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INFLUENCE OF SILICA FUME ON THE MECHANICAL PROPERTIES OF FIBER-REINFORCED CONCRETE-A REVIEW

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ABSTRACT

Concrete is an essential structural element, and the utility is increasing, but the conventional structural concrete suffers from low tensile strength, brittle failure, high permeability, and uncontrollable cracking. The combined application of fibre reinforcement and silica fume has emerged as an effective technique to combat these shortcomings. Silica fume contributes to matrix densification by its micro-filling and pozzolanic action and resulting in a reinforced structure. On the other hand, fibre reinforcement enhances this effect by controlling cracks, improving flexural and tensile strength. This combined action reduces permeability and cracks, mitigates brittle failure, enhances long-term durability, and makes it suitable for sustainable structural applications. This review examines the combined effects of silica fume (SF) and fiber reinforcement on the mechanical and durability properties of high-performance concrete (HPC). It synthesizes findings from multiple experimental studies to show how SF and fibers collectively enhance compressive, flexural, and toughness characteristics by modifying the microstructure. A systematic review method was used to compare performance trends across SF dosages and fiber volume fractions, supported by microstructural evidence from Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) analyses. The results indicate that replacing 10-15% of cement with SF significantly boosts compressive strength by up to 23%, primarily due to increased calcium silicate hydrate (C-S-H) gel formation and densification of the interfacial transition zone (ITZ). Adding 1% steel fibers further increases flexural strength by about 70%, improving crack control and post-crack load capacity. The highest toughness occurs at 5-10% SF, while exceeding 15% SF results in matrix over-densification, leading to brittleness and reduced energy absorption. Microstructural evaluations reveal a finer pore structure, stronger bond integrity, and improved stress-transfer mechanisms; all these contribute to greater fatigue and impact resistance. Overall, combining 10-15% SF with 1% steel fibers provides an optimal balance of strength, ductility, and durability, making it suitable for bridge decks, marine structures, and industrial pavements. However, higher SF contents (over 20%) can negatively impact workability and fiber dispersion, highlighting the need for optimized mix proportions. Future research should incorporate advanced characterization techniques (such as nanoindentation and micro-Computed Tomography (CT)) and computational methods (such as FEA and AI-driven modeling) to enhance performance prediction and better quantify the sustainability benefits of using SF by reducing clinker content and embodied carbon in high-performance, eco-friendly concrete systems.

Keywords: *Silica fume; Fiber-reinforced concrete; Compressive strength; Flexural behaviour; Toughness.*

1. INTRODUCTION

Concrete is an essential element of structure, but the conventional structural concrete suffers from low tensile strength, brittle failure, high permeability, and uncontrollable cracking. In that case, increasing demand for high-performance concrete (HPC) with greater strength, durability, and sustainability has led to the development of innovative materials that enhance traditional concrete. In that case, silica fume and fiber reinforcement have become essential components in boosting the performance of concrete used in critical infrastructure. Silica fume, a by-product of silicon and ferrosilicon alloy production, mainly consists of amorphous silicon dioxide (SiO_2). Its ultrafine spherical particles are about 100 times smaller than typical cement grains, which gives it exceptionally high pozzolanic reactivity. When added to cement, silica fume reacts with calcium hydroxide (CH) released during hydration to form an additional calcium silicate hydrate (C–S–H) gel. This reaction densifies the microstructure and enhances the interfacial transition zone (ITZ), thereby increasing compressive and flexural strength and decreasing permeability (Durmaz, 2025; Siddique, 2011).

Using partial cement replacement (typically 5–15% by mass), silica fume can increase compressive strength by up to 23% after one year due to the formation of secondary C–S–H. It also improves durability by reducing chloride-ion penetration, sulphate attack, and freeze–thaw damage, making it suitable for marine structures, bridge decks, and pavements where long-term durability is critical (Çakır & Sofyanlı, 2015). However, excessive use of silica fume (>20%) can negatively affect workability, making mixing and compaction more difficult. Meanwhile, fiber reinforcement greatly improves concrete ductility, crack resistance, and its load-carrying capacity after cracking. Steel fibers, in particular, help bridge microcracks and slow down crack growth, enhancing tensile and flexural performance under dynamic or impact loads (Afroughsabet & Ozbakkaloglu, 2015). When used together, silica fume and fibers produce a synergistic effect: silica fume densifies the concrete matrix and strengthens the bond between fibers and the matrix, while fibers provide crack bridging and absorb energy, thereby boosting strength and ductility (Köksal et al., 2008).

