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ARTICLE

Effects of Fiber Types on UHPC Mechanical Properties after High-Temperature Heating and Cooling Method

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ABSTRACT

The ultra-high performance concrete (UHPC) is an advanced material that stands out for its remarkable mechanical properties and durability, characterized by an exceptionally high compressive strength. When compared to traditional concrete, UHPC presents itself as a more eco-friendly option with significant potential to enhance the sustainability of infrastructure. This study unveils the mechanical behavior of ultra-high performance fiber reinforced concrete (UHPC) subject to various thermal conditions, incorporating a range of fiber types, both industrial and recycled, in a comprehensive assessment. Furthering the investigation into the influence of high temperatures on UHPC, the research incorporates not only industrially manufactured fibers but also a variety of recycled fibers in the concrete mix, subjecting the samples to intense heating and subsequent cooling regimes. Once the thermal shock is administered, the compressive strength, tensile strength in bending, ultrasonic pulse velocity, and sorptivity of the concrete samples are examined in detail. The findings of this study reveal that the fire resistance of UHPC reinforced with recycled fibers is comparable to that of UHPC reinforced with industrially manufactured fibers. Interestingly, a discernible relationship was observed between the ultrasonic pulse velocity of the samples and their post-temperature strength, suggesting a potential link between these two characteristics.

Keywords: Ultra high-performance concrete; Fire behavior; Recycled fibers; Experimental tests; Fiber type; Ultrasonic pulse velocity

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1. Introduction

Concrete is the world's most widely-used building material, largely due to its versatility [1]. The focus in construction industries has shifted towards understanding material behavior, with an aim to achieve superior strength and durability [2]. UHPC possesses a plethora of mechanical and durability advantages, such as very high compressive strength, environmentally-friendly properties, and great potential as a solution for sustainable infrastructure [3]. UHPC has been subject to thirty years of research and development, solidifying its position as a promising material for long-lasting, sustainable infrastructure [4,5]. UHPC is characterized by its impressive mechanical properties, adequate flowability (mini-slump flow of 160 mm), low water-to-binder ratio (0.14–0.20), high packing density, and high volume of steel fiber. These properties contribute to a compressive strength of more than 120 MPa and tensile strength exceeding 5 MPa with standard curing, and 150 MPa with steam curing [6,7]. UHPC also possesses impressive resistance to carbon dioxide, chloride, and sulfate ions, leading to reduced maintenance costs throughout the structure's lifespan [8]. UHPC's unique microscopic structure, with its abundance of un-hydrated cement, allows it to self-repair to some degree when structural cracks occur. This, coupled with the possibility of designing slender beams and columns, leads to weight reduction of structures (up to about 70%), which is a key factor in earthquake-prone regions. The absence of steel reinforcement further eliminates certain constructional costs, granting greater freedom in architectural design [9]. However, exposure to high temperatures poses a significant challenge for concrete, causing a significant loss in strength [10–12]. Concrete age can play a critical role in its strength, making it imperative to understand the relationship between concrete age and residual compressive strength following exposure to high temperatures [13]. Qian et al. studied the use of UHPC with low-cost, readily available coarse aggregates, discovering that high temperatures caused gradual decreases in bending strength and ultrasonic pulse velocity due to material decomposition [14].

