ISSN 2303-4521
Periodicals of Engineering and Natural Sciences *Original Research*
Vol. 10, No. 1, February 2022, pp.587-606

Strengthening of fire damaged, light weight, high strength reinforced concrete beam using SIFCON jacket

Ahmed Habeeb Albo Sabar[1], Mohammed Mansour Kadhum[2]
[1] Civil Engineering Department, College of Engineering, Babylon University, Babylon, Iraq.
[2] College of Engineering, Babylon University, Babylon, Iraq.

ABSTRACT

This study aims to extrapolate the behavior of lightweight (LECA) high strength concrete beams subjected to high temperatures. the LECA aggregate was utilized as coarse fraction in the reference mixture. a post development process in terms of jacketing the fire damaged beams with SIFCON materials layer was also investigated. In addition to the reference samples, various parameters of concrete beams and conditioning were conducted, namely, fire duration exposure, concrete cover, and SIFCON layer thickness. In details, two concrete cover thickness, half and one-hour fire duration exposure, and two SIFCON layer thicknesses were the main parameters in this study. the thermal gradient through the beam cross section was captured through installing thermocouples sensors embedded inside at various location. The physical and chemical properties were tested for all used materials in this study. Overall, fourteen concrete beam samples were tested for all the three phases (normal or reference, fire damaged samples, and post enhancement with SIFCON jacket). the level of comparison for the tested samples was focused on several parameters are; maximum shear load capacity and corresponded displacement, ductility index, cracking load, initial and secant stiffness, and energy absorption. The experimental test results under the scope of this research have shown significant improvement for the strengthened beams were observed compared with the damaged samples. Moreover, the results have cleared that the strengthened beams, in term of the mentioned indices were recovered as and comparable to the undamaged (reference beam), except the absorption energy. Where further studies and efforts have to be paid to overcome such issue.

Keywords: Lightweight concrete, LECA, SIFCON, Fire damage, High strength concrete

Corresponding Author:

Ahmed Habeeb Albo Sabar
Civil Engineering Department
University of Babylon, Iraq
ahmed.youssef@student.uobabylon.edu.iq

1. Introduction

In many new structures, the need for lightweight concrete is on a rise because of the advantages of the low density of load-carrying parts and small cross-sections which resulted in a decrease in the size of the construction foundation [1]**.** The lightweight aggregates are obtained naturally from volcanic cinders, diatomite, etc., or artificially from clay, sintered, etc. The mentioned lightweight aggregate is normally used to produce lightweight concrete [2]**.** This concrete has several advantages such as an improved strength/weight ratio, higher tensile capacity, and reduced thermal expansion owing to the higher air voids content in the concrete. Lightweight concrete production growth has accelerated. Nowadays, this concrete is produced in different varieties ranging from low-density concrete such as block manufacturing with densities up to 1200 kg/m^3 to high-density concrete with densities of up to 2000 kg/m^3 that have a compressive strength of up to 100 MPa [3]**.** paper. During fire incidents, the concrete is exposed to a significantly elevated temperature which leads to a significant loss in the properties of the concrete like compressive strength and ductility. Besides, a significant increase happens in the internal stress due to the vapor pressure in the pores which generates cracks of various sizes and lengths, particularly at high temperatures of more than 550ºC. At high temperatures like 550ºC, Dehydration of calcium hydroxide takes place and aggregates start to weaken. At higher temperatures (700ºC or above), the binding materials like hydrated cement (C–S–H) start to disintegrate which results in a significant loss in the mechanical properties (stiffness and compressive strength) of reinforced concrete (RC). Besides, the concrete suffers from losses in the bonds between the aggregate and the cement paste which leads to the development of cracking and the concrete starts to dramatic lay deteriorate. As a consequence, the capacities of the structural components cannot handle dead and living loads unless they are reinforced. Which is broadly agrees with the opinions of the following researchers [4,5]. The only viable approach for regenerating structural capacity would often be to replace heat damaged components. Many aspects should be addressed carefully for carrying out repairs for fire-damaged components, including damage size, component shape, repair materials, cost, time, and the functions of the component. Although many research studies have already been carried out on RC's structural restoration [6,7,8]. The work on the restoration of heat-damaged structures is scarce. For example, examined the performance of RC columns that are repaired after exposure to high temperatures. The authors exposed eleven columns to high temperatures and used fresh cast-in-place concrete to repair the damaged columns. The performance of the reference and restored columns in terms of ultimate strength and stiffness were tested using eccentric axial loads. The researchers reported that most restored columns have either recovered their original preference or even achieve improved performance in terms of stiffness than reference columns **[9].** on the other hand, studied the efficiency of special repair techniques that were employed in St. Elizabeth Hospital in Holland after an intense fire incident. The authors reported that the consultant team found that if suitable repair approaches were followed there is no need for taking down the hospital. Three approaches were applied, which included epoxy injection, shotcrete repairs, and stiffening, to restore the performance of the structural members of the hospital structure [10].

Repairing damaged concrete members is often accomplished by constructing outside reinforced concrete support or shotcrete concrete jacket, or by bonding metal plates to the damaged component using epoxy, etc. [11]. A novel technique involves replacing the steel plates with fiber-reinforced composites materials in the form of a laminate, such as carbon and glass fibre reinforced polymer. The use of high-performance fiber-reinforced cementitious composites in structural repairs and reinforced concrete component restoration has increasingly grown in importance. [12,13] The high strength-to-weight, enhanced toughness, superior durability, and cost-effectiveness of composite materials offer exceptional properties to replace conventional repair materials. Using composites in structure restoration projects may significantly reduce maintenance needs, improve safety and extend the service life of the structure [14].

SIFCON matrix is a flowing cement mortar or slurry of high cementitious content with no coarse aggregates. It may have fine/coarse sand, which is very different from the concrete in fiber-reinforced concrete (FRC). So, the assembly of SIFCON is different from FRC. The FRC is made by mixing the fiber with the fresh concrete. While the SIFCON is produced by replacing the fibers in the molds until it's filled and the cement slurry is then added to the fiber in the mold. If required, vibration is applied throughout to make sure the slurry infiltrates the fiber network [15,16]

SIFCON is also known as a high-performance fiber-reinforced cementitious composite (HPFRCC). The HPFRCC normally contains a fraction of fibers. Higher fibers content leads to multiple cracks in all directions in structural members under tension. On the other hand, low fibers content in a structural member under tension (Figure1-1, a) leads to the generation of a single crack only. Therefore, A strengthening in the concrete is achieved by a greater fiber volume and this is done in a similar way to strain hardening in parallel with the cracking process. Lastly, failure is located in one crack process and the concrete is weakened [16]. SIFCON is a suitable repair material since it is compatible with reinforced concrete in terms of stiffness and thermal deformation. As a result, SIFCON is widely used to repair prestressed concrete parts such as beams [17]. And is used in structures made to withstand explosion impact. The SIFCON has high compressive strength, flexural, and ductility properties. SIFCON has also showed excellent resistance against impact load on buildings.

SIFCON was used to manufacture a wide range of prefabricated components, including slabs, tunnels, and pipe sections [18].

The slurry can be prepared using minerals and chemical admixtures such as super-plasticizer (SP), fly ash, and silica fume to enhance the efficiency of the SIFCON. Vibration is frequently required to achieve effective slurry penetration of the fiber bed. [19,20].

Based on scientific research, it can be deduced that the SIFCON has very good mechanical properties improved tension, enhanced compression and shear strengths, and optimized ductility and energy absorption capabilities [21]. These properties are affected by several factors including:

i. The strength characteristics of the cement slurry.
ii. The fiber of the SIFCON.
iii. The installation of the fiber and their alignment.
iv. The type and characteristics of the fiber [22].

This research aims to investigate the effects of applying a U-shaped thin jacket made from SIFCON on the behavior of fire-damaged LWRC beams. In light of this, the origin of this research was the needed to conduct comprehensive research on the development and applications of SIFCON thin jackets to strengthen or repaired damaged regions after burning. This includes investigating the contribution of several parameters like concrete cover, the thickness of the SIFCON jacket, and fire duration on the performance of the repaired LWRC beams.

2. Experimental work

In brief, the experimental program is divided into two sections. The first stage involves the selection, preparation, and testing of the physical and chemical properties of raw materials applied in this research. As part of the overall structural LWC program, high strength concrete grade of LWAC have been produced. The target compressive strength was (67 MPa) designated as high strength lightweight concrete respectively. The manufactured lightweight aggregate, ‘LECA’ was used for lightweight concretes of normal and higher strengths. Currently, adequate criteria for LWAC mix proportioning are very limited, and those that exist are also not clearly specified. As a consequence, experimental mixes are required to achieve the required strength and work-ability when using any type of lightweight aggregate, therefore many trial mixes were done in this study. To achieve the desired workability, superplasticizers and mineral admixtures were utilized in all formulations. The chosen ingredients are next blended using the optimal mix proportions and an appropriate mixing technique. Then, the beam specimens were casted in the prepared wood molds After 24 hours, the beam specimens were taken out of the casting molds. finally, the casted samples and beam specimens were cured for the appropriate ages. After achieving the specified age (56 days), the LWC beam specimens and samples are burned for two durations of fire exposure (30 and 60 minutes). While the third stage, after the burning process is finished, this stage deals with the repaired and strengthened post-fired beams by using U-shaped SIFCON jacket, then preparing and testing of the exposed (with and without repaired) and unexposed concrete samples and LWC beams. The following subsection shall describe the experimental work in detail.

