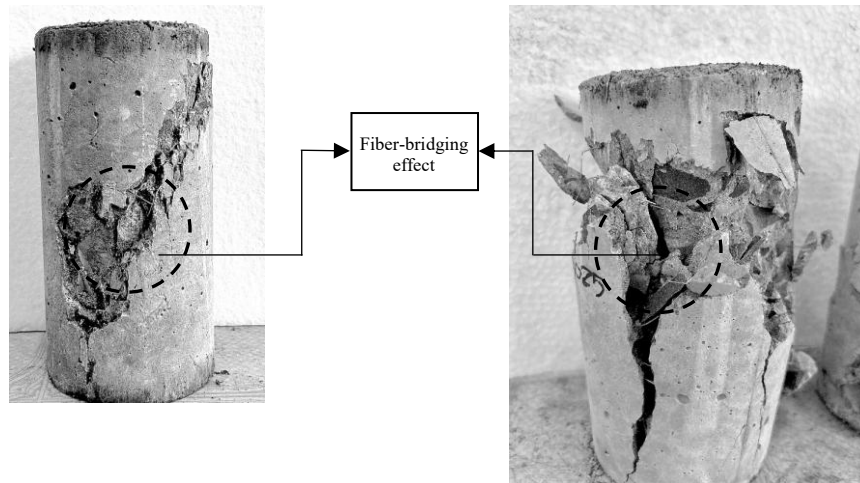


Figure 6: Fiber-bridging effect of GIF in concrete

4. CONCLUSIONS

This study examines the mechanical and durability properties of HPC incorporating GIF and SF in various configurations, which is particularly crucial in a country like Bangladesh, where rapid urbanization is a significant challenge and improving infrastructure is essential.

- i. The slump value of concrete decreased by 61.4% with the incorporation of 20% SF in fiberless concrete. The slump shows a 90% decrement when 20% SF and 0.50% GIF are added. This indicates that GIF and SF decrease the workability of the concrete mix. Additionally, the results suggest that SF has a greater effect on the workability of concrete than GIF, due to its higher water demand and finer particle size.
- ii. The combination of 20% SF and 0.25% GIF achieved a maximum compressive strength of 76.4 MPa, which represents a 31.27% increase compared to the control sample in 28 days. When the SF content was kept constant, the addition of 0.25% GI fiber resulted in the best performance as the amount of fiber increased. However, the combination of 20% silica fume and 0.5% GI fiber had an adverse effect, resulting in a 13.57% decrease in compressive strength compared to the control sample. However, a higher fiber content led to ductile failure due to the fiber-bridging effect.
- iii. The synergistic effect of GIF and SF enhances the durability of concrete when mixed in an optimum amount. The combination with 20% SF and 0.25% GIF shows a 29.39% increase in UPV value and a surface resistivity value 3.16 times than that of the control sample, indicating higher material integrity and improved permeability.

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DECLARATION OF USE OF AI

The authors declare that no artificial intelligence (AI) tools were used in writing, editing, or interpreting the results of this research paper. All works presented in this paper are the original work of the authors.

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