NOVEMBER 2021 M.Sc. in Civil Engineering ANMAR MOHAMMED JASIM

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INVESTIGATION OF THE FLEXURAL BEHAVIOR OF STEEL FIBER REINFORCED CONCRETE HOLLOW BEAMS EXPOSED TO ELEVATED TEMPERATURE

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CIVIL ENGINEERING

BY

ANMAR MOHAMMED JASIM

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Supervisor

Prof. Dr. Mustafa ÖZAKÇA

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ABSTRACT

INVESTIGATION OF THE FLEXURAL BEHAVIOR OF STEEL FIBER REINFORCED CONCRETE HOLLOW BEAMS EXPOSED TO ELEVATED TEMPERATURE

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Hollow concrete beams, when adopted in structures, must meet the required structural safety at both conditions of ambient and high temperature. The behavior of this type of beam, with the influence of high temperature, has not been investigated by any previous study yet. This study aims to experimentally explore the behavior of concrete beams of circular hollow sections (80mm diameter) using conventional steel reinforcement and with or without steel fibers (SFs) under flexural loads prior to and after exposure to high temperatures. Besides, the investigation also included the mechanical characteristics (compressive strength and splitting tensile strength) of four mixtures were used to produce the beams specimens and studied their response to different inclusions of SFs (0, 0.5, 1, and 1.5% for each) under similar conditions of the beams test. A total of ten beams of square cross-section with similar external dimensions and lengths (150 × 150 × 950 mm) were prepared, eight of which were hollow, and two were solid. All these beams specimens were loaded until failure under four-point to assess and compare their behavior in terms of temperature evolution, load versus deflection at different stages of loading, ductility, failure mode, and cracks before and after being subjected to 550°C temperature. Based on the test findings, SFRC hollow beams exhibited a more ability to preserve load carrying capacity after heating than plain concrete beams. SFRC hollow beams can be a desirable structural solution and provides a reduction in weight and an increase in ductility without a significant reduction in flexural performance even after direct exposure to a source of intense heat.

Key Words: Steel fiber reinforced concrete, Flexural behavior, Hollow beam, Ductility, High temperature.

ÖZET

YÜKSEK SICAKLIĞA MARUZ KALMIŞ ÇELİK LİFLERLE ĞÜÇLENDİRİLMİŞ BETONARME DELİKLİ KİRİŞLERİN EĞİLME DAVRANIŞININ İNCELENMESİ

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71 sayfa

Delikli beton kirişler, yapılarda kullanıldığında hem ortam hem de yüksek sıcaklık koşullarında gerekli yapısal güvenliği sağlamalıdır. Bu tür kirişin yüksek sıcaklığın etkisiyle davranışı daha önce yapılmış herhangi bir çalışma ile araştırılmamıştır. Bu çalışma, yüksek sıcaklıklara maruz kalmadan önce ve sonra, geleneksel çelik takviyeli ve çelik lifli veya lifsiz dairesel boşluklu kesitlerin (80 mm çapında) beton kirişlerinin davranışını deneysel olarak araştırmayı amaçlamaktadır. Ayrıca, araştırma, kiriş numunelerini üretmek için kullanılan dört karışımın mekanik özelliklerini (basınç mukavemeti ve yarma gerilme mukavemeti) benzer koşullar altında incelenmiş ve farklı çelik lif (her biri için %0, 0,5, 1 ve %1,5) oranlarının etkiside araştırılmıştır. Benzer dış boyut ve uzunluklarda (150 × 150 × 950 mm) sekizi içi boşluklu, ikisi ise deliksiz olmak üzere toplam on kare kesitli kiriş hazırlanmıştır. Tüm bu kiriş numuneleri, 550°C sıcaklığa maruz bırakılmadan önce ve sonra, yüklemenin farklı aşamalarında yüke karşı sehim, süneklik, kırılma modu ve çatlaklar açısından davranışlarını değerlendirmek ve karşılaştırmak için dört nokta yük testi uygulandı. Test bulgularına göre, delikli çelik lifli betonarme kirişler, düz beton kirişlere göre yüksek sıcaklığa maruz kaldıkdan sonra dahi yük taşıma kapasitesini koruduğu gözlemlenmiştir. Delikli çelik lifli betonarme kirişler arzu edilen bir yapısal çözüm olabilir ve bir yüksek sıcaklığa doğrudan maruz kaldıktan sonra bile eğilme performansında önemli bir azalma olmaksızın, ağırlıkta bir azalma ve süneklikte bir artış sağlamaktadır.

Anahtar Kelimeler: Çelik lifli betonarme, Eğilme davranışı, İçi boş kiriş, Süneklik, Yüksek sıcaklık.

To my dear Father…To my dear Mother

And to my dear Wife

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CHAPTER I

INTRODUCTION

1.1 General

Structural concrete is still the most widely utilized material in the construction industry. This is due to the appealing properties of concrete, such as its high compression capacity, the availability of its constituents, and the convenience with which it can be produced, as well as the reasonably acceptable production cost for such applications. However, concrete is a brittle material with low tensile strength, limited ductility, and is vulnerable to growing cracks. Reinforced Concrete (RC), in the structural system, is a combination of concrete and steel reinforcing bars, that is extensively used in the civil engineering field because of its sufficient mechanical strength, durability, fire resistance, and ease of forming in complex geometrical shapes [1].

The continuous acceleration of improvement in the performance of concrete to meet structural and innovative needs indicates that this composite will continue to be a fertile ground for innovation and improvement, and its development will follow developments in ongoing engineering research [2]. Several innovative materials have been produced in recent decades to overcome the low tensile strength flaw of concrete and increase its energy absorption capacity. The use of dispersed short fibers was introduced as a method to improve the tensile strength of normal concrete. For this, a variety of metallic and synthetic fibers can be employed. However, the utilization of Steel Fibers (SF) with high tensile strength and the ability to bridge and resist crack formation received the most attention. Under tensile stress conditions, SF with such properties can be utilized to change concrete's brittle behavior to a more ductile behavior before ultimate failure. in addition, under the seismic, impact, and fatigue loading, Steel Fiber Reinforced Concrete (SFRC) is shown to be more ductile and better performing than conventional concrete [3-11]. RC has a heavy self-weight and this is considered as another disadvantage associated with the use of such materials. This leads to more imposed loads which result in heavier and relatively larger members. This is becoming an increasingly important issue and required important considerations in tall buildings and long-span structures, where the huge dead weight of concrete has a significant impact on the overall structural behavior. Consequently, the total cost and material consumption in the construction projects would increase. To minimize the overall self-weight of RC structures, such procedures as developing structurally suitable cross-sectional forms such as hollow concrete members have been employed. Such an optimized member can positively contribute to the structural performance of the RC by reducing dead load which leads to better response against the seismic effect, improving the heat insulation, and material saving.

For most buildings and structures, fire continues to be one of the most potential hazards. The widespread use of concrete as a structural material necessitates a thorough understanding of the effects of elevated temperature resulting from the fire on the structural behavior of concrete. The idea is that structural integrity is the last line of defense when other measures for controlling the fire fail, is the basis for fire protection systems, or what is generally indicated as fire resistance. When exposed to fire, fire resistance is defined as the duration it takes for a structural member to maintain structural integrity, stability, and temperature transmission [12]. Fire resistance can have a crucial impact on a structure's capacity to perform in the incident of a fire.

1.2 Hollow Reinforced Concrete Members

In recent years, research efforts have shown an increased interest to develop the structural system by finding better and more effective construction methods. Different theories relating to structural analysis have been developed to decrease the structural elements' self-weight for a given load-bearing capacity. Optimization of structural materials can be employed to minimize the dead load in tall buildings and long-span structures. Hollow concrete members have been introduced as one of the possible solutions to minimize the overall self-weight of RC structures leading to improve their response during the seismic event, contributing to heat insulation, and vibration damping [13, 14].

A hollow cross-section is a good option for members subjected to combined bending and torsion since it meets most of the requirements for this combination type of loads. It fully satisfies the bending requirement and, in prestressed concrete, is even more beneficial than a solid member due to the reduction in dead load and bending moment as a result of the material savings in the hollow core. In terms of the torsional component, the hollow-section member comes the closest to the ideal one, the hollow circular section, in terms of practicality [15]. Hollow section is frequently used in the design of highly raised RC bridges piers to improve flexural rigidity and decrease pier self-weight. However, because it is often difficult to achieve efficient concrete confinement and the thin web causes the members' shear resistance to deteriorating, RC members with hollow sections may not have an adequate plastic deformation capacity and energy dissipation. This behavior must be thoroughly investigated to ensure the seismic safety of bridge piers [16].

Nowadays, adopting hollow cross-section in the structural elements are becoming widespread in modern building design and have been increasingly utilized in constructing various civil facilities, bridges, towers, and offshore structures. The longitudinal opening is utilized to implement hollow-core RC members that are either cast in site, precast, or prestressed for decreasing weight, saving materials, reducing the size of the other structural elements such as columns and foundations, and consequently reducing cost. Furthermore, it can also be employed to pass the electrical and mechanical services and various other utilities as well as to meet aesthetic aspects and architectural requirements [17-19].

1.3 Steel Fiber Reinforced Concrete

In general, fiber reinforced concrete, which is referred to as (FRC), is mainly a composite mixture of hydraulic types cements, aggregates (fine and coarse), water, and one or more types of dispersed short fibers. Steel, glass, carbon, natural materials, and synthetics can all be utilized to produce fibers in different sizes and shapes, some of these are illustrated in Figure 1.1 [20]. However, SF was the most used type of fiber and received the most attention in FRC applications, owing to steel's substantial properties, such as tensile strength, ductility, modulus of elasticity, as well as the known compatibility with cement-based matrix, promoting superior reinforcing efficiency [21]. SF inhibits or delays the formation of cracks under tensile stress, whether caused directly by load application or indirectly due to shrinking. SF, the commonly used, have an aspect ratio (length to diameter) up to 100 (typically, ranging from 20 to 100) with various lengths (ranging from 10 to 65 mm) and diameters (from 0.2 to 1.3 mm).

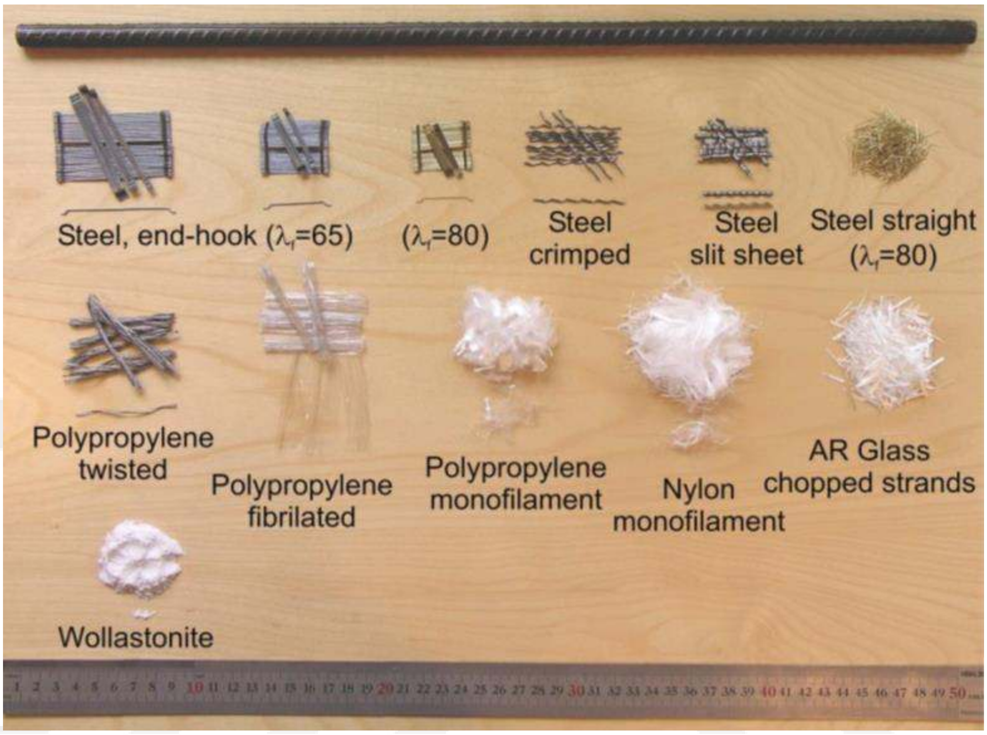


Figure 1.1 Varios types of fiber used in concrete [20].

Adopting SF in a wide range of RC structures for improving the post-cracking tensile resistance is a primary objective through the role of fibers in controlling cracks [22]. The SFRC essential principle is straightforward. The tensile resistance of traditionally RC is boosted in the reinforcement orientation since normal concrete is weak under tension, and reinforcing bars only continue to specific positions. on the other hand, SF is discontinuous and randomly dispersed, these properties allow the fibers to bridge cracks in each direction and facilitate stress transmission across cracks. As a result, flexural and shear resistance is significantly enhancing in the post-cracking stage [23]. Moreover, fibers' ability for bridging also permits for controlling the openings of cracks, resulting in reduced cracks width and their spacing, increased post cracking ductility, and increased energy absorption capacity [21, 24, 25]. Under tension, failure of the SFRC occurs when fibers are fractured or pulled out from the concrete matrix [26], whereas under compression, incorporating SF mainly leads to improving toughness and ductility beyond the peak load [27].

In some structures, such as walls, foundations, and slabs on grade, fibers can fully substitute traditional reinforcement. While in other types of structures, such as suspended slabs and beams, fibers can be applied in combination with traditional or prestressed reinforcement. The main cause for the incorporation of fibers in structural applications is to improve fracture properties and structural behavior by the ability of fibers to bridge the cracks, as shown in Figure 1.2. Both the serviceability and the ultimate limit states are influenced by this mechanism. Controlled crack propagation, which primarily reduces crack spacing and size, and enhances flexural stiffness have effects on service load behavior. The behavior in the ultimate limit state is greater load resistance, and fibers also improve ductility in shear failures [20]. Furthermore, the FRC technology contributes to providing more toleration related to the architectural aspects for the design and construction of complicated and non-perpendicular forms that may be difficult to implement with conventional RC. However, the structures with FRC are yet challenging to design, according to structural engineers, which can be explained by lack of experience, but primarily owing to the lack of development of standard procedures to design the SFRC, results in a shortage of design guidance available for use by designers. Enhancing the structural engineering community's confidence in the concept of relying on a randomly dispersed fiber in the critical structural members to obtain the required strength can only be achieved through extensive research work.

1.4 Effect of Steel Fibers on Reinforced Concrete at Elevated Temperature

Due to fires or any other reasons, exposure to elevated temperatures is one of the most extreme conditions throughout the lifetime of RC structures. Consequently, the concrete undergoes a change which often leading to strength deterioration, cracking, spalling, and a decrease in the bond between reinforcing bars and concrete [28, 29]. For this reason, several measures have been suggested to enhance structural safety, including the use of SFRC that is showed to be better performing than conventional concrete in terms of tensile strength, flexure strength, toughness, impact resistance, and post cracking ductility [30].

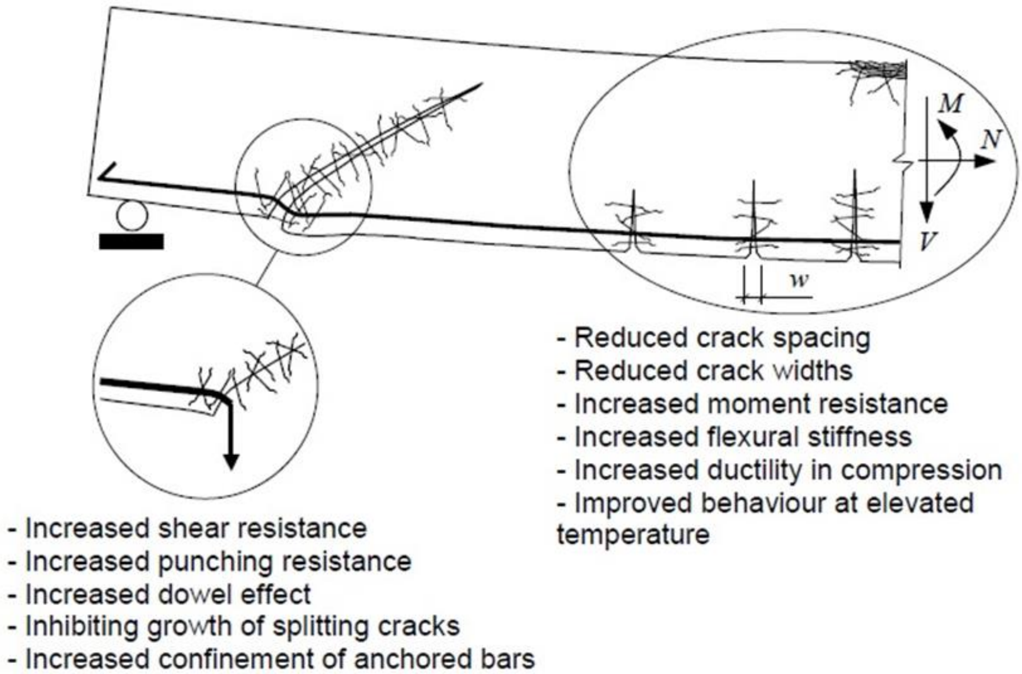


Figure 1.2 Fibers' impact on structural behavior [20].

It is well known, as stated in previous researches, that the inclusion of SF in concrete matrix mitigates the passive impact of high temperatures. SFRC retains strength and performs better than normal concrete at elevated temperatures. In addition, the presence of SF substantially improves fire resistance [31, 32]. It enhances materials properties and resistance to deterioration under thermal stresses, shrinkage, impact, and fatigue, resulting in better structural performance and expanding the utilization of SFRC in various applications of fire fields. With the presence of fibers, the ultimate strain of the SFRC member increases and the ductility improves, and the resulting restraint stresses are more than normal concrete [33]. At exposure to high temperatures, SF can significantly improve the residual mechanical properties of the SFRC, which are highly beneficial to resist fires.

Additionally, some studies [34, 35] have indicated that, although using hybrid fibers such as SF and polypropylene fibers (PP) can reduce the strength loss and mitigates concrete spalling, the SF seems to be the only one that can offer optimal post-cracking performance, improved mechanical conduct, energy absorption, and stability to the fibrous concrete at ambient and high temperatures. This means that SF provides more consistency to the SFRC members to maintain the load-bearing capacity, especially at a long duration of exposure.

1.5 Study Objectives

Based on the aforementioned, it is clear that heavy weight, low tensile strength, and brittle behavior are the most disadvantages of structural concrete that represent a challenge to designers and motivation to researchers to provide reliably safe and serviceable RC structures. In this regard, several methods, concepts, and new superior materials have been put forward to counter these deficiencies. The heavyweight of the RC member, as the beam, leads to more loads and stresses that are transferred to the other supporting structural members, including foundations, resulting in heavier and larger members. Consequently, increasing the amount of consumed material, construction cost, and the environmental damages that result from consuming a large amount of cement and steel materials. This is becoming an increasingly significant issue and priority in multi-story and long-span structures.

