The Combined Impact of Imposed Loads and Elevated Temperature on Steel Fiber Reinforced Concrete Samples

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Abstract. Reinforced concrete buildings and structures are exposed to fire, and the concrete's qualities can vary in the case of an uncontrolled fire. It is essential to know how concrete's properties may change as a result of exposure to high temperatures and loading for normal concrete with or without fiber reinforcement. Understanding the strength characteristics of concrete structures exposed to high temperatures is important in order to be able to predict how these structures will perform after exposure to this condition. This study investigates the combined impact of loading and high temperature on the properties of concrete samples by testing the compressive, flexural strength, and ultrasonic pulse velocity (UPV) of normal-strength concrete (NSC) with or without steel fiber. The type of steel fiber employed in this investigation is hooked-end steel fiber with a 1% volume fraction of concrete. The concrete samples were subjected to four sustained load cases (0, 20, 40, and 60% of ultimate load) and exposed to elevated temperatures (25, 300, and 500°C) for about 2 hours. In addition, using an unrestrictive test before and after loading and heating, the results indicated the maximum deference of compressive strength decreasing is 4% for the steel fiber (SF1) mixture compared with NSC mixture at 300°C for all load cases. While at 60% sustained load and 500°C, the maximum deference of compressive strength decreasing is 12% for the NSC mixture as compared with the SF1 mixture. The maximum difference in flexural strength is 20% for mixtures with steel fiber (SF1) compared to NSC mixtures at 500°C for all load cases. In addition, the UPV test was used to investigate the microstructure and quality of concrete. This test indicated no difference or approximately equal values for SF1 and NSC mixtures at 25 and 300°C for all load cases, while at 500°C, the UPV test for NSC had a higher value than the UPV value of the SF1 mixture.

Keywords: Elevated temperature, imposed load, compressive strength, ultrasonic pulse velocity, steel fiber.

1. INTRODUCTION

Due to its many benefits over other building materials, including strength, durability, simplicity of manufacture, and no combustibility, concrete is commonly utilized as a major structural element in construction. When utilized in structures, concrete structural members must conform to the necessary fire safety criteria outlined in building standards [1]. When there is a fire or close to furnaces and accelerators, concrete may be subjected to higher temperatures [2]. These conditions greatly decrease concrete's mechanical characteristics, such as its strength. Unfavorable structural failures could result from this [3]. In order to evaluate the load-carrying capacity and repair fire-damaged constructions, it is still important to consider the characteristics of concrete that has undergone a fire [4]. The chemical composition and physical properties of concrete are significantly affected by high temperatures. Above a temperature of around 110°C, the dehydration, such as the release of chemically bonded water from the calcium silicate hydrate (CSH), becomes considerable [5]. Internal stresses are increased by the dehydration of the hydrated calcium silicate and the aggregate's thermal expansion, which causes 300 1C microcracks to be produced throughout the material [4].

Among all building materials, concrete typically has the best fire-resistance characteristics [6]. It is obvious that general knowledge of the properties of concrete at room temperature is rarely helpful in the design of fire resistance [7]. Steel fibers have been used in place of bar reinforcement in traditional concrete to reduce fracture width, boost flexural strength, and enhance post-cracking behavior. Concrete cracks are affected by steel fiber reinforcing, which may also increase the surface roughness of individual cracks, improve fracture growth resistance, and increase the possibility of multiple crack development and crack branching. As a result, steel fiber reinforcing can be employed to drastically reduce concrete's permeability and increase durability [8]. It has excellent toughness and high tensile strength, and it can help make up for typical plain concrete's problems, such as its lower tensile strength and brittleness [9]. Because cement and aggregates, which make up concrete, are chemically mixed to create an inactive compound with low thermal conductivity, high heat capability, and a slower strength depreciation with temperature, concrete has good fire resistance. Concrete can operate as an excellent fire shield between nearby places and protect itself from fire damage because of the slow heat transfer rate and strength loss.

2. EXPERIMENTAL WORKS
2.1 Cement
This study employed ordinary Portland cement (CEM I/A-L 42.5 R), which has a specific gravity of 3.15 and a SO_3 content of 2.6%. It complies with Iraqi Specifications [10].

2.2 Coarse Aggregate

Aggregate has the following characteristics: rounded shape, particle size 19 mm, specific gravity 2.6, and SO_3 (0.07) %. Table 1 shows the grading of coarse aggregate.

