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An Experimental Study on Steel Fiber Effects in High-Strength Concrete Slabs

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Abstract

This study investigated the impact of varying steel fiber ratios by volume on the performance of HSC slabs. Incorporating steel fibers into high-strength concrete (HSC) has been shown to significantly enhance its mechanical properties, particularly by improving its load-bearing capacity. Furthermore, the addition of steel fiber reduces the reliance on traditional reinforcement bars, leading to a more efficient use of materials. This not only simplifies the construction process but also contributes to a reduction in overall construction costs. This study investigated the behavior of HSC slab specimens under loading and elevated temperatures. Three groups of specimens were created based on their thickness (8 cm, 12 cm, and 16 cm) using a single high-strength concrete mixture and four varying steel fiber proportions (0, 37.5, 75, and 150 kg/m³). Two-point monotonic loading was applied to each slab specimen until failure. To determine the splitting tensile strength, 12 cylinders were cast. Additionally, 84 cubes were cast to assess the effects of elevated temperatures and different cooling techniques on compressive strength (f_{cu}). The results revealed that incorporating steel fibers into high-strength concrete slabs has a negligible effect on the concrete's density and compressive strength. However, it notably enhanced the splitting tensile strength and modulus of rupture. These improvements significantly boosted the material's resistance to cracking, making it more durable and better suited for applications requiring superior tensile performance. This is particularly important in structures subjected to dynamic or cyclic loading, where the risk of cracking and failure is greater.

Keywords: Slabs; HSC; Compressive Strength; Steel Fiber; Flexural Behavior; Splitting Tensile Strength.

1. Introduction

In the past 20 years, the demand for concrete has significantly increased due to the rapid growth of the global building industry. This increase was due to a variety of factors, such as its high compressive strength, ease of production, and relatively low manufacturing cost. These aspects facilitated the widespread adoption of concrete in construction projects [1]. One of the greatest challenges with concrete was its low ability to resist tensile stress. To overcome this limitation, steel reinforcements were commonly used to enhance the tensile strength (TS) of concrete. Consequently, structural elements, such as slabs, beams, columns, and foundations, were commonly reinforced with steel to improve their overall performance and durability. This practice had an important effect on the improvement of modern infrastructure and the construction industry as a whole [2]. The complexity of modern structures and the demanding environments in which they must operate have highlighted the limitations of conventional concrete. As a result, concrete

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alone is no longer sufficient to provide the necessary strength and durability required for structures, such as skyscrapers, bridges, offshore, and hydraulic structures. These structures require advanced materials and design approaches to ensure their performance and longevity under challenging conditions. High-strength concrete (HSC) offered several advantages over conventional concrete, such as a high elastic modulus, enhanced durability, and higher compressive strength. As a result, HSC has been increasingly applied to numerous structures in recent years [3].

The flexural behavior of HSC beam specimens has been extensively investigated through various experiments, supporting researchers in understanding and foreseeing the performance of HSC in various applications. The insights obtained from these studies have contributed to the development of more efficient and reliable structures that can withstand the challenges posed by their environments [4]. According to Ashour et al. [5], the flexural rigidity of concrete has a positive correlation with its compressive strength. Similarly, Mohammadhassani et al. [6] stated that as the tensile rebar ratio increases, the ultimate load capacity of high-strength concrete (HSC) improves, while deflection ductility decreases. These findings emphasize the substantial effect of the tensile rebar ratio on the ductility index (DI) of HSC structures.

Due to the higher strength of HSC, HSC is more brittle and has a lower resistance to crack propagation and opening. As a result, tensile reinforcement of HSC beams effectively controls their deflection and prevents cracks from developing within them. Therefore, appropriate reinforcement ratios and materials must be selected to balance the load-carrying capacity, deflection control, and ductility requirements of HSC structures [7].

Furthermore, the mechanical properties of concrete can be substantially improved by the inclusion of fibers, whether synthetic or natural. This enhancement is primarily due to the fibers' ability to bridge cracks, distribute loads more evenly, and increase the material's toughness and resistance to tensile forces. Synthetic fibers, such as polypropylene or glass, offer durability and are resistant to environmental degradation, making them suitable for long-term structural applications. Natural fibers, such as coconut coir or hemp, provide an eco-friendly alternative, contributing to sustainability while still improving the concrete's performance. These advantages led to the extensive use of fiber-reinforced concrete in various applications, including but not limited to industrial floors, pavements, bridges, and even architectural projects where both strength and flexibility are critical. By tailoring the type and quantity of fibers used, engineers can customize the material properties to meet specific project requirements, further expanding its versatility and utility [8-10]. The use of steel fiber reinforcement in ultra-high-strength concrete (SFR-UHSC) has been the subject of extensive experimental investigation [11, 12]. These studies have provided valuable insights into the mechanical properties of SFR-UHSC, including their crack resistance, ductility, and tensile strength. Mixing steel fibers into these concretes maximizes their overall performance, making them more suitable for use in structures that require enhanced mechanical properties and durability.

Eswari et al. [13] reported that fibers can increase energy absorption, damage tolerance in flexure, strength, and ductility of concrete. Adding fibers into the mixture slows the propagation of cracks. Compared with plain concrete, adding 2% hook-end steel fibers improved the rupture modules of the material, deflection ductility, and energy ductility by approximately 59%, 46%, and 59%, respectively. Atiş & Karahan [14] also stated that the addition of steel fibers into concrete significantly increases its flexural tensile strength, fracture toughness, and impact resistance. These findings demonstrate the potential of steel fiber reinforcement to enhance the mechanical properties of concrete and make it more suitable for various applications. Beddar [15] used steel fibers with an approximate length of 10 cm and a diameter of 0.1 cm to enhance the performance of plain concrete. The results obtained from this study were remarkably comparable to those observed in modern fiber-reinforced concretes. The study revealed that the tensile strength of concrete can be effectively enhanced by incorporating steel fibers.

Nili & Afroughsabet [16] added steel fibers to concrete specimens with silica fumes, resulting in more impact-resistant and ductile concrete. Moreover, Hadi [17] experimented with comparing the performance of steel-reinforced concrete slabs and polypropylene-reinforced concrete slabs. Their findings revealed that a one percent increase in the volume of steel fibers had the most significant effect on the ductility of the concrete slabs. Furthermore, Hasan-Nattaj & Nematzadeh [18] conducted a research on the effects of steel and forta-ferro fibers on the mechanical properties of high-strength concrete. The study found that steel fibers contributed more significantly to the improvement of compressive strength in high-strength concrete compared to forta-ferro fibers due to their higher tensile strength and modulus of elasticity. On the other hand, forta-ferro fibers were found to reduce the workability of concrete more significantly than steel fibers.

The impact of the steel fiber shape, hybrid steel fibers, and aspect ratio has been frequently studied [12, 19-21], and notable increases in tensile strength and toughness have been observed. This improvement was particularly evident when the aspect ratio of the fiber was increased, resulting in a lower slump. The addition of steel fibers enhanced the impact resistance and reduced crack propagation. Que et a. [19] found out that the fiber diameter of 0.02 cm and the fiber length ranging from 0.9 cm to 2.2 cm resulted in 1.86%, 20.65%, 35.73%, and 31.38% improvements in the compressive strength of ultra-high performance concrete, respectively. With the same fiber lengths, the compressive strength increased by 9.82%, 23.32%, 37.09%, and 37.60% for fibers with a 0.16 mm diameter, respectively.