For the problems stated above, researchers have offered a variety of proposed solutions to reduce the impact of concrete's heavy self-weight, reducing cost, reducing environmental effect, and improving the characteristic of RC. Adopting hollow-section concrete members was introduced as one of the proposed solutions to decreasing structures' heavy weight and their environmental and financial impact. Such optimized structural members can create a balance between their weight and the structural requirements. Hollow section beams reduce a dead load of structure and thus result in structural members with a smaller cross-sectional area. However, the presence of a hollow section in the RC beam may often lead to reduced strength and less resistance to anticipated loads and more deformation. For this reason and to compensate for the decrease in the strength of hollow members, SF can be used and positively contribute to improving the tensile strength and inhibiting cracks' growth and propagation.

Another significant aspect to investigate when it comes to structural integrity. Similar to the various structural elements, hollow concrete beams, when adopted in structures, must meet the required structural safety in case of fire because fire exemplifies one of the most severe threats that a structure may encounter through its service life.

The review of the previous studies revealed a considerable amount of research works concerned with the structural behavior of hollow beams under torsion. However, only a limited body of researches in the literature was focused on the flexural behavior of hollow-section beams, and these studies were limited to the use of normal concrete or reinforced with a few amounts of SF. Moreover, to the best knowledge of the researcher, no study has investigated the flexural performance of SFRC hollow beams at elevated temperatures.

Therefore, and with the intent of providing the research field with some information and data related to this topic as a beginning and to be a stimulus for upcoming research studies to further exploration, an experimental investigation was performed to evaluate the flexural behavior of SFRC hollow-core beams and investigating the materials' mechanical characteristics at ambient and elevated temperatures. This research aims to address the following:

- Conduct a comprehensive review of the literature covering experimental studies related to hollow beams, SFRC, and the behavior of concrete under high temperatures conditions.
- Study the influence of various percentages of SF up to 1.5% on concrete's mechanical properties in normal and excessive temperatures.
- Comparison of the flexural response and ductility of the hollow RC beams with or without the presence of SF at ambient temperature and after exposure to direct elevated temperatures.
- Characterization of failure mode, cracks pattern, and mid-span deflection after specimens' failure.
- Effect of longitudinally hollow portion presence on the performance of tested beams after loading.

1.6 Thesis Layout

To meet the above goals, this thesis is structured into five chapters.

- Chapter 1, the study objectives and problem statement are presented along with a general background related to hollow members, fibrous concrete, and the effect of SF on RC.
- Chapter 2 covers a review of the relevant literature, which involves the behavior of beams with the presence of longitudinally hollow portion, SF role in concrete, and the response of ordinary concrete and SFRC in terms of concrete material and structural members in conditions of high temperature.

- In Chapter 3, the experimental testing program, which comprises the study parameters, used materials and mixtures, steps to be followed to conducting tests, and testing SFRC beams specimens, is presented.
- Chapter 4, discussion of the obtained results depending on various parameters.
- Chapter 5 introduces the conclusion of this study based on the offered results and discussion from the preceding chapter.

CHAPTER II

LITERATURE REVIEW

2.1 General

As with various structural materials, the design of RC structures is based on the principle of safety and serviceability through its design life. This structural system must have the strength required to withstand a variety of anticipated loads such as imposed loads, earthquakes, and fires that the structure may experience without fail. Before the failure, the structure components must have enough ductility and deformation capacity to maintain structural safety.

The reduction in cross-sectional area, in the case of hollow beams, can be compensated for by increasing strength to preserve the adequate performance of structural members. Nevertheless, this can lead to members with more brittle behavior. Incorporating discrete fibers has been proposed as an accepted approach for improving ductility while also greatly increasing the tensile strength [36]. Therefore, concrete properties have been the subject of extensive research and improvement during the last decades. As a result, novel concrete varieties such as FRC have emerged, and research efforts continued to investigate the effect of this type of concrete on the ductility, durability, energy absorption, and tensile strength of RC members.

Moreover, SF concrete has been one of the suggested measures for enhancing structural safety when exposed to high temperatures by enhancing materials properties to resist concrete deterioration under thermal stresses, and it has the potential to substantially improve the fire resistance of RC elements by boosting concrete's tensile strength, and also decreasing spalling by its capacity to resist deformation. This chapter involves a thorough review of the relevant studies available in the literature and related to the different topics of this research.

2.2 Reinforced Concrete Hollow Beams

The current section will present and discuss the behavior of the hollow beams under various loadings without the usage of SF.

Under cyclic load, Inoue et al. [16] studied the behavior (in flexural and shear) of three concrete beams having longitudinal hollowing of (10 × 12 cm) dimensions and three other beams with solid sections. All beams are the same in cross-section with dimensions of (20 × 20 cm). Beams were reinforced longitudinally with ten rebars Ø10 mm, and Ø6 mm bars as shear reinforcement. Results of this experimental study, in terms of the capacity of energy dissipation and ultimate deformation, showed a reduction and brittle behavior in hollow beams compared to solid counterparts, In addition to the appearance of cracks diagonally at early-stage loading. The authors concluded that a decrease in shear strength must be taken in design considerations for RC structural elements at earthquake risk, especially hollow ones.

Alnuaimi et al. [37] presented 14 RC beams in experimental and analytical research. 7 solid and 7 hollow beams, with similar dimensions and reinforcement, were tested and compared under the same load. To withstand the combined loads of both torsion and shear as well as bending. Beams are designed as hollow-section members, as displayed in Figure 2.1.

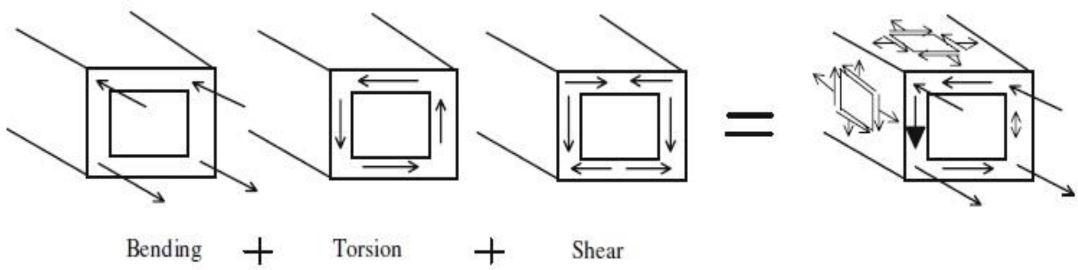


Figure 2.1 Direct stresses conditions in a beam section [37].

Many variables were evaluated by the researchers, including the bending to torsion ratio and also the torsion to shear ratio. According to the findings, all hollow beams cracking at lower loads than their solid equivalent. The solid beams failed at a load greater than design loads, while the hollow ones failed close to it. Moreover, Hollow members acted softer than their solid equivalent (further deflection and further strain in steel) in most cases, while all of them showed a ductile behavior at failure. This means that the hollow cores contribute to the section's resistance under ultimate loads and should not be ignored when such combined loads are considered.

Murugesan and Narayanan [38, 39] examined, experimentally, the flexural behavior of sixty-eight RC beams (76 hollow and 10 solid). Cross-section, steel reinforcement, and concrete grade (M20) are the same in all beams. Circular holes of different diameters ranging from 25 - 64 mm were adopted in the hollow beams and located at various locations. These were the main variables in this test, in addition to the length of the shear span. The researchers noted that when the ratio of shear span to the effective depth (a/d) is 2.69, the hollow RC beams fail in a flexural mode, as with the solid beams. Forming of extra flexural cracks and the growing of the initial cracks till fail were observed in both hollow and solid beams. Also, they stated that the size of the holes did not affect the type of failure, but that the ultimate capacity was affected by the size and location of holes. Furthermore, in the case of beams with the same hole diameter, beams with a hole completely above the neutral axes had the lowest load capacity, while the others with a hole located below the neutral axes had the maximum load capacity.

A study conducted by Manikandan and co-workers [13] showed that removing 25% from the tension zone would not affect the performance of the beams under bending. In this investigation, specimens of 150 cm length RC beams with circular and rectangular holes were cast and tested by a four-point load. Dimensions of cross-section and holes are shown in Figure 2.2.

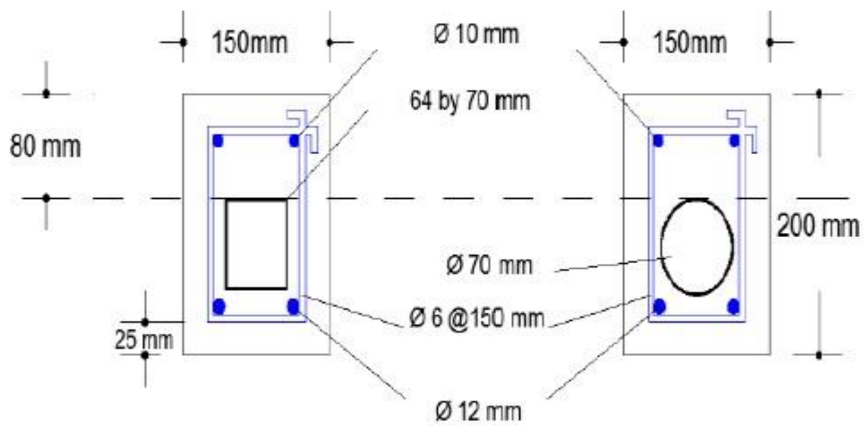


Figure 2.2 Details of sections and reinforcement [13].

This study revealed the preference of beams with circular cores over those with rectangular ones in flexure and deflection, at both yield and ultimate states, and exhibited the same strength of solid beams with a slower prevalence of cracks. Figure 2.3 presents the response of beams to the load in terms of deflection.

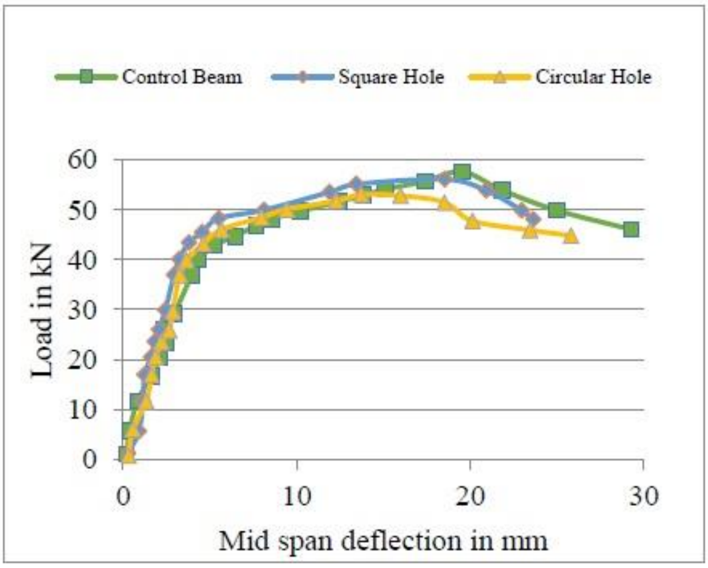


Figure 2.3 Load-deflection of the beams [13].

Abtan and Abdul-Jabbar [40] examined, in experimental work, the flexural performance of thirteen RC beams containing longitudinal hollow cores and side openings. These beams have a cross-section of (15 cm width × 25 cm height) and 180 cm span length. The concrete mixture, reinforcement, and square hollow core (5 cm × 5 cm) in all beams were the same. Locations of the holes were at the center, upper zone, and lower region of the cross-section. This work intended to evaluate and select the ideal hollow-section, the effect of side openings location to hollow beams, and the lateral openings strengthening effect by carbon fiber reinforced polymer laminates. The findings evidenced that the decrease in strength for the beams with holes in the center was lower than those with holes in the lower or upper third of cross-section, and this reduction in resistance increases further and up to 22 percent in case of an existing lateral opening. Furthermore, strengthening the lateral openings by surrounding them with carbon fiber reinforced polymer delays cracks formation and results in strength enhancement by 29 percent.

In experimental work, Balaji & VetturaSudharsanan [41] investigated the behavior of beams with single and double circular hollow parts, focusing on optimizing the members using PVC and galvanized iron pipes instead of concrete in the tension region. Five RC beams with (15 × 20 × 120 cm) dimensions were poured and tested under a two-point load. The hollow portions have a diameter of 6.35 and 3.175 cm for single and double holes, respectively, as shown in Figure 2.4. According to their conclusions, the yield stage deflection of hollow specimens was lower than the solid ones, and the flexural resistance is nearly the same, while the ductility was higher in the case of hollow beams. They also pointed out that the deflection of single holes' beams was lower than those of double-holes at all stages. Finally, they recommended that if the concrete is reduced by 25 % at the tension region, the use of galvanized iron pipes would be an economical option compared to solid members.

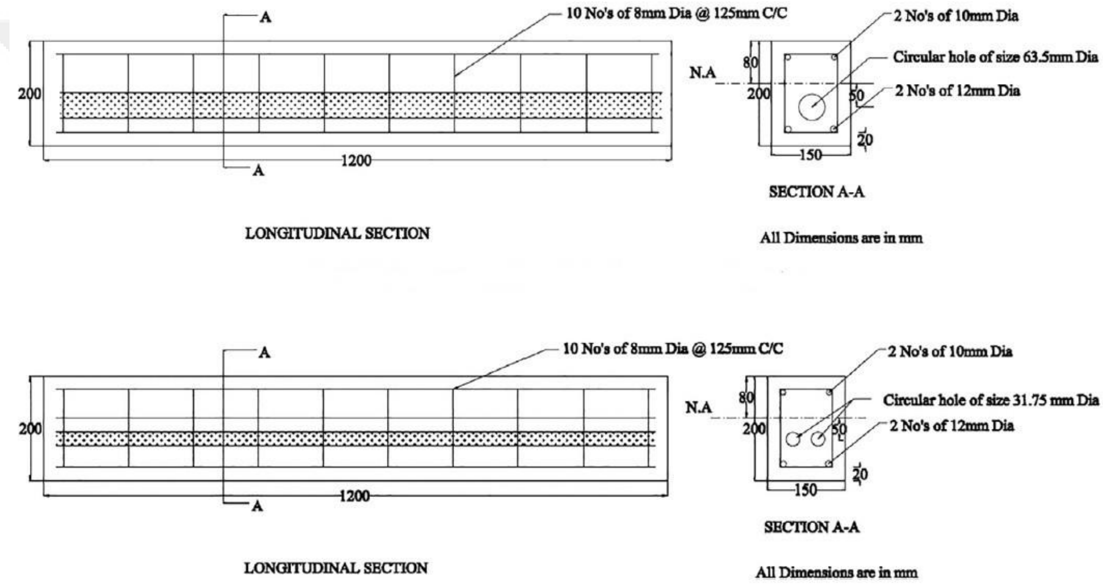


Figure 2.4 Reinforcement and holes details [41].

2.3 Steel Fiber Reinforced Concrete at Ambient and Elevated Temperature

One of the most extreme conditions that RC structures face during their lifetime is exposure to high temperatures. As a result, the concrete starts to change, which frequently results in strength loss, cracking, spalling, and a reduction of the bond between reinforcing bars and concrete [28, 29]. In addition, high-temperature increases pore pressure and, due to the incompatibility of thermal expansion, decreases the bonding between aggregates and cement paste [42], and depending on the severity of the temperatures, these changes have different effects on the concrete mechanical characteristics.

In this regard, investigating the role of fibers to mitigates the passive impact of high temperatures by its potential in controlling cracks initiation and propagation is interesting. Microcracks that emerge because of shrinkage or imposed loads intersect with SF that limit their growth and give higher tensile capacity throughout a concrete mix with SF spread in all orientations. Over recent years, the SFRC mechanical properties after exposure to high-temperature have gotten a lot of attention. They found that SFRC possesses a variety of great properties as a composite mix, including compressive strength, flexural strength, tensile strength, and ductility, based on the findings [30].

2.3.1 Compressive Strength of steel fiber reinforced concrete

Song and Hwang [43] assessed the impact of SF on the compressive strength of High Strength Concrete (HSC) at different fiber dosages of (0.5, 1.0, 1.5, and 2.0 %) of concrete mix volume. The highest percentage for compressive strength was achieved with the addition of 1.5 % fiber, which was 15.3 percent higher than the fiber-free high-strength concrete, while the strength, at 2 %, decreased slightly relative to 1.5 %, yet it was 12.9 % higher than concrete without SF.

The content (% V_f) and aspect ratio (*l/d*, length to diameter ratio) of the SF, according to Eren and Çelik [44], are considered as the major factors which influence the compressive strength when it is embedded in concrete. The recorded results show that the high content and (*l/d*) aspect ratio of SF resulted in a larger increment in compressive strength in this investigation.

Lie and Kodur [45] looked at the strength characteristics of Normal Strength Concrete NSC with or without using SF at high temperatures. They discovered that SFRC compressive strength deteriorates at a considerably higher temperature than fiber-free ordinary concrete. They also concluded their experimental and theoretical investigation that SF result in improved ductility and ultimate strain, and SFRC offers similar thermal properties of normal concrete at elevated temperature, and aggregates type does not affect compressive strength.

The residual compressive strength for NSC and HSC was examined at temperatures from 20 to 1200°C by Chan et al. [46]. They evaluated the loss of compressive strength based on three separate ranges of temperatures, (20-400°C), (400-800°C), and (800-

1200°C). The recorded results demonstrated that, at a temperature, less than 400°C, both types of concrete lost a little part of its strength, but that substantial loss occurred in the second range at 600°C and above due to calcium silicate gel dehydration. They proposed that the temperature range of (400-800°C) be considered crucial for concrete strength loss, and research work to improve thermal performance should be limited to temperatures in this range since the concrete loses most of its strength above 800°C.

After being exposed to increased temperatures, Poon et al. [47] investigated the compressive properties of fiber reinforced-high performance concrete. SF or PP fiber, or both, were used to reinforce the concrete mixes. Figure 2.5 shows that following exposure to 600 and 800ºC, the average residual strength was 45 and 23 %, respectively. The fibers had a significant effect in reducing the influence of heating on the concrete strength deterioration. They also mentioned that the use of PP and SF together has few benefits compared to using SF alone.