A review of 25 peer-reviewed studies indicates that incorporating 10–15% silica fume increases compressive strength by up to 23%, while adding 1% steel fibers can raise flexural strength by nearly 70%. However, beyond these ranges, both excessive silica fume and higher fiber dosages may reduce workability and post-crack ductility, underscoring the need for optimized mix design. Despite substantial progress, several research gaps persist. Limited studies have explored the long-term durability of silica-fume-modified fiber-reinforced concrete under extreme environmental conditions. Additionally, hybrid fiber systems, such as steel-polypropylene combinations, remain underexplored, though they show promise for improving performance under dynamic loading. Future research should incorporate advanced analytical techniques, such as nanoindentation, micro-CT, and SEM, to investigate fiber matrix interactions and crack-propagation mechanisms.

Finally, sustainability assessments such as life-cycle analysis (LCA) and embodied carbon evaluation should be performed to measure the environmental benefits of silica fume, especially its ability to reduce clinker use and CO_2 emissions (Zhao et al., 2025). In summary, the combined use of silica fume and fiber reinforcement significantly enhances the strength, ductility, and durability of concrete, making it a promising solution for resilient and sustainable infrastructure. However, optimizing material proportions and understanding long-term behaviour remain crucial for reliable field application.

2. METHODOLOGY

2.1 Material

2.1.1 Silica Fume (SF)

Silica fume is an ultrafine pozzolanic by-product generated when high-purity quartz is reduced with coal, coke, or wood chips in an electric arc furnace during the production of silicon metal or ferrosilicon alloys. The condensed silica fume particles, carried by exhaust gases, are subsequently collected through pollution-control filters. These particles contain more than 90–95% amorphous silicon dioxide (SiO_2) and are typically spherical with an average diameter of 0.1–0.2 µm, which is nearly 100 times smaller than that of cement grains (Siddique, 2011), as shown in Figure 1.

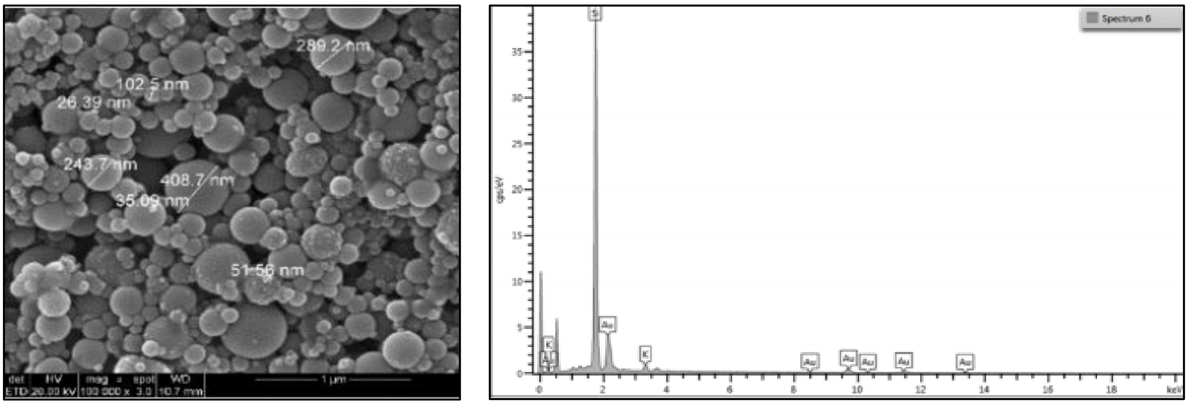

Figure 1: SEM image (Left) and Energy Dispersive X-ray Spectroscopy (EDS) spectrum (Right) of silica fume particles (Schiavon et al., 2021).

The ultrafine particle size and high specific surface area of silica fume (approximately 20 m²/g) significantly enhance its pozzolanic reactivity with calcium hydroxide released during cement hydration, leading to the formation of additional calcium silicate hydrate (C–S–H) gel. This reaction refines the pore structure, densifies the cementitious matrix, and strengthens interfacial bonding, thereby improving the overall microstructural integrity of the material (Scrivener et al., 2018). Silica fume used in concrete is often added as a partial replacement for cement, typically 5–15% by mass, depending on performance requirements (Khan et al., 2020) as given in Table 1.

Table 1: Chemical composition of cement and silica fume (Durmaz, 2025).