The enhancement of the properties of steel fiber-reinforced self-compacting concrete has been extensively investigated in various research studies [22, 23], revealing significant improvements in flexural strength, tensile strength, and toughness. Elbialy et al. [24] discovered that the incorporation of sodium hydroxide (NaOH) as an alkaline activator, along with metakaolin (MK) and steel fibers, significantly improved the bond strength and flexural performance of the NaOH-activated geopolymer self-compacting concrete (SCC) specimens.

In summary, studies discovered that the incorporation of fibers, particularly steel fibers, into concrete significantly enhanced its mechanical properties, including tensile strength, crack resistance, and overall durability. These improvements make fiber-reinforced concrete a more versatile and reliable material for a wide range of engineering applications, such as bridges, high-rise buildings, industrial floors, and pavements. By improving the structural performance and lifespan of concrete, steel fibers contribute to more efficient and sustainable construction practices.

Although considerable research exists on the effects of steel fibers on the behavior of beams under bending and shear, there is limited literature on their impact on the performance of slabs and columns. To address this research gap, this study explored the influence of steel fibers in a high-strength concrete mixture on slabs.

This study aims to identify the optimal amount of steel fiber that can improve the performance of HSC slabs while minimizing costs. The study also explores how steel fibers affect the mechanical behavior, load-bearing capacity, and reinforcement ratio of HSC slabs. Furthermore, the study investigates the impact of temperature exposure and the addition of steel fibers on the performance of concrete structures, specifically HSC slabs and steel fiber HSC mixes, under different cooling techniques and high temperatures.

2. Research Methodology

This study adopts a sequential methodology, as illustrated in Figure 1. The subsequent sections provide a detailed explanation of each step in the process.

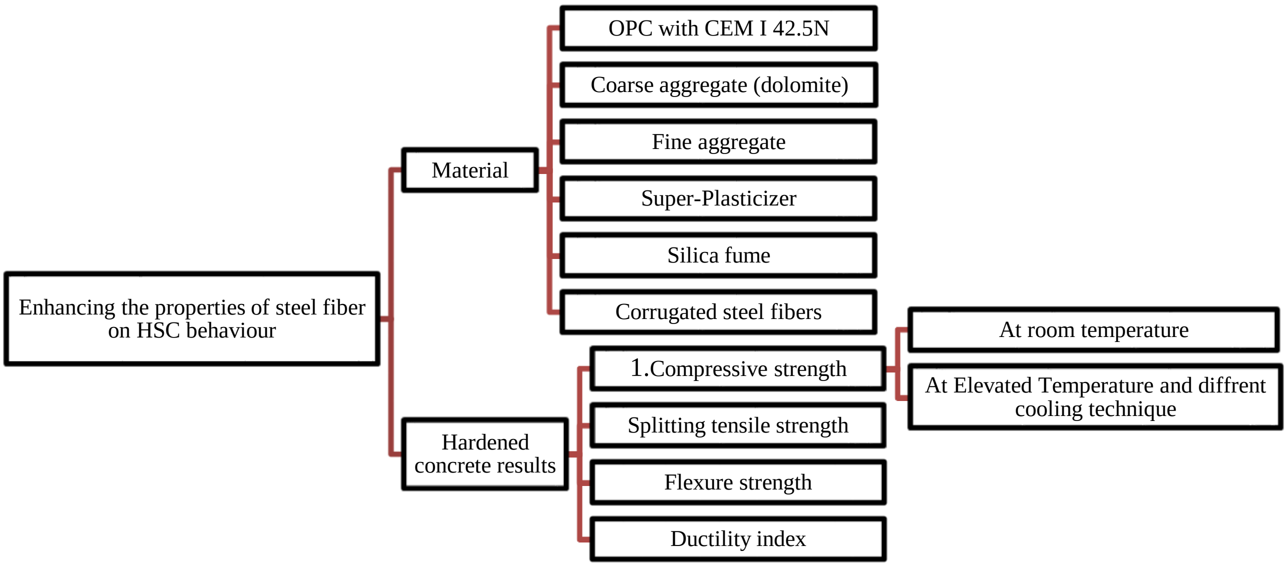


Figure 1. The flowchart of methodology

2.1. Materials

Aggregate

For the high-strength concrete utilized in this study, crushed stone (dolomite) with a maximum particle size of 1 cm served as the coarse aggregate. Natural sand, the fine aggregate is used. The weight density of the sand aggregates is 2.53, whereas the weight density of the dolomite aggregates is 2.7. According to the American Society for Testing and Materials (ASTM), Figure 2 displays the results of the sieve analysis conducted on both the coarse and fine aggregates. The two figures demonstrate that the fine and coarse aggregates used both fall within the tolerance limits of ASTM C33M-18 [25] sieve analysis.

Cementitious Materials

Concrete mixtures were prepared using Ordinary Portland Cement with CEM I 42.5N as the cementitious material. This type of cement meets the specifications of ES 4756-1 [26] and En197-1 [27], and was manufactured by the Tourah **C**ement **C**ompany in Egypt. In addition to OPC, micro-silica (silica fume) was added to enhance the strength of the concrete mixtures. According to ASTM C-1240 [28] the silica fume used in the study has the following characteristics: it looks like a gray powder, has a particle size of 0.2µm, a surface area of 14 m^2/g, and density of 20 kN/m^3.

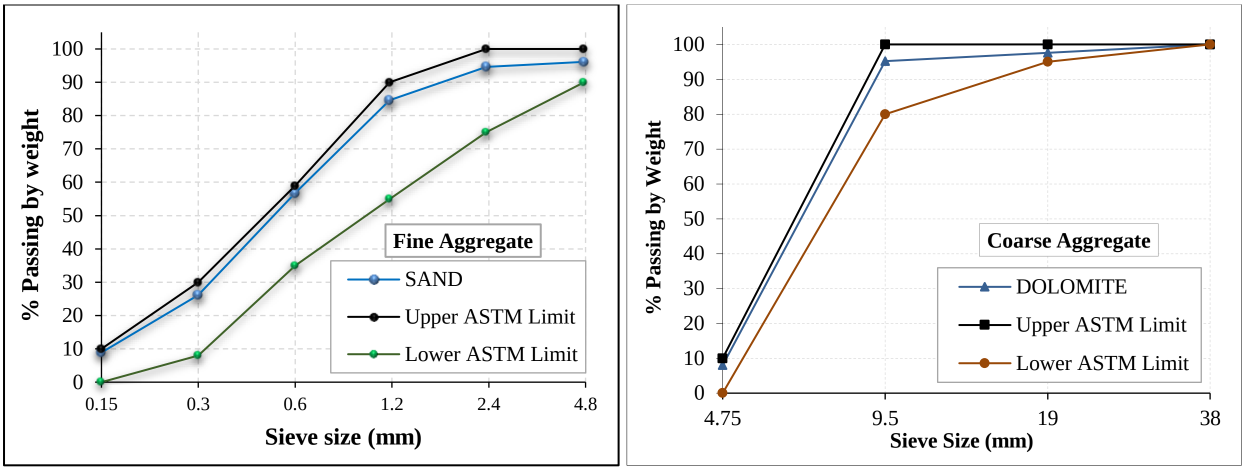


Figure 2. Sieve analysis of course and fine aggregates *(Upper and lower limits according to ASTM C-33)

Super-Plasticizer

Addicrete BVF was used as a super-plasticizer in the high-strength concrete mixtures, which complies with ASTM C-494 Type (F) [29] and BS-5075 Part 3 [30]. The Addicrete BVF was a brown liquid with a density of 11.8 kN/m^3, zero chloride content, and approximately zero air entrainment. It is compatible with all types of Portland cement and is designed to improve the workability of concrete mixtures without reducing their strength.