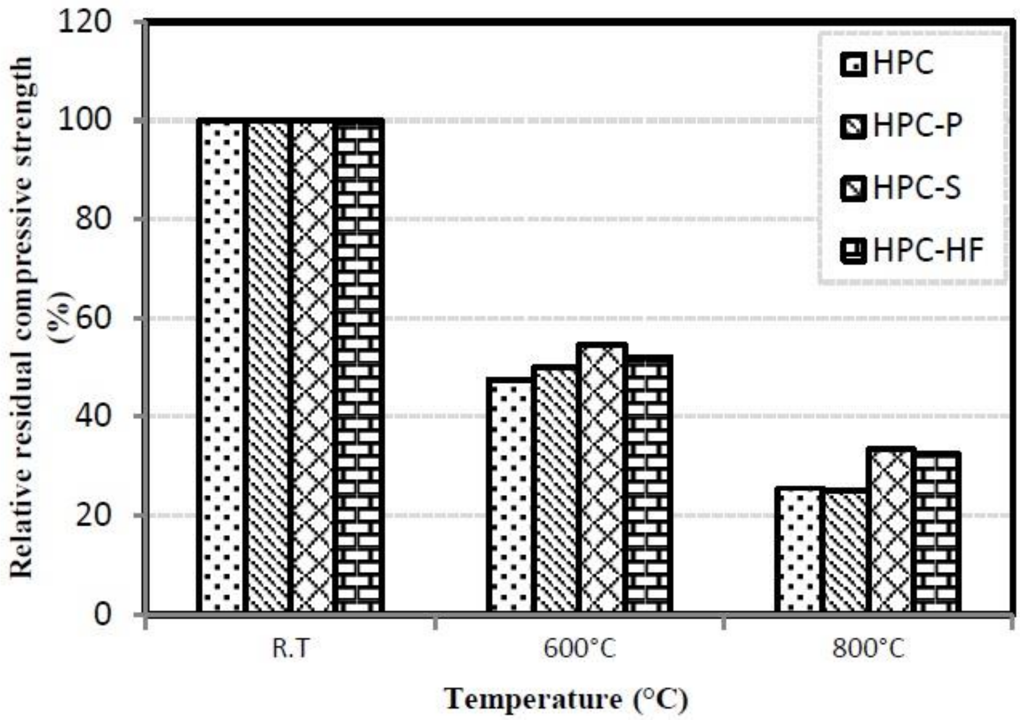


Figure 2.5 Residual compressive strength at room temperature, 600 ºC, and 800 ºC [47].

Peng et al. [48] explored, in their experimental work, the mechanical properties of FRC when exposed to high temperatures up to 800 ºC. It was observed that compressive strength begins to degrade when the temperature exceeds 400ºC. However, the study showed the superiority of concrete with SF over all types at ambient and high temperatures, as shown in Figure 2.6.

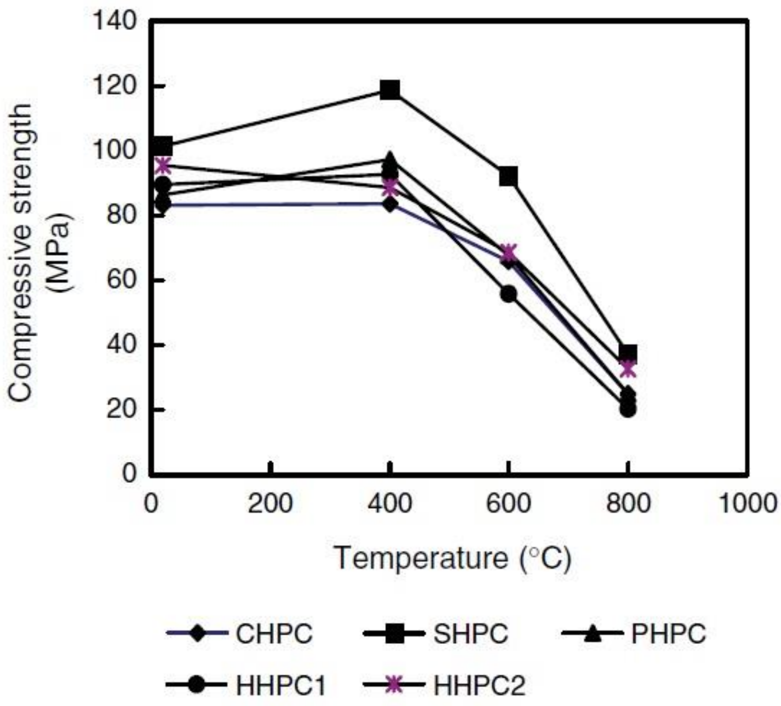


Figure 2.6 Results of compressive strength of different types of concrete at various temperatures. [48].

Lau and Anson [49] inferred that adding SF into concrete that had been subjected to the extreme heat of up to 1200°C is still beneficial, and SF dosage of 1 % has no negative impact on SFRC. In addition, SF incorporation into the concrete matrix offers high resistance to thermal stresses, and the material's improved mechanical properties are usually preserved even after exposure to extreme temperature.

Xie et al. [50] discovered that the compressive strength of SFRC specimens that contain 1% V_f of SF with silica fume was enhanced by 19, 24, 93, and 123 % at 200, 400, 600, and 800°C respectively when compared to specimens without SF.

2.3.2 Splitting Tensile Strength of steel fiber reinforced concrete

Song and Hwang [43] reported that the higher the content (V_f) of SF, the higher the splitting tensile strength. It can be seen from Figure 2.7 that using SF with percentages of 0.5, 1, 1.5, and 2 led to an increment in the strength by 19, 50, 86, and 98%, respectively compared to zero percent of SF.

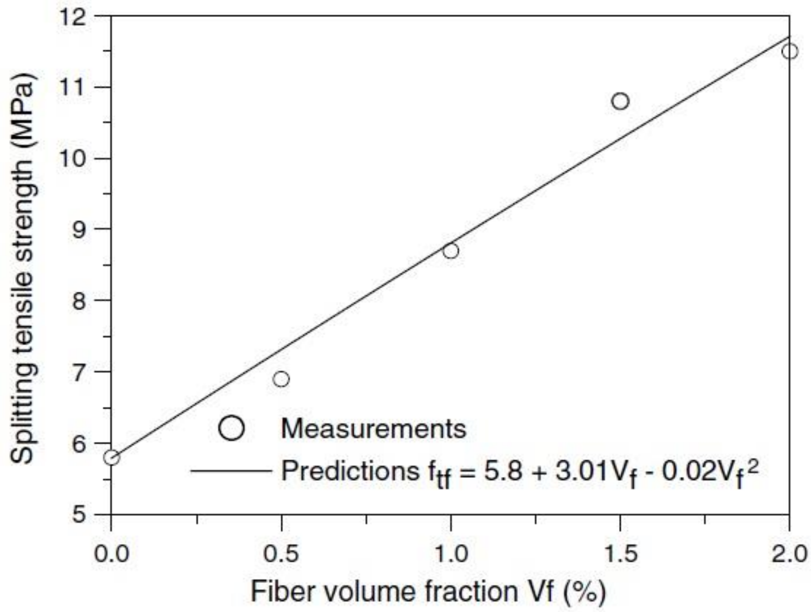


Figure 2.7 Splitting tensile strength for each volume fraction of fiber [43].

The influence of aspect ratio (*l/d*) and Hooked-end SF volume fraction (V_f) on the splitting tensile strength of SFRC was experimentally examined by Yazici et al. [51]. Three different *l/d* ratios of 45, 65, and 80 were used, as well as three different V_f of 0.5, 1.0, and 1.5 % by the total volume of concrete. The addition of fiber gave rise to the tensile strength of SFRC from 11 to 54 % when compared to the reference mixture, as it was indicated. The potential of the SF to control the cracks spreading, inhibiting cracks widening, anchorage mechanism, and lowering the concentration of stresses at crack's tips can explain this improvement in tensile strength. The adoption of 1.5 % SF, in particular, was more efficient in increasing the splitting tensile strength. Similarly, the same conclusion was reached by Wafa and Ashour [3] with a rise in tensile strength of SFRC of 160 %, using 1.5 % SF.

Zheng et al. [52] investigated the SF content and relative tensile strength of reactive powder concrete, finding that at a temperature below 600°C, when the SF percentage raised from 1 - 3%, the relative concrete tensile strength raised. however, a reduction in tensile strength was observed at a temperature between 600 and 800°C where shown in Figure 2.8. The surface available for load-bearing decreases with the formation of new cracks, which are subject to stresses at the cracks' critical tips, and under tensile load, they widen rapidly unlike compression loading where cracks tend to close. For this reason, the deterioration in compressive strength under thermal load is lower and gradual than in tensile strength.

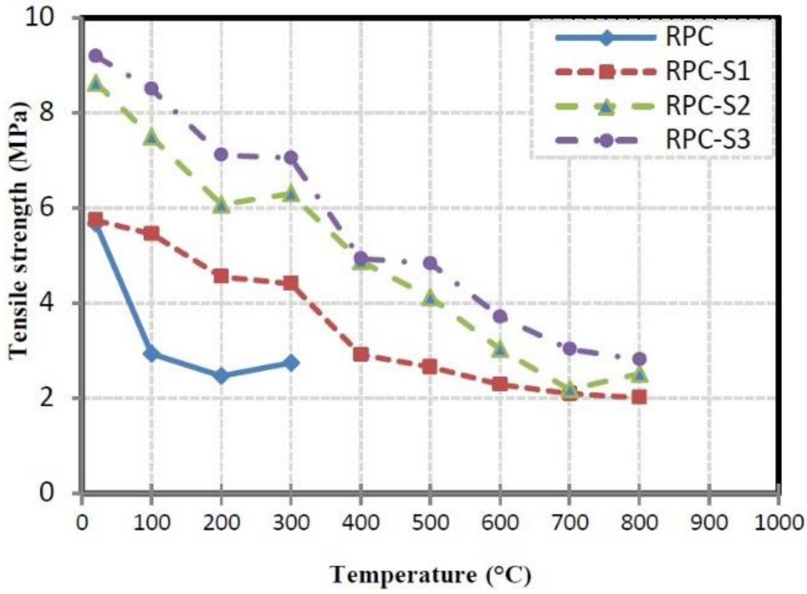


Figure 2.8 Tensile strength at different temperatures [52].

In comparison between SF, Carbone fiber, and PP, Chen and Liu [53] studied the performance of HSC under increased temperatures up to 800ºC. The role of SF in improving the residual tensile strength of SFRC specimens is demonstrated in Figure 2.9, which maintains relatively higher values up to 600 ºC to the other types of fibers.

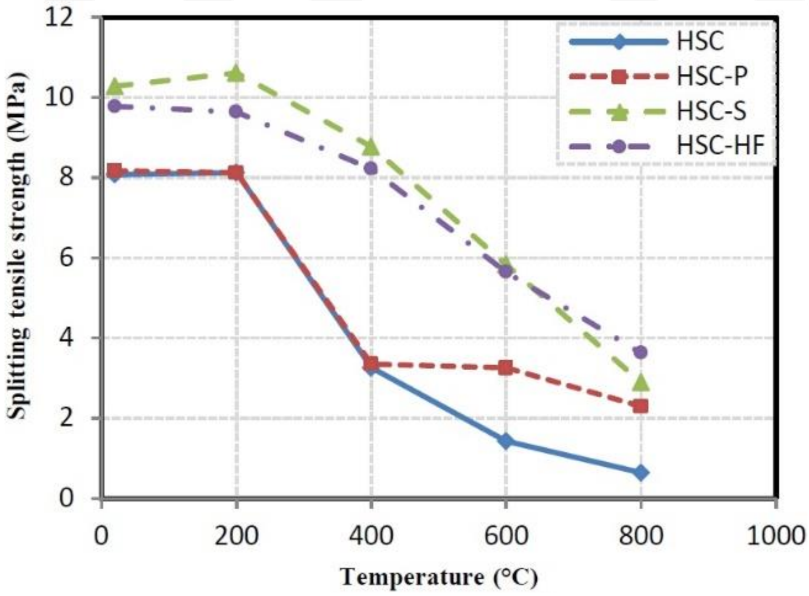


Figure 2.9 Splitting tensile strength for each volume fraction of fiber [53].

2.3.3 Flexural strength

Reinforcing concrete with SF has been shown to boost the flexural strength of SFRC. The basis for this enhancement is that the bonding feature between the concrete mixture and SF gives the fibers the ability to carry loads after cracks appear in the concrete. These cracks are resisted by fibers and inhibit their spread, thus giving the concrete a higher bearing capacity and diminishing sudden collapse.

It was reported by Song and Hwang [43] that adding SF in proportions 0.5 to 2% provides a rise in rupture modulus by 28 to 126% respectively compared to fiber-free concrete samples, and this is shown in Figure 2.10.

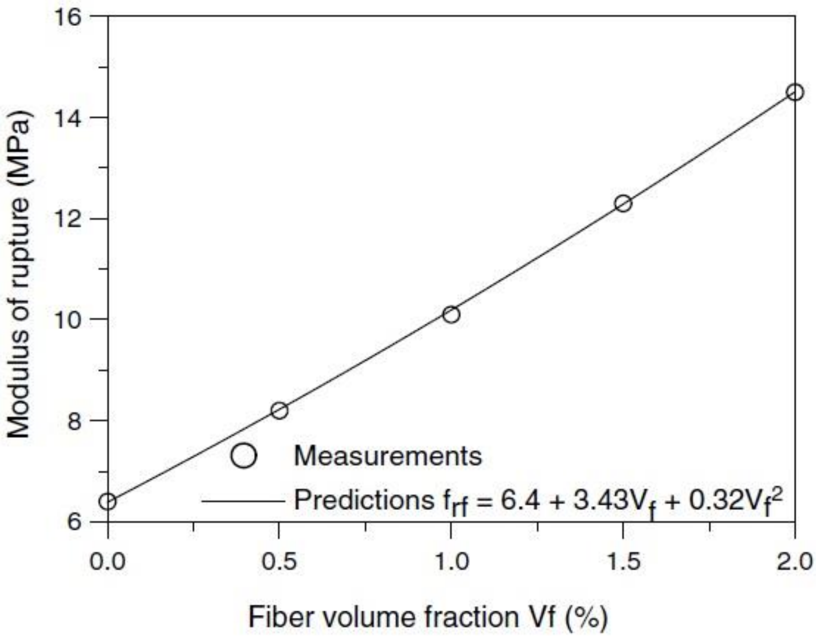


Figure 2.10 Fibers effect on rupture modulus [43].

In a research work carried out by Soroushian and Bayasi [54], three types of SF, including straight, hooked-end, and crimped, were utilized in HSC to investigate the flexural behavior. Two aspect ratios *l/d* of 60 and 75 and fibers volume of 2%, were adopted in the experiment. Research findings revealed that the hooked-ends type of SF resulted in flexural strength and absorption of energy higher than the other two types of SF.

Jameran et al. [55] examined the flexural strength of five hybrid FRC mixes. SF and PP fibers of constant dosage (1.5 %) were used to reinforcing concrete. The adopted concrete mixes in this study were involved proportions of (100% SF), (75% SF and 25% PP), (50% SF and 50% PP), (25% SF and 75% PP), and (100% PP) fibers. After exposure to high temperature, it is obvious from Figure 2.11 that the residual flexural strength of the SFRC mix that contains only SF was the highest among all of the mixes.

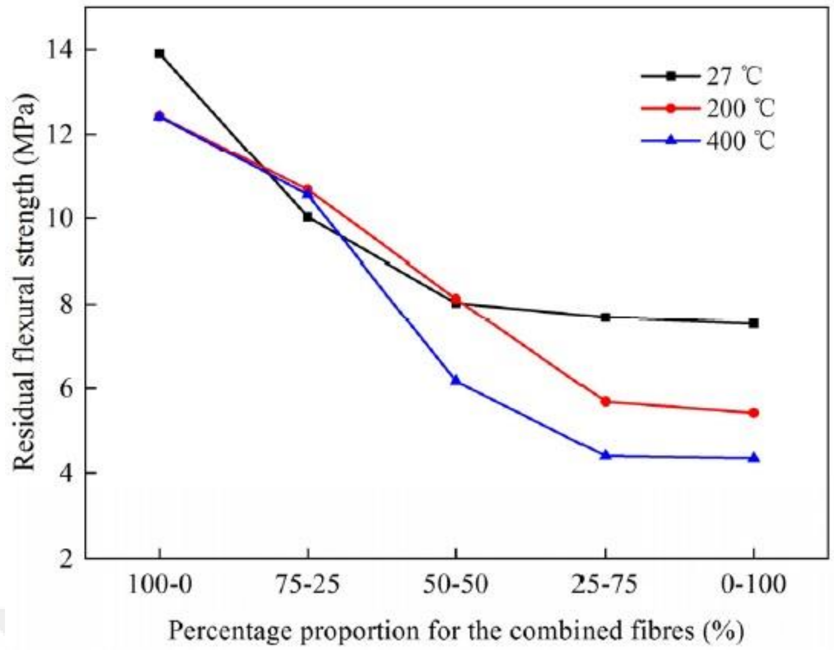


Figure 2.11 Residual flexural strength of five fibrous concrete mixes [55].

2.4 Flexural Behavior of Reinforced Concrete Beams with Steel Fibers at Ambient and Elevated Temperature

Shoeib and Mostafa [56] investigated the SF effectiveness on the RC beams' behavior under simultaneously applies the loads and fire exposure at 500ºC temperature. 12 RC beams that have cross-section dimensions of (12 × 25 × 16.5 cm), including the use of SF of 0, 0.5, and 0.75 %, were prepared for testing. These beams were divided into four groups, two groups with compressive strength of 35 and 65 MPa were loaded and tested at ambient conditions, and two groups with the same compressive strength in fire conditions. The obtained results show that, in all cases, the SF of higher content (0.75%) has a better performance. In ambient temperature, the increase in ultimate load was 16% for NC and 15% for HSC, while in 500ºC was 14% for NC and 17% for HSC. Moreover, they indicated that the stiffness and ductility of beams improved with the increase of SF dosages at both ambient temperature and fire conditions.

Heek et al. [57] in an experimental and analytical investigation, to exploring the SF impact on concrete thermal loading, deduced that the presence of SF in concrete does not lead to an increase in the heating rate and that the thermal conductivity of SFRC can be ignored, in case of SF content does not exceed the usual proportions. In addition, the combined use of rebars and SF in RC members improves the fire resistance, increased bending stiffness, decreased spalling, and leads to pronounced deflection, and thus a ductile behavior would be dominant at external exposure to heating up to around 1000ºC compared with traditional RC members.

The same conclusion was reached by Shariq et al. [58] in their study related to examining the flexural response of concrete beams reinforced by traditional reinforcing bars and SF under conditions of various temperatures. It has been reported that adding fiber to RC beams offers ductile failure and retards the onset of cracks at flexural and shear, both at ambient temperature and after being exposed to increased temperatures. The efficiency of high-strength SFRC beams is demonstrated by a higher deflection when compared to one without SF, confirming that the bonding between the rebars, concrete, and SF is still sound even at 600°C. That also applies to the ultimate load, proving fibers' efficiency under tensile loads. Figure 2.12 presents the deflection of beams at different temperatures.

