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Experimental Investigation on the Effect of Varying Fiber Mix Proportion on the Mechanical and Thermal Performances of Fiber-Reinforced Self-Compacting Concrete under Hydrocarbon Fire Condition

Noraniza Mohammad Jani [1], Mohammad Shakir Nasif [1,*], Nasir Shafiq [2,*] and Ian Holt [3]

1 Department of Mechanical Engineering, Universiti Teknologi PETRONAS, Seri Iskandar 32610, Perak, Malaysia; nizajani@gmail.com
2 Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, Seri Iskandar 32610, Perak, Malaysia
3 Passive Fire Consult, Kuala Lumpur 50490, Malaysia; ian.holt@passivefireconsult.com
* Correspondence: mohammad.nasif@utp.edu.my (M.S.N.); nasirshafiq@utp.edu.my (N.S.)

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Abstract: This paper presents the experimental analysis of the effects of simulated hydrocarbon fire exposure on the mechanical properties and the heat transmission in fiber-reinforced self-compacting concrete, FR-SCC. For that purpose, 300-mm thick, and 1200-mm square-shaped slabs were cast. Basalt and polyvinyl alcohol (PVA) fibers were added using the content of 1, 1.5, and 2% in self-compacting concrete. For investigating the heat transmission within 300-mm thick slabs, five external thermocouples were installed at the unexposed face to the fire of the slabs. Similarly, eleven internal thermocouples were installed at an interval of 25 mm throughout the slab thickness. It has been found that fibers have shown better insulation than the controlled concrete; the unexposed to fire surface of FR-SCC showed temperatures lower by ten degree Celcius than the controlled concrete. Compressive strength results showed that fiber addition caused a higher reduction in strength because of softening and stiffness reduction due to high-temperature exposure. After 120 min of fire exposure, basalt fibers caused an average reduction of 30% in the compressive strength, and PVA fibers caused an average reduction of 25%. Whereas, the addition of fibers improved the split cylindrical tensile strength even after exposure to 120 min of fire exposure in comparison with the unreinforced samples.

Keywords: fiber-reinforced self-compacting concrete; basalt fibers; PVA fibers; compressive strength; tensile strength; hydrocarbon fire; thermal performance

1. Introduction

Fire is considered as one of the hazards that can substantially affect the integrity of the building that causes serious harm to human life and damage to the property. Ignition of hydrocarbon-based fuel is one of the common causes of high-intensity fire. Such types of fire experience a rapid rise in temperature from the flashover stage to about 1100 °C in just a few minutes [1,2]. In such circumstances, the fire can cause severe damages to urban structures such as buildings, and hence, many lives may be affected. Various codes, such as ISO, have also specified the procedure for simulating the standard time–temperature relationship in the form of fire curves for different causes of fire, such as cellulosic and hydrocarbon fire curves. These standard fire curves are referred to in researching developing new passive materials as well as used by structural engineers for design and specification. In modern buildings, concrete is the most widely used material. Therefore, since the beginning of this century, advancements in the form and properties of concrete have been made.

In a closed environment such as in industrial buildings, when a combustible material ignites, some other similar materials in the vicinity could also become part of the fire load to the building. In such situations, concrete acts as an insulator and resists heat transfer among different compartments [3,4]. Therefore, concrete members are required to be designed to resist anticipated fire load. Although concrete has excellent fire endurance characteristics, it also has limits to its fire resistance and tolerance to high temperature. When concrete is subjected to beyond the limiting temperature regime, its properties and strength may be degraded [3,5].

In the case of a reinforced concrete member, the effects of heat on the embedded steel reinforcement result in an expansion of the embedded steel bars. Hence, loss of bond around the steel and concrete surface occurs, which causes massive spalling of concrete. Structural members are designed to satisfy the requirements of ultimate and serviceability limit states for various specified conditions [6]. Therefore, analyzing the fire endurance of a given concrete and improving its performance, if needed, is becoming a field of interest for many researchers.

In such efforts, concrete mechanical and thermal properties have been significantly enhanced using various types of admixtures and additives. For example, the inclusion of discrete fiber improves the tensile, post-cracking, and durability properties of concrete. This type of concrete is called fiber-reinforced concrete or FRC. FRC also increases in elastic deflection or ductility, elastic modulus, and energy dissipation. There are various kinds of fibers used in many FRC designs; such as metallic, synthetic, and natural fibers. In the 1990s in Japan, another form of concrete called self-compacting concrete, SCC, was developed, which can flow and consolidate by itself without the aid of mechanical compaction and placement technique. In some research studies, researchers have focused on investigating the performance of fiber-reinforced SCC or FR-SCC [7]. In such studies, research was focused on investigating the effects of metallic, synthetic, or natural fibers on the mechanical properties of SCC [7–9]. However, minimal research work is available on evaluating the performance of FR-SCC subjected to fire.

Mohamed Salih [7] did an experimental study on FR-SCC using basalt and polyvinyl alcohol (PVA) fibers. The mechanical properties of such FR-SCC have shown promising enhancement in the mechanical and structural properties of the concrete in ambient conditions. Alonso et al. [10] performed an experimental investigation on FR-SCC under high-temperature conditions. In that study, polypropylene fibers were used, and the temperature limit was limited at 300, 500, and 700 °C. They found that the relative values of compressive strength slightly increased for FR-SCC as compared to SCC without the addition of fibers. However, the indirect strain decreases more quickly for SCC + PPF than SCC when temperature is increased. Mohamed et al. [11] investigated the effects of steel fiber content on the biaxial stress behavior of steel fiber self-compacting concrete. They found that one percent fiber volume content in SCC showed the highest increments in biaxial compression and compression-tension, which were 55% and 84%, respectively, when compared to plain concrete. They attributed the improvement due to the integration of steel fiber.

Jadhav et al. [12] found that using Alkali-Resistance glass fiber and crimped type steel fiber in SCC significantly improved the SCC compressive strength under high temperature (up to 500 °C). Weerasinghe et al. [13] tested large scale flat slabs (3.78 × 4.75 m) under standard fire complying to ISO 834. The research aimed to modify the cover requirements under specified fire rating as specified in the design codes and standards. The slab was made of concrete containing 1% poly fibers and achieved a compressive strength of 39 Mpa after 28 days curing. During testing, the slab was partially restrained at the ages. The study reported that the 180-mm thick slabs and the cover to steel reinforcement that were kept at 35 mm sustained more than two hours of fire exposure, whereas the prevailing codes have specified 200 mm slab thickness with 35 mm cover depth for a two-hour fire rating. The transmission of heat inside the concrete depends on various properties of concrete. With the advancement in the composition of concrete and its physical and mechanical properties, it is anticipated that the coefficient of thermal conductivity of concrete would have been significantly changed. Asadi et al. [14] presented a review of the thermal conductivity of concrete. The review has indicated that various factors control the thermal conductivity of concrete. In modern concrete, various types of phase change materials such as fibers in concrete also affect the thermal properties.

It has been argued in many research studies that high-performance concrete is one of the solutions for meeting the new challenges faced by the global construction industry. Fiber-reinforced self-compacting concrete is considered in the category of high-performance concrete; however, very little research is available in the literature as reported after an extensive review made by Salari et al. [15]. All previous studies showed that research on fiber-reinforced used steel and GFRP fibers as the popular types for investigating the effects of curing conditions and the density of concrete. In contrast, many types of fibers, such as PVA and basalt, are also available on the market. Similarly, Al-Hadithi and Hilal [16] discussed the possibility of adding waste plastic fibers in the self-compacting concrete.