Reinforcement Bars

High-tensile steel bars of grade 52 were employed as reinforcing bars in this study. The diameters were 10 mm and 12 mm, the Young's modulus is 2000000 N/mm^2, the yield strain was 0.002, the density was 78 kN/m^3, the weights per meter length were 6.17 and 8.88 N, respectively, the ultimate stress was 600 MPa, and the yield stress was 400 MPa.

Steel Fiber

The corrugated steel fibers used are shown in Figure 3 these fibers have a unique shape that allows them to be oriented in multiple directions, which can help to distribute stresses and strains more uniformly throughout the concrete mixture. Additionally, this can help improve the load-bearing capacity. The tensile strength of these fibers is 1200 MPa, which is greater than that of conventional steel fibers.

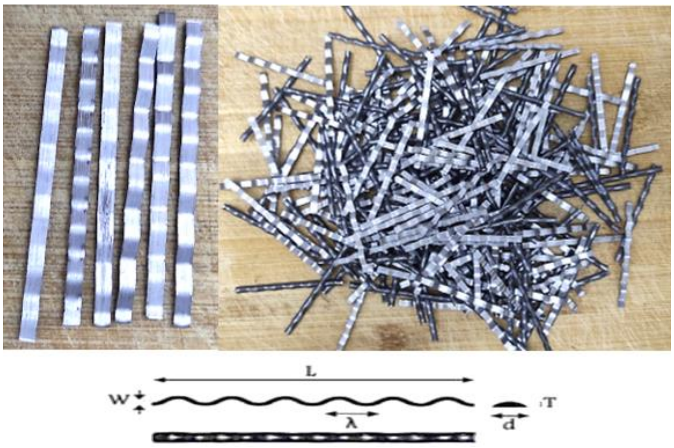


Figure 3. Corrugated steel fibers

The corrugated steel fibers also have a relatively low density of 7.870 Kg/m^3, length (L) =50 mm ± 3 mm, width (d) = 2 mm ± 1 mm, thickness (t) = 0.7 mm ± 0.1 mm, wave depth (W)=2.0 mm ± 0.2 mm, and wavelength (λ) =6.5 mm ± 0.5 mm., which contributes to reducing the overall weight of the concrete slabs. This can be particularly important for large-scale concrete structures, where weight reduction can help reduce the overall cost and complexity of the construction process.

2.2. Mix Design

ACI 211.1-91 [31] was followed in the design of four trial mixes to provide a 60 MPa compressive strength for HSC slabs reinforced with steel bars and steel fibers. Three volumetric contents of steel fibers 37.5, 75, and 150 kg/m³ are used in the other mixtures; the first was a control mixture without steel fiber. Table 1 contains the material quantities for the water-cementitious ratios and concrete mixes. Moreover, 1.5 percent of the volume of steel fiber (Vf) lowers the workability [32].

Table 1. Quantities of materials for concrete mixtures

Mixture ID	W/C	Concrete Ingredients (Kg/m^3)						
		Cement	Water	Aggregate		Silica fume	Super-Plasticizer	Steel Fiber
				Dolomite	Sand			
M0	0.29	470	160	1130	600	70.50	14.10	-
M1	0.29	470	160	1120	600	70.50	14.10	37.5
M2	0.29	470	160	1105	600	70.50	14.10	75
M3	0.29	470	160	1080	600	70.50	14.10	150

2.3. The Process of Preparing, Casting, and Curing Test Specimens

For each concrete mixture, 21 standard cubes (150×150×150) mm are cast to evaluate the f_{cu} (as shown in Figure 4). After 28 days, three cubes from each mixture were tested in compression at room temperature, while the remaining cubes were divided into two groups and exposed to 400 °C and 600 °C for two hours. Each group was thermally treated using three different techniques, as shown in Figure 5. The first group was cooled in air to room temperature and then tested in compression, the second group was treated using water, and the third group was treated with a fire extinguisher. Three cubes were tested for each technique, and the results were compared with the control cubes tested at 28 days and not exposed to elevated temperatures. The splitting tensile strength of each mixture was also measured via the casting of three standard cylinders of 150 mm diameter and 300 mm high.

Figure 4. Standard cubes and cylinders after casting

Figure 5. Cooling techniques, (a): Air to room temperature, (b): Using water, (c): Using a fire extinguisher

A total of fifteen slab specimens were fabricated and tested to evaluate the flexural strength of high-strength concrete (HSC) slabs with and without steel fibers. All the slabs were 500 mm wide and 1300 mm long, with five slabs in each group having different thicknesses of 80, 120 mm and 160 mm as shown in Figure 6.

Figure 6. Reinforcement and casting of slabs

After casting, the specimens are molded and immersed in a curing tank with saturated water at a temperature of 25ºC until they reach the age required for testing. Additionally, the reinforced concrete slabs were cured by spraying them with water and covering them with burlap.

2.4. Test Setup for Concrete Slabs

To investigate the flexural performance of reinforced concrete slabs, two concentrated forces are applied at 200 mm from the mid-span of the span by using distributed steel I-beams shown in Figure 7. The slabs were supported along two edges with unrestrained lifting corners, and concentric loading was exerted via a 300 kN hydraulic jack. The slabs were set on two steel supports with a clear span of 1100 mm. Crack propagation is visually observed during testing, and the tested specimen's surface was marked with the locations of the cracks. As shown in Figure 7, three LVDTs were mounted on the slabs to measure the deflection during the loading operation.