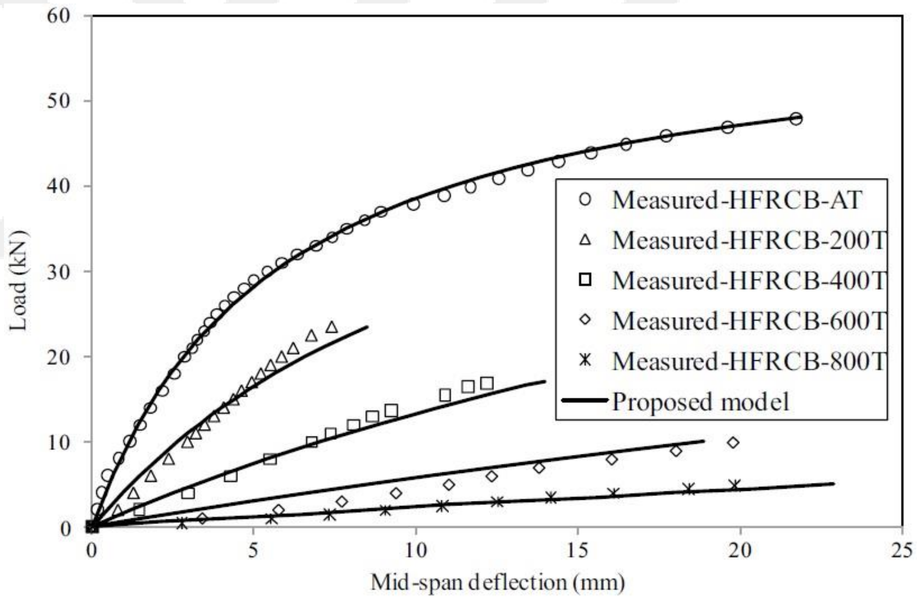


Figure 2.12 Deflection at mid-span of high strength SFRC beams [58]

2.1 Structural Behavior of the Hollow Reinforced Concrete Beams with Inclusion of Steel Fibers

Altun et al. [14] tested six box (hollow) beams and three solid 200 cm long beams each, and 30 ×30 cm cross-section to evaluating the flexural performance. The hollow specimens are divided into two groups, where every three beams have holes measuring 10 × 10 cm and the others 20 × 20 cm in the center of the cross-section. SFRC reinforced by 0.37 % volume of fibers and C20 compressive strength were used in this work. Table 2.1 shows the average reduction of the ultimate loads corresponding to the decrease in concrete volume. Also, Figure 2.13 presents the resulting deflection under monotonous loads. Finally, the researchers concluded that such a concrete box beam could be a viable alternative to a traditional solid one. This conclusion is established on the fact that the lower the weight of the structural elements, the lower the moments and seismic loads will be, and thus reducing the external impact on them.

Table 2.1 Summary of results for box (hollow) beams.

Type of Beam	Ultimate load capacity decrement	Concrete reduction per unit length
100 x 100 mm hole	1%	11.11%
200 x 200 mm hole	29%	44.44%

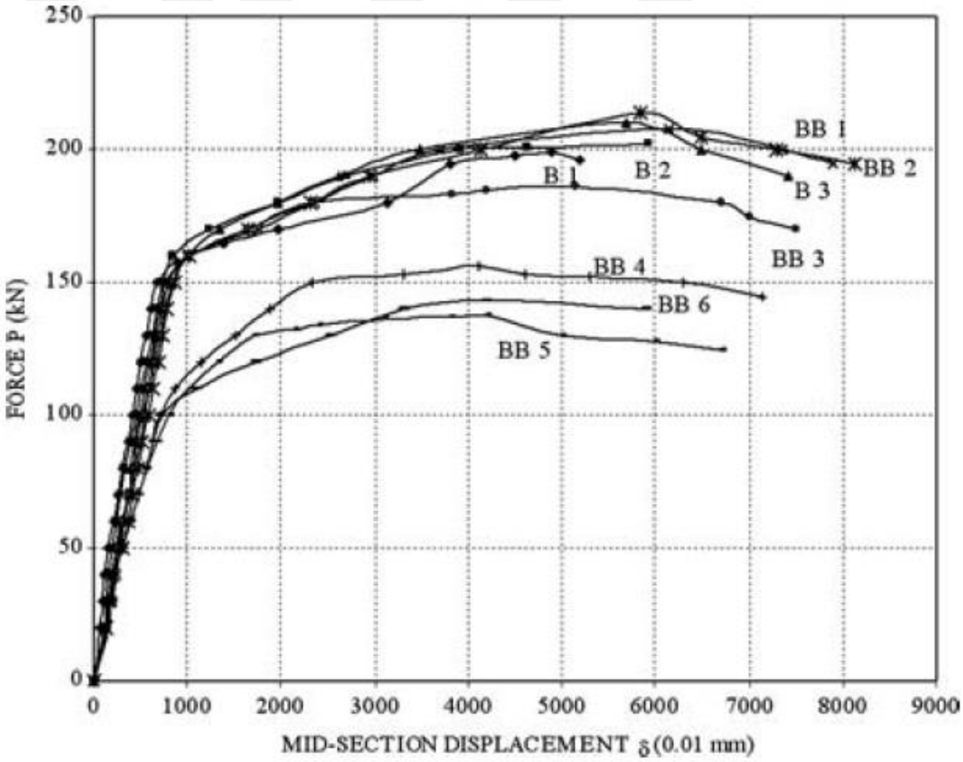


Figure 2.13 Load versus deflection relationships of nine beams [14].

Abbass et al. [59] performed experimental research on four hollow-core beams with other four reference solid beams to investigate the flexural behavior under loading of four points. All beams were with similar dimensions of 15 × 15 cm and traditionally reinforced with rebars in addition to three volumetric percentages of hook-ended SF (0.5, 1, 1.5 %). The longitudinal hollow was square, with dimensions of 8 × 8 cm. The research findings indicated that the fibers have an exceedingly efficient role and perform better in terms of the maximum load capacity, post-peak behavior, and ductility than the reference specimens, where the highest percentage of 1.5% of SF had the highest strength values in all stages of loading. Moreover, all SFRC hollow-core beams exhibit a more ductile behavior than their solid counterparts, as shown in Figure 2.14 below. Also, findings revealed that the failure of all fibrous RC beams was due to flexure, whilst the failure of those without fiber was due to flexural and shear.

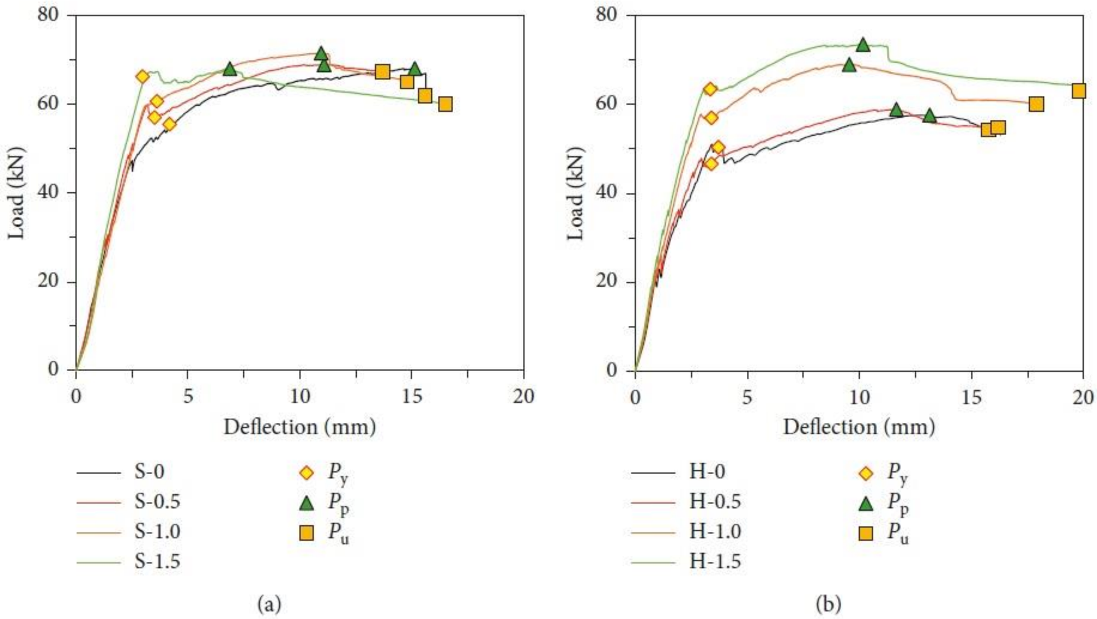


Figure 2.14 Load-deflection curves for SFRC beams with various volume fractions of SF. (a) solid specimens (b) hollow specimens [59].

CHAPTER III

EXPERIMENTAL WORK

3.1 General

The current chapter characterizes in detail the experimental work that was carried out to accomplish this study. This study aimed to investigate the response of hollow-core RC beams using SF to the flexural loads in ambient and thermal conditions, where elevated temperature and SF contents were the main parameters in this study. In addition to evaluating the deterioration of the mechanical properties for concrete specimens such as compressive and tensile strength. The experimental work of this study was implemented entirely in the structural engineering laboratories of the Civil Engineering Department of Gaziantep University.

A comprehensive depiction of the experimental program is presented in this section, which involves the number and details of all specimens (beams and cylinders), proportions and properties of materials used in the concrete mixture, steel reinforcement details, the process for casting and curing of test specimens, and heating program. In addition, the test instruments and devices, the setup and procedures of the loading test, are all detailed.

Mechanical tests were executed in the laboratory in a two-step. The first one is used to assess material characteristics adopting standard tests on cylindrical specimens according to known standards such as the splitting tensile strength and compressive strength, which are included in the experimental work. The four points flexure test on the RC hollow and solid beams is the second step that is used to observe and record the load and corresponding deflection.

3.2 Research Parameters

In the present research, an experimental investigation was performed to evaluate the flexural behavior of SFRC hollow core beams. In this context, two main approaches were followed The first one was devoted to exploring the influence of various dosages of SF on the behavior of hollow-core RC beams. To fulfill this objective, five RC beams were cast and then tested and compared, where three of those beams were hollow beams and reinforced with a different dosage of fiber (0.5, 1, 1.5 % for each), while the remaining two beams were adopted as control specimens, one of them is hollow and the other is solid, and both are free of fibers. The second group was to explore the effect of intense heat on the residual strength of SFRC hollow beams, and similar to the first one, five RC beams were used and exposed to temperature up to 550°C. In addition, this investigation was expanded to include the influence of the elevated temperature on the compressive and splitting tensile strengths of SFRC.

3.3 The Reinforced Concrete Beams Specimens

3.3.1 Beams details

Based on the above-mentioned research parameters, a total of 10 beams were produced and tested in this study to investigate the SFRC's hollow beams flexural performance. These beams include eight hollow-core beams and two solid beams employed for the test. SF was used in the hollow-core beams in diverse volumetric dosages ranged from 0 to 1.5 % in 0.5 percent increments for each beam. All adopted beams have a square cross-section with similar exterior dimensions and the same lengths. The width and height of each beam's cross-section were 150 mm for both and with a total length of 950 mm. All the hollow beams were provided with a circular hole with a diameter of 80 mm, and this hole is centered in the cross-section and extended longitudinally to the end of the beam. Figure 3.1 and Table 3.1 present all beam's details and geometry.

3.3.2 Beams reinforcement

The 8 and 5.3 mm conventional reinforcement bars are used in all the 10 beams specimens as longitudinal and shear reinforcement. The 8mm diameter reinforcement bars, with the yield strength of 530 MPa. The 2 bottom bars in the flexural zone and 2 top bars in the compression zone were provided as longitudinal reinforcement. The reinforcing bars with a diameter of 5.3 mm with the yield strength of 400 MPa, were employed for shear reinforcements (stirrups) at a spacing of 75mm. The clear nominal concrete covers were 15mm for all RC beams. Reinforcement details are illustrated in Figures 3.1 and prepared beam reinforcement cages are shown in Figure 3.2.

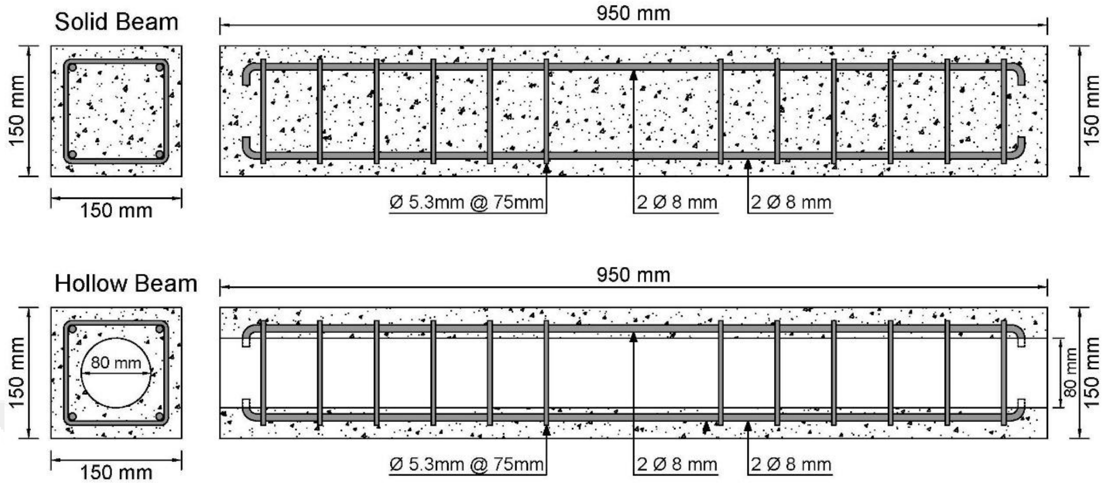


Figure 3.1 Beams geometry and details of reinforcement.

Table 3.1 Details of hollow & solid beams.

Beam code	Cross-section	Steel fiber V_f (%)	Temperatures Exposure	Reinforcement	
				longitudinal	stirrups
SB-0	Solid	0	Ambient	Top 2Ø8 Bottom 2Ø8	Ø5.3@75
HB-0	Hollow	0			
HB-0.5	Hollow	0.5			
HB-1	Hollow	1			
HB-1.5	Hollow	1.5			
SB-T-0	Solid	0	550 °C		
HB-T-0	Hollow	0			
HB-T-0.5	Hollow	0.5			
HB-T-1	Hollow	1			
HB-T-1.5	Hollow	1.5			

In Table 3.1 above, the letters (SB) in the beam code means Solid beam, whereas (HB) means Hollow beam. The numbers after the letters (0, 0.5, 1, or 1.5) refer to the steel fiber percentages. Finally, the letter (T) refers to the beams that were exposed to high temperatures.

Figure 3.2 Beams reinforcement cages

3.3.3 Beams specimens' molds

Four molds were designed and prepared for casting beams specimens. These molds were manufactured using thick plywood plates, and all of them have the same dimensions of (150 × 150 × 950mm). In the case of a hollow cross-section, a circular hole was made in the center of the cross-section of both sides of the wooden mold to facilitate the extension of the circular plastic pipe that forms the inner hollow core of the beam as shown in Figure 3.3. The circular pipe is lubricated with grease and then wrapped with bubbled nylon to ease the removal of the pipe when the mold is opened after the concrete has hardened.

3.4 Concrete Mixtures and Used Materials Properties

3.4.1 Mixtures

A total of four concrete mixtures were planned and produced. Materials of Cement, fine aggregates (sand and fine sand), coarse aggregates, and water, SF, superplasticizer, and silica fume, were utilized in the concrete mixture. The first mixture is a reference and free of SF and was designed to realize a compressive strength of or greater than 60 MPa at age of 28 days, while the remaining three mixes contain fibers in three volumetric proportions, namely 0.5, 1, and 1.5% as given in Table 3.2.

Figure 3.3 Details of beams molds

Table 3.2 Details of the reference mix and SFRC mixes for one cubic meter

<table>
<tr><th rowspan="2">Mix Code</th><th rowspan="2">C (kg)</th><th colspan="2">FA (kg)</th><th rowspan="2">CA (kg)</th><th rowspan="2">Sfu (kg)</th><th rowspan="2">SF (kg)</th><th rowspan="2">SP (kg)</th><th rowspan="2">W (kg)</th><th rowspan="2">W/(C+Sfu) (%)</th></tr>
<tr><th>S</th><th>FS</th></tr>
<tr><td>MS-0</td><td rowspan="4">470</td><td rowspan="4">1020</td><td rowspan="4">150</td><td rowspan="4">685</td><td rowspan="4">30</td><td>0</td><td rowspan="4">7.3</td><td rowspan="4">200</td><td rowspan="4">0.4</td></tr>
<tr><td>MS-0.5</td><td>39.25</td></tr>
<tr><td>MS-1</td><td>78.5</td></tr>
<tr><td>MS-1.5</td><td>117.75</td></tr>
</table>

C- cement; FA- fine aggregate; S- sand; FS-fine sand; CA- coarse aggregate; Sfu- silica fume; SP- superplasticizer; W- water.

3.4.2 Materials

Ordinary Portland Cement 42.5R, which is locally made and meets EN 197-1 standard criterion, was employed throughout this experimental work. The used cement content in the mixture per m^3 was 470 kg/m^3. 6% of silica fume from the total cement weight was used and replaced with equivalent weight to be (Cement 470 kg + Silica fume 30 kg). Generally, using silica fume is due to its efficient reactivity with cement ingredients and to raise the percentage of fine particles, which leads to mixture mechanical characteristics enhancement, as stated in previous studies. The chemical and physical characteristics of silica fume and cement are shown in Table 3.3.

The coarse aggregate utilized in this experiment was crushed stone supplied from the local origin and graded with a size of 10 mm as a maximum. Figure 3.4 shows the gradation of the used aggregate. For fine aggregate, a grade of up to a size of 4.7 mm, clean, and impurity-free sand was used, Figure 3.5. It is worth mentioning herein that the fine aggregate amount is substantially higher than the coarse aggregate. That raises the available surface area for efficient absorption of free water, resulting in a homogeneous mixture of granular distributing, decreasing porosity, and enveloping the coarse aggregate and thus improving the bond between the aggregate and the fibers, and a good stress distribution with less concentration.

Table 3.3 Silica fume & cement properties

Test	**Retained** 45µm	SiO_2	H_2O (humidity)	LOI	Relative Density
Cement	0.75%	62.49%	0.24%	1.96%	3.14
Silica fume	0.59%	93.08%	0.18%	1.80%	2.26

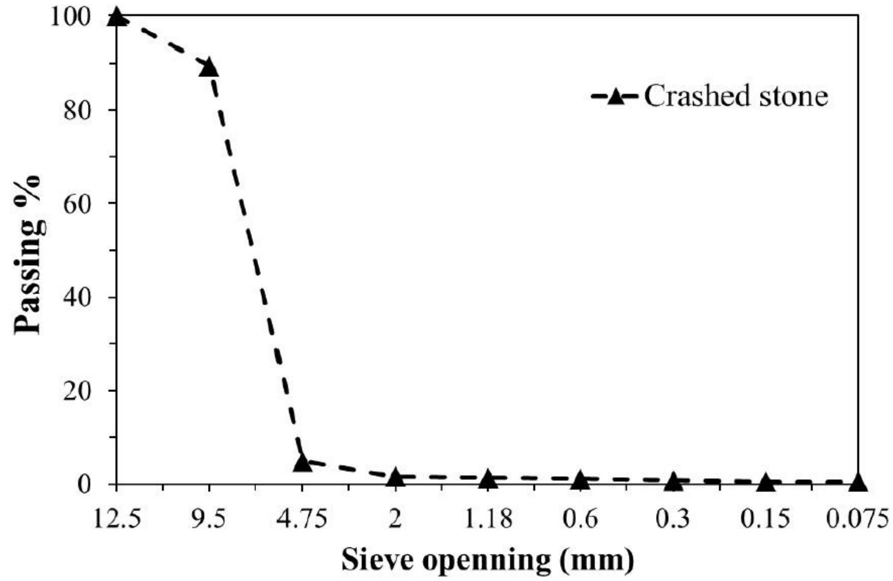


Figure 3.4 Coarse aggregate gradation.