2.1 Material properties

Concrete is a composite material consisting of components such as cement, coarse aggregate, fine aggregate, water, and admixtures, thus it is important to test the properties of the ingredient of it.

The cement type utilized in current investigation was ordinary Portland cement. It was made in Iraq. and commercially known as (Karasta), supplied from local markets.

Natural sand from local resource, which was supplied from Kerbala, has been utilized as a fine aggregate in the main concrete mixture. The size of the sand used in SIFCON slurry very important; it must be small enough to guarantee thorough penetration into the thick steel fiber without causing clogging. In the preparation of SIFCON slurry, only the fine sand which was sieved through (1.18 mm sieve) to filter the coarser particles can used during the experimental work for all SIFCON mixtures. Table (3-3) shows the sieve analysis of the sand used. It conforms to the limits of Iraq specification No. 45/1984 Zone (2). Figure (1) shows the grading curve of the natural sand in accordance with (IQS No. 45/1984), and the physical and chemical properties of natural sand are illustrated in Table (3-4).

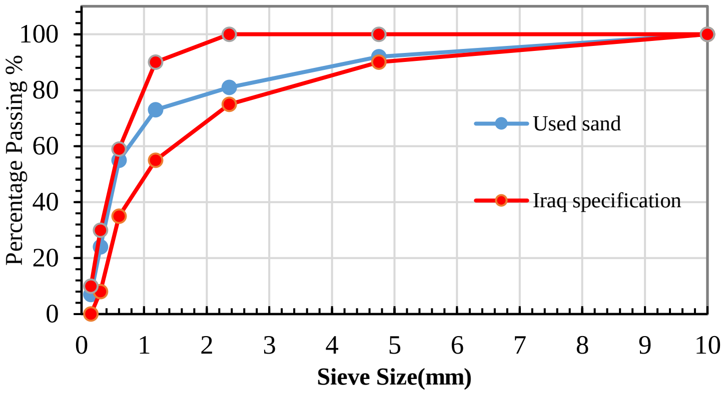


Figure 2. Grading curves for fine aggregate compared in accordance with (IQS NO.45/1984, Zone 2)

Expanded clay aggregate (LECA) was used with regular sizes of between 0.475 cm and 1 cm, which was brought from north of Tehran City, Iran. This type of lightweight aggregate is characterized by porous ceramic materials with uniform, small, closed-cell pores, as well as tightly sintered and strong exterior surfaces. LECA made from raw materials of clay minerals which are burned in rotary kilns at a temperature ranging between 1100 and 1200° C, which resulted in swelling of the volume of the particles significantly. Table (1) clarifies the physical and chemical properties of LECA.

silica fume, which is commonly branded as Mega Add MS (D) produced by CONMIX, was used in this investigation as a replacement material by roughly 10% by weight of cement to generate both High strength lightweight concrete and SIFCON mixes. Silica fume enhances the microstructure of cement paste, making it more resistant to external influences. The chemical analysis of the silica fume used is tabulated in Tables (2, and 3).

Potable water has been utilized in all concrete mixes (high strength mixture and SIFCON) and in the samples curing which was free of salts, turbidity and, organic matter content. Moreover, The high-performance water-reducer admixture employed in this investigation is a third-generation super-plasticizer for concrete and SIFCON mortar marketed commercially as (Hyperplast PC200). The percentage of 3.7% was used to produce appropriate slurry for SIFCON.

Table 1. Physical and chemical properties of LECA

Physical Properties	
Properties	**Test Results**
Specific Gravity	1.2
Absorption	12%
Bulk density Kg/m^3	700
Chemical Properties	
Chemical Composition	**Percentage by Weight%**
CaO	3.78
SiO_2	61.58
Al_2O_3	16.99
Fe_2O_3	7.62
MgO	2.56
SO_3	0.19
TiO_2	0.80
MnO_2	0.10
Na_2o	1.03
K_2 o	2.34
Loss on Ignition (L.O.I.)	0.2

Table 2. Silica Fume chemical analysis

Oxide composition	Oxide content %	ASTM C1240-05 limitations
SiO_2	89.41	Min. 85%
Al_2O_3	0.63	-
Fe_2O_3	0.45	-
CaO	0.82	< 1
SO_3	0.87	< 2
K2O+Na2O	1.35	-
L.O.I.	4.10	Max. 6%
CI	0.18	-
CaO (free)	2.15	-

Table 3. Physical properties of silica fume

Physical properties	Result	ASTM C1240- 05
Strength activity index	130%	≥ 105
Percent retained on 45 µm (No.325) sieve, max, %	1.7	≤ 10
Specific surface, min, (m^2/g)	23	≥ 15

Moreover, hooked steel fiber, which was supplied from ATLAS company, was incorporated to prepare SIFCON jacket, as shown in Figure (1). The type of fiber was hooked end, with length of 30 mm, diameter of 0.5 mm, aspect ratio of 60, and tensile strength of 1100 MPa.

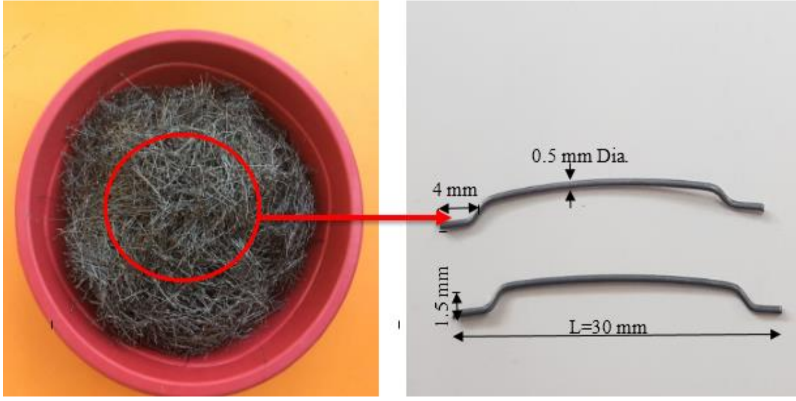


Figure 1. Geometrical configuration of hook end steel fiber steel fiber used before and after magnification

The mechanical properties of the used reinforcement steel bars were presented in Table (4).

Table 4. Specifications and test results of steel reinforcing bars

Nominal Bar Diameter (mm)	Actual bar Diameter (mm)	Yield Stress Fy (MPa)	Ultimate strength Fu (MPa)
8	7.95	550	678
10	10	581	724
12	11.96	663	828

2.3 Specimens manufacture and testing setup

For all of the study stages of lightweight HS reinforced concrete beams, the adopted dimensions are; 120 mm width, 200 mm depth, and 2000 mm length. In addition, two deformed steel bars of 10 mm diameter in the top, and three deformed steel bars of 12 mm diameter in the bottom, were used as longitudinal reinforcement. for stirrups reinforcement, 8 mm steel bars were used each 200 mm, as shown in Figure (2). Figure (3) illustrates steel bars reinforcement configuration before concrete pouring. Moreover, two different concrete covers were investigated are, 20mm and 30 mm. The final mix design, after several comprehensive trails for HSC and SIFCON mixtures were illustrated in Figures (4) and (5), respectively. for simplification process, each beam's configuration and exposure conditions was designated in this study, as shown in Table (5).

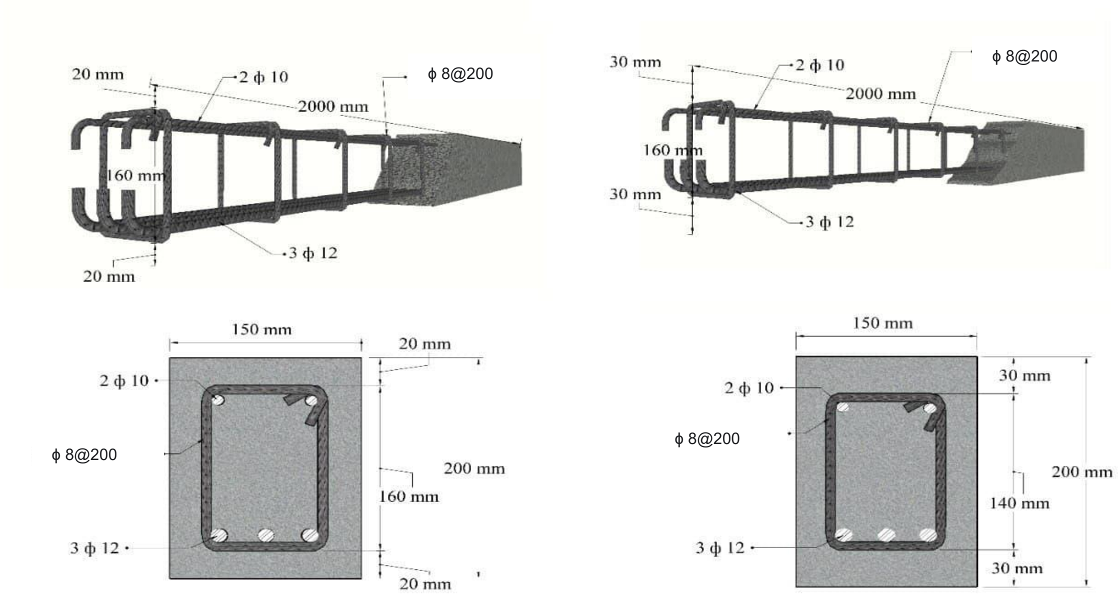


Figure 2. Main section geometry and typical LWC beam cross-section (dimensions are in mm).