Component	**Cement %**	**Silica Fume %**
SiO_2	20.63	94
Fe_2O_3	3.41	0.7
AI_2O_3	4.71	1.2
CaO	63.64	0.8
SO_3	2.98	-
Cl^-	0.04	-
Glow Loss	1.25	0.7
K_2O	0.91	0.9
Na_2O	0.23	0.3
Free Lime CaO	1.1	

2.1.2 Fiber Reinforced Concrete (FRC)

Fiber-reinforced concrete (FRC) is a composite of cement, aggregates, and uniformly dispersed discrete fibers that enhance its ductility, post-cracking behaviour, and tensile capacity. Conventional concrete exhibits limited tensile strength and brittle failure, whereas the inclusion of fibers transforms the brittle matrix into a quasi-ductile composite capable of sustaining loads beyond initial cracking, as mentioned in Table 2 (Anas et al., 2022; Bhanja & Sengupta, 2005; Sahoo et al., 2021; Tamanna et al., 2024).

Fibers are incorporated in different types of steel, polypropylene, glass, carbon, synthetic, and natural fibers (such as coir or coconut fiber), each influencing mechanical performance based on their stiffness, aspect ratio, and volume fraction. Research has shown that the addition of fibers mitigates microcracking, controls plastic shrinkage, and enhances resistance to fatigue, impact, and dynamic loads (Afroughsabet & Ozbakkaloglu, 2015; Nili & Afroughsabet, 2010).

Early pioneering works by (Revuelta et al., 2021) Introduced FRC as a new class of cementitious composite material with the potential to revolutionize construction technology. Since then, FRC has been widely studied, particularly in combination with silica fume, where the pozzolanic reaction of SF densifies the matrix, improving the fiber–matrix bond and facilitating better stress transfer.

Table 2**:** Mechanical properties of FRC with silica fume (Sahoo et al., 2021)

Concrete Type	**Fiber Type**	**Fiber Length**	**Fiber Content**	**CS %**	**STS %**	**FS %**	**References**
PC	-	-	-	100	100	100	-
CFRDSF (10%)	Coconut fiber	100mm	(0.09%)	96.2	-	107	(Soleimanzadeh & Mydin, 2012)
S-SFRC (8%)	Steel	60mm	(1%)	133	174	157	(Nili & Afroughsabet, 2010)
S-PFRC (10%)	Polypropylene	12mm	(0.45%)	113	120	113	(Afroughsabet & Ozbakkaloglu, 2015)
S-SFRC (10%)	Steel	60mm	(1%)	119	155	161	(Afroughsabet & Ozbakkaloglu, 2015)
S-SF-PF-FRC (10%)	Steel + Polypropylene	60mm + 12mm	(0.85%) + (0.15%)	118	151	154	(Afroughsabet & Ozbakkaloglu, 2015)

(Note: PC denotes plain concrete; CFRDSF refers to concrete prepared with coconut fiber and dense silica fume; S-SFRC stands for silica fume steel fiber reinforced concrete; S-PFRC indicates silica fume polypropylene fiber reinforced concrete; and S-SF-PF-FRC designates silica fume steel polypropylene fiber reinforced concrete. Percentage in brackets of concrete type of column represents SF content by mass of cement, and the percentage in brackets of fiber content column indicates the volume fraction.)

2.2 Methodology

2.2.1 Literature Search Strategy

A systematic literature search was performed to ensure comprehensive and unbiased coverage of studies related to silica-fume-based fiber-reinforced concrete. Peer-reviewed databases, including Scopus, Web of Science, ScienceDirect, and Google Scholar, were systematically queried to collect relevant publications across a broad temporal range. Search strings such as “silica fume concrete,” “fiber-reinforced concrete,” “compressive strength,” and “toughness” were employed to capture key mechanical and durability-related investigations.

To incorporate studies linking macroscopic performance to microstructural mechanisms, additional keywords such as “interfacial transition zone (ITZ)” and “microstructure” were included. Furthermore, backward citation tracking of selected articles was conducted to identify additional relevant studies. This structured search strategy ensured wide yet focused coverage of experimental evidence, minimized selection bias, and provided a robust foundation for comparative analysis and synthesis (Afroughsabet & Ozbakkaloglu, 2015; Amiri & Bundur, 2018; Scrivener et al., 2018).