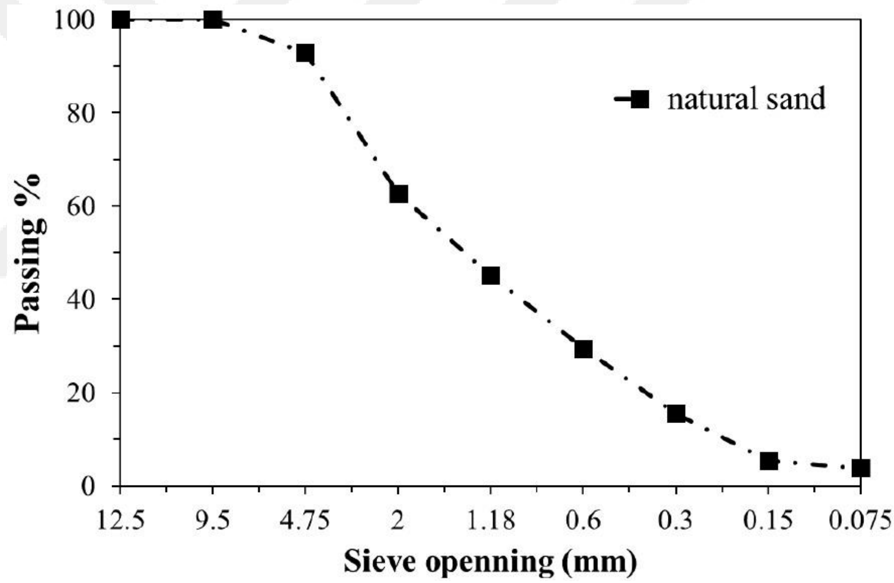


Figure 3.5 Fine aggregate gradation.

Steel reinforcement that was provided to reinforce all the beams were deformed steel bars with a diameter of 8 mm for longitudinal reinforcements in both tension and flexure zone and a diameter of 5.3 mm for transverse reinforcement as shear reinforcement. For SF, a hooked at both ends fiber, 30 mm length, 0.55 mm diameter, and 55 aspect ratio, were employed in SFRC mixtures. Three proportions of fibers were adopted in fibrous concrete, which are 0.5, 1, and 1.5%. Table 3.4 and Figure 3.6 describe the properties and shape of the employed SF.

Table 3.4 The employed steel fiber characteristics

Fiber type	Density (kg/m^3)	L_s (mm)	D_s (mm)	L_s/D_s	Tensile strength (MPa)	Fibers (kg)
KMX 55/30 BL	7850	30	0.55	55	1500	16750

L_s- length of SF; D_s- diameter of SF

It is well known that the use of SF and a high content of fine materials leads to decrease concrete workability. For this purpose, a Superplasticizer of type MasterGlenium® ACE 30 that complies with the ASTM C494 Type F requirements and is compatible with all cement types was used to attain the desired workability of mixtures and significantly improves concrete strength. Also, clean pure tap water freed from contaminants was utilized throughout this experiment in concrete production and curing all test specimens.

Figure 3.6 The adopted steel fibers.

3.4.3 Mixing

The mixing process of the SFRC mix was carried out in sequential phases. In the beginning, the fine and coarse aggregates materials were mixed for 5 - 10 minutes, after which the cementitious materials (cement and silica fume) were added and thoroughly mixed for extra five minutes. Following that, the addition of water was progressively, and the materials were left to mix for a few minutes. The superplasticizer (water reducer) was added, following fiber addition, to improve the workability of the mix, and then the slump test was carried out. Table 3.5 lists slump test values. Moreover, simultaneously with the casting of beams specimens, standard concrete cylinders measuring (100mm diameter × 200mm height) were cast for each mix. All molds were prepared and well-oiled before mixing and casting. The molds were opened and all beams and cylinders specimens were extracted 24 hours after casting, then after they were coded and transferred to a water container for the curing process for 28 days, at the same conditions. Figure 3.7 shows processes of mixing, casting, and curing beams and cylinders specimens.

Table 3.5 Slump test values

Mix Code	Slump (mm)
MS-0	103
MS-0.5	76
MS-1	70
MS-1.5	64

Figure 3.7 Processes of mixing, casting, and curing of specimens.

3.5 Heating Process

After completing the curing process for 28 days, all the specimens (beams and cylinders) were removed from the water, their surfaces dried well, and then they were placed in the furnace for drying for 24 hours by exposing to a temperature of 105 °C (see Figure 3.8). The adoption of the drying process leads to diminishing the pore pressure resulting from the free water in it and thus protecting the specimens from sudden damage. An 1100 °C capacity furnace with a dimension of 130 × 136 × 62 cm was used in this experimental work for the heating process (see Figure 3.8). The furnace is equipped with heaters on all sides except for the top and bottom sides, and these heaters ensure uniform heat distribution over all test specimens.

Figure 3.8 Heating process (a) the furnace (b) cylinder specimens drying (c) beams specimens drying (d) beams specimens heating.

The following procedure is the process of heating the samples to the desired temperature of 550 degrees Celsius through three successive stages, where it began with gradual heating at a heating rate of 10 degrees Celsius per minute until reaching a temperature of 550 °C (approximately in 1 hour), and then the samples remained exposed to this constant temperature (550°C) for an hour to enable for temperature distributing and ensuring that the specimens were heated uniformly. Thereafter, the furnace was switched off, and the samples were left for gradual cooling after opening the upper ventilation of the furnace to avoid sudden cooling causing unwanted thermal strain.

Figure 3.9 presents the stages of the heating process through the time versus temperature curve of the heated specimens. Keeping the test specimens exposed to a constant temperature for an hour, to assure good heat distribution, was adopted by previous studies [49, 60]. Additionally, the ultimate temperature that the specimens were exposed to was selected within the temperature adopted through several studies [47, 61-62].

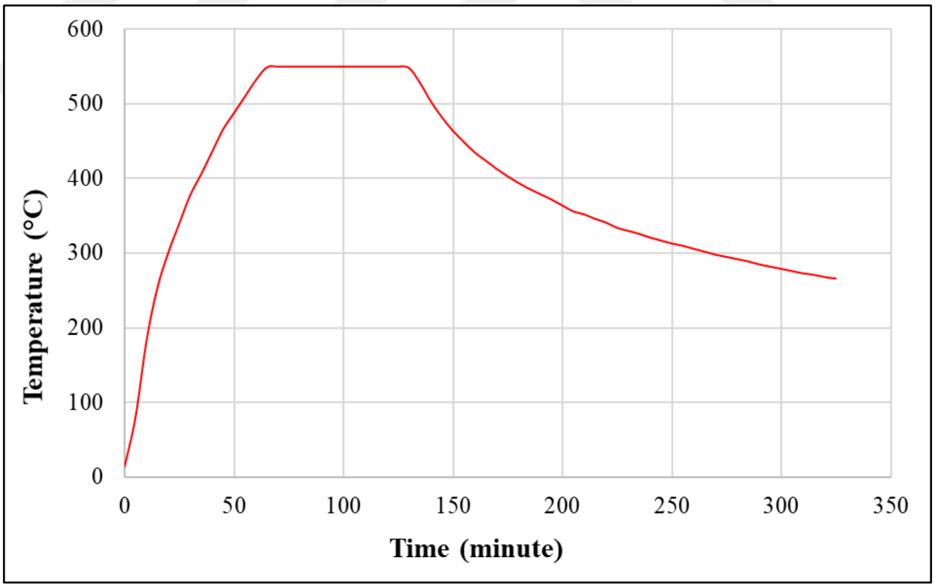


Figure 3.9 Heating process of the specimens.

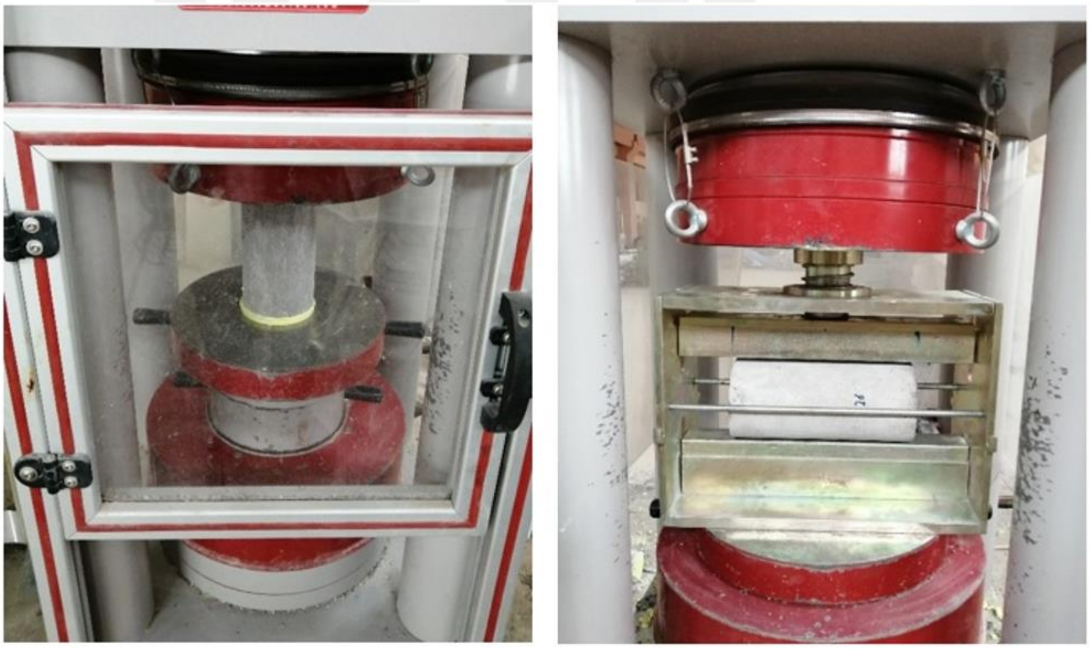
3.6 Mechanical Properties Tests

3.6.1 Compressive strength

A compressive strength test was conducted at the laboratory-based on ASTM C-39 standards [63] for all adopted mixtures (both with or without SF) in this study. The standard size of concrete cylindrical specimens with a diameter of 100 mm, and height of 200 mm was cast and tested after 28 days. Capping of all specimens was executed with sulfur mortar on both ends of the cylinder before the test, following ASTM C-617, to assure a smooth and parallel bearing surface. A universal testing machine was used to perform the compression test with a loading rate of 1.5 kN/s. The average test results were taken for three cylindrical specimens of each mix. the capping and testing of specimens are shown in Figure 3.10 (a).

3.6.2 Splitting tensile strength

The concrete cylinders with similar dimensions (100 × 200mm) were tested to determine the tensile strength based on the ASTM C-496. According to test procedures, the specimens were placed horizontally in a steel frame with wooden strips under and above the specimen and tested under a compression load, as demonstrated in Figure 3.10 (b).



(a) (b)

Figure 3.10 Mechanical test (a) compressive strength (b) splitting tensile strength.

3.7 Flexural Test Setup and Instruments

All RC beams specimens were prepared for flexural loading test. The test specimens were coded and painted white color to facilitate detection, observation, propagation, and marking all cracks (see Figure 3.11). It is worth mentioning here that the test of cylindrical specimens was carried out in conjunction with the beams test. As for the beams loading tests, it was carried out in the central laboratory of Gaziantep University.

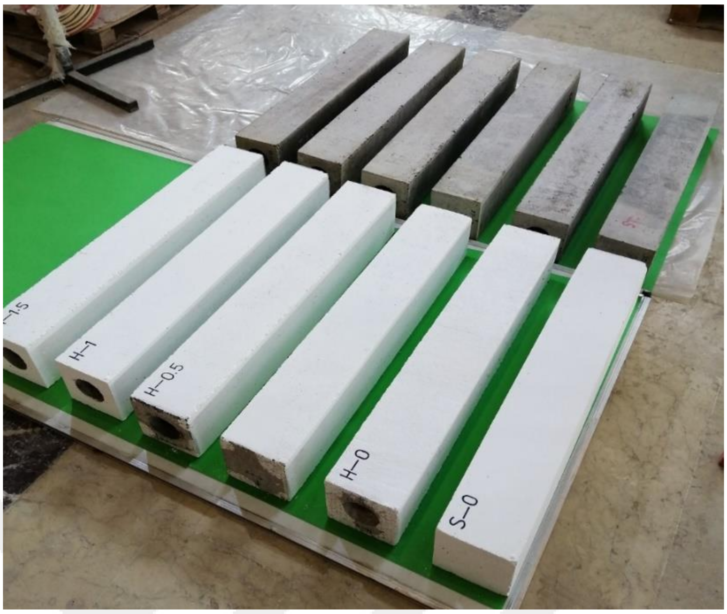


Figure 3.11 Painting and coding the beams

During the test, all specimens were subjected to a four-point flexural loading with a span of 750mm, see Figure 3.12, where the distance was exactly 250mm between the centers of the loading points. To perform the load-bearing capacity tests, the INSTRON testing machine with a static load capacity of 250 kN, see Figure 3.13, was used. The testing machine is computerized controlled and also is equipped with a digital panel to record and display the values data of load, displacement, and time as well as controlling the precise lifting and lowering of the hydraulic jack.

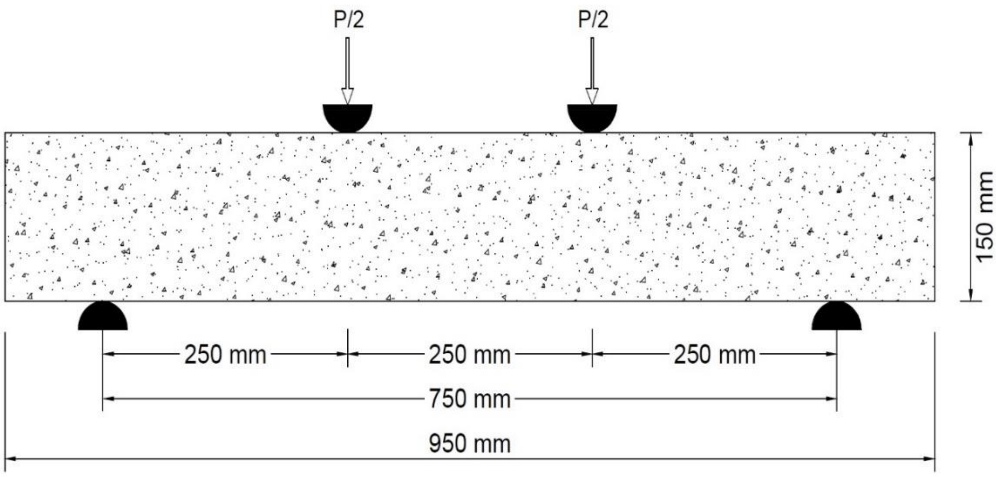


Figure 3.12 Beams loading test arrangement

Figure 3.13 The testing machine

At the beginning of the test, the load was monotonic and gradually applied through the load-cell, with a steady pre-calibrated displacement rate of 0.4mm/minute, and the loading continued to increase until specimens' failure. In addition to the displacement recorder built into the test device, an electromechanical sensor (LVDT, Linear Variable Differential Transformer) was installed at the bottom center of the specimens to recording values of the deflection as shown in Figure 3.14. After completing the test, specimens were removed, all cracks paths were marked, and all data was collected.

Figure 3.14 Beam test setup.

CHAPTER IV

RESULTS AND DISCUSSIONS

4.1 General

Research work related to the structural performance of RC hollow-section beams is very limited when it comes to the flexural behavior of such members, especially those supplied with different amounts of SF up to 1.5 percent, not to mention that were no studies previously conducted to investigate the behavior of hollow beams under the influence of extreme heating.

The results of the experimental work and their discussion for each section according to the research parameters are presented in this chapter, focusing on two main aspects. The first one focuses on the tested mechanical properties of fibrous concrete specimens, the amounts of fibers used and their influence, and understanding the behavior of the tested specimens under compression, indirect tension with the presence and absence of fibers in the mixture in ambient and elevated temperatures. The second one emphases the behavior of RC hollow-core beams under flexure loading and comparing the SFRC beams responses with various SF quantities in terms of load values at different stages of loading, deflection, ductility, failure mode, and cracks before and after being subjected to elevated temperatures.

4.2 Temperature Evolution in SFRC Hollow Beams Specimens

To better understand the heat development within the SF reinforced hollow beams specimens, one thermocouple was installed in each hollow beam before starting the heating process. These thermocouples record the change and development of temperatures and their variation between the furnace and the FRC specimens separately by connecting the thermocouples to a digital thermometer to monitor and obtain temperature data over time until the completion of the test. The thermocouple was placed inside the hollow core at the middle of the beam length, as can be seen in

Figure 4.1, where the arrangement and location of the thermocouple are shown. Each thermocouple was coded with a different symbol to indicate the SF content of the tested beam, where the symbol SF – 0% refers to the thermocouple installed within the hollow beam that has zero percent fibers, and so for the rest of the specimens with percentages from 0.5 to 1.5 percent, while TF refers to furnace temperature.

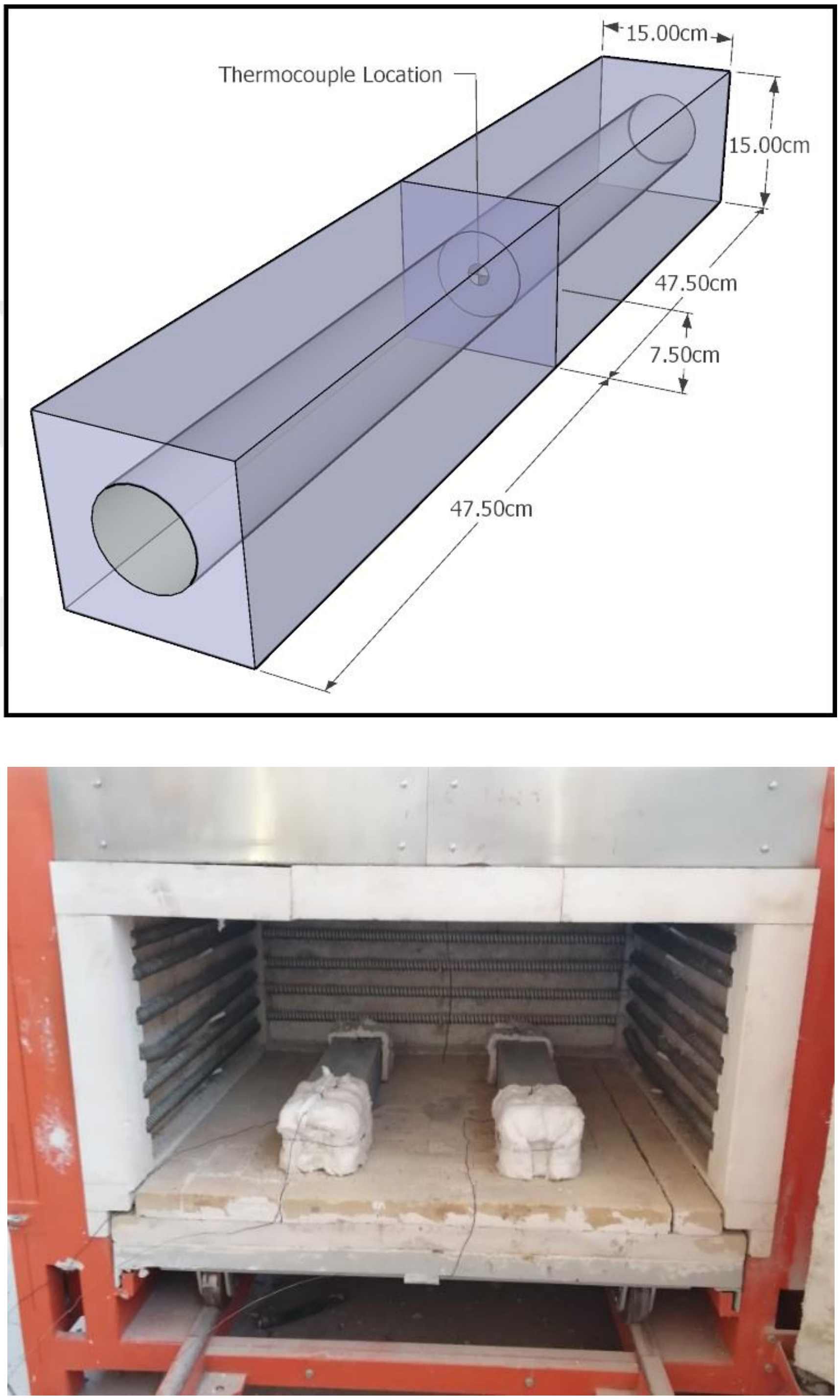


Figure 4.1 Thermocouple location and arrangement

Figure 4.2 illustrates the temperature patterns that were recorded for all hollow beams specimens over time. All hollow specimens with four different percentages of SF were subjected to the same stages of the heating process up to 550°C. At the thermocouple location, the temperature is found to rise with exposure duration. Also, it is shown that after nearly 155 minutes of heating and irrespective of SF content, all specimens reached the utmost temperature in approximately similar development with a slight variation in their values. That leads to the fact that SF varying dosages have no significant influence on the temperature fields inside RC compared to its greater benefit, where the SF prohibit the interior structure deterioration of concrete under heating by prohibiting the excessive cracking in the SFRC, and this remains possible as long as it is capable of transmitting stresses through cracks adequately.