As seen, past research on FR-SCC behavior under high temperatures found that the strength of FR-SCC may be affected by the type of fiber used. However, and to the authors' best knowledge, minimal research has been done on the effect of fire on FR-SCC strength, which is very important and benefits buildings, researchers, and designers. Hence, the principal aim of this research was to assess the strength and thermal performance of FR-SCC (FR mixed with PVA and Basalt fibers) subjected to hydrocarbon fire conditions. For that purpose, a simulated hydrocarbon regime was developed using standard hydrocarbon fire curves. The effects of hydrocarbon fire on the compressive and split tensile strength of FR-SCC and plain SCC was investigated in the simulated condition. Hydrocarbon fire was used because some industrial buildings may contain hydrocarbon fuels that make concrete exposed to hydrocarbon fires. The study is significant for the application of fiber reinforced concrete for various kinds of retrofitting and repair jobs, such as bridge decks and process industry floors, which have a high risk of being exposed to the hydrocarbon fire.

2. Standard Fire Tests

Concrete structural members may be exposed to different types of fires and subjected to different intensities during service life [6]. In a standard fire test, structural members (beams, slabs, prisms) are exposed to a controlled fire condition in a specially constructed furnace. Fire intensity and the rate is defined in various codes and standards for evaluating any structural element. Fire intensity and the rate at any specific time are defined with the help of time–temperature curves, which are called standard fire curves. The purpose of conducting a fire test is to determine the time duration for the endurance of fire by a structural element within the prescribed limits (maximum allowable strength).

During exposure to fire, the temperature gradient in the test specimen is obtained by measuring the temperature from the exposed surface and inner part of the specimen by installing thermocouples. The selection of the standard fire curve depends on the application of structure and intensity and type of fire that the building may receive. The most common standard fire curves are used for structural testing are ISO 834 [17] and ASTM E119 [18] standard fires. Hydrocarbon standard fire is also used to investigate the effects of high-intensity fire on structures. Figure 1 shows the time-temperature curves for the most commonly used standard fire test.

Hydrocarbon fire occurs due to the burning of hydrocarbon-based fuel. In fire protection studies, hydrocarbon fire is usually referred to as fire with a high-temperature rate, which means that hydrocarbon fire achieves peak temperature very quickly. It takes only 8 min to achieve 900 °C, as shown in Figure 1. Usually, ASTM E1529 [19] standard is used to determine structural member fire performance under hydrocarbon fire. The rapid increase in temperature is hazardous, especially for a brittle material like concrete. High temperature develops a high amount of pore pressure, which can exert on the concrete in the cover zone and hence cause spalling [20].

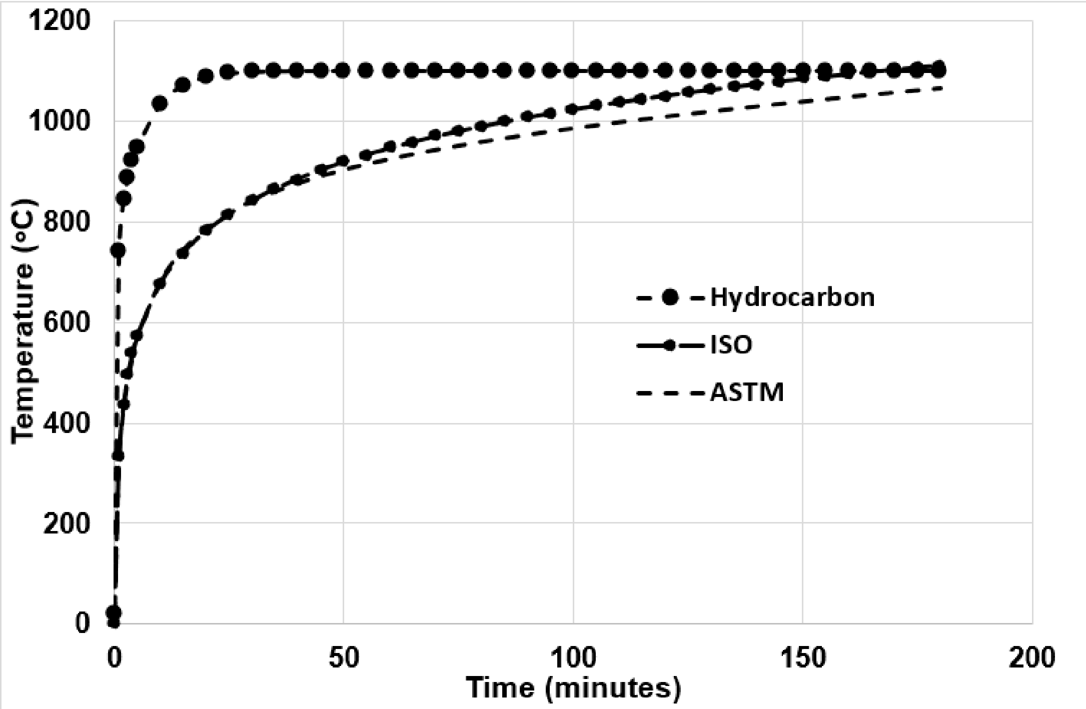


Figure 1. Standard fire curves.

3. Material and Properties, Specimen Casting, and Testing

3.1. Materials

For this experimental study, ordinary Portland cement type-1 was supplied by YTL Cement Malaysia, and it complied with the requirements of the Malaysian Standard MS 522: Part 1: 1989. Natural sand obtained from the state of Perak-Malaysia was used as the fine aggregate; the nominal diameter was less than 5 mm. Crushed granite stones as coarse aggregate were acquired from a quarry in the state of Perak, Malaysia.

In this study, two types of fibers; polyvinyl alcohol, PVA and basalt, BF fibers, for fiber reinforcement. Properties of fibers are detailed in Table 1, which were supplied by the fiber supplier in Malaysia. Sika® ViscoCrete® 250MP is a high range water reducer, and it was used as a superplasticizer for achieving a high slump of SCC. It complied with the requirements of BS EN 934-2, a yellow liquid of modified polycarboxylate chemical content, and having a density of 1.06 kg/L and a pH value of 4.5 ± 0.5.

Table 1. Properties of Fibers.

Fiber Characteristics	Basalt Fiber	Polyvinyl Alcohol (PVA) Fiber
Length (mm)	25.0 mm	30.0 mm
Diameter (mm)	0.00018 (0.18 μm) (138.89 aspect ratio)	0.70
Density (g/cm^3)	4100 to 4840	400
Tensile strength (MPa)	3200	455
Elastic Modulus (MPa)	100 to 110	24 to 40
Color	dark brown	milky white

3.2. Mix Design

The mix design for this experimental program was selected from earlier research [7]. Details of mix design are given in Table 2.

Table 2. Concrete Mix Design Details.

Mix Type	Cement	Fine Aggregate	Coarse Aggregate	Water	Superplasticizer	Fiber	W/C
	Kg/m^3	Kg/m^3	Kg/m^3	Kg/m^3	%	%	
M1-0F	600	900	750	200	2	0	0.34
M2-1BF	600	900	750	200	2	1	0.34
M3-1.5BF	600	900	750	200	2	1.5	0.34
M4-2BF	600	900	750	200	2	2	0.34
M5-1PF	600	900	750	200	2	1	0.34
M6-1.5PF	600	900	750	200	2	1.5	0.34
M7-2PF	600	900	750	200	2	2	0.34

Note: BF is Basalt fibers, PF is PVA fibers, W/C is water to cement ratio.