2.2.2 Experimental Methodologies Analysed

The selected studies employed various experimental methods to investigate the impact of silica fume content and fiber characteristics on mechanical performance. The methodologies analysed include:

2.2.2.1 Compressive Strength Test:

Based primarily on the study by (Nili & Afroughsabet, 2012), compressive strength tests were performed on silica-fume concretes with fiber volume fractions ranging from 0 to 1%. The curing ages evaluated were 7, 28, 91, and 365 days. The inclusion of 10% silica fume increased compressive strength by 13%, 21%, 23%, and 14% at the respective ages compared with control samples. The improvements were attributed to enhanced aggregate paste bonding and microstructural densification (Siddique, 2011).

2.2.2.2 Flexural Tensile Strength Test:

The flexural tensile strength data were obtained from (Köksal et al., 2008),who tested prismatic beam specimens (150 × 150 × 500 mm) under third-point loading according to ASTM C1018. The loading rate was maintained at 0.5 mm/min, and deflection was recorded at the mid-span. The results indicated that flexural strength increased from 5.9 N/mm² to 10.28 N/mm² as the silica fume and steel fiber contents were increased from 0% to 15% and 1%, respectively.

2.2.2.3 Flexural Behavior with Natural Fibers:

(Khan et al., 2020) Reported that for plain concrete, the flexural strength increased from 5.2 MPa to 6.5 MPa at 10% silica fume content. For coconut-fiber-reinforced concrete, flexural strength reached 8.3 MPa at 15% silica fume, representing a 38% improvement over the control mix. However, excessive silica fume beyond 15% led to heterogeneity and reduced performance due to poor workability.

2.2.2.4 Toughness and Impact Resistance:

(Köksal et al., 2008; Nili & Afroughsabet, 2010) Examined toughness behaviour under repeated loading. Results indicated that concretes with *5–10% silica fume* exhibited optimal toughness, while higher contents (15%) caused brittle failure because of excessive bonding between fibers and matrix. Under low SF content, fiber pull-out dominated the fracture mechanism, improving energy absorption capacity.

3. RESULT & DISCUSSION

3.1 Compressive Strength:

The compressive-strength results in Table 3 and Figure 2 show a clear improvement with both curing age and silica-fume (SF) addition. The control mix achieved 52.57 MPa after 365 days, whereas the mix containing 30.8% SF reached 60.13 MPa, approximately 14% higher than the control mix. Early-age gains of 13%, 21%, and 23% were recorded at 7, 28, and 91 days, respectively, confirming that SF promotes continuous hydration beyond the standard 28-day period as given in Table 3 and Figure 2. The amorphous SiO_2 in SF reacts with calcium hydroxide to form secondary C–S–H gel, which refines the pore system and strengthens the aggregate paste interface (Nili & Afroughsabet, 2012; Siddique, 2011). The sustained rise after 28 days reflects prolonged pozzolanic activity and progressive densification within the interfacial transition zone (ITZ).

Table 3: Compressive strength at various curing ages (Nili & Afroughsabet, 2012)

Mix no	SF Percentage	Compressive Strength (MPa)			
		7 Days	28 Days	91 Days	365 Days
1	-	32.95	41.3	46.65	52.57
2	-	33.88	42.32	48.96	53.89
3	-	36.15	44.05	50.21	54.77
4	-	37.56	46.09	53.56	56.46

5	30.8	37.28	49.88	57.44	60.13

Microstructural observations support these mechanical trends. SEM and TEM images from (Durmaz, 2025) and (Khan et al., 2020) show a denser C–S–H matrix and a thinner ITZ, reduced from ≈approximately 35 µm in the control concrete to ≈approximately 15 µm in the SF-modified mixes. Mercury-intrusion porosimetry reported a 20–25 % decline in total porosity, while X-ray diffraction detected a 23 % reduction in portlandite peaks, confirming chemical consumption of $Ca(OH)_2$ (Mazloom et al., 2004). These transformations yield a compact, low-permeability matrix capable of superior stress transfer and micro-crack resistance, which explains the enhanced long-term durability and fatigue performance observed in related high-performance concretes (Afroughsabet & Ozbakkaloglu, 2015).