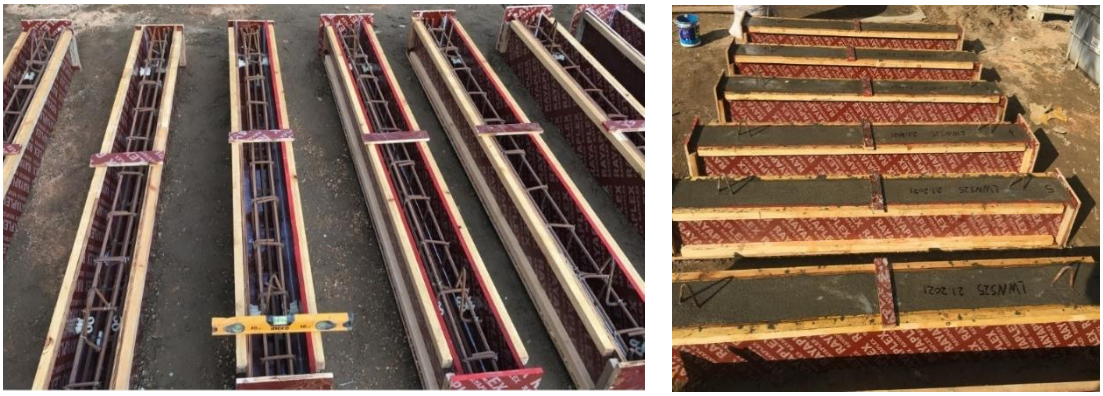


Figure 3. casting of HSC beam specimens

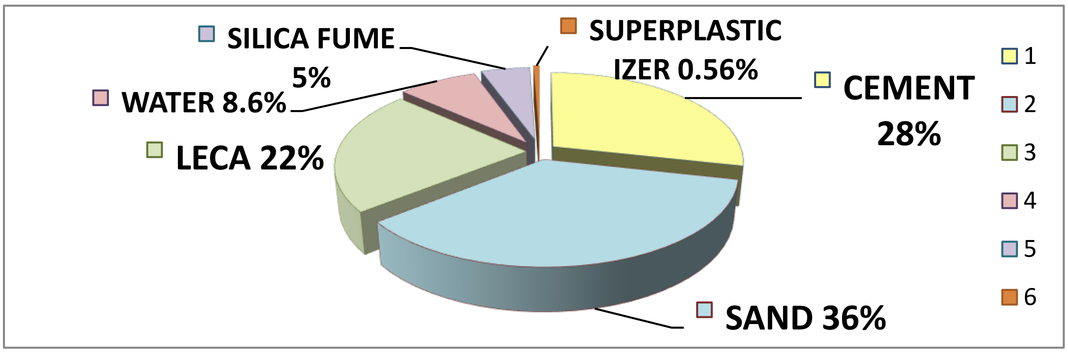


Figure 4. Materials proportion used in HSCLWC mixture (% of total mix weight)

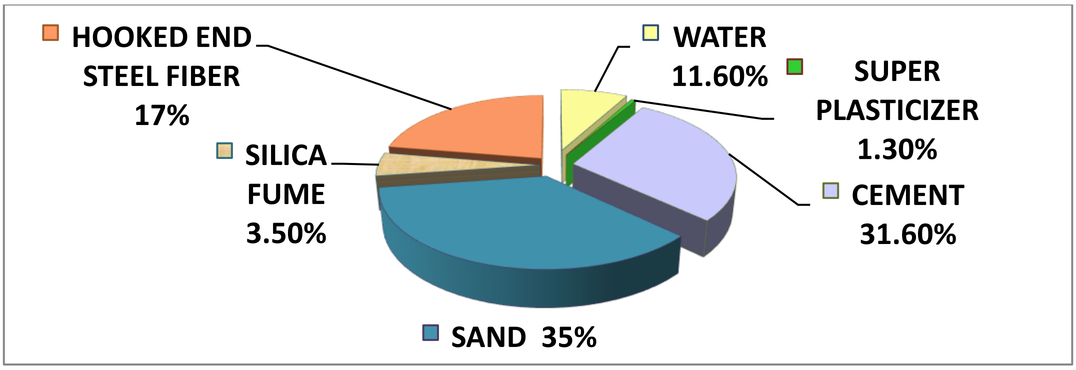


Figure 5. Materials proportion used in SIFCON mixture (% of total mix weight)

Table 5. samples' designation of various concrete beams comigration and exposure conditions

Grade	Concrete cover (mm)	SIFCON jacket thickness (mm)	Beams designation	Fire duration (Min)
HSC LWC Beams	**20**	None	HC_1-00	0
			HC_1-01	30
			HC_1-02	60
		20	HC_1-21	30
			HC_1-22	60
		30	HC_1-31	30
			HC_1-32	60
	30	None	HC_2-00	0
			HC_2-01	30
			HC_2-02	60
		20	HC_2-21	30
			HC_2-22	60
		30	HC_2-31	30
			HC_2-32	60

2.4 Fire loading protocols

To expose the prepared concrete beams to high fire temperature, a brick furnace was manufactured locally, and supplied with thermocouples sensors and portable data acquisition to capture the thermal variance with time, as shown in Figure (6) . After 56 days of LWC beams' age, specimens were exposed to fire in the furnace. The LWC beam specimens were burning in the furnace according to the standard fire of ISO-834. The furnace was designed to attain a maximum temperature of 1200 ºC. The temperature in the furnace was regulated so as to follow ISO curve. However, it should be noted that the rate of heating used is considerably lower than ISO-834 regulation. The durations of the fire loading were 0.5 and 1 hours in every case, since it was enough to raise the reinforced LWC beams to the target temperature.

Every 5 minutes, observations were conducted through the view ports in the furnace to document any notable changes in the specimen, including the development of fire-induced spalling. Following the conclusion of the fire exposure test and complete cooling of beam specimen to ambient temperature (about 35 °C), thorough assessments on cracks and spalling intensity were taken. The Matlab program was used to program the real time-temperature curve, which connected the thermocouple within the furnace to the computer, allowing the temperature readings to be recorded immediately with the time. The records of heats and timings are then saved on the computer with the final form of the time-temperature curve at the ending of the burning process. The underside, as well as the two lateral faces of beam specimen, were all subjected to fire. The test was conducted at an environment temperature of 35 °C. These three sides of the LWC beam specimens were exposed to different duration of fire loading. Readings were recorded every ten seconds at various points of the beam specimen. Next the fire exposure period, the beam was cooled after being removed out of the furnace.

The specimens were instantly extinguished with a foam spray fire extinguisher when the time of burning was completed. This cooling procedure was used in this experiment to simulate the issue under real life situations.

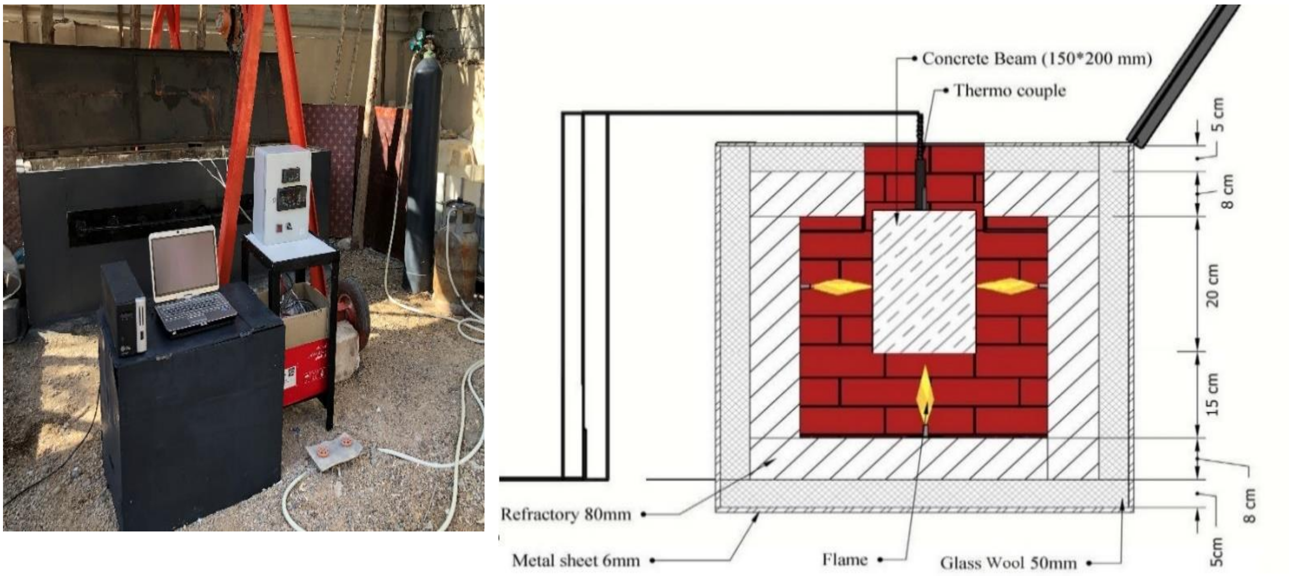


Figure 6. Graphical and on-site Burning furnace configurations

2.4 Repairing methodology

After burning process, the strengthening methodology was applied to the damaged LWC beams. The jacket was prepared using especially designed wooden mold**.** The molds with same shape and larger dimensions have been used to cast the three-faces SIFCON jacket. That mold has spaced between its surface and the specimen to allow casting of (20 and 30) mm jackets thickness and applying at the underside and two lateral sides (U-shaped jackets), as illustrated in Figure (7). After burning, before additional strengthening, the fire-damaged beams specimens that had cracked and collapsed were removed. The damaged part was removed and repaired with (SIFCON) slurry-infiltrated fiber reinforced concrete. In a word, molds were full of hooked end steel fibers in multilayers to reach the specified volume fraction. Each layer was penetrated with the slurry SIFCON mix, which was designed as previously stated. A significant amount of care was taken to ensure that the fibers were uniformly distributed and that no clogged occurred throughout the infiltration process. This was accomplished by employing a specific rubber strip as a sealant agent at the contact of the wooden parts. Figures (8) and (9) illustrates the process pf repairing and casting SIFCON jacket layer.