Table 1: Grading of natural coarse aggregate.

Size of the sieve (mm)	Percentage Passing (%)	Limits of IQS NO.45:1984
37.5	100	100
25	100	90-100
19	82	40-85
12.5	13	10-40
9.5	10	0-15
4.75	0	0-5

2.3 Fine Aggregate
Natural sand that complied with IQS: 45 – 1984 [11] zone III was used, and its characteristics are as follows: 2.57 specific gravity and 0.4% SO_3. Table 2 shows the grading of fine aggregate.

Table 2: Grading of natural sand aggregate.

Size of the sieve (mm)	Cumulative passing (%)	Limits of IQS No.45:1984
10	100	100
4.75	92	90-100
2.36	81	75-100
1.18	73	55-90
0.60	55	35-59
0.30	24	8-30
0.15	7	0-10

2.4 Water and Super-Plasticizer
Concrete has been mixed and cured using drinking water from the tap. A high-performance concrete super-plasticizer was utilized based on polycarboxylic technology, also known as High Range Water Reduction Agent HRWRA, and marketed as Hyperplast PC200. According to ASTM C494 TypeF, 2017, [12].

2.5 Fibers
This research study used hooked-end steel fiber with a cylindrical geometry. The steel fiber's dimensions length, diameter, tensile strength, and density were 35 mm, 0.5 mm, 1100 MPa, and 7800 (kg/m^3), respectively. That was followed in accordance with ASTMA820-05 [13].

2.6 Methodology
The present study's mix design methodology was based on previous studies. Table 3 displays the ratios of plain mixture with steel fibers (SF1) and normal mixture (NSC).

Table 3: Mix proportions.

Mix symbol	Cement (kg/m^3)	Sand (kg/m^3)	Gravil (kg/m^3)	w/c	S.P (kg/m^3)	V_f (kg/m^3)
NSC	400	675	1100	0.5	---------	---------
SF1	400	675	1100	0.5	1.2	78.5

The fiber volume fraction (V_f) of 1% of the overall mixture was used. Fibers were manually added to the mixer to reduce the impacts of clogging and clustering. The mixing procedure was carried out in a 0.05 m3 laboratory drum mixer to combine the concrete materials. All mixtures that require vibrator table compaction are poured into tightly fitting steel molds and compacted until full. After a 24-hour curing period, all specimens were de-molded and initially cured in tap water. Three ages (28, 56, and 90) days of curing time were required before the specimens could be evaluated.

2.7 Hardened Concrete Tests
Compressive and flexural strength are the mechanical characteristics that are being tested. Moreover, the ultrasonic pulse velocity test, a non-destructive test method, is employed. Using 100 mm cube specimens, the compressive strength test was carried out following IQS: 348-1992 [14]. Prisms measuring 100 mm, 100 mm, and 400 mm were utilized to test the flexural strength according to the instructions provided in IQS: 291-

1991[15]. Using 100 mm cube specimens, the ultrasonic pulse velocity test was carried out in accordance with IQS: 300-1993 [16].

2.8 Exposure to Heat

Based on previous studies, the heating rate and temperature selected. The specimens used in these experiments reflect the temperature changes during a tunnel fire. The concrete surface's temperature was measured to be (300 and 500) °C after being exposed to fire for two hours. The furnace used to heat the concrete samples is shown in Figure 1. In the current study, the temperature rose at a rate of 10°C per minute until it reached the maximum temperature of 300°C, which remained constant for 30 minutes. At 500°C, however, the temperature raised at a rate of 17°C per minute until it reached the maximum temperature, which remained constant for 30 minutes. The specimens were then allowed to cool in the furnace for a day to room temperature before being tested.

Figure 1: The furnace and Concrete specimens' arrangement.