3.2.1. Mixing of Concrete, Preparation, and Casting of Specimens

(1) Formwork Preparation for Slab Casting

Concrete slabs 1200 × 1200 mm in plan and 300 mm thick were prepared for exposure to fire in a furnace. From these slabs, cylindrical samples were cored (before and after exposure to fire) for compressive strength and split slender test. Before the casting of concrete thermocouples were installed, as shown in Figure 2, for monitoring the temperature change at different location and depth of the slab. There were five external thermocouples installed at the surface of the slab, which was not exposed to fire; the location of the thermocouples is shown in Figure 3, external thermocouples are indicated as TE1 to TE5.

Figure 2. Formwork for 1200 × 1200 × 300 mm slab casting and thermocouples.

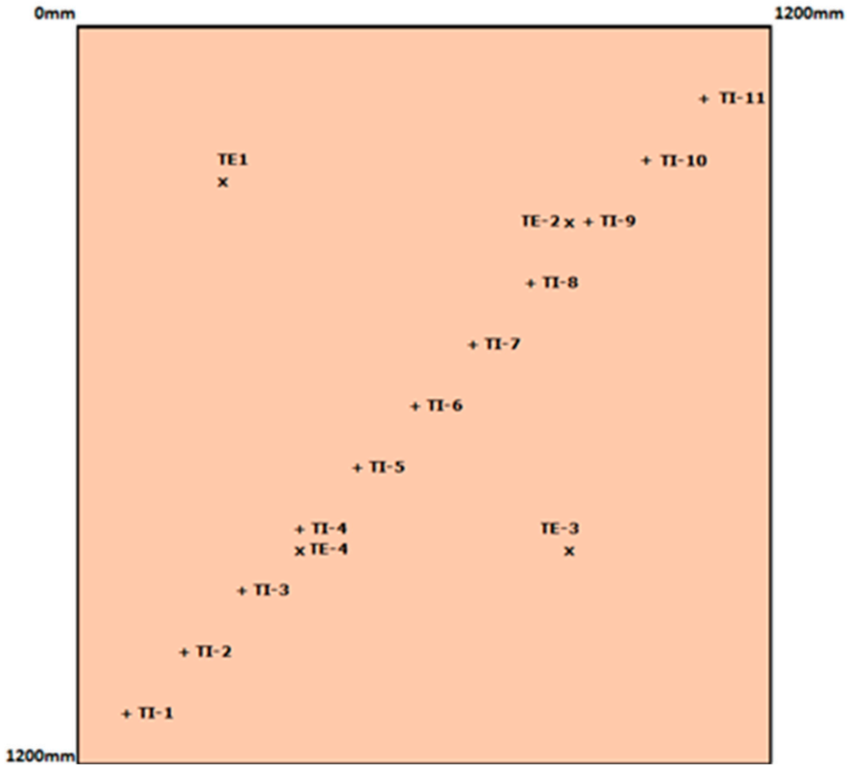


Figure 3. Location of external (TE) and internal (TI) thermocouples.

Similarly, there were 11 internal thermocouples installed at an interval of 25 mm with the thickness of the slab (300 mm thick), these are indicated as TI1 to TI11 in Figure 3. TI1 was installed 25 mm below the surface of the slab that was not exposed to the fire. The thermocouple, TI11, was installed 25 mm below the surface of the slab, which was exposed to fire. Therefore, all 11 internal thermocouples were installed in a sequence from TI1 to TI11.

3.2.2. Mixing and Casting of Concrete

A 100-kg capacity portable concrete mixer was used for concrete mixing. The fine aggregates and the coarse aggregates were mixed with water for 2 min. Then the cement was added to the water aggregates mix and mixed for 3 min; after thorough mixing, fibers were added and mixed for another 3 min. Since the aim was to develop self-compacting concrete, therefore, after mixing every batch of concrete, specified tests on fresh concrete were performed. Three tests were performed; slump flow test, V-funnel test, and L-box test, as previously discussed by [21,22]. Figure 4 shows the fresh concrete test results, which were conforming for the qualification of SCC, as discussed by [21,22]. After performing the test, concrete was poured in the formwork and left in the formwork for 24 h, after that, slabs were stripped out from the form and left for 90 days in the ambient conditions (room temperature) for curing. For ensuring the quality of concrete, 100-mm size cubes were cast for compressive strength tests at the age of 3, 28, and 90 days. It is the standard test used for the qualification of any concrete mix.

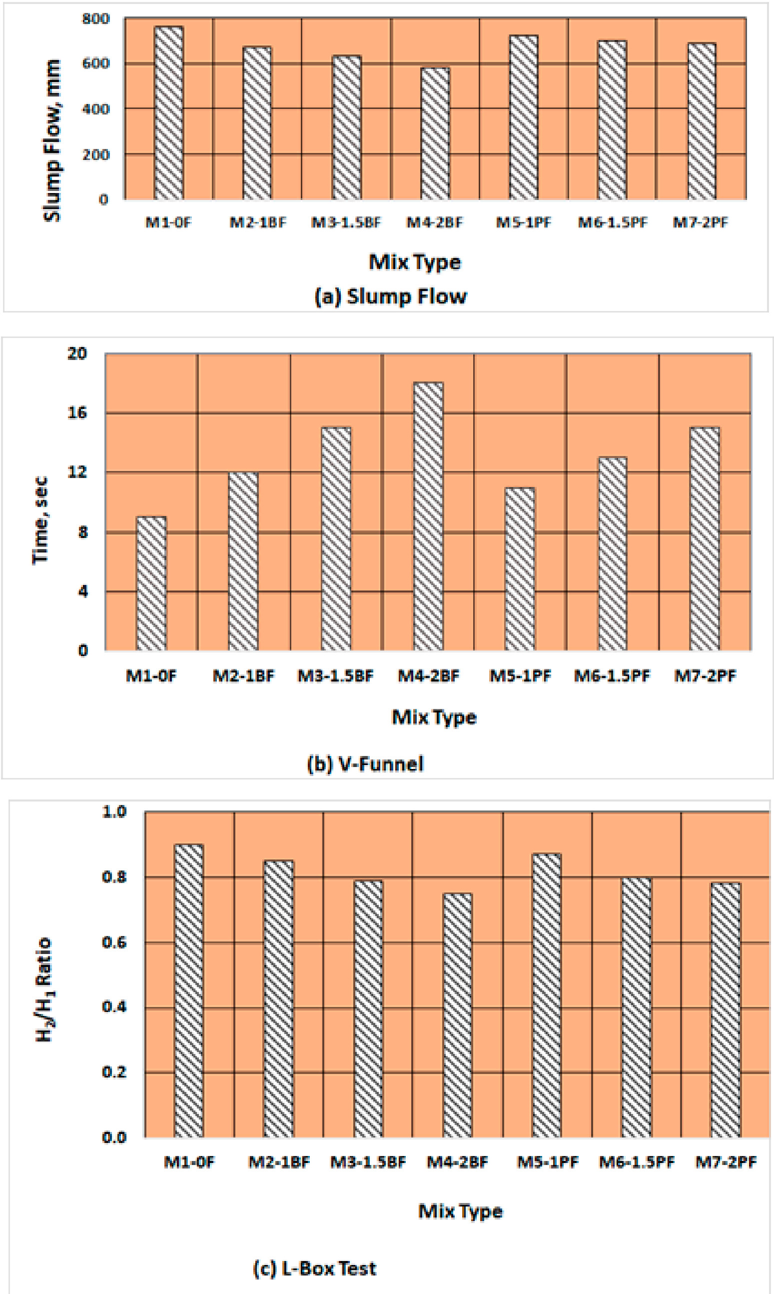


Figure 4. Fresh concrete test results (**a**) slump-flow (**b**) V-funnel (**c**) L-box.