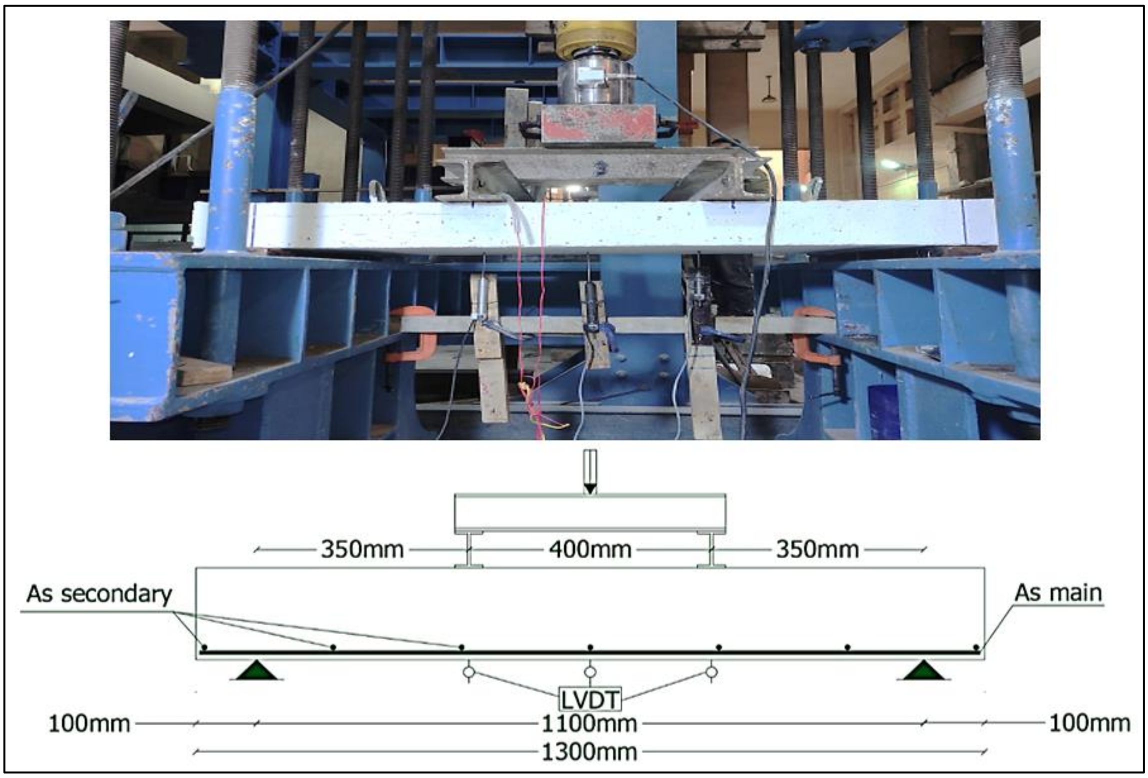


Figure 7. Test setup for concrete slabs

3. Results and Discussion

3.1. Compressive Strength

At Room Temperature

Compressive strength (Fcu) results of all the concrete mixtures tested after 28 days. The Mo mixture without steel fibers achieved a compressive strength of 80.6 MPa, while the M1 mixture with steel fibers 37.5 kg/m^3 reached 83.44 MPa, exceeding that of the control mixture Mo by 3.5%. The M2 mixture with 75 kg/m^3 steel fibers increased to 87.72 MPa, representing an 8.74% increase over that of the Mo mixture. The M3 mixture with 150 kg/m^3 steel fibers increased to 90.17 MPa, representing an 11.79% increase compared to the Mo mixture.

The test results indicate that adding steel fibers to HSC can slightly improve its compressive strength. This is because the fibers function as internal reinforcement, minimizing the formation of microcracks and halting their spread, thereby increasing the material's load-bearing capacity. Moreover, the relatively small volume fractions of steel fibers used in this study (up to 150 kg/m³) are insufficient to significantly alter the concrete's dense microstructure, which predominantly determines compressive strength.

Influence of Elevated Temperature and Cooling Technique

The study investigates the impact of HSC and SFHSC exposure to high temperatures of 400 °C and 600 °C on compressive strength values, particularly when multiple cooling methods are used. The results indicate that the cooling method used after exposure to high temperatures significantly affects the f_{cu} of the concrete mixture.

Water cooling is the least effective method, leading to a rapid decline in compressive strength values, followed by cooling with fire extinguishers and then air cooling. Overall, these results indicate that using steel fibers in concrete can help increase its resilience to high temperatures, as the compressive strength of SFHSC mixtures was found to decrease less than that of concrete without steel fiber when subjected to elevated temperatures. This suggests that incorporating steel fibers into concrete could be beneficial in improving performance under high-temperature conditions.

Figures 8 and 9 illustrate the connection between the reduction rate of f_{cu} and the incorporation of steel fibers into HSC and SFHSC mixtures, considering temperature and cooling technique. The f_{cu} of concrete with and without steel fiber decreased with increasing temperature. However, SFHSC exhibits greater overall residual strength and enhanced crack resistance after being exposed to high temperatures and helps to mitigate spalling by providing reinforcement that holds the matrix together and facilitates gradual stress release. Thus, these results suggest that the use of steel fibers in concrete may be a powerful method to improve its performance under high-temperature conditions. Consistent with this, Nili & Afroughsabet [16] reported that adding steel fibers to HSC improved impact resistance and reduced thermal degradation. This study corroborates these conclusions, emphasizing the benefits of steel fibers in maintaining residual strength and crack resistance at elevated temperatures.