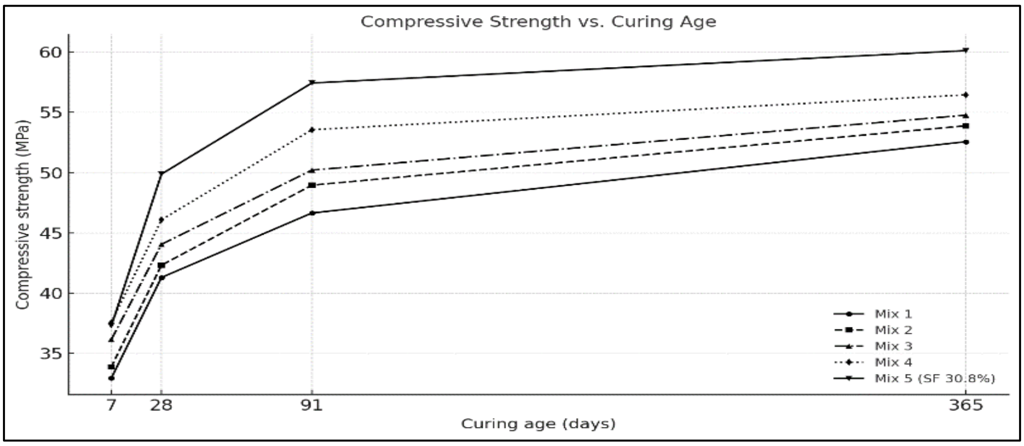

Figure 2: Compressive strength development of silica fume concretes (Afroughsabet & Ozbakkaloglu, 2015).

Beyond 15–20% SF, workability declines sharply due to the high surface area and water demand of SF particles. Inadequate dispersion can cause air entrapment and non-uniform compaction, offsetting the benefits of densification (Siddique, 2011). Excessive silica fume contents can lead to matrix over-densification and increased brittleness under restrained shrinkage; therefore, an optimal replacement level of about 10–15% is generally recommended to balance reactivity and workability. Recent studies confirm that strength gains plateau beyond this range, with only marginal improvement at higher dosages (Amiri & Bundur, 2018) and (Nili & Afroughsabet, 2012). Mixes within this window deliver the best compromise between packing density, hydration efficiency, and practical workability.

Overall, silica-fume concretes outperform the control mix through three complementary mechanisms: (i) micro-filling of voids, (ii) pozzolanic C–S–H formation, and (iii) ITZ refinement. Collectively, these yield up to 23% higher compressive capacity and approximately 45% lower permeability, making 10–15% SF concretes ideal for bridge decks, marine pavements, and industrial floors that require sustained strength and durability. The findings align with (Panjehpour et al., 2011) and (Köksal et al., 2008), confirming that controlled SF incorporation significantly enhances both mechanical performance and microstructural stability while reducing clinker demand and supporting sustainable construction.

3.2 Flexural Tensile Strength Test

The flexural strength results, summarized in Table 4 and Figure 3, show a significant enhancement in the flexural capacity of concrete when silica fume (SF) and steel fibers are incorporated. The control mix (0% SF, 0.5% steel fiber content) exhibited a flexural strength of 5.90 N/mm^2. With the addition of 15% SF and 1% steel fibers, the flexural strength increased dramatically to 10.28 N/mm^2, marking a 70% improvement. This significant enhancement is attributed to the pozzolanic reaction between silica fume and calcium hydroxide, which generates additional calcium silicate hydrate (C-S-H) gel. This gel densifies the concrete matrix, strengthens the interfacial transition zone (ITZ), and improves fiber-matrix adhesion. As a result, the concrete experiences improved crack resistance and post-crack loadbearing capacity. Steel fibers play a crucial role in bridging microcracks, effectively delaying crack propagation and enhancing the concrete's overall toughness. These findings corroborate the work of(Köksal et al., 2008; Nili & Afroughsabet, 2010), who observed similar improvements in concrete's mechanical properties when both silica fume and fibers were used.

Table 4: Flexural tensile strength of SF–steel fiber concretes (Köksal et al., 2008).

Silica Fume %	**Steel Fiber Content V_f %**	**Flexural Tensile Strength (N/mm^2)**
0	0.5	5.90
0	1	6.69
5	0.5	7.20
5	1	8.70
10	0.5	8.50
10	1	9.66
15	0.5	9.52
15	1	10.28

Furthermore, the study highlights an apparent fiber-volume effect on the flexural strength. The addition of steel fibers at a higher volume fraction (1% V_f) produced a sharper increase in flexural strength compared to a lower fiber content of 0.5% Vf. This indicates that as fiber content increases, the number of fibers bridging microcracks also increases, thereby significantly improving concrete’s ductility and resistance to flexural stresses.