3.3. Fire Exposure Test

After 90 days of curing of the slabs in ambient conditions, they were subjected to fire exposure conditions. The fire exposure test was performed according to the method explained in BS 476-20: 1987 [23]. A fire furnace, as shown in Figure 5, was used, the heating chamber dimensions are 1200 mm high × 1200 mm long × 1200 mm wide. The furnace was equipped with 4 Type-K furnace thermocouples and pressure probe with Siemens PLC (Programmable Logic Control) with proprietary interface software. The slab was placed to cover the horizontal furnace opening of 1200 mm × 1200 mm, as shown in Figure 5. All the thermocouples were connected to PLC before starting the fire resistance testing. For simulating the hydrocarbon fire, the rate of temperature in the furnace followed the procedure defined in BS 476-20: 1987 [23], and the furnace temperature based on the fire curve was recorded as shown in Figure 6, the slabs were exposed to fire for 120 min. As seen in Figure 6, the furnace-measured temperature curves fit well with the hydrocarbon fire curve, which indicates that the test complied with hydrocarbon fire curve requirements.

Figure 5. Fire test furnace (**a**) Furnace interior (**b**) with slab.

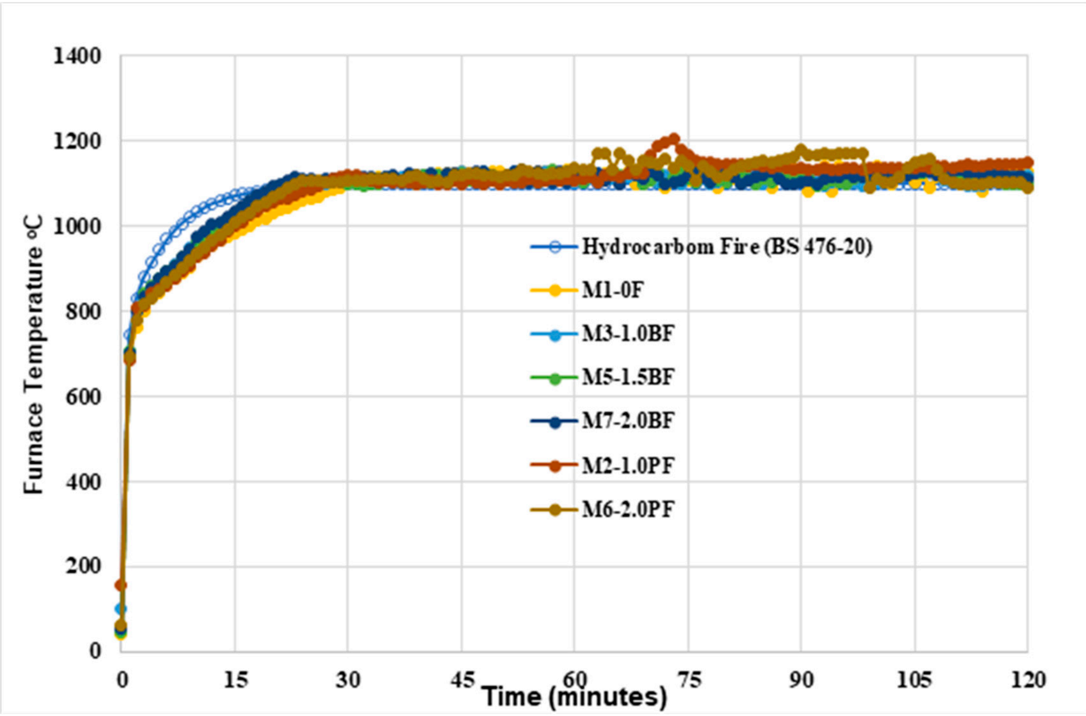


Figure 6. Furnace temperature during the tests of different slabs and standard fire curve for hydrocarbon fire according to BS 476-20: 1987.

4. Results and Discussions

4.1. Performance of Slabs upon Exposure to Fire

When the slabs were exposed to fire in the furnace, internal and external thermocouples data were monitored for determining the heat transfer behavior in different types of slabs. The five external thermocouples were placed at the surface of the slab, which was unexposed to the fire. The purpose of the installation was to assess the insulation characteristics of different slab types; the average reading of all five thermocouples indicated the temperature at the end of 120 min of fire exposure at the non-fire surface of the slab. Fire standards defined insulation as the ability of a media, in this case, concrete slab, to restrict the temperature rise at the unexposed face within the specified level. From this context, insulation failure occurs when the mean temperature of the unexposed surfaces reaches 140 °C above its initial temperature, or if any of the unexposed surface thermocouples records 180 °C above the primary mean temperature of the unexposed face.

Figure 7 shows the temperature of external thermocouples recorded at the end of 120 min of fire exposure in the furnace. This temperature indicates the insulation characteristics of different concrete mixes. Where; TE represents the thermocouple number. In X-axis, M, PF, and BF represent the mix identification number, PVA fiber, and Basalt fiber, respectively. The number associated with BF and PF represents the percentage of fiber in the concrete mix, as listed in Table 2.

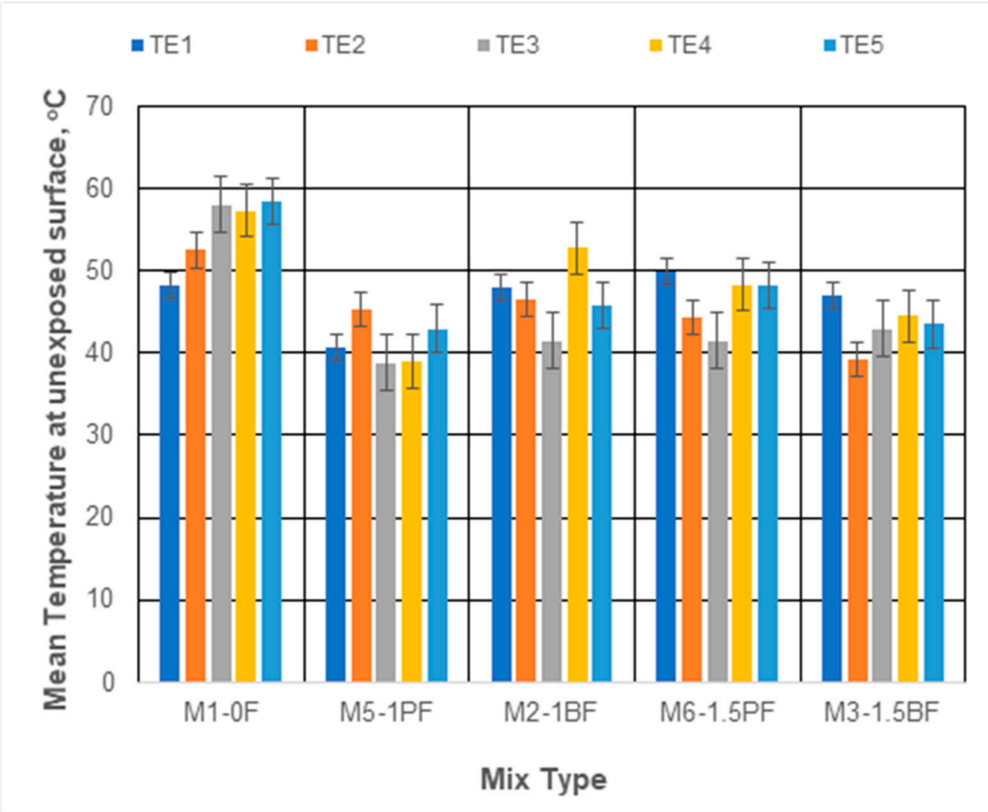


Figure 7. The temperature of external thermocouples measured at 120 min of fire exposure (at the unexposed surface).