2.9 Test of Compression

A loading rate of 0.25 MPa/sec was utilized. Cubes of dimensions (100x100x100) mm were first subjected to an ultrasonic pulse test (see Figure 2) before being exposed to cycles of loading at (0, 20, 40, and 60) % of the peak load. After loading, specimens underwent a second ultrasonic test to measure the wave velocity when cubes had internal and surface cracks. After this step, they were heated in a furnace for 2 hours at (25,300, 500) °C. The samples were removed from the furnace and left in dry air for a day to cool. Then, the samples were also subjected to an ultrasonic test, preparing cubes for the testing final step, which involves applying compression load until failure. Figure 3 shows the compression test machine.
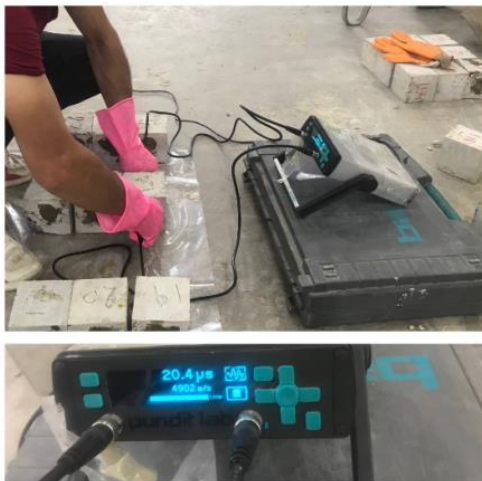

Figure 2: Ultrasonic pulse test.

Figure 3: Compression test machine.

2.10 Flexural Test

The flexural test follows the same process as the compression test, with prisms of dimensions (100x100x400) mm being subjected to imposed loading at (0, 20, 40, 60)% of the ultimate load and subjected to burning at (25, 300, 500) °C for 2 hours in the furnace. After these loading and burning steps, the samples were then subjected to flexural load until failure in the flexural test machine, as shown in Figure 4.

Figure 4: flexural test machine.

3. RESULTS AND DISCUSSIONS

3.1 Effect of Elevated Temperature and Imposed Load on Compressive Strength

One of the most crucial characteristics of concrete that has been hardened is its compressive strength. The average of the compressive strength test results at (28, 56, and 90) days of NSC and SF1 are shown in Figures 5 and 6, respectively. The results demonstrate that all specimens consistently increased compressive strength with aging. Because the hydration process continues and creates a new hydration product within the mass of the concrete, the compressive strength of the concrete increases with age [17]. While with increasing temperature, the compressive strength decreases [18]. Also, the results show that NSC has a higher compressive strength than SF1 since the fiber addition increased the amount of trapped air, which decreased the compressive strength.[19]

Figures 7 and 8 show the percentage of changes (reduction) in compressive strength for all mixtures (NSC and SF1). The results demonstrate that for all loading conditions, compressive strength at 300 °C for SF1 is reduced by a difference of (0–4) % for all ages of curing when compared to the NSC mix. Whereas at 500 °C, SF1 mix's compressive strength reducing difference at (0, 20, and 40) % imposed loading cases is higher than NSC mix by about (2-7) %. It is obvious from the results that there is a slight decrease in compressive strength due to the presence of steel fiber, which does not contribute significantly to the compressive strength [20]. When 60% of a load is imposed, the NSC compressive strength differential reduction is larger than the SF1 mix reduction by 12%. Due to the presence of steel fiber, the amount of decrease is approximately equal to one temperature, with the role of steel fiber not becoming apparent until the load reaches 60% of the ultimate load. This decreasing difference refers to the control of cracking and the form of failure using post-cracking ductility.
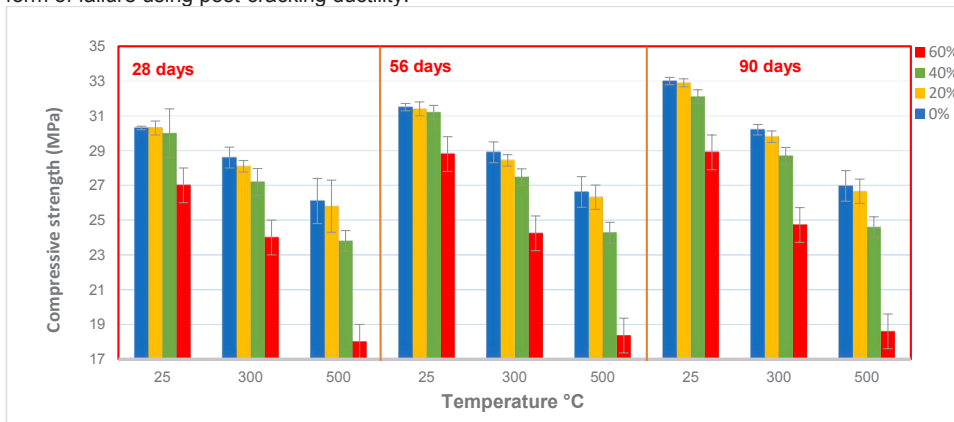