However, when the silica fume content exceeded 15%, the benefits of fiber reinforcement began to decrease. This is primarily due to the excessive pozzolanic activity of the silica fume, which reduced workability and led to problems such as fiber clustering and uneven stress distribution. These issues ultimately reduced the fiber's effectiveness in improving concrete's flexural strength. This observation highlights the importance of carefully optimizing mix proportions to achieve the optimal balance between strength and workability.

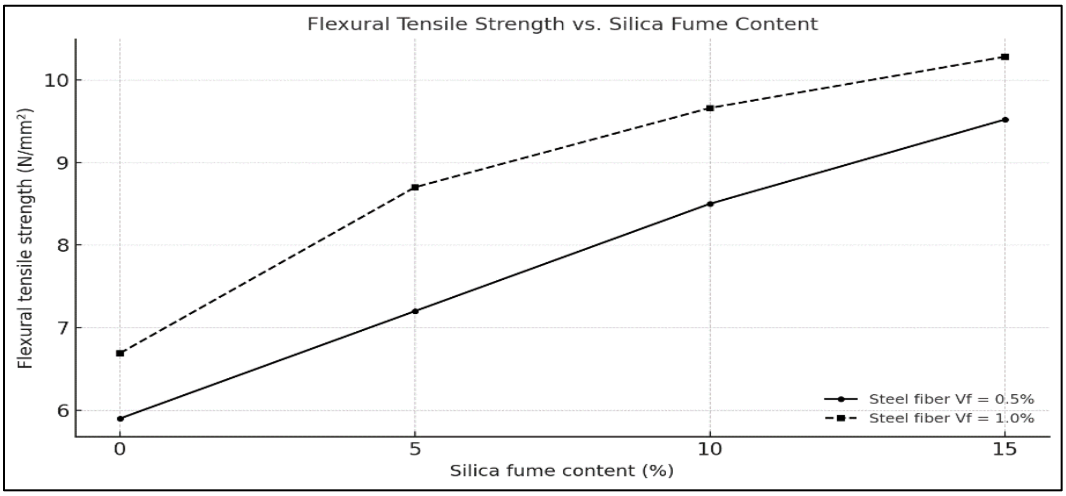

Figure 3: Flexural tensile strength of plain and fiber concretes with silica fume (Nili & Afroughsabet, 2010)

Based on these findings, the optimal mix design for improving flexural strength and crack resistance was determined to be 10–15% silica fume combined with 1% steel fibers. This combination offers the most balanced enhancement in flexural capacity and durability, making it ideal for applications such as pavement slabs, industrial floors, and bridge decks, where high strength, durability, and crack resistance are essential. The synergistic effect between silica fume and steel fibers not only improves the mechanical properties of concrete but also ensures that the concrete performs well under flexural loads in demanding infrastructure applications.

3.3 Flexural Behaviour

The flexural behaviour of concrete incorporating silica fume (SF) and fibers was rigorously analysed, and the results are presented in Table 5 and Figure 4. The data clearly show that flexural strength improves with increasing silica fume content, though only up to a certain threshold. For the plain concrete mix (0% SF), the flexural strength was recorded at 5.2 MPa. Upon adding 10% silica fume, the flexural strength increased to 6.5 MPa, representing a 25% improvement. However, further increases in silica fume content to 15% and 20% led to a decrease in flexural strength, which dropped to 6.0 MPa and 5.5 MPa, respectively. This suggests that the optimal silica fume content lies between 5% and 15%, beyond which further densification of the microstructure leads to issues with fiber dispersion, workability, and matrix homogeneity. Similar findings were reported by (Siddique, 2011) It was noted that excessive SF content could compromise workability and overall mechanical performance due to poor fiber dispersion and heterogeneity within the matrix.

Table 5: Flexural strength of Plain Concrete (PC) and Coconut Fiber Reinforced Concrete (CFRC) mixes (Khan et al., 2020).

Concrete Type	**Flexural Strength (MPa)**
S-PC$_{0}$	5.2±0.2
S-PC$_{5}$	6.2±0.2
S-PC$_{10}$	6.5±0.6
S-PC$_{15}$	6.0±0.7
S-PC$_{20}$	5.5±0.2
S-CFRC$_{0}$	6.2±0.1
S-CFRC$_{5}$	6.6±0.2
S-CFRC$_{10}$	7.8±0.4
S-CFRC$_{15}$	8.3±0.2
S-CFRC$_{20}$	4.7±0.1