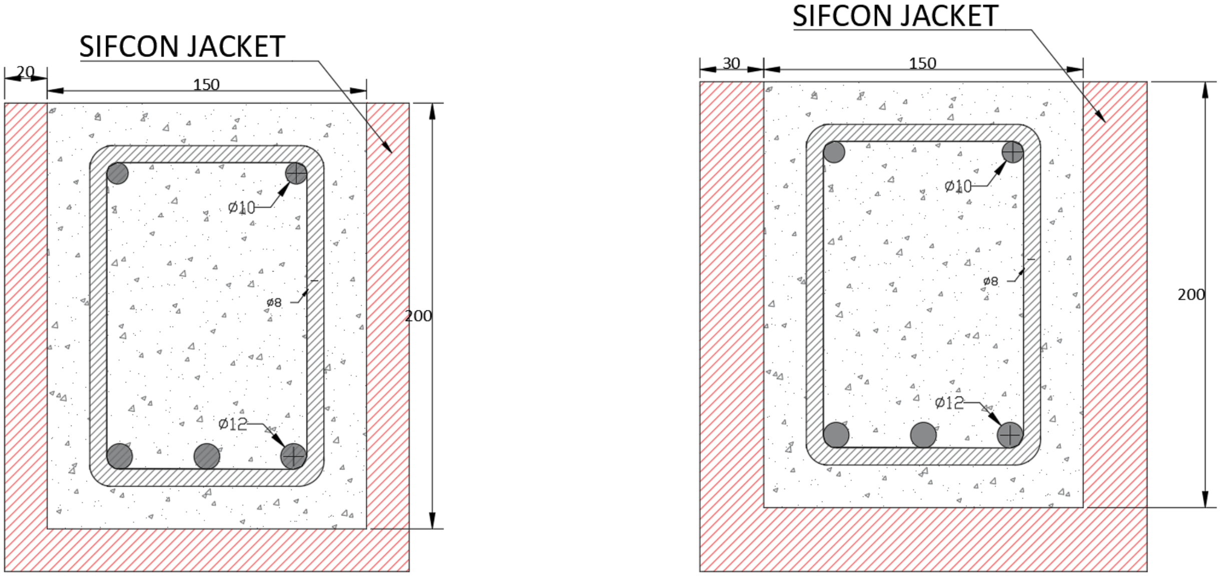
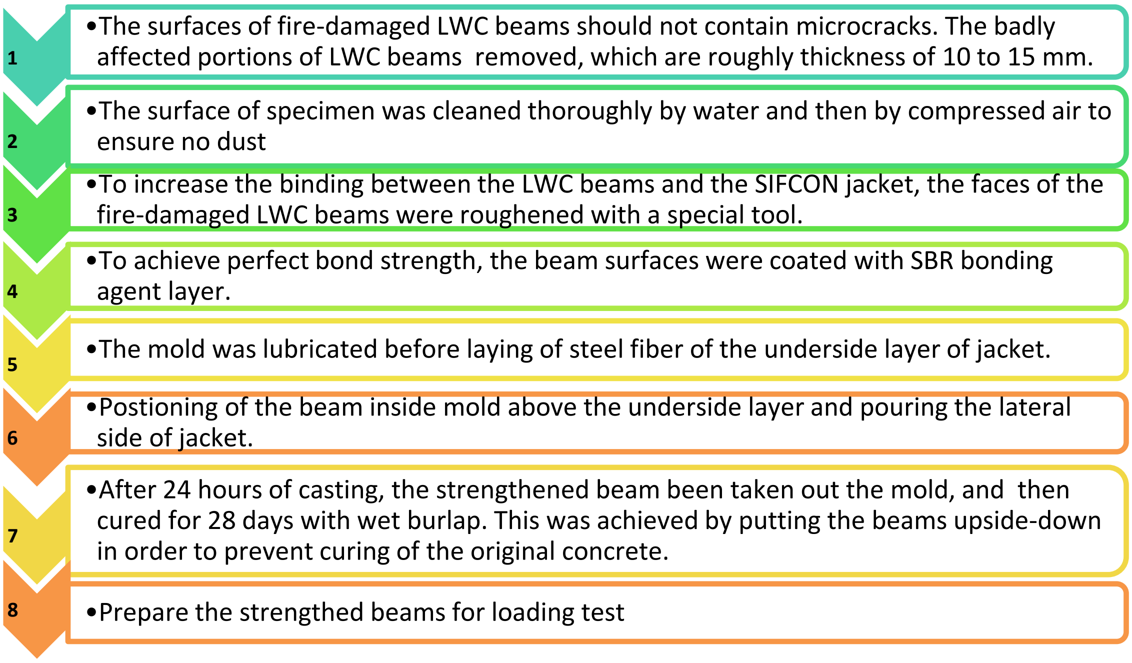


Figure 7. Process of strengthening the fire damaged LWC beam specimens



1. The surfaces of fire-damaged LWC beams should not contain microcracks. The badly affected portions of LWC beams removed, which are roughly thickness of 10 to 15 mm.
2. The surface of specimen was cleaned thoroughly by water and then by compressed air to ensure no dust
3. To increase the binding between the LWC beams and the SIFCON jacket, the faces of the fire-damaged LWC beams were roughened with a special tool.
4. To achieve perfect bond strength, the beam surfaces were coated with SBR bonding agent layer.
5. The mold was lubricated before laying of steel fiber of the underside layer of jacket.
6. Postioning of the beam inside mold above the underside layer and pouring the lateral side of jacket.
7. After 24 hours of casting, the strengthened beam been taken out the mold, and then cured for 28 days with wet burlap. This was achieved by putting the beams upside-down in order to prevent curing of the original concrete.
8. Prepare the strengthed beams for loading test

Figure 8. Repairing and strengthening technique process of LWC beams by using three-faces SIFCON jacket

Figure 9. Process of strengthening the fire damaged LWC beam specimens

2.5 Mechanical loading protocol

The beam specimen surface was usually cleaned and coated with white emulation before testing to clarify cracks propagation and make cracks observation easier. The beam specimen was then positioned in its testing position, and the LVDT were set in their locations. A steel beam was used to apply and divide the load at two locations, dividing the tested LWC beam into three parts to create a nearly equal load applied to the LWC beam. The distance between two-point load was 800 mm. bearing plates were made from hardened steel with dimension of (210×75×20) mm to sustain the applied load avoiding crushing in the contact point of specimen body that may influencing the test, the supports were designed to function as a hinge support from one end and a roller support from the other. The load was applied to all beams using a hydraulic testing machine with a capacity of 600kN. Beams were subjected to monotonic increasing load tests until they failed. five LVDT were set to measure the displacement in different location along the beam specimen, the first LVDT placed at the bottom surface of the beam's middle point and two LVDT placed under the two-point loading. The mid-span curvature obtained from other two LVDTs placed along the top and bottom fibers and measuring displacement changes over a distance of 20 cm. Figure (10) illustrates the mechanical loading configurations and sensors locations.

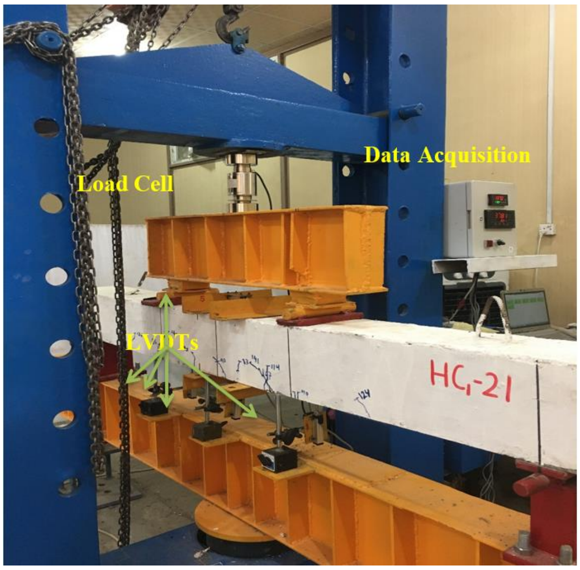


Figure 10. Arrangement of LVDTs and Load Cell within the test device

3. Results and discussions

This section presents and illustrates the resulted data of the experimental laboratory programs in details. The effect of fire exposure duration, concrete cover thickness, and effect of strengthening with various SIFCON jacket layer thickness shall be compared using several indices are, the load carrying capacity, the cracking load, midspan displacement corresponded to the maximum load carrying capacity, initial and secant stiffness, absorption energy, and ductility index.