It has been found from Figure 7, a concrete slab made of concrete mix M1-0F (slab with no fiber) shows the highest surface temperature from all five thermocouples. The highest temperature was recorded as 58.5 °C, whereas the average of all five thermocouples is 55 °C. It is the control mix that did not include fibers. When basalt and PVA fibers added to concrete, the recorded temperature is reduced at the unexposed surface. The lowest temperature was measured as 38 °C, and the highest obtained was 52 °C, whereas the mean is calculated as 45 °C. It could be concluded that the addition of fibers resulted in an average reduction of 10 °C in the unexposed surface temperature, which may be considered a significant effect. One of the reasons is that both basalt and PVA fibers are excellent heat insulators.

Figure 8 shows the internal thermocouples results, which were installed throughout the thickness of the slab at a 25 mm interval. It is worth mentioning that the location of thermocouples measured from the unexposed surface of the slab, i.e., temperature reading at 25 mm, means it is the farthest point from the fire, whereas 275 mm is the nearest point from the fire. By observing the temperature readings of the internal thermocouples, the entire thickness of a slab can be divided into three zones; near zone, middle zone, and the far zone. The first 100 mm slab thickness at the fireside is called the near zone, the middle zone is the middle 100 mm thick part of the slab, and the far zone is the 100 mm thick part of the slab at the unexposed side.

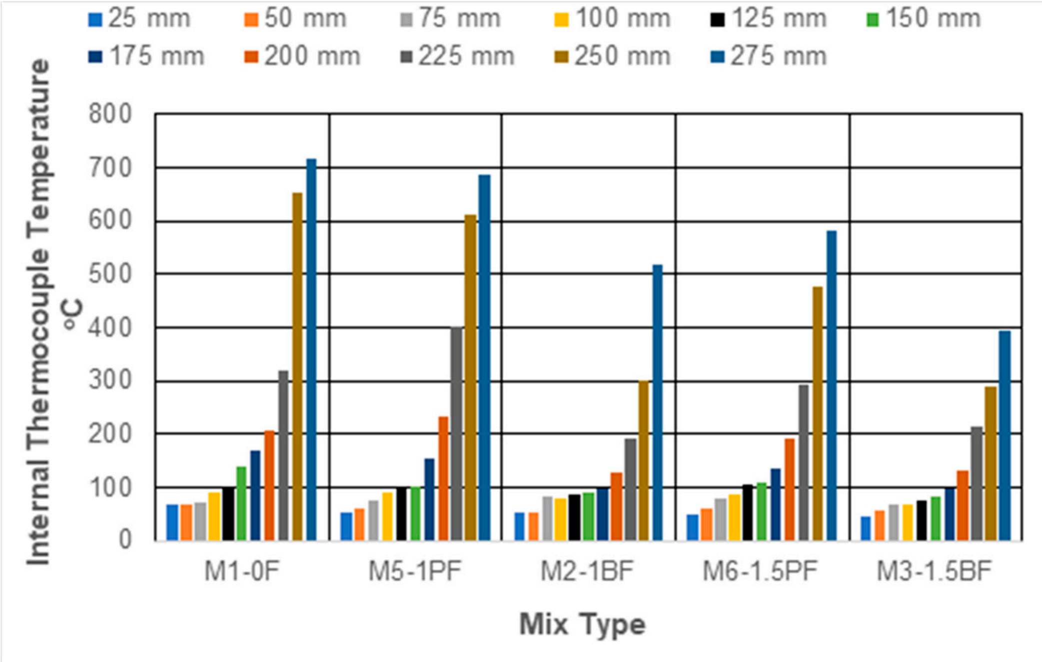


Figure 8. Temperature measurements of internal thermocouples installed at different depth of the slab at the end of 120 min of fire exposure (275 mm thermocouple is nearest to the fire).

Figure 8 shows the temperature distribution within the entire slab thickness for all concrete mixes after 120 min to fire exposure. A common observation is made that the thermocouples within the near zone showed a very high temperature. In contrast, the temperature was drastically dropped within the middle and far zones, which was less than 100 °C. Within the near zone, the first thermocouple at 25 mm from the fire face (275 mm TC) showed very high temperature, i.e., 400 to 700 °C, and the second thermocouple at 50 mm from fire showed 10 to 20% lower temperature than that measured at the first thermocouple.

By comparing the temperature distribution in various concrete mixes, it is observed that the addition of basalt and PVA fibers improved the insulation characteristics; i.e., the first two thermocouples showed 10 to 18% lower temperature as compared to the control mix. Similarly, when comparing basalt and PVA fibers, basalt fibers showed better thermal performance than the PVA fibers, where the temperature decreased by increasing the percentage of fiber in the slab.

Similarly, Figure 9 shows the temperature measurements of internal thermocouple taken after 60 min of exposure to fire. It has shown a similar trend that was observed after 120 min of exposure. In these measurements, the first thermocouple, TC at 25 mm from fire face showed temperature from 600 to 350 °C in all concrete mixes, whereas as the second TC at 50 mm from the fire case showed a decrease in temperature of up to 50% as compared with the temperature measured at the first TC. Also, the third TC at 75 mm from the fire face showed a decrease in temperature of almost 50% as compared to the second TC. The third TC and onwards showed a temperature value of 100 °C or lower.

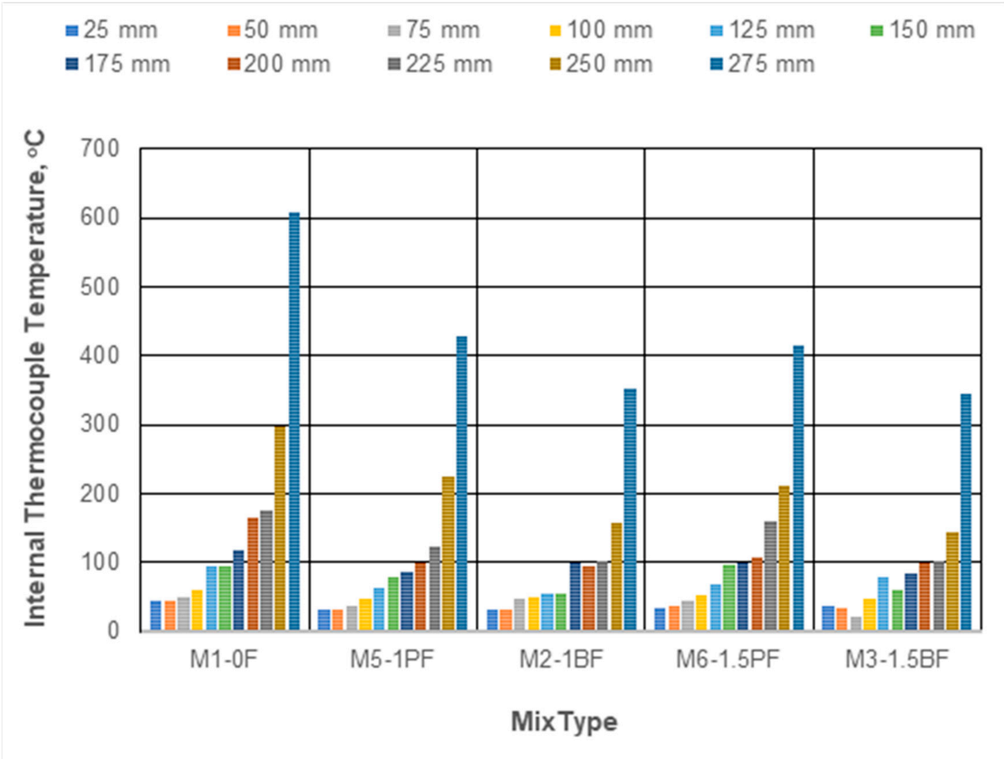


Figure 9. Temperature measurements of internal thermocouples installed at different depth of the slab at the end of 60 min of fire exposure (275 mm thermocouple is nearest to the fire).