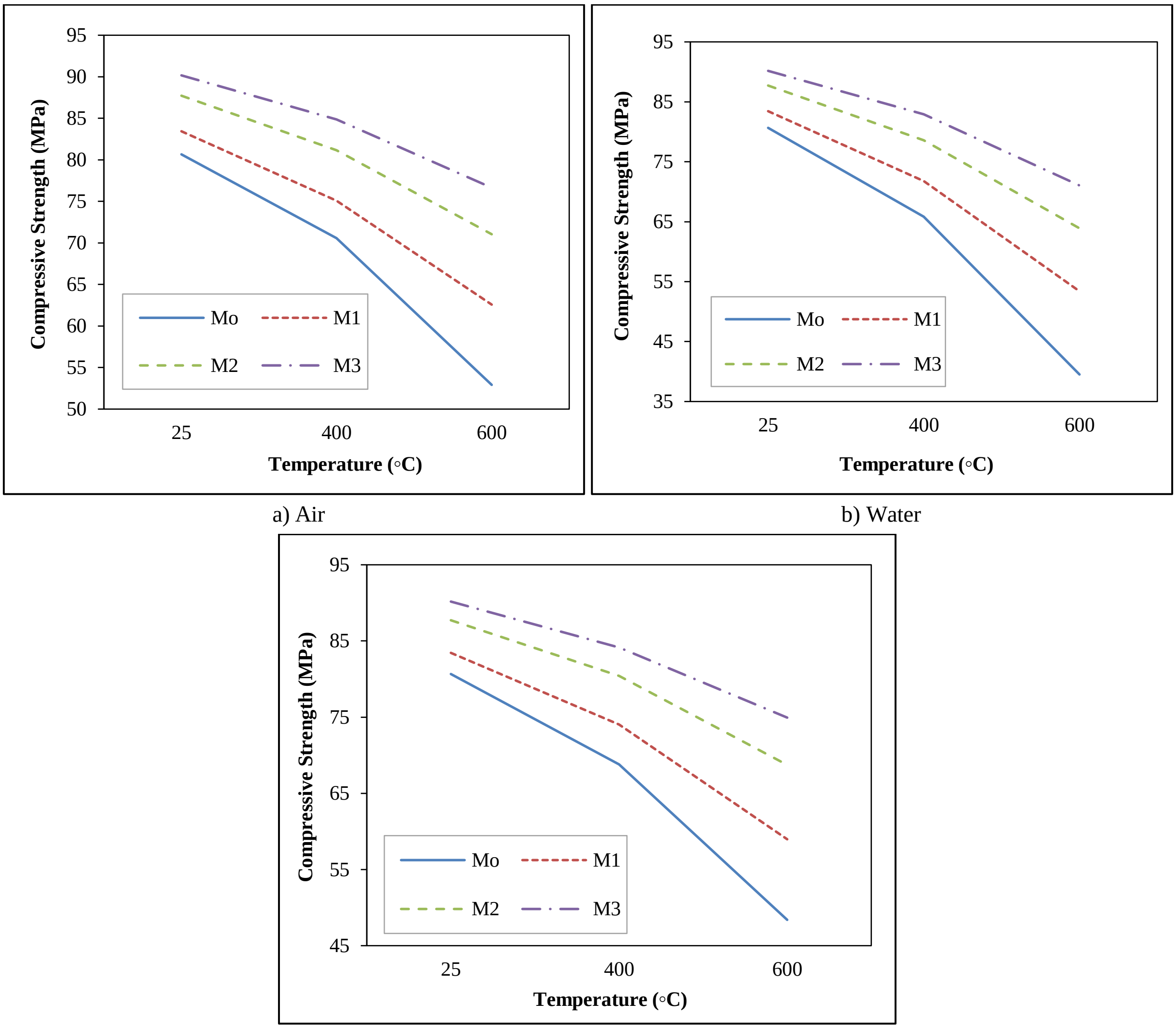
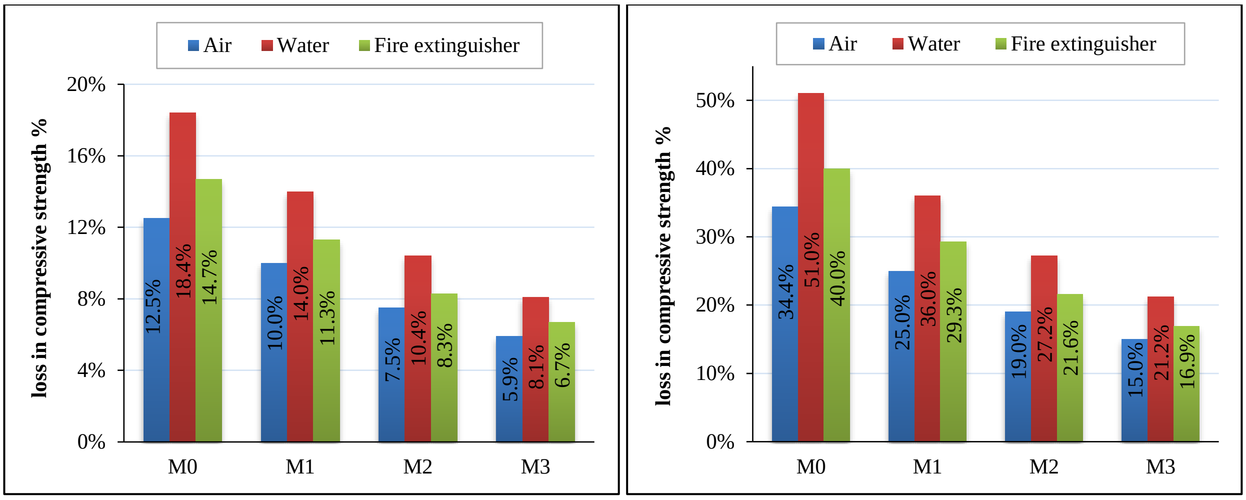


Figure 8. Influence of elevated temperature on compressive strength with different techniques



a) At Temperature 400ºC b) At Temperature 600ºC

Figure 9. Loss in Compressive strength

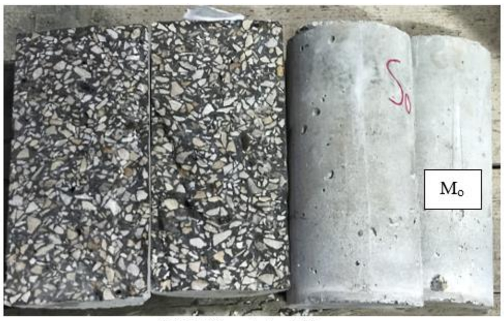
3.2. Splitting Tensile Strength

In Table 2 and Figure 10, all concrete mixtures were tested to evaluate splitting tensile strength. After 28 days, the Mo mixture without steel fibers achieved a splitting tensile strength of 4.83 MPa, while the M1 mixture with steel fibers 37.5 kg/m^3 increases to 9.11 MPa, representing an 88.5 % increase over the Mo mixture without steel fibers. The M2 mixture with 75 kg/m^3 steel fibers had a strength of 10.67 MPa which is a 120.7% increase compared to the Mo mixture. Finally, the M3 mixture with 150 kg/m^3 steel fibers had strength of 13.14 MPa, which was 171.9% higher than that of the Mo mixture.

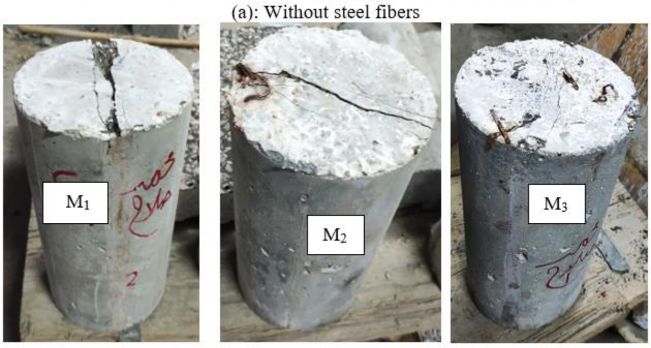
Table 2. Splitting tensile strength results

Mixture Id	Mo	M1	M2	M3
Steel Fiber (Kg/m^3)	-	37.5	75	150
Failure Load (KN)	217.5	410	480	591.5
Splitting tensile strength (MPa)	4.83	9.11	10.66	13.14

The incorporation of fibers into concrete can greatly improve its splitting tensile strength. This improvement is attributed to the fibers' capacity to prevent or delay the propagation of cracks, which is achieved through the high tensile strength and toughness of the fibers. When a crack forms in concrete, the fiber prevents the crack from expanding as shown in Figure 10. By preventing the growth of cracks, fibers can help maintain the load-bearing capacity of concrete even under tensile stress.



(a): Without steel fibers



(b): With steel fibers.

Figure 10. Splitting tensile failure for cylinders

3.3. Load-deflection Results

Table 3 and Figures 11 to 17 present the load-deflection behavior at mid-span for three groups of HSC concrete slabs, with and without the incorporation of steel fibers. For Group 1, the control slab (S0-80) without steel fibers had a failure load of 60.37 kN and a vertical deflection of 23.62 mm. Adding steel fibers at 37.5 kg/m³ and the same reinforcement ratio for (S1-80) increased the failure load to 70.37 kN (16.5% increase over S0) and the vertical deflection to 23.05 mm. Adding steel fibers at 75 kg/m³ for (S2-80) with the same reinforcement ratio increased the failure load to 74.07 kN (22.7% increase over S0) and decreased the vertical deflection to 20.21 mm. For the same reinforcement ratio when the steel fiber ratio was increased to 150 kg/m³ for (S3-80), the failure load increased to 75.37 kN (24.8% increase from S0) and the vertical deflection decreased to 17.70 mm. For a smaller reinforcement ratio (S4-80) with the same steel fibers at 150 kg/m³, the failure load increased to 73.71 kN (22.1% increase over S0) and decreased the vertical deflection to 17.73 mm.