3.1. Temperature variations with time

The furnace temperature closely matched the ISO 834 fire curve with fewer than 10% variance till reach the target temperature (600°C). After this point, it is noticed that the values of curves diverge. Because the highest temperature of the specimen bottom surface was 605°C, the strength of the specimen bottom concrete expected to reduce by amount more than deeper parts of beam specimen. Because of the low thermal conductivity of concrete, the observed temperature of the beam bottom TC1 was much higher than that of TC4, which is positioned 100 mm from the bottom surface. Temperatures TC3 and TC4 at the middle depth of the beam were kept around 100 °C for 25 minutes exposure period due to evaporation of water in the concrete and subsequent heat loss. Temperatures declined as one progressed up the depth of the beam from bottom to top, indicating a significant gradient. The highest temperatures of TC1 and TC2, which were higher than TC3, were 605 °C and

382 °C, respectively, and the concrete strength close to TC3 and TC4 reduced slightly compared to normal concrete temperature, as can be seen in Figure (11). Table (6) shows the position and nomenclature of the thermocouples. In a nutshell, the temperatures of the fire-exposed areas exceeded 600°C, and the heat dropped sharply from the out surface to the concrete interior core. The concrete core temperature was between 200 and 240 degrees Celsius. As a result, the fire exposed concrete layer was significantly affected and it must remove, while the interior concrete core still usable.

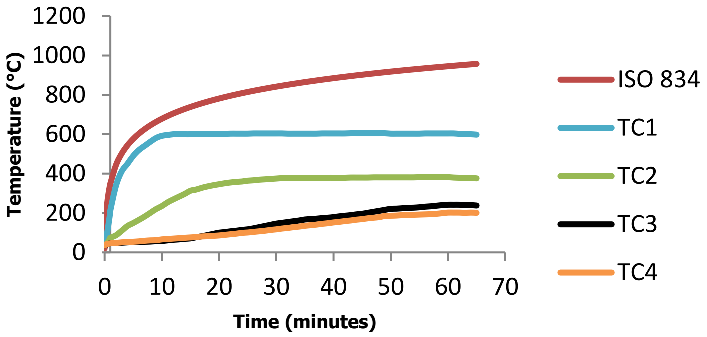


Figure 11. Experimental and ISO-834 Standard recommended temperature-time curves

Table 6. The position and naming of the thermocouples

Thermocouple	Type	Distance from exposed surface (mm)	Highest recorded temperature °C
TC1	K	0	604
TC2	K	25	382
TC3	K	50	241
TC4	K	100	202

3.2. Burned beam specimen appearance and color change

The beams specimens after they have been exposed to fire. The color of the surfaces exposed to fire was light gray with some light reddish areas. On the exposed surfaces, tiny reticular cracks occurred., as shown in Figure (12). Random tiny cracks line of varying widths (0.04–0.18) mm were seen on surfaces after exposure to high temperatures up to 600 C for 1 hr. The most significant cracks were found near the primary and transverse reinforcing points on the concrete surface. These cracks could be caused by the RC element expanding, causing large tensile strains in the concrete, particularly at the reinforcing contact, and the cement matrix and aggregate responding differently to high temperatures.

Furthermore, concrete spalling occurred on the beam's corner without exposing any steel, with a maximum spalling depth of nearly 15 mm. However, no apparent beam curvature was detected.

Figure 12. Speckle pattern of tested beam, A- Specimen surface enlarged image, B- Partial enlarge hairline cracks

3.3. Behavior of load-displacement curves and cracks patterns

The specimen beams without strengthening appeared an initial flexural crack at the midspan of the specimen., the first crack appear in the bending zone about 10 cm. from the left of load applying point. As the applied load was increased gradually a number of cracks appeared in the left of first crack heading vertically, later diagonal cracks formed and propagated along the distance between the supporting and load applying points. Figure (13) shows that the inclination angle of diagonal cracks becomes bigger after burning, the cracks extension shorter, and number of cracks was less after burning. a/d ratios greater than 2.5, in which case the failure is induced by a diagonal crack beginning located at the top of the flexural crack next to the support. the shear tension was the failure mode. in the case of (HC2-02) specimen beam, where the crack resulting in loss of bonding, while it seems to be shear compression failure in the case of (HC1-00) specimen beam as a result of crushing of concrete at the loading point.

Figure 13. Cracks pattern of HSC LWC beams before and after burning

To extrapolate effect of heating duration, results have cleared that a reduction of about 15% and 11% for 20 mm and 30 mm concrete cover, respectively when fire exposure duration increased about ½ hr.

To investigate the effect of concrete beam's cover on the load carrying capacity (LCC), the undamaged beams have shown that beams with 20 mm cover have higher LCC than beam with cover 30 mm by about 12%. This is simply because of the higher effective depth of 20 mm concrete over beam.

For the second stage, after fire exposure, specimen with 20 mm cover have LCC of about 7% and 1.6% higher than the 30 mm concrete cover beam after ½ and 1 hr. fire duration, respectively. it can be clearly shown that increasing fire duration resulted in reducing the effect of concrete cover on the beam performance. For the strengthening stage, results have shown that the concrete cover has very slight effect on the strengthened specimens, for all fire exposure durations.

By comparing the level of enhancement of the strengthened specimens with the non-strengthened (fire damaged) specimens, tests results have shown that strengthening specimens with 20 mm and 30 mm SIFCON jacket layer improved the performance by a range of 1.67-1.78 times and 2-2.2 times, respectively after a half of an hour exposure duration. On the other hand, for the same level of comparison, strengthening specimens with 20 mm and 30 mm SIFCON jacket layer improved the performance by a about 1.8 times and 2.3 times, respectively after one-hour exposure duration. Figures (14) illustrates the load displacement curves relation for beams subjected to various conditions and strengthening, while Figure (15) compares the LCC values in a bar chart illustration

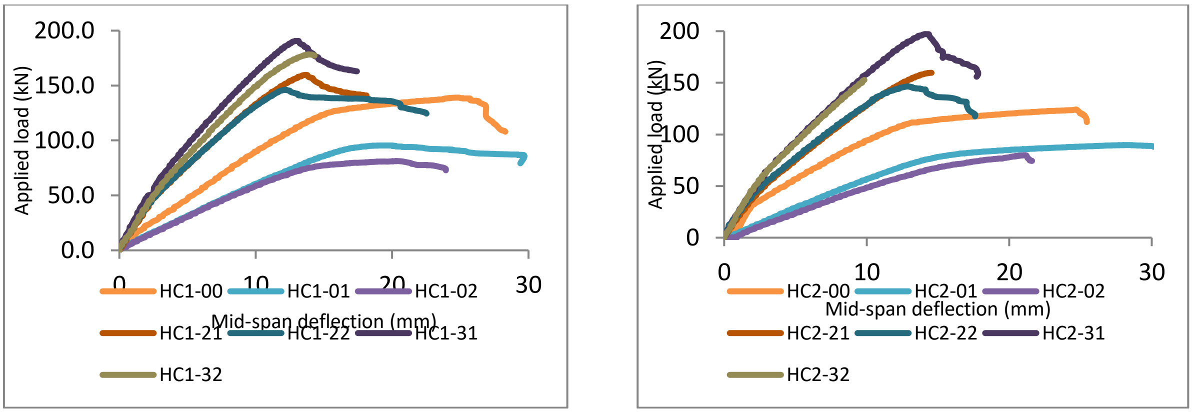


Figure 14. Load versus deflection curve at mid-span of HSC beam specimen with CC of 20mm (left) and 30mm (right) before and after exposure to fire

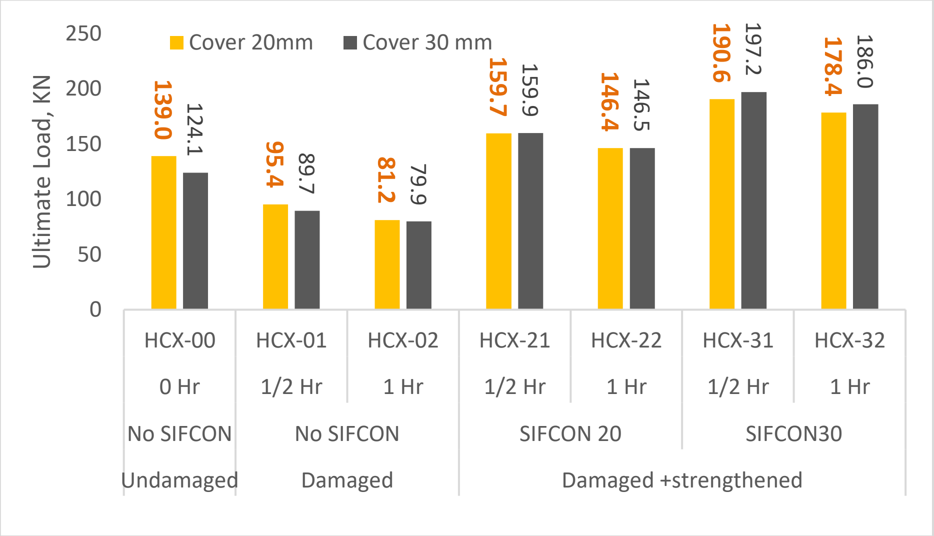


Figure 15. Cracking load capacity values at various locations for all beam phases