4.2. Effects of Fire on Mechanical Properties

4.2.1. Compressive Strength Development

For evaluating the quality of concrete and strength development characteristics of all mixes, cube compressive strength was determined at 3, 28, and 90 days, which is shown in Figure 10.

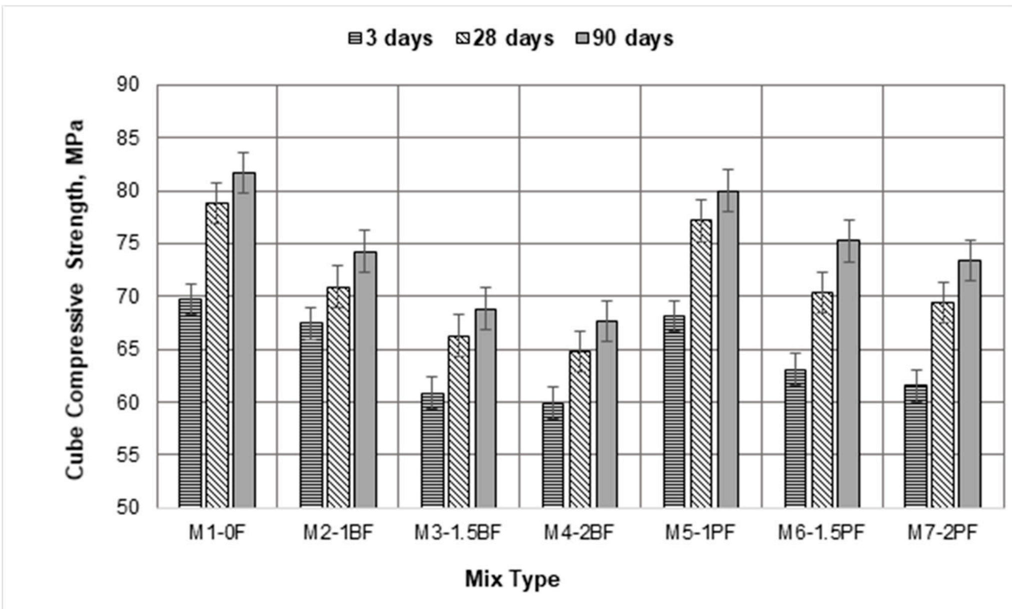


Figure 10. Concrete cube compressive strength measured at 3, 28, and 90 days.

As shown in the figure, it is observed that with the addition of the fibers of either basalt or PVA, the compressive strength of concrete dropped by 4% to 14% at all ages in comparison to the compressive strength of the control mix. Similar observations are reported in the literature [7,8]. The higher reduction (more than 10%) is observed with higher fiber content, i.e., 1.5 and 2% basalt fibers caused 12 and 14% reduction in the compressive strength, respectively. Whereas, the addition of 1.5 and 2% PVA fibers caused 9 and 12% reduction, respectively. The reasons reported in the literature include the formation of the coarser interfacial transition zone, ITZ around the fibers as well as balling effects of fibers during mixing [7,8].

(1) Effects of 120 min of fire exposure on the compressive strength

In this segment of the study, effects of 120 min of a simulated hydrocarbon fire exposure were investigated on the compressive strength of all concrete mixes. For this, 100 mm diameter and 200 mm high cores were taken out from the slabs after 90 days of ambient curing. Three cores were taken from each pair of the slab (the slab not exposed to fire, and the slab exposed to fire). From the slabs exposed to fire, cores were taken from the fire exposure side. A sample of cores taken out from different slabs is shown in Figure 11.

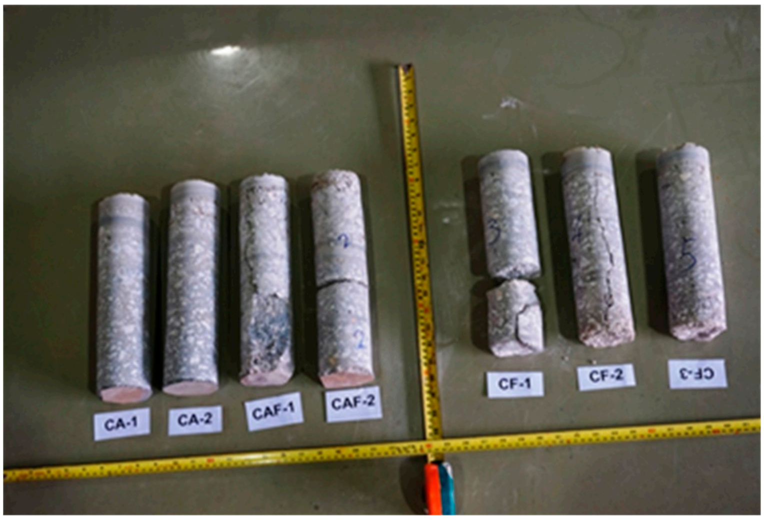


Figure 11. The sample cores, 100 mm in diameter, taken out from slabs.

Compressive strength was conducted according to the requirement of BS-EN 12504-1 [24]. The test was performed using a Universal Testing Machine (UTM) of 1000 kN capacity at a constant loading rate of 2.4 N/mm/s. As suggested by the code [20], the equivalent in-situ compressive strength, f_{ceq} was determined using the following equation:

$$f_{c,eq} = \frac{D}{\left(1.5 + \frac{1}{\lambda}\right)} f_{c.m} \tag{1}$$

where $f_{c,m}$ is the measured compressive strength estimated as the crushing load divided by the core surface area, D is taken as 2.3 for vertically drilled core, and λ is the length to diameter ratio of the core, which is 2 for this case.

Figure 12 showed the compressive strength test ($f_{c,eq}$) of all concrete samples exposed to fire and not expose to fire. It is observed that for all concrete cores, exposure to fire after 120 min has caused a reduction of strength between 21% to 35%. Among all concrete mixes, basalt fiber concrete cores showed the lowest strength. As stated earlier, all slabs were cured for 90 days in the ambient conditions. Basalt fiber (BF) concrete cores (1, 1.5, and 2% fiber content) unexposed to fire showed the compressive strength of 55, 52, and 46 MPa, respectively and the fired samples showed a value of compressive strength of 37, 33, and 32 MPa, whereas the controlled concrete M-0F showed 68 MPa and 54 MPa of strength without and with the exposure of fire, respectively.

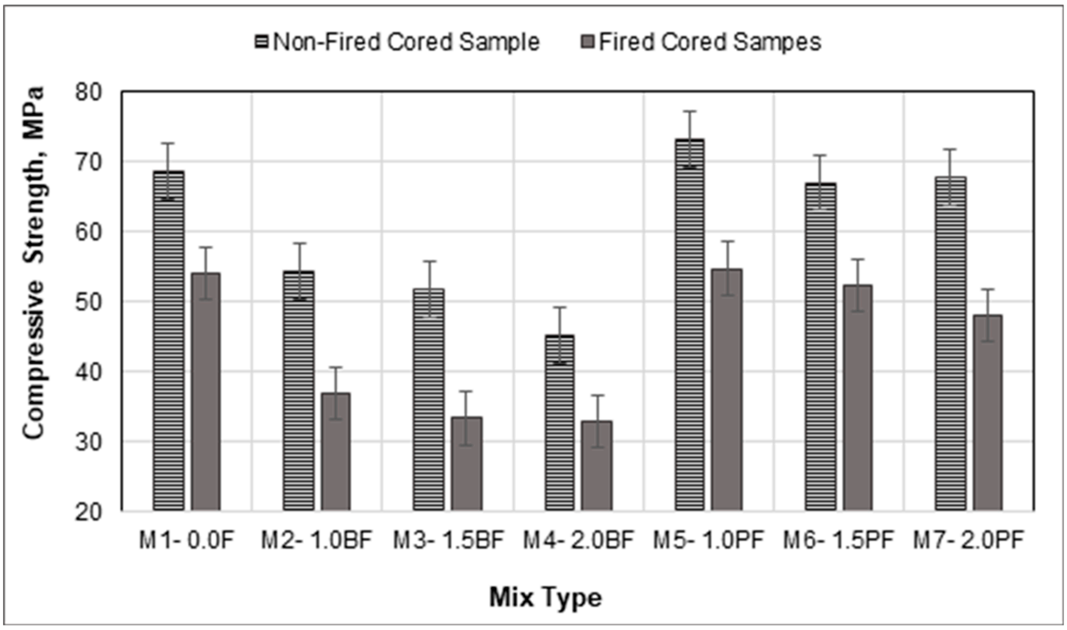


Figure 12. Effects of 120 min of fire exposure on the compressive strength.