For group 2, the control slab (S0-120) without steel fibers had a failure load of 110.1 kN and a vertical deflection of 17.27 mm. Adding steel fibers at 37.5 kg/m³ and the same reinforcement ratio for (S1-120) increased the failure load to 123 kN (11.8% increase over S0) and the vertical deflection to 17.55 mm. Adding steel fibers at 75 kg/m³ for (S2-120) with the same reinforcement ratio increased the failure load to 130.4 kN (18.5% increase over S0) and decreased the vertical deflection to 15.94 mm. For the same reinforcement ratio when the steel fiber ratio was increased to 150 kg/m³ for (S3-120), the failure load increased to 142.7 kN (29.6% increase from S0) and the vertical deflection decreased to 11.49 mm. Otherwise, for a smaller reinforcement ratio (S4-120) with the same steel fibers at 150 kg/m ³, the failure load increased to 128.2 kN (16.5% increase over S0) and decreased the vertical deflection to 11.36 mm. In group 3, the failure load for the control slab (S0-160) without steel fibers was 148.92 kN and the vertical deflection was 12.61 mm. The failure load and vertical deflection have increased for (S1-160) to 171.58 kN and 14.69 mm, respectively. Otherwise, the failure load for (S2-160) has increased to 180.25 kN (21% increase from S0) and the vertical deflection has decreased to 10.34 mm. For (S3-160), the failure load has increased to 197.48 kN (32.6% increase from S0), and the vertical deflection has decreased to 9.81 mm. For the last specimen (S4-160) with 150 kg/m ³ steel fibers and a smaller reinforcement ratio than the other specimens, the failure load increased to 181.29 kN (21.7% increase over S0), and the vertical deflection decreased to 8.88 mm.

S4 slabs across all groups achieved higher performance even with reduced main reinforcement (5Ø10 instead of 5Ø12), showcasing the potential for material savings while maintaining structural integrity. The incorporation of 150 kg/m³ of steel fibers into the concrete mix, combined with a reduction in reinforcement, resulted in a significant enhancement of load-carrying capacity across all groups. Specifically, the observed increases were 22.1% for Group 1, 16.4% for Group 2, and 15.6% for Group 3, demonstrating the effectiveness of this approach in improving structural performance

In the control slabs, cracks initiated at lower loads (36.75 kN for S0-80) and propagated rapidly, leading to brittle failure. Fiber-reinforced slabs, however, exhibited delayed crack initiation and a more gradual crack propagation. For example, cracks in the S3-80 slab began at a higher load (40.91 kN) and expanded in a controlled manner, preventing sudden failure. This behavior is a direct result of the steel fibers' ability to enhance the concrete's tensile strength and toughen its matrix, improving its ability to resist crack formation and spread.

The test results indicate that the incorporation of steel fibers significantly enhances the load-bearing capacity of concrete structures, as well as enhancing their toughness in addition to these benefits, the use of steel fibers contributes to a reduction in the amount of conventional reinforcement needed in concrete structures, leading to cost savings and a more sustainable construction process. Consistent with these results, Eswari et al. [13] and Beddar [15] reported that incorporating 2% steel fibers enhanced the modulus of rupture, energy ductility, and cracking resistance. This study aligns with their conclusions, showing increased load-bearing capacities and reduced crack widths, particularly at higher fiber contents (150 kg/m³).

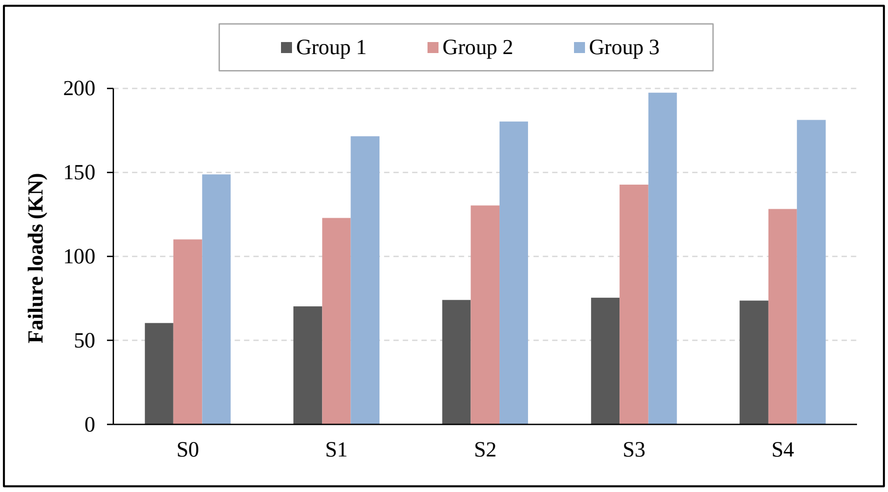
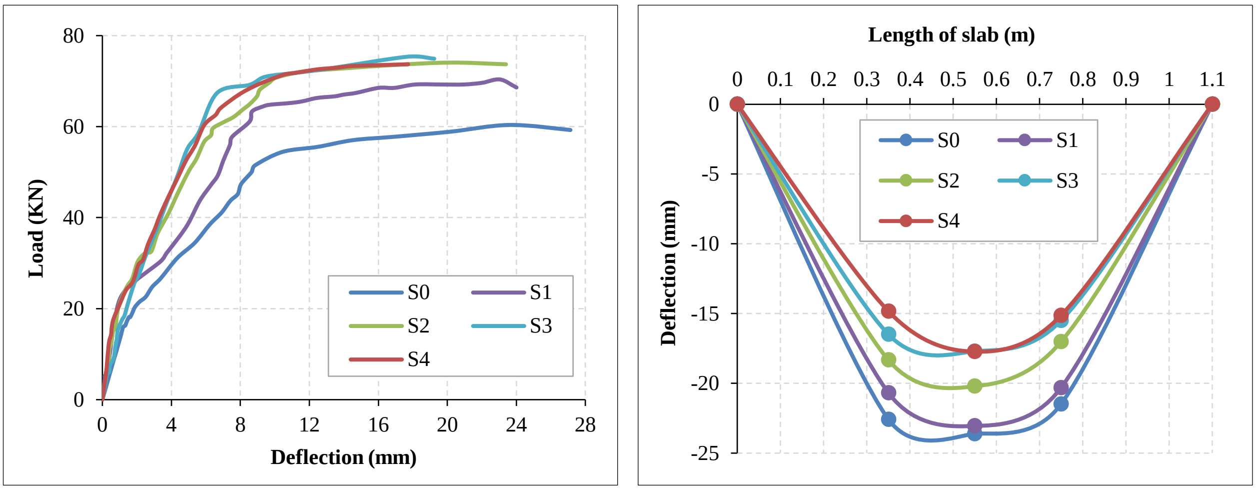