The serviceability load capacity (SLC) of various beams' conditions were also captured, as presented in Figure (16). Before fire exposure, the effect of concrete cover on SLC, the undamaged (reference) beams have shown that beams with 20 mm cover have higher SLC than beam's with cover 30 mm by about 47.7%. For the second stage, after fire exposure, specimen with 20 mm cover have SLC of about 4% lower and 15% higher than the 30 mm concrete cover beam after ½ and 1 hr fire duration, respectively. this may back to the thermal conductivity of the concrete. Moreover, before strengthening, when comparing the fire damaged beams with the reference beams, increasing cover thickness resulted in reducing the SLC reduction values, which estimated by about 23% and 9% for ½ hr. and 1 hr., respectively. which means that increasing fire exposure duration resulted in reducing the effect of concrete cover. Figure (17) presents the cracks pattern of beams failure before strengthening. Results have shown that, after ½ hour fire exposure duration, and for each beam covers, increasing SIFCON jacket layer thickness from 20 mm to 30 mm resulted in the same level of improvement of SLC values, which estimated by about 1.35, when compared with the damaged beams. On the other hand, after 1 hour exposure to fire, no observable level of enhancement was noticed when changing SIFCON thickness, for beams with cover 20 mm. while an observable level of enhancement were noticed after changing SIFCON thickness for beams with 30 mm cover, which was estimated by about 1.78 times, when compared with the damaged beams. For the third stage (after strengthening), for beams with cover 20 mm, increasing SICFCON later thickness has no observable effect of SLC values, after 1 hr. exposure to fire. On the other hand, for beams with cover 30 mm, increasing SICON layer thickness resulted in increasing beams level of improvement from 6.7 times to 11.94 times.

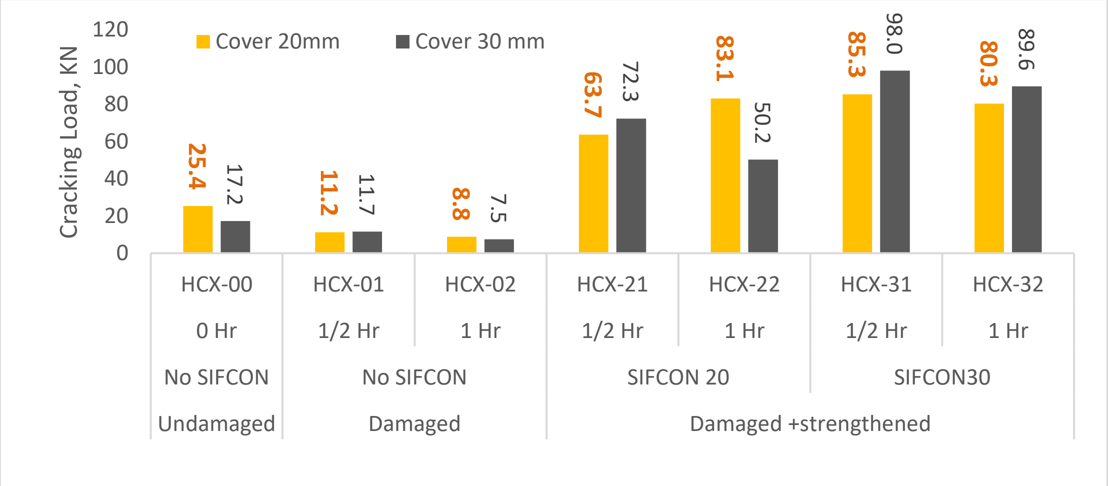


Figure 16. Maximum load carrying capacity values for all beams' phases

Figure 17. Failure of beam without strengthening of SIFCON jacket

For the maximum mid-span deflection (MMSD) corresponded to the maximum LCC, as presented in Figure (18), applying 1 hr. fire exposure duration resulted in reducing MMSD value by about 18.5%, for both of the used covers. After strengthening, beams with 20 and 30 mm SIFCON layer thickness reflected lower MMSD value by about 40% and 32%, respectively. which means, increasing SIFCON layer thickness by 10 mm resulted in reducing MMSD value by about 8%. Table (7) shows beam's deflections at different locations and for various conditions.

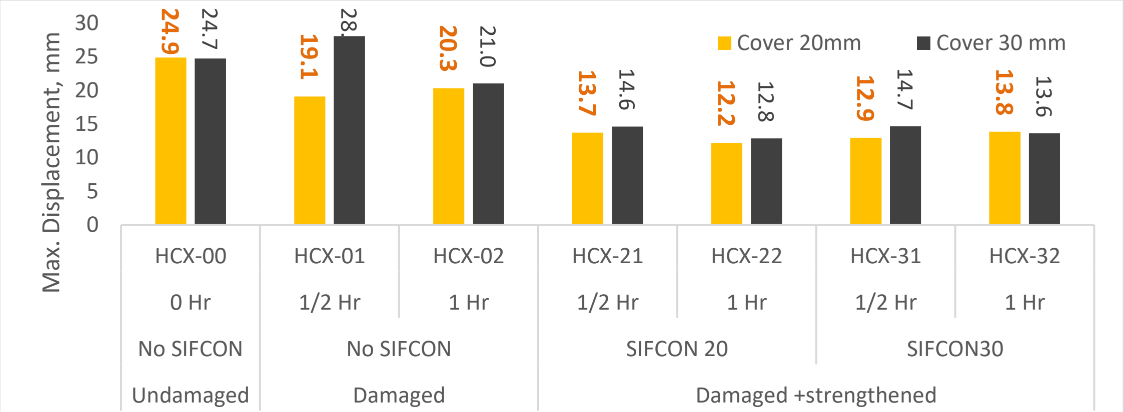


Figure 18. Mid-span displacement corresponded to the maximum load carrying values

Table 7. Load carrying capacity, cracking load, and displacement values at various beam locations

Specimen Identification	**Frist Crack Load (kN)**	**Ultimate Load (kN)**	**Max Deflection at Mid-span (mm)**	**Max Deflection at 2.5d span (mm) hinge support side.**	**Max Deflection at 2.5d span (mm) roller support side.**
HC1-00	**25.4**	**139**	**24.87**	**22.41**	**21.05**
HC1-01	11.2	95.44	19.09	16.89	16.25
HC1-02	8.8	81.23	20.31	18.65	15.39
HC1-21	63.7	159.70	13.69	13.00	11.91
HC1-22	83.1	146.40	12.19	10.79	10.59
HC1-31	85.3	190.60	12.93	11.84	9.57
HC1-32	80.3	178.40	13.84	12.21	12.62
HC2-00	**17.2**	**124.08**	**24.73**	**22.09**	**21.68**
HC2-01	11.68	89.70	28.04	25.48	20.39
HC2-02	7.5	79.88	21.04	19.25	17.21
HC2-21	72.3	159.90	14.63	13.09	11.13
HC2-22	50.2	146.50	12.83	10.88	10.38
HC2-31	98	197.20	14.67	12.44	12.04
HC2-32	89.6	186.00	13.59	12.23	11.96

3.4. Initial and secant stiffness

The stiffness of a beam is defined as the load necessary to cause a unit deflection of the beam. As shown in Figure (19), the secant and initial stiffness after burning at various exposure durations decreased dramatically with increasing fire temperature level, and the drop in stiffness is accompanied by a reduction in load carrying capacity. The secant stiffness dropped from 100% at room temperature to approximately (71 and 75%) after burning (1 hr.) at 600°C, with concrete cover (20 and 30 mm) respectively. After repairing with SIFCON jacket, the specimens with 30mm jacket shows stiffness value higher than cover 20mm. Also, the repairing specimens got stiffness value higher than control specimens in all cases as shown in the table (8). Also, Figure (20) illustrates the secant stiffness results of specimens under various conditions.

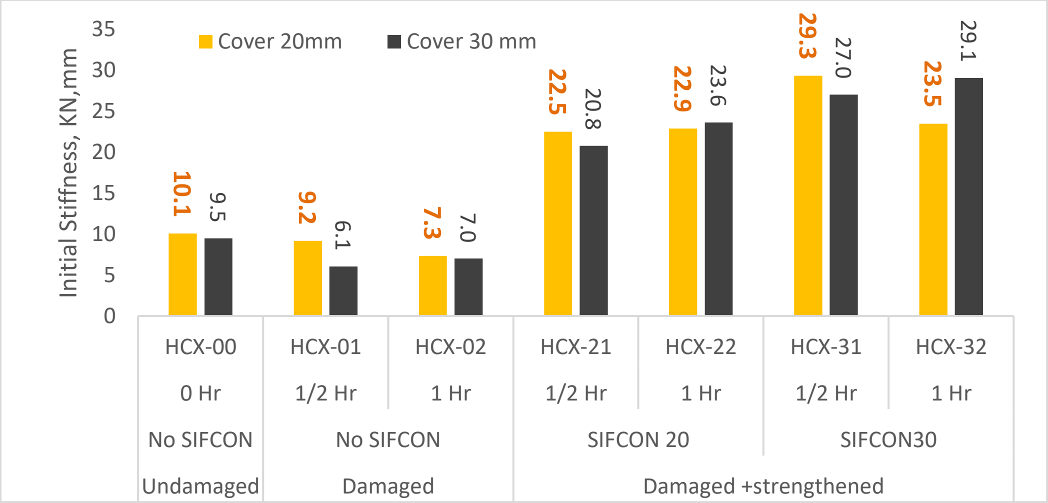


Figure 19. Initial stiffness results of beams before and after fire exposure and strengthening