Despite its various advantages, UHPC also has some drawbacks. Its high cement content, ranging from 800 to 1200 kg/m^3, can result in increased production costs and shrinkage issues due to heat generated during hydration. In addition, the need for specialized thermal curing procedures can limit UHPC's use as in-situ concrete. Importantly, the production of UHPC typically requires the use of additives like silica fume and superplasticizers. As a result, the overall production cost of UHPC can be higher than that of conventional concretes [15]. Another significant drawback of UHPC is its potential to lose strength and even undergo explosive spalling when exposed to high temperatures. This can cause aggregate expansion, cement paste shrinkage, and spalling due to increased internal pore pressure [16]. These phenomena have been further explored in studies conducted by references [17,18]. Investigations into the impact of high temperatures on the compressive strength of concrete at different ages are relatively scarce. Mohseni et al. [19] studied the thermal degradation of concrete at 7, 28, and 90 days of age and observed that compressive strength increased as concrete age increased. Felippe and Tang [20,21] reported similar findings in their work. Akhtaruzzaman et al. [22] explored the effect of curing temperature on compressive strength and found that the highest strength was achieved when concrete was cured at an optimal temperature. Furthermore, the study by Mohseni et al. [19] and Felippe and Tang [20,21] indicate that concrete age also plays a significant role in compressive strength. In addition, akhtaruzzaman et al. [22] demonstrated that the type of aggregate utilized in concrete can significantly influence its strength after exposure to high temperatures. Numerous studies have further revealed that the strength loss in high-strength concretes at high temperatures is much greater when compared to conventional concretes [23–25]. At high temperatures, particularly 800 °C, studies have shown that the strength loss in high-strength concretes can be as significant as 80% of their initial strength [26]. In another study comparing UHPC, the residual stresses in samples exposed to 1000 °C were observed to decrease to 41% of the strength at normal temperature, illustrating the destructive potential of heat on high-strength fiber-reinforced concrete and highlighting the significant risk of failure even after the fire [27]. A number of studies [28,29,30] reported even greater strength loss compared to reference [16], suggesting the wide-ranging impacts of high temperatures on UHPC. The explosive spalling of UHPC can be attributed to the increase in water vapor pressure within the pores, which can cause significant tensile strains, as suggested by [31–32].The enclosed nature of pores in high-strength concretes, along with their smaller size, leads to an increase in tensile stresses, which can be much more dangerous than in conventional concretes [33]. The complex issue of explosive spalling has been explored from various angles, including the influence of thermal gradients as studied by Li and Zhang [34]. In previous sections, the use of fibers has been highlighted as a means of improving the energy absorption, ductility, and impact resistance of UHPC. Due to the tension strength of steel and carbon-based fibers, these are frequently employed in UHPC production. A comparative study revealed that steel fibers can have a greater impact on increasing the mechanical strength of high-strength concretes compared to polypropylene and glass fibers [35], and the tensile strength of UHPC is linearly proportional to the volume ratio of fibers in the range of 0% to 5% [36]. However, excessive increase of fibers can cause different behavior and reduce the workability of the fresh concrete and thus the mechanical strength of UHPC [38]. To reduce the volume of fibers in UHPC for a better performance, a combination of different types of fibers have been used [39,40]. In a notable study, a combination of 1% long (40 mm length and 0.3 mm diameter) and 0.5% short (6 mm length and 0.1 mm diameter) steel fibers were shown to significantly enhance the stress-strain hardening behavior of UHPC [41]. Furthermore, research has examined the impact of fiber shape on UHPC properties, revealing that spring-shaped steel fibers can provide superior tensile strength, post-cracking strength, and ductility when compared to conventional fiber shapes [36,42]. When compared to long fibers with smooth surfaces, spring-shaped steel fibers and short, rough-surfaced fibers provide superior performance in enhancing mechanical properties [43,44,45]. In addition, studies have demonstrated that UHPC samples incorporating 1% large size fibers and 1% smaller size fibers exhibit 45–79% higher deformation and energy absorption capacities than samples with 2% small fibers. These results underscore the significance of fiber size, shape, and surface finish in optimizing UHPC performance.

While a wealth of research has delved into the effects of UHPC with different fibers on mechanical properties, studies focused on the influence of high temperatures on such UHPC are relatively scarce. The current study aims to address this gap by comparatively examining the mechanical properties of UHPC with various fibers, including a type of steel fiber conforming to ASTM A820, a hooked steel fiber manufactured industrially, recycled fibers sourced from lathing waste, steel fibers recycled from car tire waste, steel fibers recycled from tow cable, and a non-steel fiber made of polypropylene, all under high temperature conditions. This study builds upon the well-established relationship between concrete pore volume and degree of closure, which affects its compressive and tensile strength at high temperatures. By evaluating the potential of ultrasonic wave velocity and water absorption as indicators of concrete behavior after fire exposure, this research seeks to expand upon existing knowledge. The effects of different fibers—including both industrially manufactured and recycled fibers—on concrete properties at high temperatures (250°C and 800°C) are compared to control (unheated) concretes.