Figure 11. Failure loads (KN) for Group 1, Group 2, and Group 3 slabs

Table 3. Structural slab details, Load deflection and Ductility index results

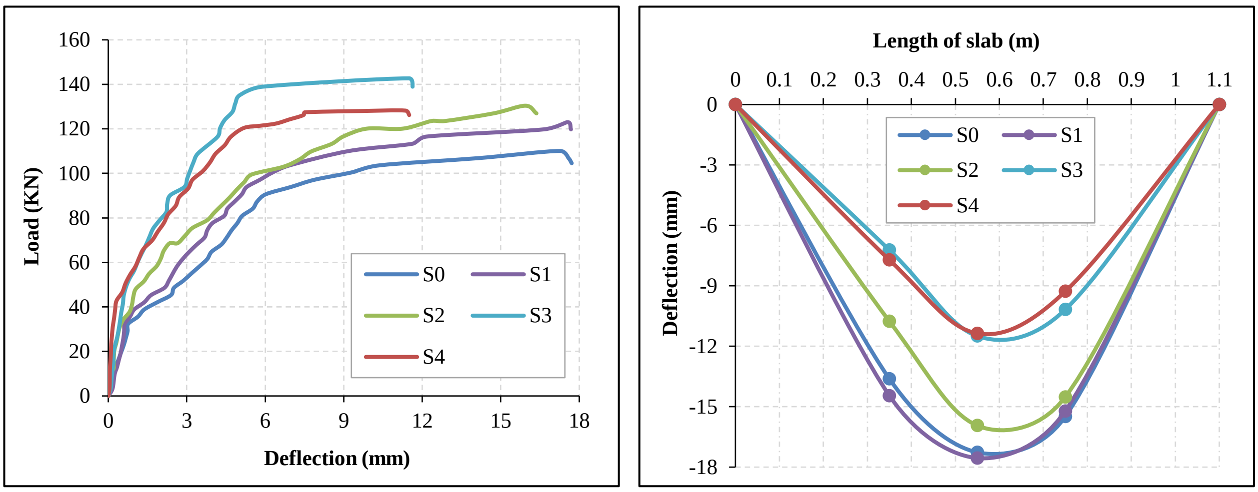
Slab Dimensions	Slab Code	Steel fiber kg/m^3	Pu KN	Δ_u mm	Δ80%	Ductility index	As main\m		As Secondary\m	
							N	Φ (mm)	N	Φ (mm)
Group (1) B=0.5 m L=1.3 m ts=0.08 m	S0-80	-	60.37	23.62	8.05	2.933	5	12	4	10
	S1-80	37.5	70.37	23.05	7.43	3.102				
	S2-80	75	74.07	20.21	6.40	3.158				
	S3-80	150	75.37	17.70	5.69	3.111				
	S4-80	150	73.71	17.73	5.68	3.120	5	10		
Group (2) B=0.5 m L=1.3 m ts=0.12 m	S0-120	-	110.1	17.27	5.95	2.905	5	12	4	10
	S1-120	37.5	123	17.55	5.80	3.026				
	S2-120	75	130.4	15.94	5.14	3.101				
	S3-120	150	142.7	11.49	3.71	3.102				
	S4-120	150	128.2	11.36	3.60	3.155	5	10		
Group (3) B=0.5 m L=1.3 m ts=0.16 m	S0-160	-	148.92	12.61	4.3	2.932	5	12	4	10
	S1-160	37.5	171.58	14.69	4.6	3.192				
	S2-160	75	180.25	10.34	3.17	3.219				
	S3-160	150	197.48	9.81	3.05	3.218				
	S4-160	150	181.29	8.88	2.92	3.041	5	10		

Note: B: Width of slab -L: Length of slab -ts: Thickness of slab; As: Reinforcement- N: Number of bars- Φ: Bar; diameter (mm); Pu: Failure Load, -Δu: Deflection at failure load.



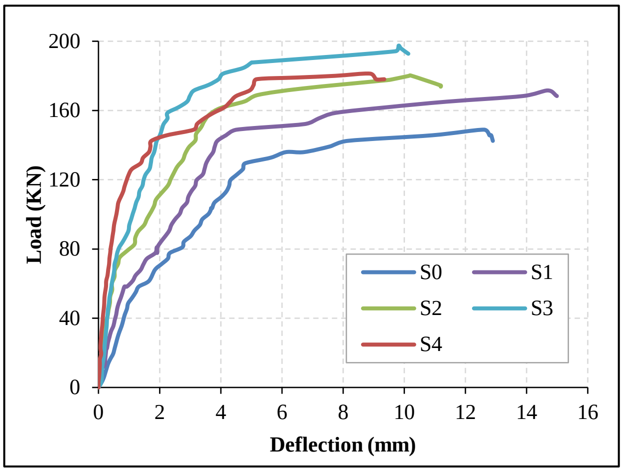
a) Load–deflection curves b) Deflection shape

Figure 12. Slabs in Group 1

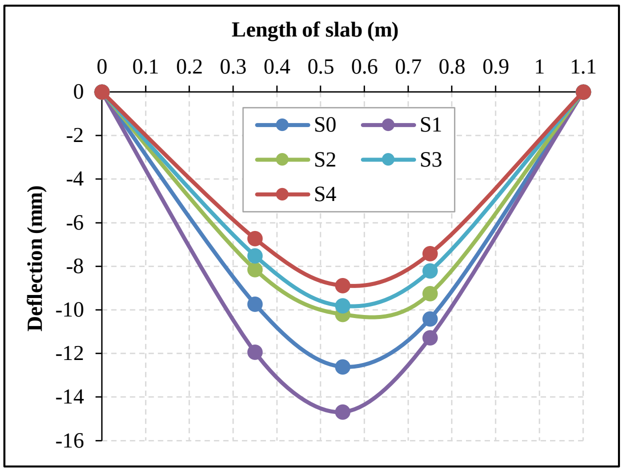


a) Load–deflection curves b) Deflection shape

Figure 13. Slabs in Group 2

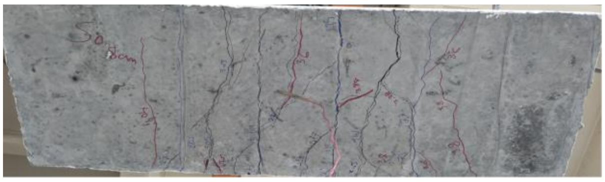


a) Load–deflection curves

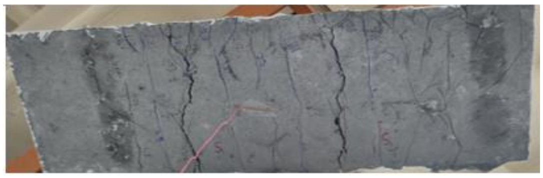


b) Deflection shape

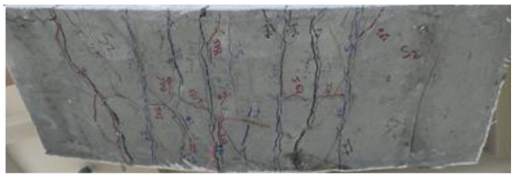
Figure 14. Slabs in Group 3



S0-80



S1-80



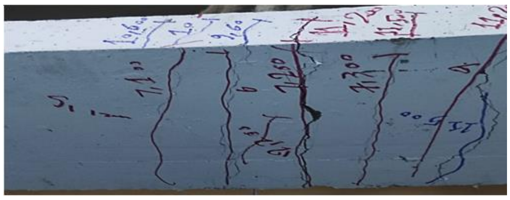
S2-80

S3-80

S4-80

Figure 15. Crack pattern for high-strength concrete slabs for Group (1)