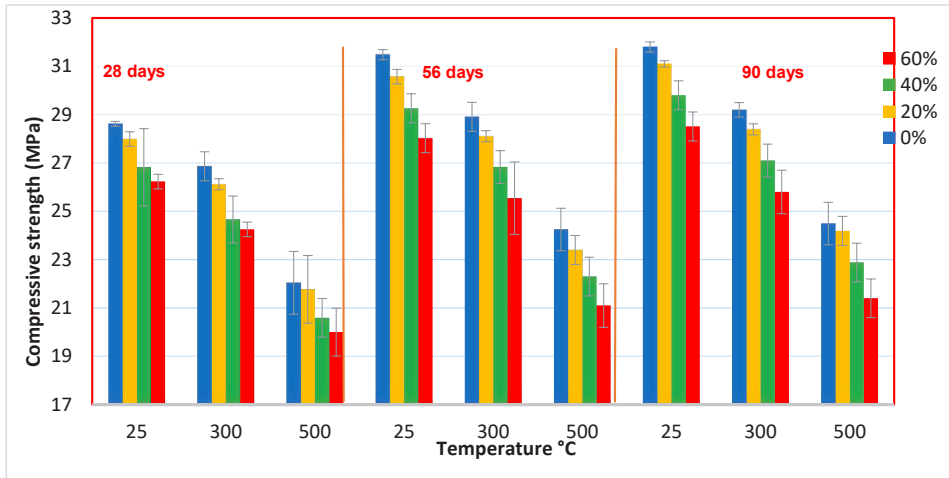Figure 5: Compressive strength of NSC under the effect of an imposed load and elevated temperature.

Figure 6: Compressive strength of SF1 under the effect of an imposed load and elevated temperature.
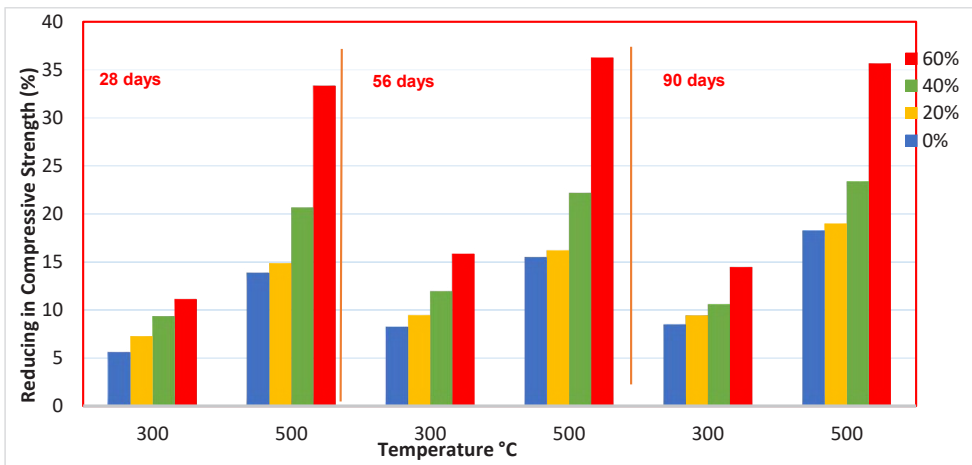

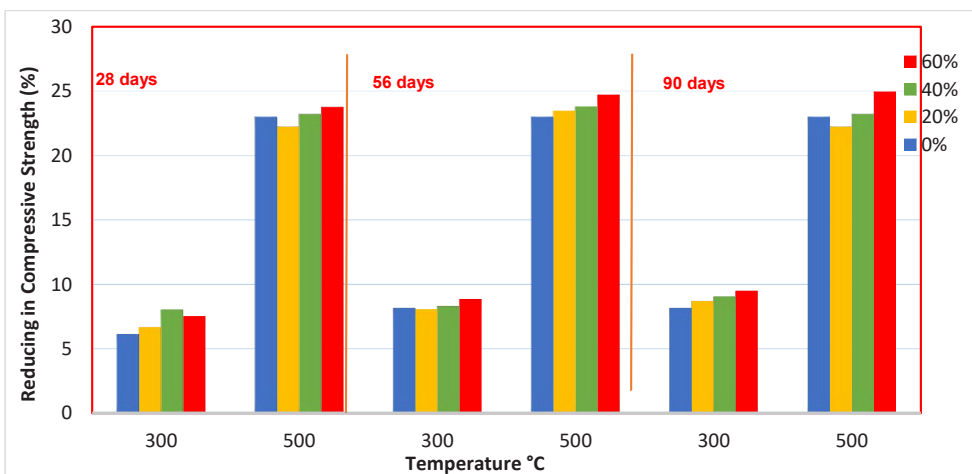Figure 7: Reducing the Compressive Strength of NSC (%).