Table 3 showed the average reduction in the compressive strength after 120 min of exposure to fire. The lowest reduction in strength (21%) is observed in the controlled concrete mix. Basalt fibers (1, 1.5, and 2% addition) showed an average reduction of 30% in the compressive strength after 120 min of fire exposure. Whereas, PVA fibers (1, 1.5, and 2% addition) showed an average reduction of 25% in the compressive strength after 120 min of fire exposures. The possible reason for the higher reduction in strength in the fiber-reinforced concrete after exposure to fire could be; fibers would have become soften after exposure to high temperatures such as 400 °C or above. The softening of fibers would have resulted in a reduction in stiffness; hence, the strength reduction factor is high in FRC. Because with a reduction in stiffness of fibers, their crack arresting capability is reduced.

Table 3. Reduction in compressive strength after 120 min of fire exposure.

Mix Type	Core Compressive Strength (Mpa) at 90 Days Curing (Average of 3 Samples)		Reduction in Strength (%) (After 120 min of Fire Exposure)
	Unfired Samples	Fired Samples	
M1-0F	68.7	54.2	21.1
M2-1.0BF	54.4	36.9	32.2
M3-1.5BF	51.9	33.4	35.6
M4-2BF	45.3	32.9	27.4
M5-1PF	73.3	54.8	25.2
M6-1.5PF	67.1	52.3	22.1
M7-2.0PF	67.8	48.2	28.9

The test was conducted using a Universal Testing Machine, UTM, and the load was applied at a rate of 0.94 kN/s [25–27]. Figure 13 shows the splitting cylindrical tensile strength of all concrete core samples, which were and were not exposed to fire. In this case-controlled concrete samples showed the lowest strength than the fiber-reinforced sample; the reason is evident that the addition of fibers arrested the cracks. Hence the tensile strength is increased. Table 4 showed a reduction in the split tensile strength of all concrete mixes. In this case, the reduction in strength was reported between 17%

and 27%. As compared to the compressive strength test, strength reduction factor in fiber reinforced concrete is reduced. The reason could be the post elastic characteristics of the fibers has improved even after being softened upon exposure to high temperature.

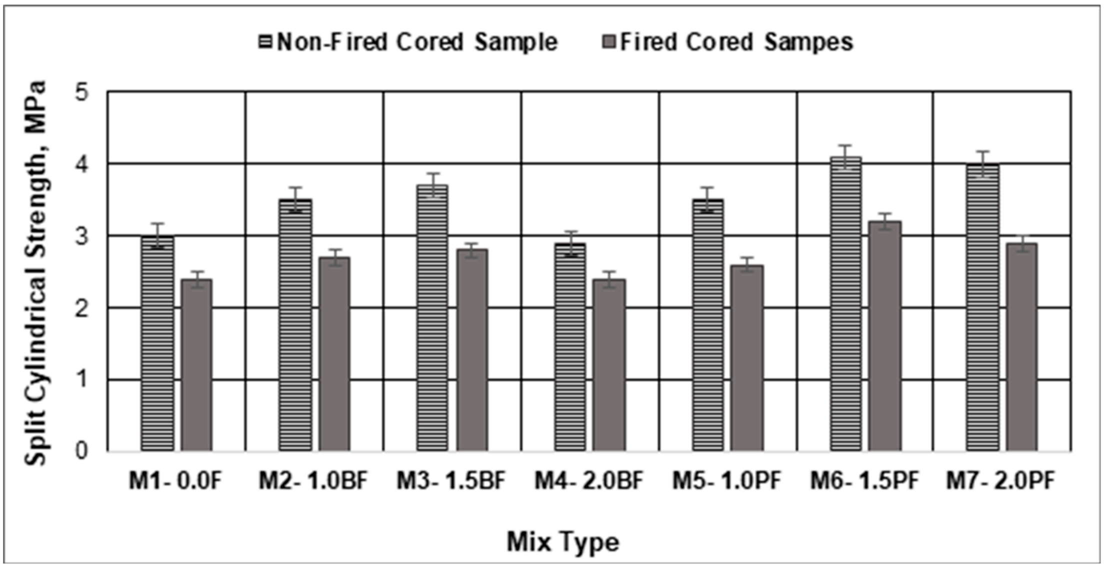


Figure 13. Effects of 120 min of fire exposure on the split cylindrical tensile strength.

Table 4. Reduction in split cylindrical tensile strength.

Mix Type	Split Cylindrical Tensile Strength (Mpa) at 90 Days Curing (Average of 3 Samples)		Reduction in Strength (%) (After 120 min of Fire Exposure)
	Unfired Samples	Fired Samples	
M1-0F	3.0	2.4	20.00
M2-1.0BF	3.5	2.7	22.86
M3-1.5BF	3.7	2.8	24.32
M4-2BF	2.9	2.4	17.24
M5-1PF	3.5	2.6	25.71
M6-1.5PF	4.1	3.2	21.95
M7-2.0PF	4.0	2.9	27.50

(2) Effects of 120 min of fire exposure on the split cylindrical tensile strength

Split cylindrical tensile strength is an indirect tensile strength of concrete for this study 100 mm diameter and 200 mm long cores taken from the slabs that were and were not exposed to fire. The test was carried out by ASTM C496M-04 [25].

4.2.2. Effects of Fire on the Microstructure

In fiber-reinforced concrete, the microstructure of the hydrated product, as well as around the fibers, influences various mechanical and durability properties of the matrix. Therefore, in the study, microstructural analysis of the samples taken from the top of the surface of the slab (the surface directly exposed to fire) was conducted using Hitachi Mode; S-2500 Scanning Electron Microscope (SEM) and Polaron Model SC7620 Sputter Coater. SEM micrographs were obtained using 1000 times magnification of the samples before exposure to fire and after exposure to fire for 120 min in the furnace. The main focus of the interpretation of SEM micrographs was to determine the effects of fire on the microstructure of the matrix around the fibers as well as any changes that happened to fibers after 120 min of exposure to fire.

Figures 14(a1,a2) and 15(a1,a2) showed the effects of fire on FRC containing 1% and 1.5% PF. It can be observed that after 120 min of exposure to fire, a large void area formed (dark black spots around fiber). However, some crystals are formed at the fiber surface. Figures 14(b1,b2) and 15(b1,b2) showed the effects of fire on FRC with 1 and 1.5% BF. It is observed that the outer layer of basalt fiber is restructured, and mineral crystals are formed. In the unfired FRC-BF, the poor interface of basalt fiber in the cement matrix is formed, which may be due to the weak or unbonded nature of the connection between basaltic glass and the cement matrix. It is because a large surface area of basalt fibers was present in the cement paste. This lack of adhesion consequently resulted in the reduction of the compressive strength, as observed in this study. After exposure to 120 min to fire, some distortion (bulging and contraction) in PF can be seen. Whereas, basalt fiber condition after 120 min of fire exposure looked good and undistorted, because the BF melting point is quite high.