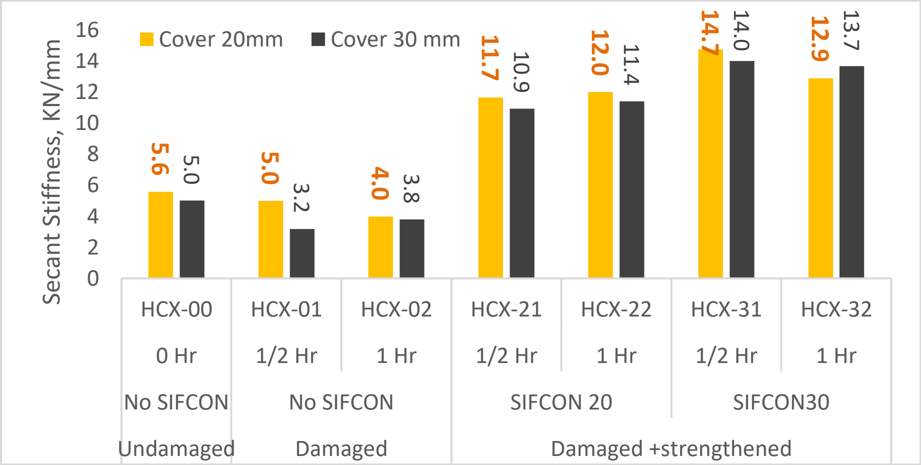


Figure 20. Secant stiffness results of beams before and after fire exposure and strengthening

Table 8. Secant and initial stiffness test results of HSC LWC beam specimens

Specimen	**Secant Stiffness**			**Initial Stiffness**		
	Pu	**Δu**	**KN/mm**	**Pu**	**Δy**	**kN/mm**
HC1-00	139	24.87	5.58	139	13.8	10.07
HC1-01	95.44	19.09	4.99	95.44	10.4	9.18
HC1-02	81.23	20.31	3.99	81.23	11.1	7.32
HC1-21	159.7	13.69	11.66	159.7	7.1	22.49
HC1-22	146.4	12.19	12	146.4	6.4	22.88

Specimen	Secant Stiffness			Initial Stiffness		
	Pu	Δu	KN/mm	Pu	Δy	kN/mm
HC1-31	190.6	12.93	14.74	190.6	6.5	29.32
HC1-32	178.4	13.84	12.89	178.4	7.6	23.47
HC2-00	124.08	24.73	5.01	124.08	13.1	9.47
HC2-01	89.7	28.04	3.19	89.7	14.8	6.06
HC2-02	79.88	21.04	3.79	79.88	11.4	7.01
HC2-21	159.9	14.63	10.92	159.9	7.7	20.77
HC2-22	146.5	12.83	11.41	146.5	6.2	23.63
HC2-31	197.2	14.07	14.01	197.2	7.3	27.01
HC2-32	186	13.59	13.68	186	6.4	29.06

3.5. Absorption energy

The concrete beam's energy absorption capascity can be defined as the area under the load-displacement curve until the maximum load is attained, which shows the energy absorption of the concrete beam that might be sustained before exhibiting a significant decline in load carrying capacity. Previous research found that energy absorption capacity is the most appropriate indicator of concrete structures not only for its structural response against earthquake motion, but also for concrete structures that must withstand fires and impact loads produced by events or terrorist attacks

Figure (21) shows the results of the energy absorption of beams before and after fire exposure, and after strengthening. It is also demonstrated that HSC severely affected after 1 hr burning at 600 ºC. According to the results, the absorption energy of damaged concrete beams, after 1-hour duration exposure to fire, was reduced by about 54% and 56%, respectively for beams with cover 20mm and 30 mm, when compared with the undamaged beam. on the other hand, strengthening of damaged beams with 20 mm and 30 mm SFICON jacket thickness resulted in an improvement of the energy absorption by about 17.9% and 38.4% for concrete cover of 20 mm, and by about 40% and 54% for 30 mm concrete cover, respectively compared with the damaged beams. Table (9). The results of energy absorption capacity HSC lightweight concrete beams before firing, after fire exposure, and after strengthening the damaged samples.

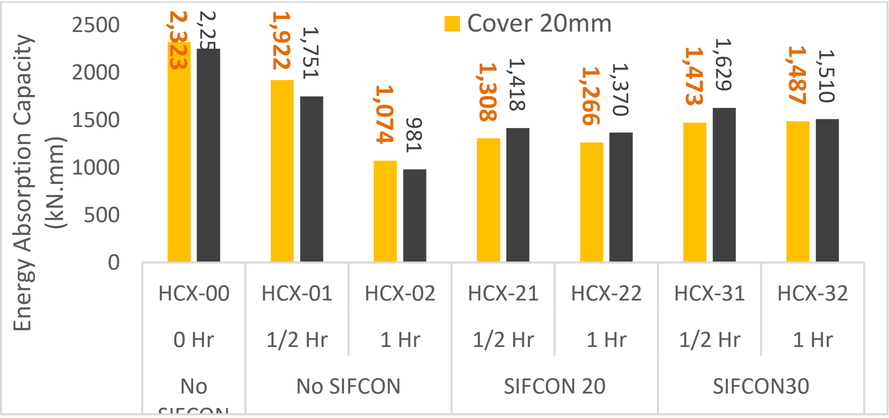


Figure 21. Energy absorption results of beams before and after fire exposure and strengthening

Table 9. Absorption energy result of various beam specimens before and after fire

Specimen Identification	Energy Absorption Capacity (kN.mm)
HC1-00	2323.0
HC1-01	1921.91
HC1-02	1073.7
HC1-21	1308.0
HC1-22	1265.6
HC1-31	1473.4

Specimen Identification	Energy Absorption Capacity (kN.mm)
HC1-32	1486.5
HC2-00	2251.1
HC2-01	1751.06
HC2-02	980.50
HC2-21	1417.60
HC2-22	1369.70
HC2-31	1628.60
HC2-32	1509.70

3.6. Ductility index

The results of beams show that the ductility index not effected by burning. On the contrary, a slight increase was observed. Where for beams that exposed to (0.5 hr.) with concrete cover (20 and 30 mm) shows increase in ductility index of (1.8% and 0.37%) and increase (1.6%) for cover 20mm and decrease of (2.17%) after exposed to (1.0 hr.). The results of ductility index were between 1.717 and 2.284 for the tested beam specimens before and after burning. The experimental results have cleared that a 1 hour fire damage has a negligible effect on the ductility index, for both concrete covers. While strengthening of damaged beam resulted in improving the ductility index by about 5% and 14% for beam with 20 mm and 30 mm concrete cover, respectively compared with the unstrengthen members. On the other hand, the ductility index was enhanced by about 14% and 11% for 20 and 30 mm concrete cover, respectively when comparing the strengthened beams with the undamaged (reference) beam, as can be seen in Figure (22).

In general, a high ductility index indicates that a structural member can withstand considerable deformations before failing. For beams with ductility indexes ranging from 3 to 5, appropriate ductility is deemed essential, particularly in the fields of seismic design and moment redistribution.

Overall , The Experimental results have cleared that a 1 hour fire damage has a negligible effect on the ductility index, for both concrete covers. While strengthening of damaged beam resulted in improving the ductility index by about 5% and 14% for beam with 20 mm and 30 mm concrete cover, respectively compared with the unstrengthen members. On the other hand, the ductility index was enhanced by about 14% and 11% for 20 and 30 mm concrete cover, respectively when comparing the strengthened beams with the undamaged (reference) beam. Table (10) presents the results of yield deflection, ultimate deflection, and the ductility index values of specimens under various conditions.

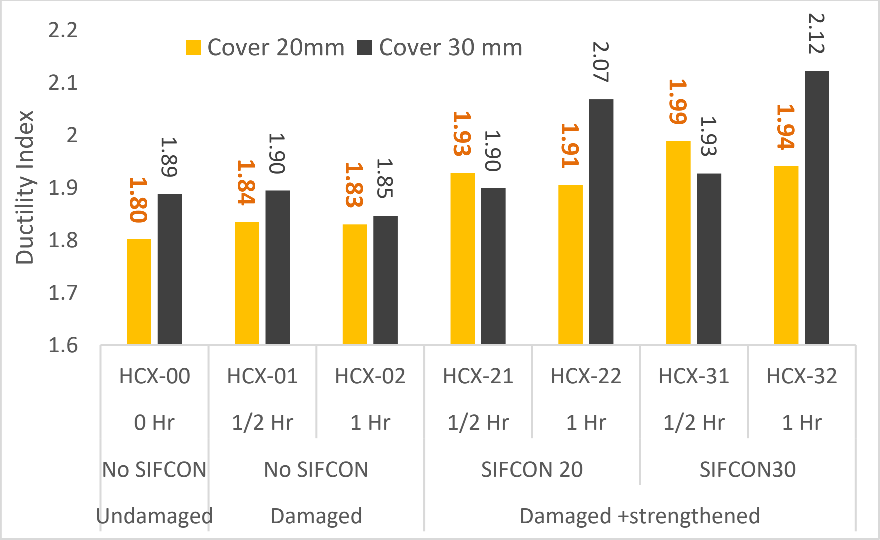


Figure 22. Initial stiffness results of beams before and after fire exposure and strengthening