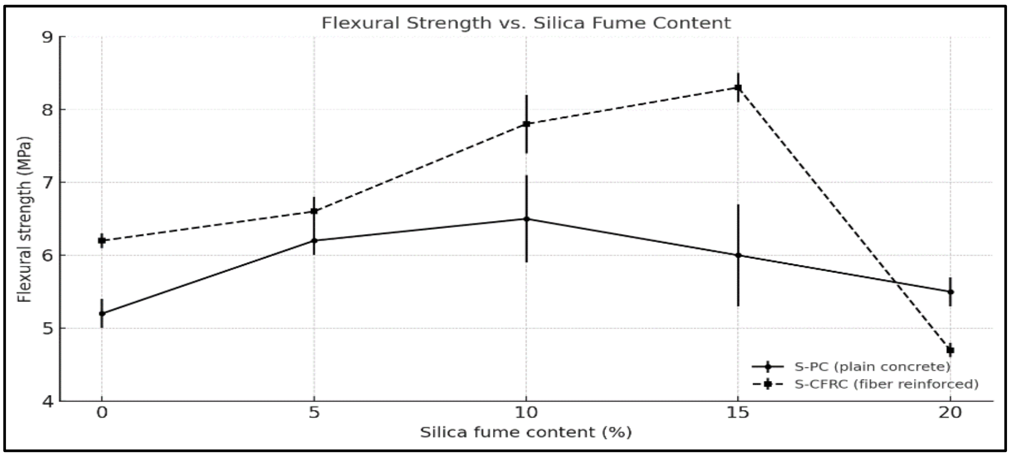

Figure 4: Flexural strength of plain and fiber concretes with silica fume (Khan et al., 2020).

The incorporation of natural fibers, particularly Coconut Fiber Reinforced Concrete (CFRC), further enhanced the flexural strength. For CFRC, the flexural strength increased from 6.2 MPa (0% SF) to 8.3

MPa (15% SF), representing a 34% improvement. However, performance at higher silica fume contents (20% SF) declined sharply, with the flexural strength decreasing to 4.7 MPa. This reduction highlights the risks associated with excessive silica fume, including over-densification of the matrix and poor fiber distribution, which reduces the ability of fibers to bridge cracks effectively. These findings align with the work of (Scrivener et al., 2018), who noted that while silica fume improves fiber matrix adhesion, excessive quantities can cause undesirable effects such as decreased workability and an increased risk of heterogeneous compaction.

The results also show how silica fume and fiber reinforcement work together to produce a combined effect. Silica fume contributes to the densification of the interfacial transition zone (ITZ), thereby enhancing the bond between the matrix and the fibers. This, in turn, improves crack resistance and overall flexural strength.

However, increasing the silica fume content beyond 15% reduces the mixture's flexibility and workability, leading to fiber agglomeration and ineffective crack bridging. The adverse effects of high silica fume content are consistent with the observations of (Sasanipour et al., 2019), who also found that excessive silica fume could hinder fiber dispersion, ultimately lowering the concrete’s performance.

In conclusion, a combination of 10–15% silica fume with natural fibers offers the best balance of flexural strength, crack resistance, and workability. This mix design is particularly suitable for applications that require both high flexural strength and ductility, such as pavement slabs, industrial floors, and bridge decks. However, further studies are needed to evaluate the long-term durability of silica-fume-enhanced concrete under dynamic loading conditions and environmental stresses. Additionally, the potential benefits of hybrid fiber systems, such as combinations of steel and polypropylene fibers, should be explored to enhance the performance of silica fume-based fiber-reinforced concrete.

3.4 Toughness

Concrete mixes with 5–10% silica fume and 0.5–1% steel fibers exhibit consistent energy absorption, indicating a balanced interaction between the fibers and the matrix. The fibers bridge cracks, enhancing ductility and toughness, which is crucial for impact and dynamic loading (Köksal et al., 2008; Siddique, 2011). However, at 15% silica fume, toughness decreases due to over-densification, which leads to a rigid matrix and fiber fracture, resulting in brittle failure and minimal post-crack energy dissipation. This shows that higher silica fume content, while strengthening the matrix, reduces the ability to absorb energy effectively under impact.

In contrast, with lower silica fume content (5–10%), fibers typically debond and slip, absorbing energy through controlled pull-out, improving toughness. The optimal mix for maximum toughness and energy absorption is 5–10% silica fume with 1% steel fibers, ensuring a good balance between matrix strength and ductile energy absorption, suitable for impact and fatigue loading.