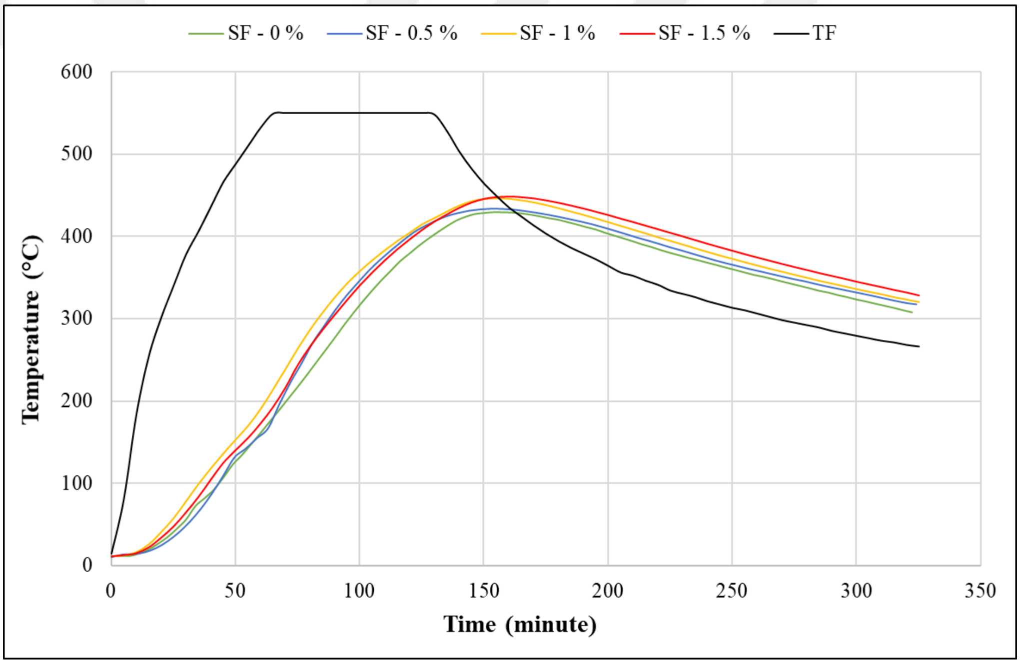


Figure 4.2 Curves of temperature evolution over time for the furnace and SFRC beam specimens

4.3 Mechanical Properties of SFRC at Ambient and Elevated Temperature

4.3.1 Compressive strength

Each result of the table represents the average results of three cylinders (size 100 × 200 mm) of the same mixture. Figure 4.3 demonstrates the results values of compressive strength at ambient and elevated temperatures, while Figure 4.4 demonstrates the increment percentages in compressive strength for diverse dosages of SF. Compressive strength test results are summarized in Table 4.1.

From both figures, as a general trend, it is evident that compressive strength decreases with the increase in exposure temperatures. Findings exhibit that at ambient temperature, concrete of 1% and 1.5% SF had compressive strengths higher than that of fiber-free by 12% and 15%, respectively, while 0.5% dosage of SF granted only 3.5% increment. At 550°C temperature, while including fibers content from 0.5 - 1% improved the residual strength from 8.62% - 21.24% compared with ordinary concrete specimens, the compressive strength increment was 23.25% at 1.5% of SF.

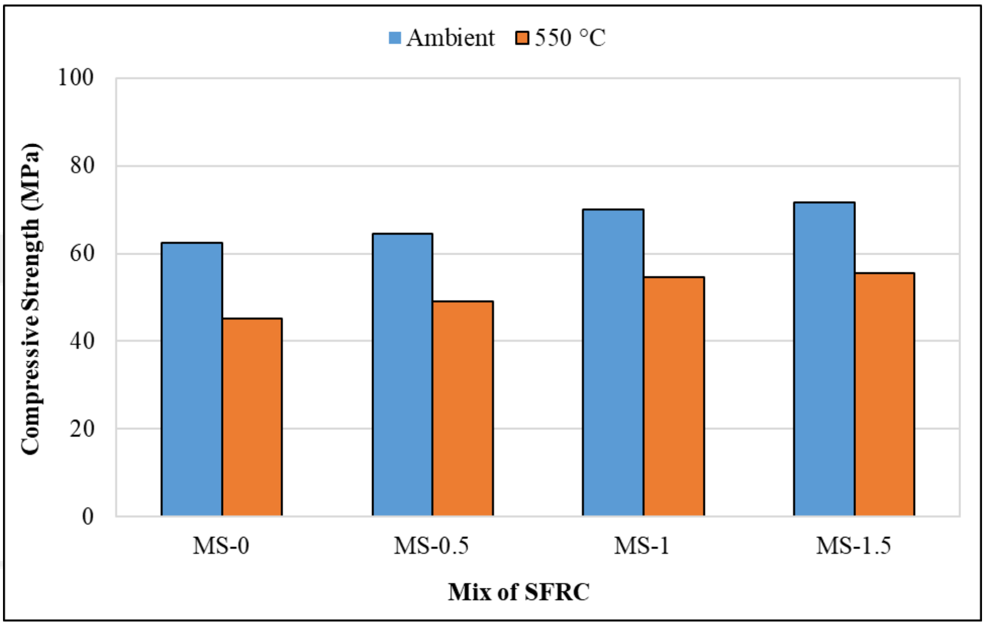


Figure 4.3 Effect of SF V_f on compressive strength

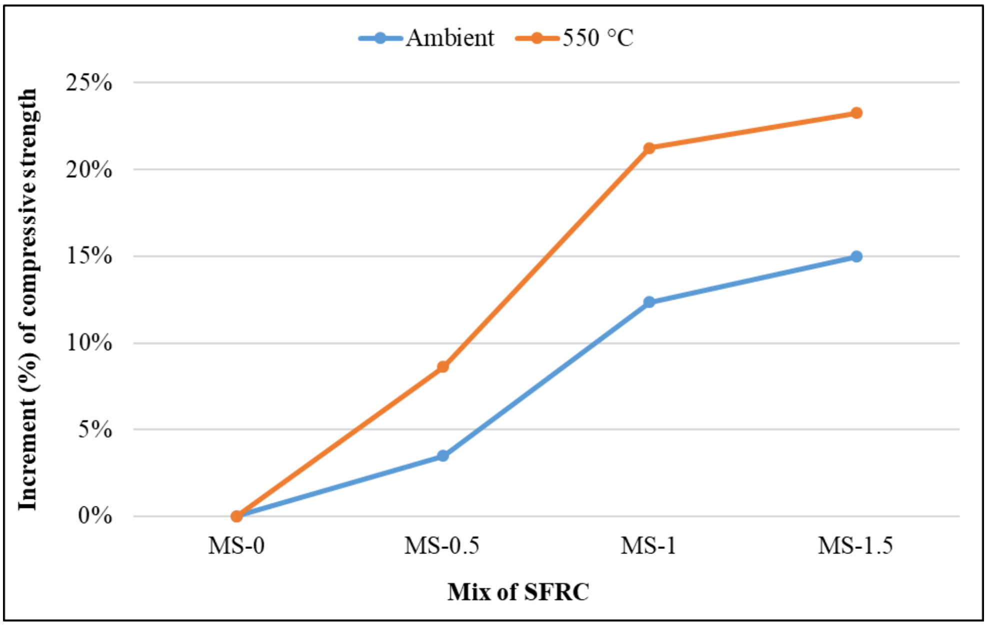


Figure 4.4 Percentage increment in compressive strength

Table 4.1 Test results of mechanical properties

Code	**Steel fiber** V_f %	**Temperatures Exposure**	**Compressive strength** f'_c (MPa)	**Splitting tensile strength** f_{sp} (MPa)
MS-0	0	Ambient	62.41	4.74
MS-0.5	0.5		64.58	5.90
MS-1	1		70.11	6.98
MS-1.5	1.5		71.75	7.2
MS-T-0	0	550 °C	45.11	3
MS-T-0.5	0.5		49	4.01
MS-T-1	1		54.69	5.17
MS-T-1.5	1.5		55.6	5.22

As demonstrated in the preceding discussion, the improvement in compressive strength was achieved by the contribution of SF at ambient temperature as well as after exposure to extreme heat at 550°C. Yet, the effect on compressive strength by incorporating fibers in varied percentages was more evident on the SFRC tested specimens at the temperature of 550°C than at ambient conditions. This improvement can be attributed to the combining of (silica fume) with SF in the concrete mixtures, which offers better mechanical characteristics and bond strength than those with (silica fume) only. Moreover, in the adopted concrete mix, fine aggregate amount constitutes the highest percentage in the total aggregate quantity, providing a uniform dispersion of particles in the concrete mixture and increase the bonding with SF with a good distribution for stresses.

4.3.2 Splitting tensile strength

Table 4.1, Figures 4.5 and 4.6 display the results of splitting tensile strength for the specimens with (0, 0.5, 1, and 1.5%) of SF dosages and the increment percentages of tensile strength at ambient and at 550°C of the elevated temperatures. When comparing the residual strength results for both compressive and tensile strengths, it can be noted that the deterioration in the splitting tensile strength is more severe than the compressive strength of heated concrete specimens. However, the role of SF herein was more apparent, as the presence of SF raised the tensile strength with each extra dosage of fibers considerably. As compared to the normal concrete mix, at ambient condition, the 0.5% volume fraction of SF provided a 24.47% increment in splitting TS, whereas this increment was significantly higher by 47.26% and 51.9% at 1 and 1.5% dosages of SF, respectively. After exposing the specimens to high temperature, the test results of the residual tensile strength revealed that the achieved increases were 33.67%, 72.33%, and 74% by each 0.5% addition of fibers, comparing with the reference mix without fibers.

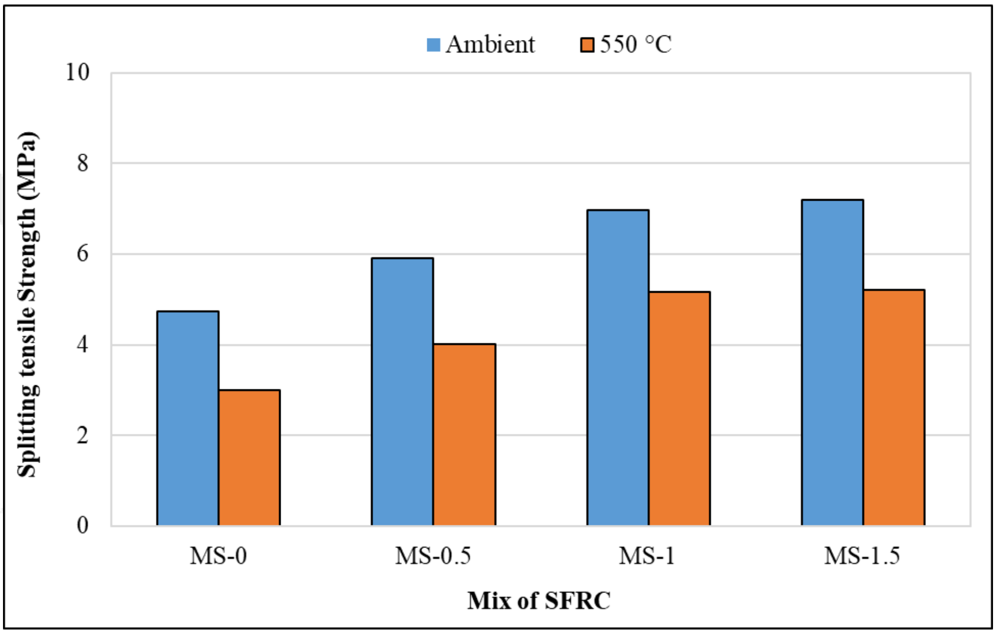


Figure 4.5 Effect of steel fiber (V_f) on splitting tensile strength

By reviewing the results, it can be concluded that the detrimental impact of intense heat is greater on ordinary concrete than concrete containing steel fibers, where the effectiveness of fiber lies in their ability to bridge cracks under tensile loads and inhibiting their propagations.

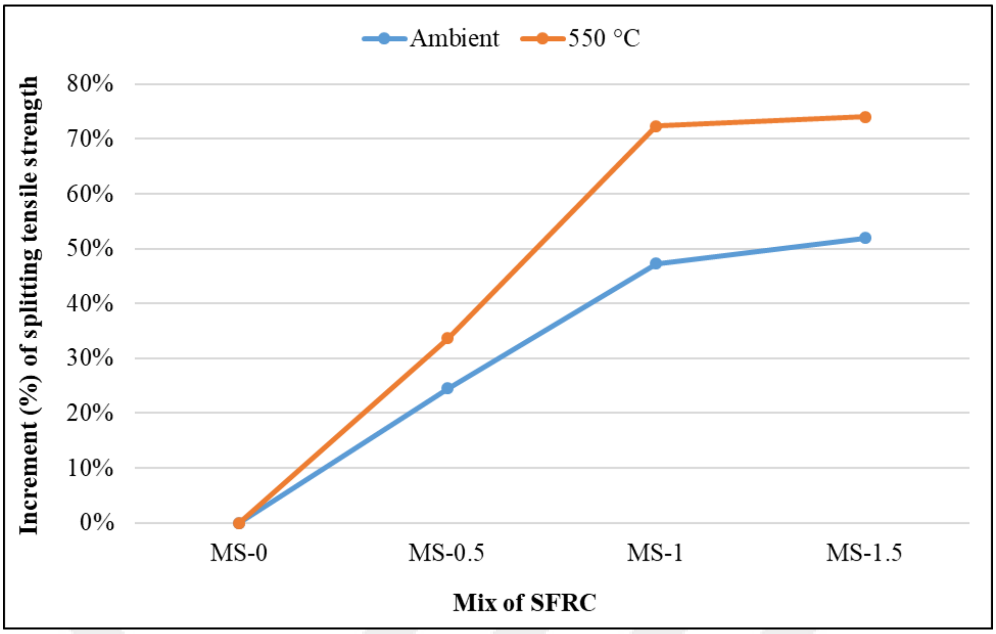


Figure 4.6 Percentage increment in splitting tensile strength

4.4 Flexural Behavior of SFRC Hollow Beams Before and After Heating

For investigating the response of SFRC beams to flexural loads, ten RC beams were tested under four points loading. Five of these beams were tested at the surrounding conditions without exposing them to excessive heat and consisted of one solid beam without SF and four longitudinally hollow beams in which the percentage of fibers started from zero to 1.5 %. The remaining five concrete beams, which have the similar specification as the first set of specimens, were loaded after being exposed to a temperature of 550°C for a total period of two hours of heating and then naturally cooling. This section discusses the flexural performance of the RC hollow-core beams and the influence of utilizing SF on this performance, focusing mainly on load-deflection behavior, ductility, and failure mechanism.

The experimental results data for all examined hollow beams specimens until failure are given in Table 4.2 include the loads and corresponding deflections recorded at the stages of cracking, yielding, and peak, at both ambient and post exposing to elevated temperature.

Table 4.2 Load and deflection results for SFRC hollow beams

Beam Code	Temperatures Exposure	P_{cr} (kN)	Δ_{cr} (mm)	P_y (kN)	Δ_y (mm)	P_p (kN)	Δ_p (mm)	P_y/Δ_y
SB-0	Ambient	22.98	1.2	49.35	3.53	64.77	17.28	13.98
HB-0		19.94	0.94	46.07	3.46	56.34	14.98	13.32
HB-0.5		21.78	0.97	45.76	3.21	58.44	14.53	14.26
HB-1		22.60	1.01	56.95	3.28	67.27	12.05	17.36
HB-1.5		24.86	1.03	62.92	3.31	70.96	12.48	19.01
SB-T-0	550 °C	19.31	1.75	41.46	3.77	57.43	17.16	11
HB-T-0		16.94	1.76	39.14	4.06	44.96	16.74	9.64
HB-T-0.5		18.53	1.86	38.94	3.9	47.98	17.66	9.98
HB-T-1		18.19	1.58	45.83	3.97	56.34	21.69	11.54
HB-T-1.5		20.47	1.53	51.81	3.86	61.39	23.11	13.42

4.4.1 Load-Deflection behavior at ambient conditions

Figure 4.7 compares four hollow beams with different dosages of fibers from 0% to 1.5%, in addition to one solid beam free of SF. The curves of deflection versus load for the tested specimens at ambient conditions demonstrate the superior flexural performance of hollow beam specimens containing SF specifically at 1 and 1.5% percentages, which had a significant influence on the general structural behavior than those without fibers, while there was a slight improvement at 0.5% percentage. It can be observed from Figure 4.7 that the fibrous concrete beams show a steeper curve at the ascending portion as the fiber content increases, indicating that they have higher rigidity under flexure. The SF incorporation led to enhancement in the first cracking loads for the hollow beams. The values of cracking loads were 19.94, 21.78, 22.60, and 24.86 kN at fibers volume fractions from 0 to 1.5%, which indicates the ability of the beams reinforced with the SF to withstand stresses. That also applies to the yielding loads where the hollow SFRC beams HB-1 and HB-1.5 with 1% and 1.5% SF possess a higher-yielding load with less corresponding deflection than the hollow (HB-0) and solid (SB-0) beam specimens of the plain concrete. At the yield stage, the ratio of (load/deflection) reflects the beam's ability to resist the deflection, where the higher the (load/deflection) ratio, the higher the beam resistance to deflection. Table 4.2 show that the (load/deflection) values raised to 42% when the SF proportion raised from 0 to 1.5%.