Figure 8: Reducing the Compressive Strength of SF1 (%).

3.2 Effect of Elevated Temperature and Imposed Load on Flexural Strength

According to the results, all specimens showed a consistent rise in flexural strength as they aged, and the flexural strength of steel fibers was higher than the flexural strength of normal concrete, as seen in Figures 9 and 10. use hooked-end steel fibers, which improve the fiber-matrix bond and improve flexural strength for specimens [21, 22]. This tendency is mostly related to steel fibers' ability to release fracture energy near crack locations, which is necessary to extend crack growth by moving it from one side to another [23]. The dissolution of cement compounds and a drop in flexural strengths at high temperatures, internal specimen cracks that lower the flexural strengths [24]. The effects of load and high temperature are clear in normal concrete at all ages, while the effect of load in symbols of steel fibers is slightly at the same temperature. In general, with increasing load, the crack width increases, which allows the temperature to reach the inside of samples rapidly, demonstrating the internal skeleton of specimens. Figures 11 and 12 show the proportion of changes (reductions) in flexural strength for all mixtures (NSC and SF1). The results clearly indicated the effect of steel fiber on the flexural strength of the SF1 mix and the advantage of steel fibers in improving flexural strength when exposed to elevated temperatures and imposed loads [25]. The difference between NSC mix and SF1 mixture for all loading situations in terms of flexural strength reduction with rising temperature and imposed load is (9-17) % for 300°C and (12-20) % for 500°C.
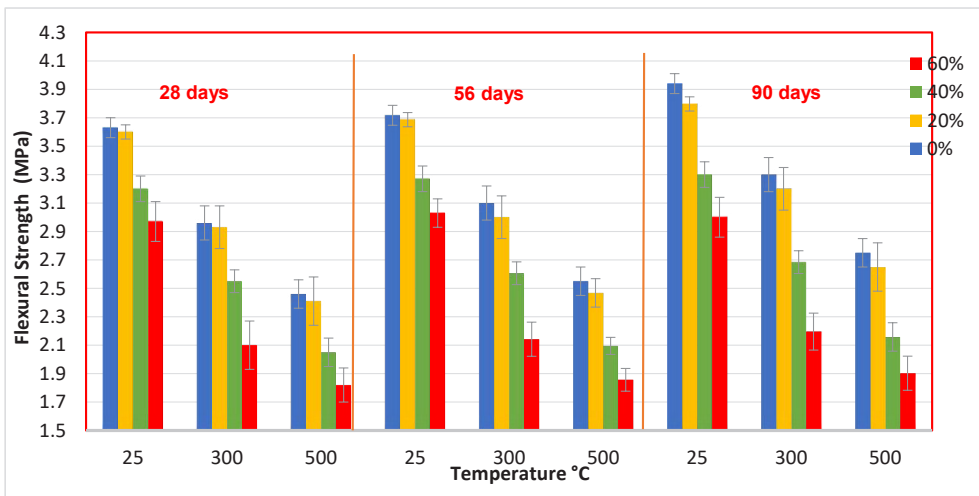

Figure 9: Flexural strength of NSC under the effect of an imposed load and elevated temperature.
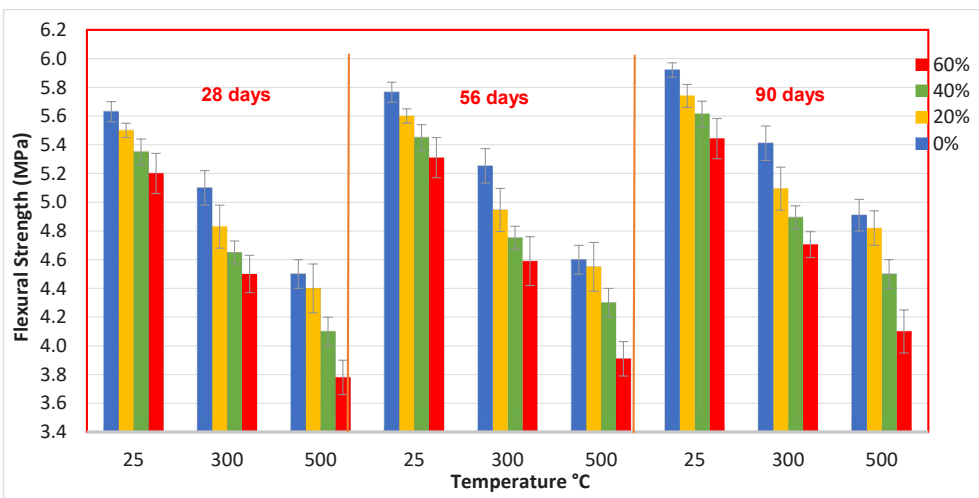