Table 10. Ductility Index of HSC LWC beam specimens before and after exposed to fire flame

Specimen Identification	Yield deflection Δy in mm	Ultimate deflection Δu in mm	Ductility Index

			$\mu = \frac{\mathbf{\Delta u}}{\Delta y}$
HC1-00	13.8	24.87	1.802
HC1-01	10.4	19.09	1.835
HC1-02	11.1	20.31	1.830
HC1-21	7.1	13.69	1.928
HC1-22	6.4	12.19	1.905
HC1-31	6.5	12.93	1.989
HC1-32	7.6	13.84	1.941
HC2-00	13.1	24.73	1.888
HC2-01	14.8	28.04	1.895
HC2-02	11.4	21.04	1.847
HC2-21	7.7	14.63	1.900
HC2-22	6.2	12.83	2.069
HC2-31	7.3	14.07	1.927
HC2-32	6.4	13.59	2.123

4. Conclusions

This study investigates the level of enhancement of fire damaged LECA light weight high strength concrete beams using three sided SIFCON jacketing layer. Fire duration exposure concrete cover, in addition to the SIFCON layer thickness were the main parameters of this study. accordingly, the following conclusions were drawn:

1- It has observed that the temperature was varied slightly between the mid and the quarter distances of beam cross section, which was about 16%. While the temperature reduction between the concrete mid core and the steel bar location was about 89%. Overall, temperature gradient reduction between the outer beam surface and the mid core was about 66%.

2- Results have shown that subjecting the concrete beams to a 1-hour firing, resulted in reducing cracking load (service loading) by a range of 57%-65%, when compared with the reference beam. On the other side, strengthening of fire damaged beams with SIFCON jacket layer resulted in a superior improvement ranged between 3.16-3.27 times the reference beam for 20 mm jacket thickness, and 2.86-5.12 times for 30 mm jacket thickness.

3- In terms of shear load capacity, the one-hour fire damaged beams compared with the undamaged beam, have reflected a noticeable reduction of about 41.5% and 35%, respectively for beams with 20 mm and 30 mm concrete cover.

4- Beams' strengthening with SIFCON jacket layer of thickness 20 mm and 30 mm resulted in an improvement in shear load capacity of about 80% and 119% for 20 mm concrete cover, and 83% and 133% for 30 mm concrete cover, respectively compared with the fire damaged beams. It is worth mentioning that the strengthened beams reflected comparable shear load capacity values to the undamaged beam (reference) value, which were found to be 5.3% and 28.3% for jacket layer thicknesses of 20 mm and 30 mm respectively for 20 mm concrete cover. while for the same degree of comparison, the level of enhancement was about 18% and 50% for jacket layer thicknesses of 20 mm and 30 mm, respectively for 30 mm concrete cover.

5- The experimental results have cleared that a 1 hour fire damage has a negligible effect on the ductility index, for both concrete covers. While strengthening of damaged beam resulted in improving the ductility index by about 5% and 14% for beam with 20 mm and 30 mm concrete cover, respectively compared with the unstrengthen members. On the other hand, the ductility index was enhanced by about 14% and 11% for 20 and 30 mm concrete cover, respectively when comparing the strengthened beams with the undamaged (reference) beam.

6- The absorption energy of damaged concrete beams, after 1-hour duration exposure to fire, was reduced by about 54% and 56%, respectively for beams with cover 20mm and 30 mm, when compared with the undamaged beam. on the other hand, strengthening of damaged beams with 20 mm and 30 mm SFICON jacket thickness resulted in an improvement of the energy absorption by about 17.9% and 38.4% for concrete cover of 20 mm, and by about 40% and 54% for 30 mm concrete cover, respectively compared with the damaged beams.

7- Tests results have cleared that when firing samples to 1 hour, the initial stiffness values have reduced by about 26% for both 20 mm and 30 mm cover thickness. On the other hand, the strengthened members have reflected a superior stiffness estimated approximately by about 3 times and 3.5 times the initial stiffness of the damaged members, and about 2.25 and times the undamaged (reference beam) value, respectively for 20 mm and 30 mm concrete cover.

References

[1] K. G. Babu and D. S. Babu, “Behaviour of lightweight expanded polystyrene concrete containing silica fume,” Cem. Concr. Res., vol. 33, no. 5, pp. 755–762, 2003, doi: 10.1016/S0008-8846(02)01055-4.

[2] A. Kiliç, C. D. Atiş, E. Yaşar, and F. Özcan, “High-strength lightweight concrete made with scoria aggregate containing mineral admixtures,” Cem. Concr. Res., vol. 33, no. 10, pp. 1595–1599, 2003, doi: 10.1016/S0008-8846(03)00131-5.

[3] I. B. Topçu and T. Uygunoğlu, “Properties of autoclaved lightweight aggregate concrete,” Build. Environ., vol. 42, no. 12, pp. 4108–4116, 2007, doi: 10.1016/j.buildenv.2006.11.024.

[4] L. Alarcon-Ruiz, G. Platret, E. Massieu, and A. Ehrlacher, “The use of thermal analysis in assessing the effect of temperature on a cement paste,” Cem. Concr. Res., vol. 35, no. 3, pp. 609–613, 2005, doi: 10.1016/j.cemconres.2004.06.015.

[5] R. H. Haddad and L. G. Shannis, “Post-fire behavior of bond between high strength pozzolanic concrete and reinforcing steel,” Constr. Build. Mater., vol. 18, no. 6, pp. 425–435, 2004, doi: 10.1016/j.conbuildmat.2004.03.006.

[6] A. Khalifa and A. Nanni, “Kalifa2002.Pdf,” vol. 16, pp. 135–146, 2002.

[7] A. F. Ashour, S. A. El-Refaie, and S. W. Garrity, “Flexural strengthening of RC continuous beams using CFRP laminates,” Cem. Concr. Compos., vol. 26, no. 7, pp. 765–775, 2004, doi: 10.1016/j.cemconcomp.2003.07.002.

[8] B. B. Adhikary and H. Mutsuyoshi, “Shear strengthening of RC beams with web-bonded continuous steel plates,” Constr. Build. Mater., vol. 20, no. 5, pp. 296–307, 2006, doi: 10.1016/j.conbuildmat.2005.01.026.

[9] J. Zhou and L. Wang, “Repair of fire-damaged reinforced concrete members with axial load: a review,” Sustainability, vol. 11, no. 4, p. 963, 2019.

[10] Y. C. Kog, “Practical Guide for the Assessment and Repair of Fire-Damaged Concrete Building Structures,” Pract. Period. Struct. Des. Constr., vol. 26, no. 2, p. 4021010, 2021.

[11] C. K. Ng and K. H. Tan, “Flexural behaviour of externally prestressed beams. Part I: Analytical model,” Eng. Struct., vol. 28, no. 4, pp. 609–621, 2006.

[12] V. S. Kumar and P. Ariyannan, “Retrofitting of RC beam using SIMCON laminate,” Int. J. Emerg. Technol. Comput. Sci. Electron., vol. 20, no. 3, pp. 219–225, 2016.

[13] M. J. Shannag and R. Al-Rousan, “Shear strengthening of high-strength reinforced concrete beams using fibrous composites,” Mag. Concr. Res., vol. 56, no. 7, pp. 419–428, 2004, doi: 10.1680/macr.2004.56.7.419.

[14] O. Sengul, “Mechanical properties of slurry infiltrated fiber concrete produced with waste steel fibers,” Constr. Build. Mater., vol. 186, pp. 1082–1091, 2018.

[15] P. Deepesh and K. Jayant, “Study of mechanical and durability properties of SIFCON by partial replacement of cement with fly ash as defined by an experimental based approach,” Int. J. Innov. Res. Sci. Technol., vol. 5, no. 5, pp. 8568–8574, 2016.

[16] M. A. Elnono, H. M. Salem, A. M. Farahat, and A. H. Elzanaty, “Use of slurry infiltrated fiber concrete in reinforced concrete corner connections subjected to opening moments,” J. Adv. Concr. Technol., vol. 7, no. 1, pp. 51–59, 2009.

[17] A. S. Ali and Z. Riyadh, “Experimental and Numerical Study on the Effects of Size and type of Steel Fibers on the (SIFCON) Concrete Specimens,” Int. J. Appl. Eng. Res., vol. 13, no. 2, pp. 1344–1353, 2018.

[18] A. M. Hashim and M. M. Kadhum, “Compressive strength and elastic modulus of slurry infiltrated fiber concrete (SIFCON) at high temperature,” Civ. Eng. J., vol. 6, no. 2, pp. 265–275, 2020.

[19] S. Salih, Q. Frayyeh, and M. Ali, “Fresh and some mechanical properties of sifcon containing silica fume,” in MATEC Web of Conferences, 2018, vol. 162, p. 2003.

[20] K. Dagar, “Slurry infiltrated fibrous concrete (SIFCON),” Int. J. Appl. Eng. Technol., vol. 2, no. 2, pp. 99–100, 2012.

[21] S. Saleh and M. M. Kadhum, “Experimental and Numerical Investigation for the Behavior of Hollow Slurry Infiltrated Fibrous Concrete (SIFCON) Columns,” 2015.

[22] M. S. Abdulraheem and M. M. Kadhum, “Effect of Fire Exposed on the Behavior of Reactive Powder Concrete Columns under Concentric Compression Loading,” 2017.