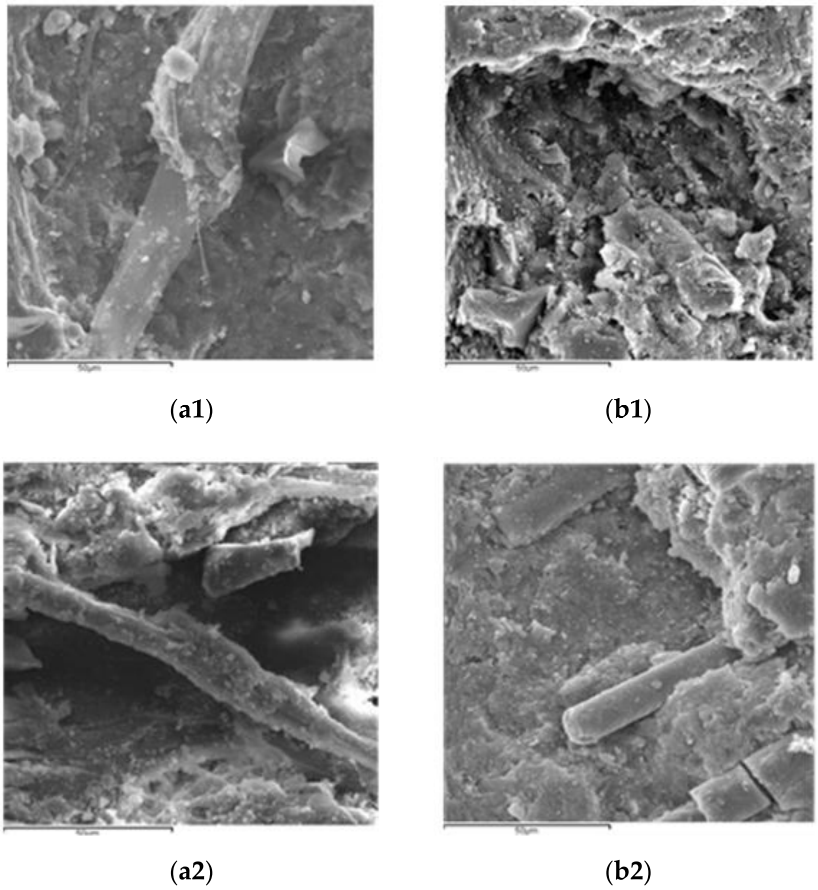


Figure 14. Effects of fire on fiber reinforced concrete, FRC with 1% fiber content, (**a1**) unfired FRC-1%PF, (**a2**) FRC-1%PF after 120 min of fire, (**b1**) unfired FRC-1%BF, (**b2**) FRC-1%BF after 120 min of fire.

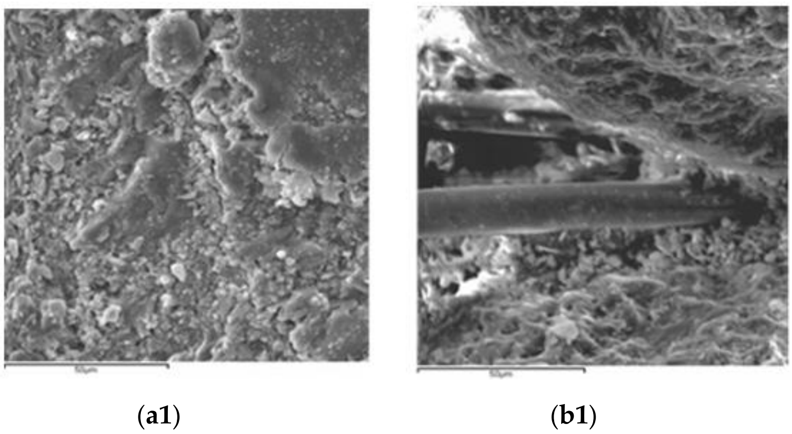
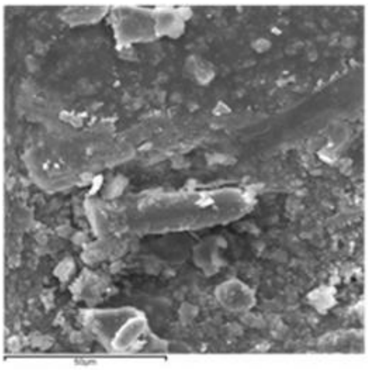
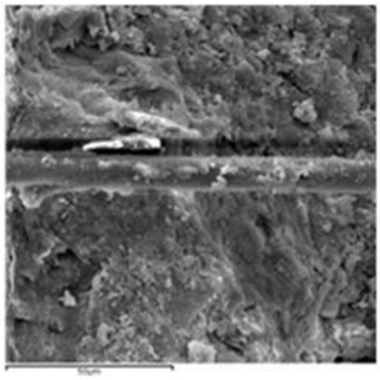


Figure 15. *Cont.*



(**a2**)



(**b2**)

Figure 15. Effects of fire on FRC with 1.5% fiber content, (**a1**) unfired FRC-1.5%PF, (**a2**) FRC-1.5%PF after 120 min of fire, (**b1**) unfired FRC-1.5%BF, (**b2**) FRC-1.5%BF after 120 min of fire.

5. Conclusions

This research investigates Self Compacting Fiber mix concrete slabs' performance under the exposure of hydrocarbon fire, where the addition of PVA and Basalt fiber, under ambient conditions, improves the tensile, post-cracking, and durability properties of concrete. It has been found:

In the temperature measurement of slab sufaces unexposed to fire, it was found that the addition of fibers resulted in an average reduction of ten degrees Celsius in temperature, which may be considered as a significant effect. One of the reasons is that both basalt and PVA fibers are good insulators of heat.

When comparing the temperature distribution within the slab sections after 120 min of fire exposure, it was concluded that the addition of fibers improved the insulation characteristics; i.e., the first two thermocouples (at 25 and 50 mm from the fire face) showed a 10 to 18% lower temperature as compared to the control mix. Similar observations were made after 60 min of fire exposure. It is found that the first 50 mm of slab thickness, which is directly exposing to fire, is most critical for 60 min and 120 min of fire exposure, whereas the rest of the 250 mm thickness of slab experienced 100 °C or below.

It is concluded that the addition of fibers caused a reduction in compressive strength in the range of 4 to 15% compared to the strength of the controlled concrete. After 120 min of exposure to simulated hydrocarbon fire, fiber reinforced concrete resulted in high strength reduction (25 to 38%) compared to the controlled mix (21%). The higher reduction could be due to softening and stiffness reduction in fibers after exposure to high temperature for 120 min.

With the addition of fibers, the split cylindrical tensile strength has improved because of the crack bridging effects of fibers. Similarly, after exposing to 120 min of fire, the samples showed a lower reduction in strength than that observed in the compressive strength test.

Microstructure analysis using SEM showed that after exposure to high temperatures, PVA fibers suffered the peeling of a thin layer from the fiber surface. Whereas, with the use of basalt fibers, at high temperature, mineral crystals are formed on the surface of the fibers. It is also observed that the lower performance of basalt fiber reinforced concrete was due to the weak bond of fibers with cement matrix despite high fire resistance.

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Conflicts of Interest: The authors declare that there is no conflicts of interest.

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