Figure 10: Flexural strength of SF1 under the effect of an imposed load and elevated temperature.
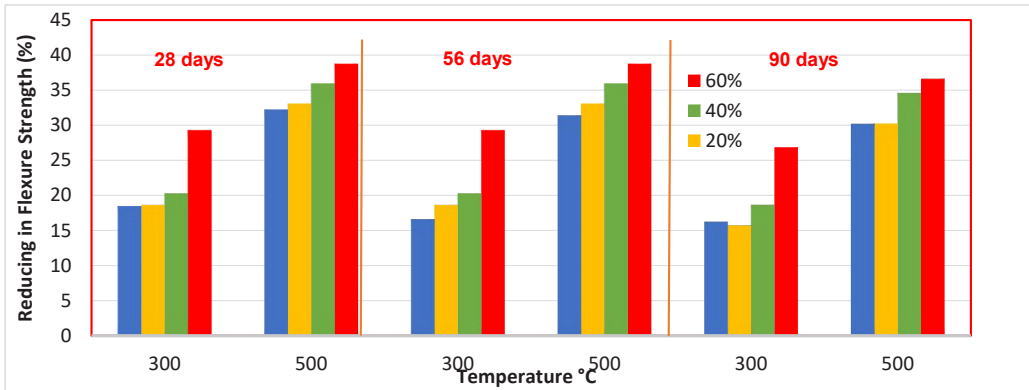
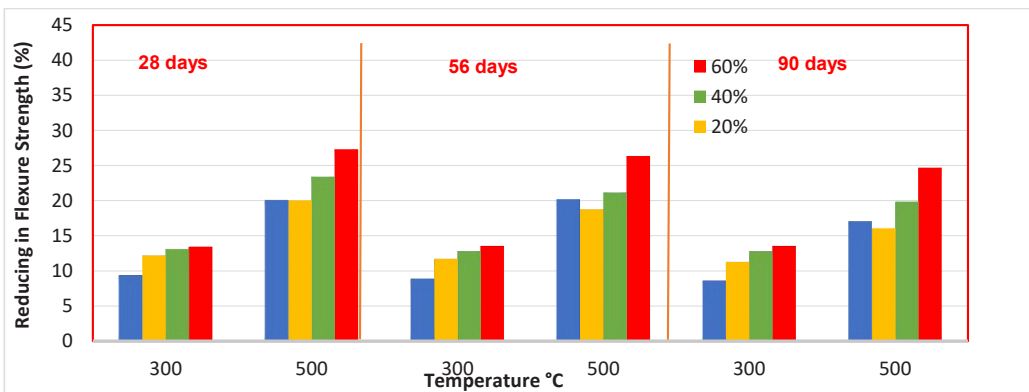Figure 11: Changes (reduction) in flexural strength for NSC.

Figure 12: Changes (reduction) in flexural strength for SF1.