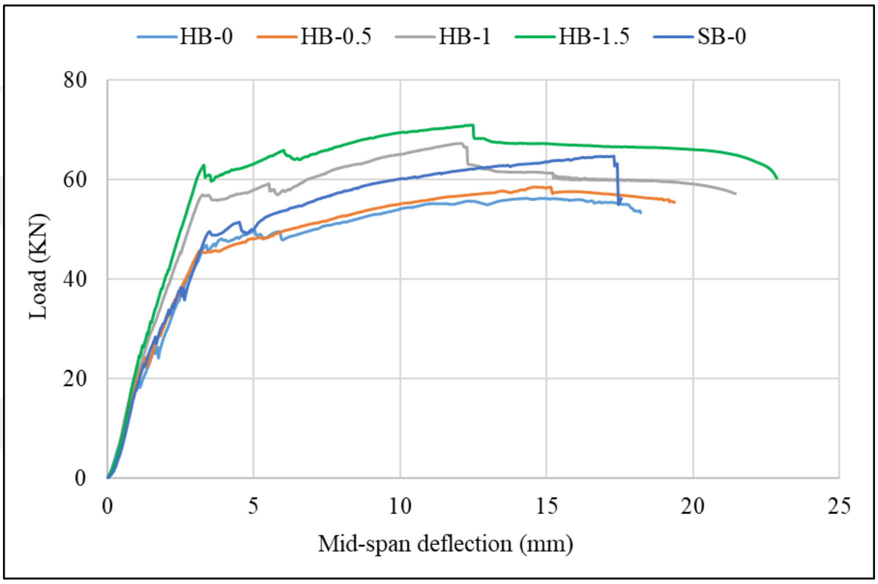


Figure 4.7 Load deflection curves of the beams at ambient conditions

Similarly, the findings also revealed that the peak load that the RC hollow specimens can resist increased when increasing the SF contents, as can be seen in Figure 4.7. The peak loads results were 56.34, 58.44, 67.27, and 70.96 kN for the dosages 0, 0.5, 1, and 1.5% of fibers, respectively. It is worth mentioning here that the peak load results for fibrous beams specimens HB-1 and HB-1.5 are higher than that of solid beam SB-0 without SF by 4% and 10%. Figure 4.7 also demonstrates that SFRC hollow beams have the larger deflection values at the ultimate load and their curves at the post-peak stage show a gradual slope with lower steep than non-fibrous concrete beams, which indicates better ductile behavior with the presence of SF. The ductility will be discussed separately and in detail in another section.

4.4.2 Load-Deflection behavior of beams exposed to elevated temperature

After being subjected to 550 °C temperature, the general behavior of the load and displacement curves showed a decrease in the load values at all stages. The residual loads at cracking, yielding, and peak and their corresponding deflections are tabulated in Table 4.1. Figure 4.8 shows the load-deflection curves of five tested beams after exposure to intense heating. The effectiveness of the fibers appears again after heating, as can be observed that the beam samples with the largest content of SF are superior to those without fibers or that with a little percentage at all stages of loading. The hollow beams residual peak loads increased by 36.5% from 44.96 to 61.39 kN at 1.5% content of fiber, and also the corresponding mid-span deflection increased, with SF dosages increase, by 38% as compared to the plain concrete specimen. In addition, the hollow sample HB-T-1.5 reinforced with 1.5 percent fibers showed a higher bearing capacity than the solid sample SB-T-0 without fibers by 7%, as shown in Figure 4.8, which reflects the influence of SF also to resist loads at extreme heating.

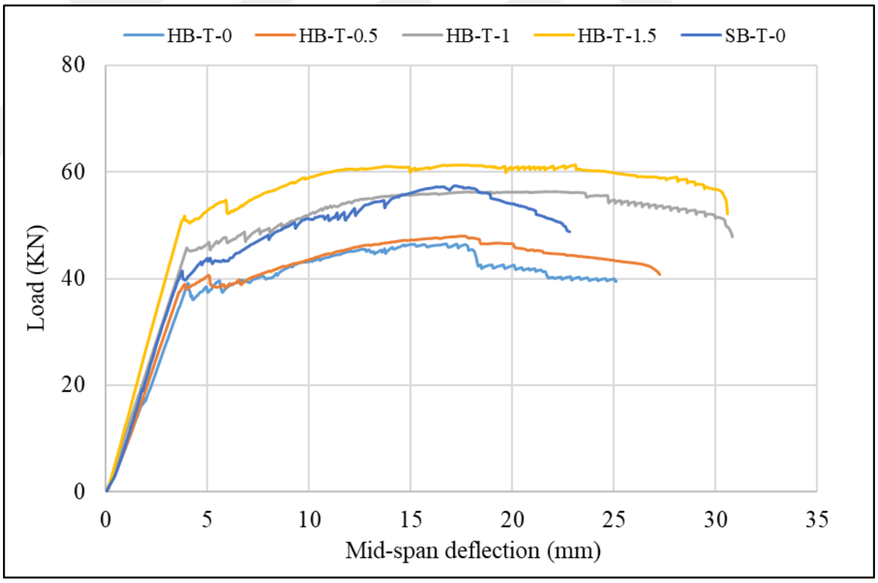


Figure 4.8 Load deflection curves of the beams exposed to elevated temperature

In comparison with the hollow beam specimen HB-T-0 of normal concrete, the cracking and yielding loads were enhanced with the SF volumetric content increasing by 21% and 32%, respectively at 1.5% percentage of SF, whereas this increment was limited to 7% and 17% at 1% percentage of SF. The rise in the temperatures up to 550°C applied to the hollow beams resulted in a significant increase in the deflection rates at the post-peak stage, and this increase is directly proportional to the increase in the fiber contents, as shown in Figure 4.8. This emphasizes the impact of SF in post-peak behavior.

4.4.3 Residual load carrying capacity of hollow beams after exposure to high temperature

The RC hollow beams reinforced with various volume fractions of fiber were subjected to high temperatures to explore the residual load-carrying capacity. Figures 4.9 and 4.10 illustrate the residual peak loads and the percentages of reduction after a one-hour duration of heating under a constant temperature of 550°C, while Figure 4.11 compares the curves of load versus deflection for each pair of RC hollow beams specimens that have the same properties, at both ambient and elevated temperatures with different SF dosages.

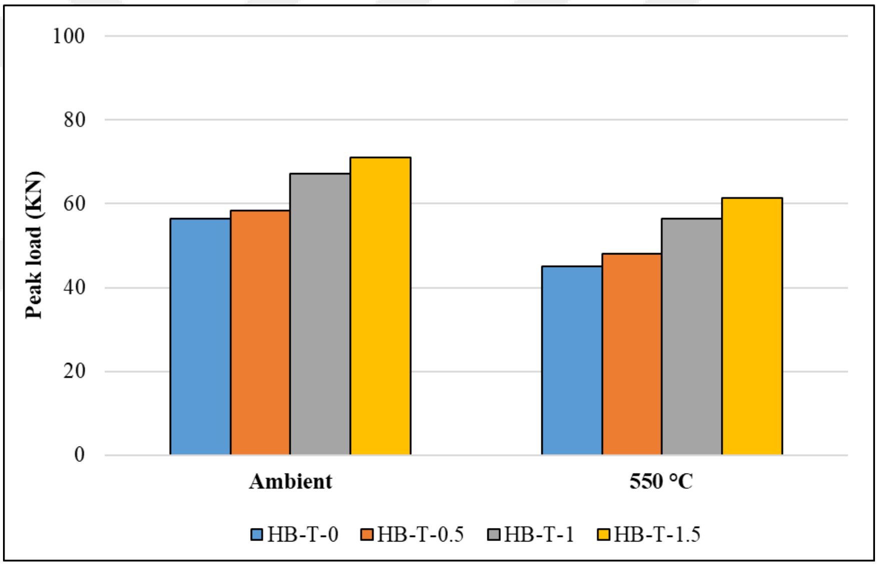


Figure 4.9 Peak load results of hollow beams with different SF percentages

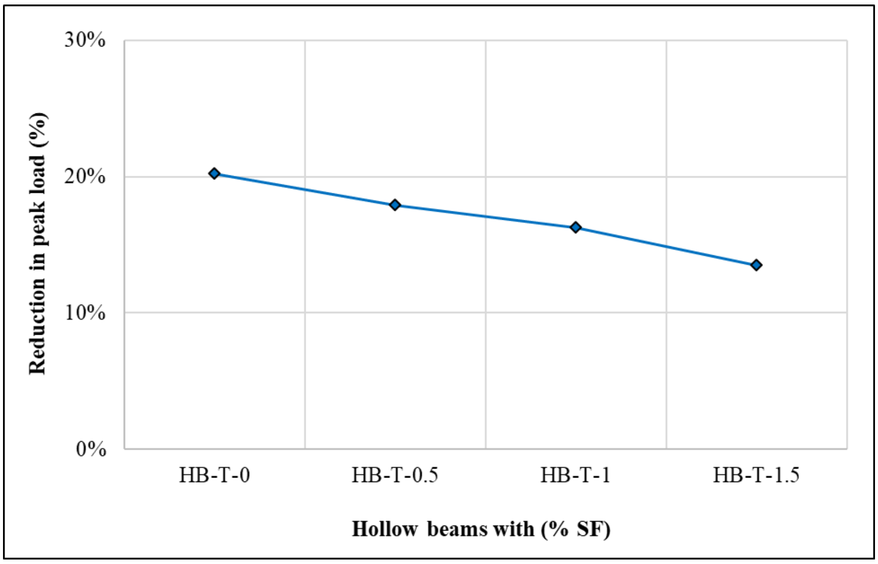
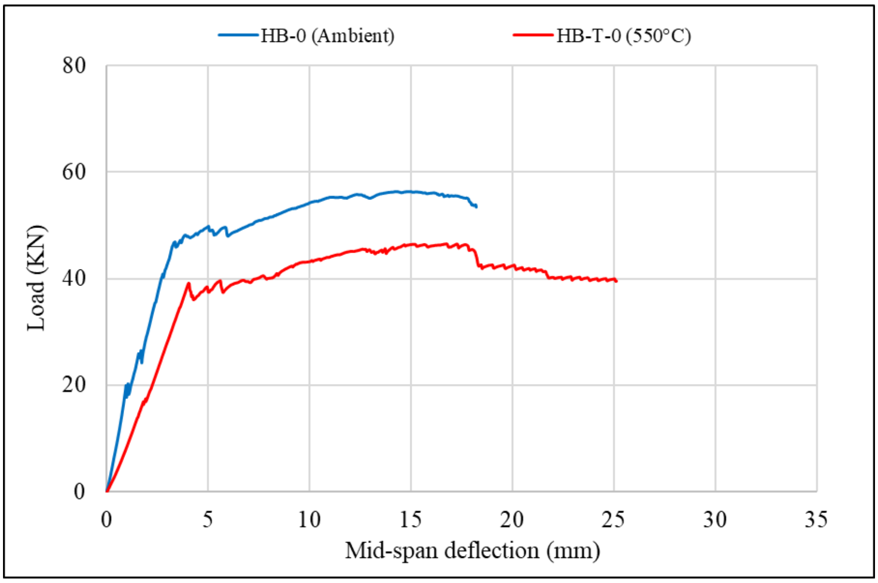


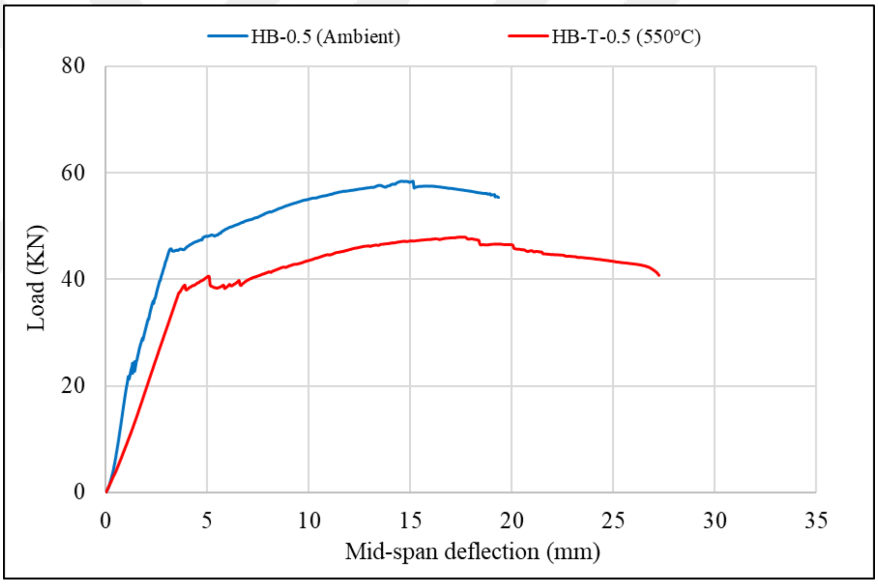
Figure 4.10 Percentage reduction in peak load after exposure to elevated temperature

Generally, the load-bearing capacity of RC hollow-beams decreased when the exposure temperature raised to 550°C, but varying extents. This reduction may be attributed to the bond weakness between (SF and reinforcing bars) and concrete after subjection to the intense heating up to 550°C, resulted in tensile strength reduction. At that temperature, the reduction ratios in peak load compared to the hollow beams specimens tested at ambient conditions were 20.2%, 17.9%, 16.25%, and 13.49% for specimen HB-T-0, HB-T-0.5, HB-T-1, and HB-T-1.5, which contain 0, 0.5, 1, and 1.5% SF, respectively.

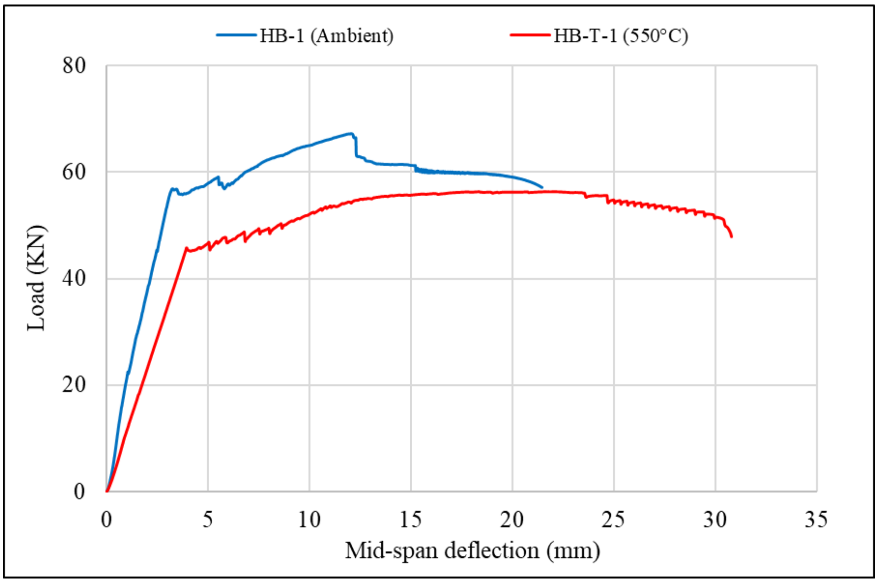
It is clear from this comparison, and as demonstrated in Figures 4.10 and 4.11, that the specimens with SF exhibited a lower loss in peak loads and this loss decreased with the increase in SF content compared to the hollow plain concrete specimen. This demonstrates that increasing the amount of hooked-end SF enhances the ability to carry loads while lowering the percentage strength loss. It reduces cracks produced by the thermic gradient inside the concrete matrix by the uniform transmission of heat through SF, providing redistribution of stresses uniformly when the concrete is heated and cooled.



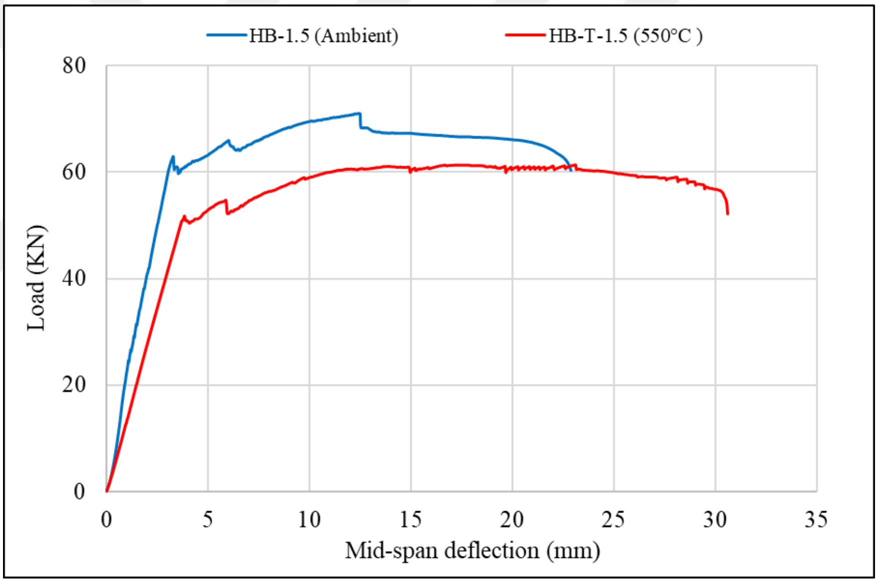
(a) 0% Steel fiber



(b) 0.5% Steel fiber



(c) 1% Steel fiber



(d) 1.5% Steel fiber

Figure 4.11 Load deflection curves for each hollow beam at ambient and elevated temperature

4.5 Ductility of SFRC Hollow Beams

Ductility is a significant and desirable feature in the structural behavior of RC, and it is a required parameter in the flexural members' design. To resist the earthquake forces, the structure is necessary to be ductile enough. The ability to preserve load-bearing capacity when being moved beyond the elastic stage can be referred to as ductility, which means the structural member exhibits high plastic deformation without a considerable loss in loads resistance before failure. Generally, during periodic deformations, ductile structures can dissipate a large amount of energy and preventing brittle rupture, which is a failure mechanism that should constantly be avoided. Ductility has a direct relationship with the ability to re-distribute internal forces, and thus with structural integrity. It should constantly be kept in mind during the design phase of RC structures. The ultimate deformations are commonly expressed through ductility factors, which are defined as the ultimate deformation (at ultimate load) per the equivalent deformation at yielding. Using ductility factors in design allows ultimate deformations to be defined in non-dimensional terms as indices of in-elastic deformation. The numerous response parameters linked to deformations, including displacements, curvatures, and rotations, have been typically represented in terms of ductility factor (μ) [64].

The deflection of the member is easier to record, and therefore can be used to determine the deflection ductility factor, $\mu = \Delta_u/\Delta_y$, where Δ_u is the ultimate deflection, and Δ_y is the deflection at yield. To evaluate ductility, it is substantial to specify the ultimate deflection, which is related to the ultimate load (P_u). Several approaches or assumptions have been followed by researchers to define the ultimate deflection load, where Figure 4.12 illustrates some possible definitions in this regard [64].