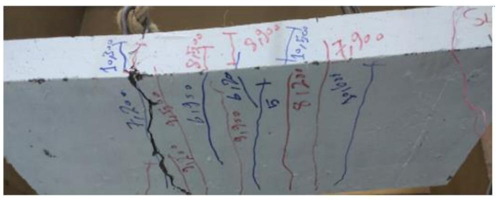
S0-120



S1-120

S2-120

S3-120



S4-120

Figure 16. Crack pattern for high-strength concrete slabs for Group (2)

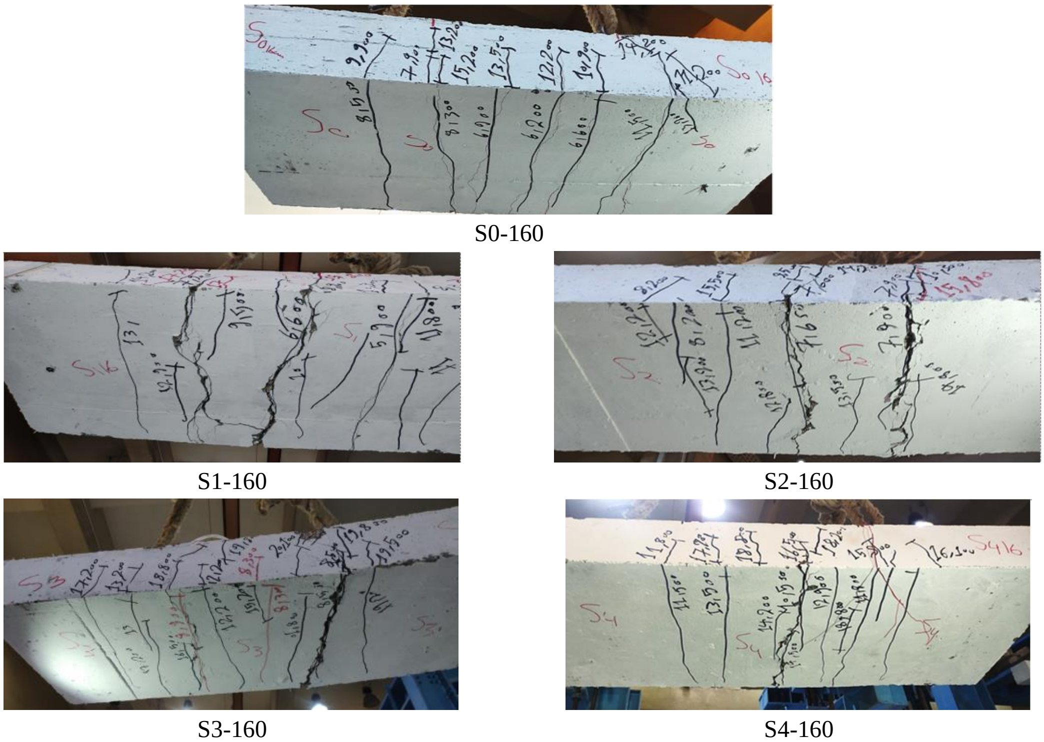


Figure 17. Crack pattern for high-strength concrete slabs for Group (3)

3.4. Ductility Index

The ductility of a slab increases in direct correlation with its ductility index, reflecting the structure's enhanced ability to undergo plastic deformation before failure [33]. Previous researchers have made various attempts to identify the most acceptable ductility index. Some studies have utilized the high deflection, which represents the maximum load that the slab can withstand, whereas others have used the ultimate deflection, which reflects the failure load.

According to Park [34] the ultimate point (Δu) of a tested slab can be estimated via various techniques based on its load-deflection. After reaching the peak load, a 20% reduction in load is one of the methods that can be used. In this case, the deflection in the plastic zone, which corresponds to 80% of the peak load beyond the peak load, is recognized as the ultimate deflection. Previous research has examined the ductility of HSC specimens via the 20% load-reduction method [35-37]. During the current experiment, a concrete structure is observed to fail at 80% or more of its peak load, at which point the curve for the load-deflection becomes unstable. This study, therefore, also used the 20% load-reduction approach to calculate the ultimate deflection. Structures built in high-seismic zones must have a minimum ductility index of 3.0 [33].

Table 3 shows that tested slabs without steel fiber have a ductility index of less than 3.0 but when steel fiber is incorporated into the concrete mix with different ratios the ductility index increases with a small value which increases above 3. This threshold is often regarded as a minimum requirement for structures in high-seismic zones or those subjected to dynamic forces.

A higher ductility index allows the slabs to deform plastically before failure, meaning they can bend or stretch under stress instead of cracking abruptly. This transition from brittle sudden failure without any warning to ductile behavior with visible deformation and energy dissipation before ultimate failure which significantly enhances the safety and resilience of the slabs in real-world applications requiring flexibility and energy absorption. This gradual failure mode provides additional warning and reduces the risk of catastrophic collapse, making steel-fiber-reinforced slabs a more reliable choice in critical structural applications.

4. Conclusion

This study investigated the effect of incorporating steel fibers into high-strength concrete (HSC) slabs, concentrating on enhancing their mechanical properties under various conditions, such as elevated temperatures. The findings revealed that increasing the steel fiber content to 37.5, 75, and 150 kg/m³, respectively, had a negligible impact on the compressive strength and density of the concrete. However, it significantly improved the splitting tensile strength and modulus of rupture, with the highest being 171.9% compared to the control mix. The inclusion of steel fibers also enabled a reduction in the reinforcement ratio without compromising the structural performance, as evidenced by a failure load increase of up to 29.6% in certain slab configurations.

This study investigated the performance of steel fiber-reinforced high-strength concrete (SFHSC) slabs under elevated temperatures of 400 °C and 600 °C. While the compressive strength of the slabs declined with increasing temperature, the addition of steel fibers greatly reduced this drop, resulting in higher residual strength and better crack resistance than standard HSC. Furthermore, the addition of steel fiber enhanced the ductility index of the slabs, achieving values above the critical threshold of 3.0. This enhancement adds to greater resilience and safety, particularly in situations where flexibility and energy absorption are crucial, such as structures located in high seismic zones or subjected to dynamic loading conditions. These findings imply that steel fibers are a sustainable and cost-effective solution that will improve the performance and longevity of modern high-strength concrete structures.

5. Declarations

5.1. Author Contributions

Conceptualization, W.I. and S.E.; methodology, W.I., A.A., and M.E.; software, M.S. and A.A.; validation, W.I., S.E., and M.E.; formal analysis, M.S. and A.A.; investigation, W.I., M.E., and S.E.; resources, S.E., M.S., A.A., and W.I.; data curation, M.S. and W.I.; writing—original draft preparation, M.S.; writing—review and editing, S.E. and W.I.; visualization, M.S. and A.A.; supervision, W.I., A.A., and M.E.; project administration, S.E. and M.E.; funding acquisition, S.E. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding and Acknowledgments

The authors confirm that the data applied in this study is primary data and were generated at the building materials laboratory of the Faculty of Engineering at Mataria, Helwan University, Egypt in cooperation with the Department of Civil and Environmental Engineering in Kingdom University, Bahrain. The authors would like to acknowledge that this research work was partially financed by Kingdom University, Bahrain from the research grant number KU-SRU-2024-06.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

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