3.3 Effect of Elevated Temperature and Imposed Load on Ultra-Sonic Pulse Velocity

For all cube samples, the ultrasonic pulse velocity increased as the curing age increased. Figures 13 and 14 show the ultrasonic pulse velocity results for the various types of (NSC and SF1) mixes at (28, 56, and 90) days. The results demonstrate that at 25 and 300°C temperatures, NSC mixture may have the same ultrasonic pulse velocity as SF1 for all load conditions. In contrast, at 500°C, NSC mixture has a higher ultrasonic pulse velocity than SF1 for all load cases. Since the effect of steel fiber is obvious at 500°C, this causes an increase in thermal conductivity in the interior of the samples, which increases heat absorption and causes an increase in cracks and wave transmission time, resulting in a drop in ultrasonic pulse velocity.
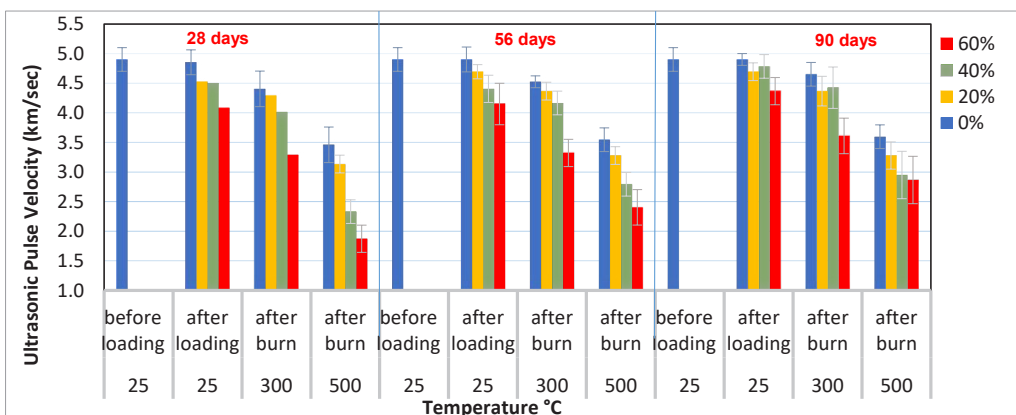

Figure 13: Effect of imposed load and elevated temperature on ultrasonic pulse velocity in NSC at ages (28, 56 and 90) days.
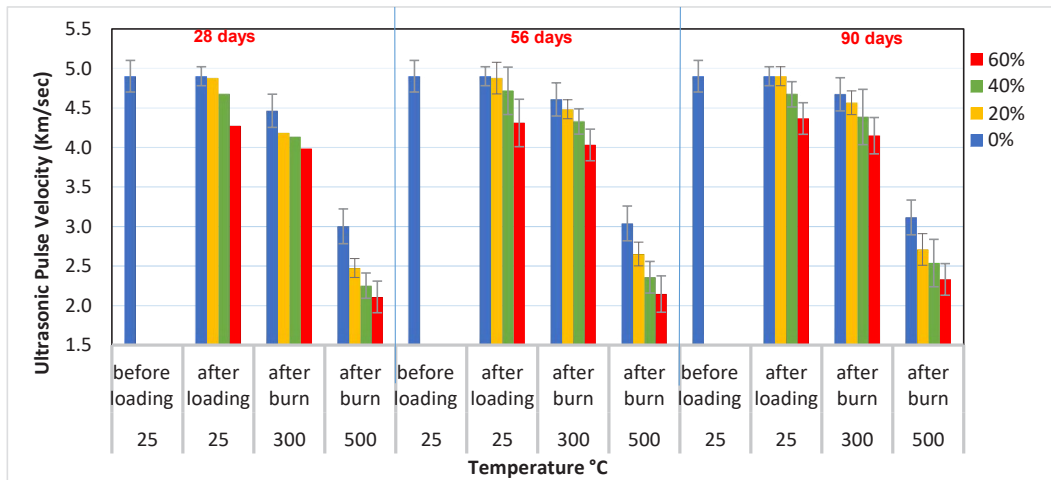
Figure 14: Effect of imposed load and elevated temperature on ultrasonic pulse velocity in SF1 at ages (28, 56, and 90) days.

4. CONCLUSIONS

This study investigates the effect of elevated temperature and imposed load on compressive strength, flexural strength, and the ultrasonic pulse velocity test. According to the experimental results, the following conclusions are drawn:

- The compressive strength, flexural strength, and ultrasonic pulse velocity increased with progressive age.
- When SF1 is compared to the NSC mixture, compressive strength at 300°C is decreased slightly at all loading conditions for all ages of curing.
- The NSC compressive strength difference reduction is larger than the SF1 mix decrease by 12% when 60% of a load is applied at 500°C.
- The decreasing compressive strength of the steel fiber mixture is slightly affected by changing loads at the same temperatures.
- SF1 has greater flexural strength than the NSC mix; the highest difference between the two mixtures for all loading conditions is 17% for 300°C and 20% for 500°C in terms of flexural strength reduction with increasing temperature and imposed load.
- At temperatures of 25 and 300°C, the NSC mixture has the same ultrasonic pulse velocity as SF1 for all load cases. In contrast, at 500°C, the NSC mix has a higher ultrasonic pulse velocity than SF1 for all load cases.

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