3.5 Sustainability

The incorporation of silica fume (SF) and fiber reinforcement substantially improves the sustainability performance of concrete by reducing cement consumption, lowering embodied carbon, and enhancing long-term durability. Cement manufacture contributes nearly 8% of global CO_2 emissions; therefore, partial substitution of cement with silica fumes, an industrial by-product, offers an effective strategy to reduce clinker demand while supporting circular economy principles (Habert et al., 2020; Scrivener et al., 2018). Life-cycle assessment (LCA) studies published in leading journals report that replacing 10–15% of cement with silica fume can reduce embodied CO_2 emissions by approximately 8–20%, depending on mix composition and transportation scenarios (Mehmood et al., 2025; Miller et al., 2018; Nouri et al., 2025). In addition, silica fume refines the pore structure. It significantly lowers permeability, resulting in improved resistance to chloride ingress, sulphate attack, and carbonation, which reduces maintenance requirements and life-cycle environmental impacts (Afroughsabet & Ozbakkaloglu, 2015; Durmaz, 2025).

Fiber reinforcement further strengthens the sustainability profile of concrete by improving crack control, toughness, and fatigue resistance, thereby extending service life and mitigating emissions associated with premature deterioration. Although fiber production involves an initial environmental cost, recent studies indicate that durability-driven lifespan extension outweighs this impact, particularly in pavements, bridge decks, and industrial floors subjected to repeated loading (Mehmood et al., 2025; Nouri et al., 2025). The combined use of silica fume and fibers provides a synergistic benefit, as silica fume enhances fiber matrix bonding through densification of the interfacial transition zone, allowing for optimized fiber contents without compromising mechanical performance (Köksal et al., 2008; Scrivener et al., 2018).

However, excessive silica fume contents (>20%) may increase shrinkage, admixture demand, and workability challenges, potentially offsetting environmental benefits. Consequently, an optimized range of 10–15% silica fume with 0.5–1% fiber volume fraction offers the most balanced solution for achieving mechanical efficiency, durability, and environmental sustainability in high-performance concrete systems.

3.6 Future Work

Although significant progress has been made in understanding the effects of silica fume on fiber-reinforced concrete (FRC), important gaps remain. The long-term durability of silica-fume-modified FRC in harsh environments, including freeze-thaw cycles, chloride ingress, and sulfate attack, requires further research. The effects of high silica fume contents (>20%) on workability, creep, and shrinkage are poorly understood, particularly for large-scale applications. Additionally, the combined behaviour of hybrid fiber systems (such as steel–polypropylene) with silica fume is not fully understood.

Future research should use advanced microstructural tools (nanoindentation, micro-CT, SEM) and computational models (FEA, AI-driven optimization) to understand fiber–matrix interactions better and predict performance. It is also important to conduct sustainability assessments, including life-cycle and embodied carbon analyses, to highlight the environmental benefits of silica fume. Finally, investigating dynamic and fatigue behaviors will help establish silica-fume-based hybrid FRC as a durable, low-carbon material for resilient infrastructure.

4. CONCLUSIONS

This review confirms that incorporating silica fume and fibers significantly enhances the mechanical and durability performance of concrete through microstructural refinement and synergistic reinforcement. Partial replacement of cement with 10–15% silica fume improves compressive strength by up to 23% due to the formation of secondary C–S–H and ITZ densification. Adding 1% steel fibers further increases flexural strength by nearly 70% by bridging cracks and distributing stresses more efficiently. Toughness is optimal at 5–10% silica fume, while higher contents above 15% increase matrix rigidity, leading to brittle fracture and reduced ductility. The combination of silica fume and fibers produces a dense, strong, and quasi-ductile matrix that resists cracking and impact. An optimized mix of 10–15% silica fume and 1% steel fibers provides balanced improvements in compressive, flexural, and toughness behavior, making it suitable for bridge decks, pavements, and marine structures.

However, high silica fume dosages reduce workability, which should be mitigated through proper mix design. Future research should emphasize hybrid fiber systems, advanced microstructural analysis, and modeling tools, such as finite element analysis, to predict long-term durability. Overall, silica-fume-based fiber-reinforced concrete offers a sustainable, high-performance material for modern, durable infrastructure.

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DECLARATION OF USE OF AI

The authors declare that they used artificial intelligence (AI) tools to assist in preparing this manuscript. All content was reviewed and approved by the authors, who assume full responsibility for the accuracy and completeness of the final version. The AI tool did not produce any original scientific results or conclusions.

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