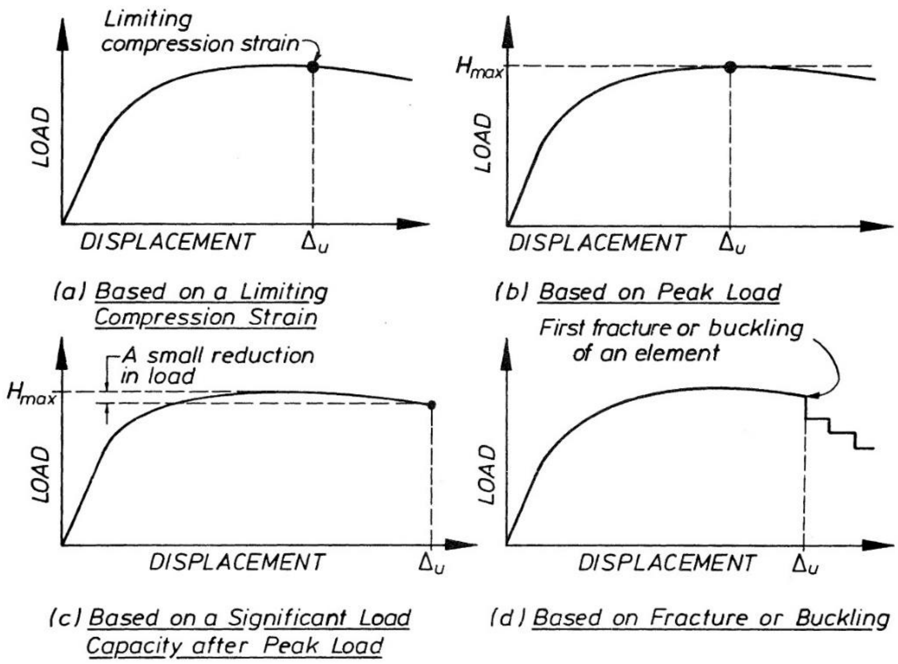


Figure 4.12 Different definitions for ultimate deflection [64]

To consider the most convenient definition, it's important to realize that most structural members may deform beyond the peak region (non-elastic deformation) without losing considerable strength. At least, a portion of this post-peak deformation ability should be recognized. Based on that, the criterions presented in Figures 4.12c and 4.12d, whichever happens first, are regarded as the most practical and realistic definition for the ultimate deflection. In this study, the aforementioned two definitions adopted were the ultimate deflection (Δ_u) has been taken at 85% of the peak load in the post-peak region of the load-deflection curve or at the sudden fracture of the member and the load declines sharply, whichever occurred first.

The deflection ductility factors for each tested specimen, calculated depending on load-deflection curves (Figures 4.7 and 4.8) before and after exposure to 550 °C, are given in Table 4.3 and Figure 4.13, which also compare the ductility of the hollow SFRC beams versus the plain concrete beams. The values of ductility factors for the four hollow specimens indicate that the ductility improved significantly with the increment in SF dosages. At ambient conditions, using the dosage of 0.5% SF resulted in a 14.42% improvement in ductility factor (μ), while this improvement was about 24.10% with a content of 1% SF. The super ductile behavior, as evident in Figure 4.13, was for the hollow beam (HB-1.5) with ductility factor increment by 31.12% when increasing the SF dosage to 1.5%, over the comparable (fiber-free) hollow beam. Moreover, the ductility factor of hollow beam HB-1.5 was higher than that of the solid beam SB-0 clear of fiber. Since the steel reinforcement ratio is the same in all beams specimens, it can be said that the SF volume fractions (V_f) are the dominant factor that impacts the SFRC hollow beams ductility and has a significant role in flexural performance enhancement. After increasing the temperature to 550°C, all hollow beams exhibited a higher ductility factor than those tested at ambient temperature by 18.65% as a maximum. Although the relative increase in the ductility of the hollow SFRC beams under the influence of high temperature was slightly less than that at ambient temperature, the presence of SF had an evident impact on this increase and depending on the various contents of the fiber. The inclusion of 1% and 1.5% dosages of SF in the specimens HB-T-1 and HB-T-1.5 enhanced the ductility by about 25% and 28%, respectively, whereas the ductility enhancement was limited to 12.76% for beam HB-T-0.5. This suggests that SF contributes to the elevated temperature ductility influence, with beams specimens with 1.5 percent fiber being able to endure the high deformations while also increasing the ultimate load and thus showing a remarkable ductility behavior at both ambient and high-temperature conditions.

Table 4.3 Ductility factors for the examined beams

Beam Code	Temperatures Exposure	Δ_y (mm)	Δ_u (mm)	$\mu = \Delta_u/\Delta_y$	Failure mode
SB-0	Ambient	3.53	17.42	4.93	F-S
HB-0		3.46	18.23	5.27	F-S
HB-0.5		3.21	19.36	6.03	F
HB-1		3.28	21.45	6.54	F
HB-1.5		3.31	22.87	6.91	F
SB-T-0	550 °C	3.77	22.84	6.06	F
HB-T-0		4.06	25.13	6.19	F
HB-T-0.5		3.9	27.24	6.98	F
HB-T-1		3.97	30.81	7.76	F
HB-T-1.5		3.86	30.59	7.92	F

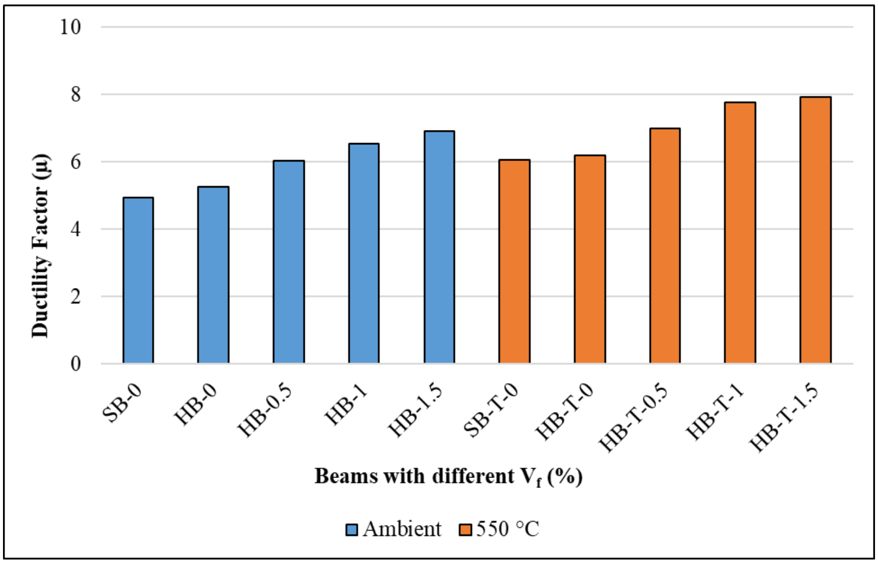


Figure 4.13 SF effect on ductility of the tested beams before and after heating.

4.6 Failure Mode and Cracks Pattern

All tested beams specimens were loaded until failure under four-points loading. The steel reinforcement details are the same in all beams, including the control specimens, and are designed to fail due to flexure. Table 4.3 lists the failure mode of all tested hollow beams, Figure 4.14 presents the cracks patterns of examined beams at ambient conditions, and Figure 4.15 presents cracks patterns of beams after heating at 550 °C and after testing. All the SFRC hollow-beams have failed in flexure and showed an excellent shear strength due to shear reinforcement (stirrups) and SF, except the specimen (HB-0) without SF was showed a (flexure-shear) cracks. In general, the number and width of cracks increase with increasing load, and the beams' curvature varies dramatically with increasing load as they approach failure. The failure patterns in the illustrations show that the cracking of SFRC beams (HB-0.5, HB-1, HB-1.5, HB-T-0.5, HB-T-1, and HB-T-1.5) somewhat differs from those fiber-free. After the beginning of the loading test, all fiber-free beams started to cracks earlier than those containing fibers. In ambient conditions and at the cracking stage, the fine vertical cracks began to appear at the middle of the beams (flexure zone) and continued to propagate perpendicularly with increasing load. In addition to flexure cracks, the specimens without fibers (SB-0 and HB-0) exhibited flexure-shear cracks. The specimens' cracks which were clear of the SF, and even that with low fiber dosage (0.5%), spread farther into the compression region than fibrous specimens. On the other hand, SFRC hollow specimens with 1% and 1.5% had flexural cracks with shallow depths because cracks diffusion was efficiently inhibited by the bridging ability of SF. In these SFRC beams, the major flexure cracks (one or two) located at the middle third of beams began to widen further due to the pulling-out of fiber and continued beyond the peak load, becoming the widest among the flexural cracks. Hence, this led to the failure of hollow SFRC beams due to rebars rupture accompanied by some crushing at the compression region.

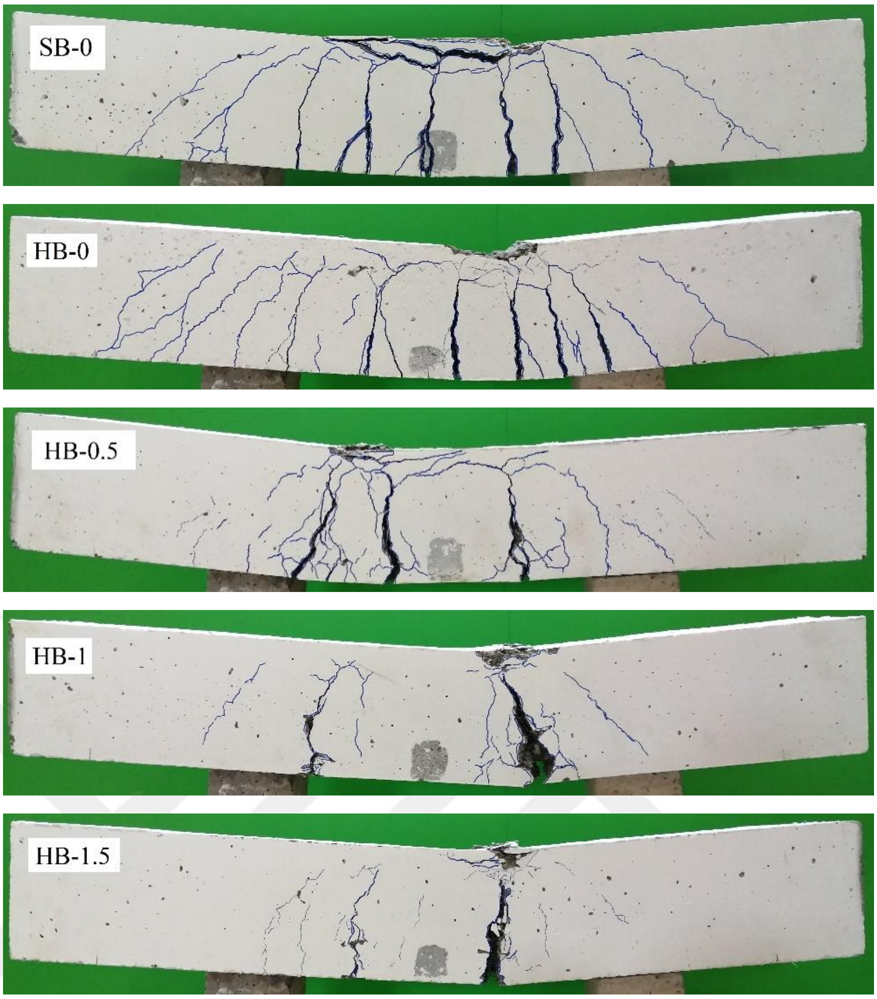
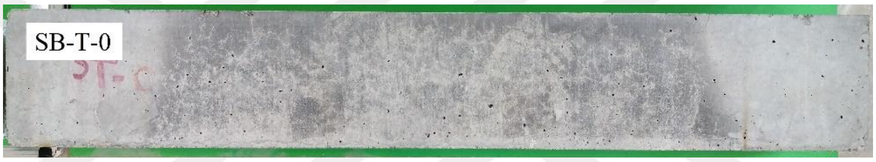


Figure 4.14 Cracks pattern of the tested beams at ambient conditions

As for the heated hollow specimens, the cracking patterns occurred through two stages. The first stage is the cracks that resulted after heating at a temperature of 550 degrees Celsius, and the second is the cracks that appeared after carrying out the loading test. The surfaces of the heated specimens are depicted in Figure 4.15. It can be observed that the color of the specimens' external surface became a light grey after exposure to 550 °C. Also, it can be observed that some small pits have formed on the beams' surface, and it can be due to the evaporation of water under high temperatures. However, no spalling occurred in concrete throughout the heating process. Regarding the cracks after heating, scattered cracks were observed on the surfaces of the heated specimens, and these cracks were interrelated to each other in more than one position, as offered in Figure 4.15. After loading started, all the heated specimens cracked earlier than the unheated ones and under fewer loads. When load increasing, some flexure cracks were observed in the middle region of the beams with the widening of the heating cracks width as the load increases. Again, the effect of SF was obvious in terms of cracks patterns in hollow SFRC beams HB-T-1 and HB-T-1.5, which exhibited cracks with less intensity compared to specimens SB-T-0 and HB-T-0 without SF. Moreover, it was noted that the heating cracks in non-fibrous beams widened after the loading test and extended to the compression region to a greater degree than fibrous beams.

At the final stage of loading, all beams were failed due to flexure with a considerable change in curvature. Additionally, peeling and losing parts of concrete and exposing the rebar at the major widened cracks were seen in most heated specimens except specimen HB-T-1.5 which was reinforced with 1.5% SF. To summarize, the SF can change the cracking pattern of beams and change the failure behavior from brittle to ductile even at high temperatures where cracks can be inhibited or mitigated using SF.



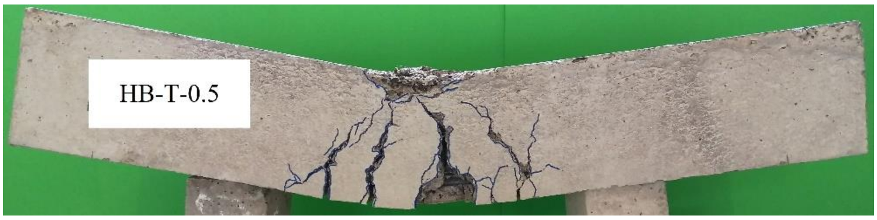
After heating

After testing

After heating

After testing

After heating



After testing

After heating

After testing

After heating

After testing

Figure 4.15 Cracks pattern of the beams after heating at 550 °C and after testing

CHAPTER V

CONCLUSION

The performance of RC hollow beams under flexure loading and comparing the SFRC beams responses with various SFs quantities in terms of temperature evolution, load values at different stages of loading, deflection, ductility, failure mode, and cracks before and after being subjected to excessive temperature, were experimentally explored through this study. Besides, the investigation also included the mechanical characteristics of mixtures used to produce the specimens and studying their response to different inclusions of SFs under normal and high-temperature conditions. The conclusions drawn from the findings of the experimental study based on the above research parameters can be summarized in the following points:

1- SF's various contents (up to 1.5%) have no significant influence on the temperature fields inside RC where all specimens reached the utmost temperature in the approximately same development with a slight variation in their values. The SFs inhibit the interior structure deterioration of concrete under heating by inhibiting the excessive cracking in the SFRC, this remains possible as long as it is capable of transmitting stresses through cracks adequately.

2- The influence on compressive strength by incorporating SF was more evident on the SFRC specimens at high temperatures than ambient temperature. SFRC with a 1.5% dosage of SFs provided an enhancement by 15% at ambient conditions, whereas at 550°C, the enhancement in residual strength was 23.25% compared with plain concrete. The loss in compressive strength of plain concrete was more than that of fibrous concrete at high temperatures. A reduction of 22% in compressive strength of SFRC was observed against 28% for plain concrete compared to its unheated counterparts.

3- Based on test findings, the deterioration in the splitting tensile strength was more severe than the compressive strength of heated concrete specimens.

However, the role of SF herein was more apparent, as the presence of 0.5%, 1%, and 1.5% SFs raised the tensile strength to 24.47%, 47.26%, and 51.9%, respectively comparing to the plain concrete mix. After exposure to 550°C temperature, each 0.5% addition of fibers increased the tensile strength by 33.67%, 72.33%, and 74%. Again, as compared with specimens at ambient conditions, the percentage of decrease in tensile strength of heated concrete specimens without fibers was higher than that containing fibers. The residual splitting tensile strength of SFRC with 1.5% after heating was 73%, while it was 63% for non-fibrous specimens.

4- Under ambient conditions, the hollow SFRC beams' flexural behavior was better than that of hollow fiber-free beams regarding cracking load, yielding load, and peak load. The increases in load-carrying capacities for these three stages when using 1% and 1.5% SFs were 13.34% and 24.67%, 23.62% and 36.57%, and 19.4% and 25.95%, respectively. At the yield stage, the ratio of load/deflection was increased up to 42% when the SF dosages raised from 0 to 1.5%, reflecting the hollow beams' ability with SF to resist deflection and exhibiting better flexure rigidity. As compared to the solid beam without fibers, the peak load results for the hollow fibrous beams were higher by 4% at 1% SF and 10% at 1.5% SF, while 0.5% SF showed a peak load less than the solid beam.

5- The general flexural behavior after being exposed to 550 °C temperature revealed a decrease in the load values of the hollow beams at all stages. However, the SF effectiveness was also pronounced in post-heating load-carrying capacity improvement, where the hollow beam's residual peak load increased by 36.5% at 1.5% SFs compared to the corresponding hollow beam without fiber. Comparing with the solid beam without fibers, it was observed that the hollow beam with 1.5% SFs was the only one that exhibited a higher peak load than the solid beam by about 7%. The reduction in peak loads capacities after exposure to high temperature was 20.2%, 17.9%, 16.25%, and 13.49% at 0, 0.5, 1, and 1.5% SF, respectively, where the higher the fiber dosage, the lower the loss percentage in the peak load of the hollow beam.

6- Exposure the hollow beams to 550°C temperature led to a significant increase in deflection at the ultimate load, and this increase is directly proportional, under the impact of high temperature, with the increase in SFs content as compared to the plain concrete specimen, and also to their counterparts that tested at ambient conditions. This emphasizes the SFs' influence on post-peak performance.

7- Concerning the ductility, the SF content was the dominant factor that affected the ductility of the hollow SFRC beams before and after heating. The ductility factors of all the hollow fibrous beams were greater than those of non-fibrous hollow and solid beams. The ductility factor of the hollow beam with 1.5% SF was higher by 31.12% than that of the fiber-free hollow beam and higher by 40.16% than that of the fiber-free solid beam. At 550°C, all the hollow beams revealed ductility factors greater than their counterparts tested at ambient temperature by 18.65% as a maximum. Besides, the greater the SF dosage, the greater the ductility of beams.

8- The RC hollow beam, with a reduction in cross-section area by 22.34% (circular opening of 80mm diameter) and with the addition of hooked-end SF, can be a good structural solution to reduce weight and provide more ductile structural members without a reduction in load-carrying capacity even at post-heating.

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