2. Materials and mix design

2.1 Materials

In order to ensure uniformity and compliance with relevant standards, the cement utilized in the mix design of concrete samples was selected in accordance with ASTM-C150 type I, while the superplasticizer was based on naphthalene dicarboxylate and met the requirements of ASTM C494-Type D. The microsilica had a verified amorphous content greater than 99.5%. Fine siliceous sand with a particle size between 0.15 to 9.5 mm was applied in this study. Specific gravity and water absorption of the sand were measured at 3000 kg/m^3 and 0.5%, respectively.

2.2 Fibers

To delve into the impact of various fibers on ultra-high-performance concrete (UHPC), six diverse fiber types were utilized in the manufacturing process of UHPC in this research study (**Figure 1**). A list of abbreviations used to represent the concrete mixed with these fibers can be found in **Table 1**. (*Dramix Fibers (F1)*) This study employed fibers manufactured by the Ukrainian Dramix factory under the brand name OL6/016. The fibers were made from high carbon steel, conforming to ASTM A820 standards.With an average length of 6 mm and a circular cross section with a diameter of 0.16 mm, the nominal tensile strength of the stainless steel fibers was recorded at 3000 MPa, while the modulus of elasticity was measured at 200 GPa. (*Manufactured hooked steel fibers (F2)*) These fibers, denoted as KX-CSF, were sourced from the Kimix factory (**Figure 1**). The aforementioned F2 fibers, manufactured by Kimix factory, possess a length of 3 cm, and a circular cross-section with an average diameter of 0.7 mm. To enhance the anchorage of the fibers within the cement paste, two hooks were fabricated at each end of the fibers by a process of bending. (*Recycled lathing waste fiber (R1)*) were prepared with an average length of 2cm and a diameter of 3mm. The average tensile strength of these fibers was about 700 MPa (**Figure 1**). (*Steel fibers recycled from car tire waste (R2)*) The extraction of these fibers includes heating the car tires and separating the inner wires. The extracted fibers are then screened so that they have an average length of 20 mm and a diameter of 1 mm. The diameter of the circular cross section of these fibers is 1.5 mm. Fiber strength was about 600 MPa on average.

(*Steel fibers recycled from tow cable (R3)*) The tangled waste of tow cables was processed by cutting them into pieces of approximately 20 mm in length, producing the fibers used in this study. These fibers presented an average diameter of 1.5 mm, with a tensile strength measured at approximately 1500 MPa. (*Polypropylene fibers (PP)*) Polypropylene a type of polymer that is flexible and experiences a significant strength loss at high temperatures. It is possible to make the polypropylene fibers from recyclable materials as well. Due to (strength loss at high temperature and recyclability), it has been compared with other steel fibers, in this research project. The polypropylene fiber has been provided from NSG company, has a specific gravity of 0.91 gr/cm^3, a tensile strength of 400 MPa and a modulus of elasticity of 2.7 GPa.

Table 1. Abbreviations of concrete made with different fibers.

Designation	Used fiber	Tensile strength
F1	Dramix fibers	3000 mpa
F2	Manufactured hooked steel fibers	800 to 1200 mpa
R1	Recycled lathing waste fiber	700 mpa
R2	Steel fibers recycled from car tire waste	600 mpa
R3	Steel fibers recycled from two cables	1500 mpa
PP	Polypropylene fiber	400 mpa
NF	No fiber	none

2.3 Mix design

The production of high-strength concretes involves a range of mixing methods, each designed to produce a dense and compact cement matrix, while ensuring adequate fresh concrete workability and high mechanical strength in hardened concrete. Nevertheless, a definitive mixing method has yet to be established, and research continues to explore effective techniques for achieving the desired mechanical strength and pore volume reduction in high-strength concretes. Numerous researchers have investigated alternative mixing techniques to improve the mechanical strength and porosity characteristics of high-strength concretes. The utilization of vacuum mixing, as well as the application of internal or external pressure before and during the setting of the samples, has proven to be an efficacious approach for minimizing the pore volume in high-strength concretes, leading to superior strength and durability [46,47].

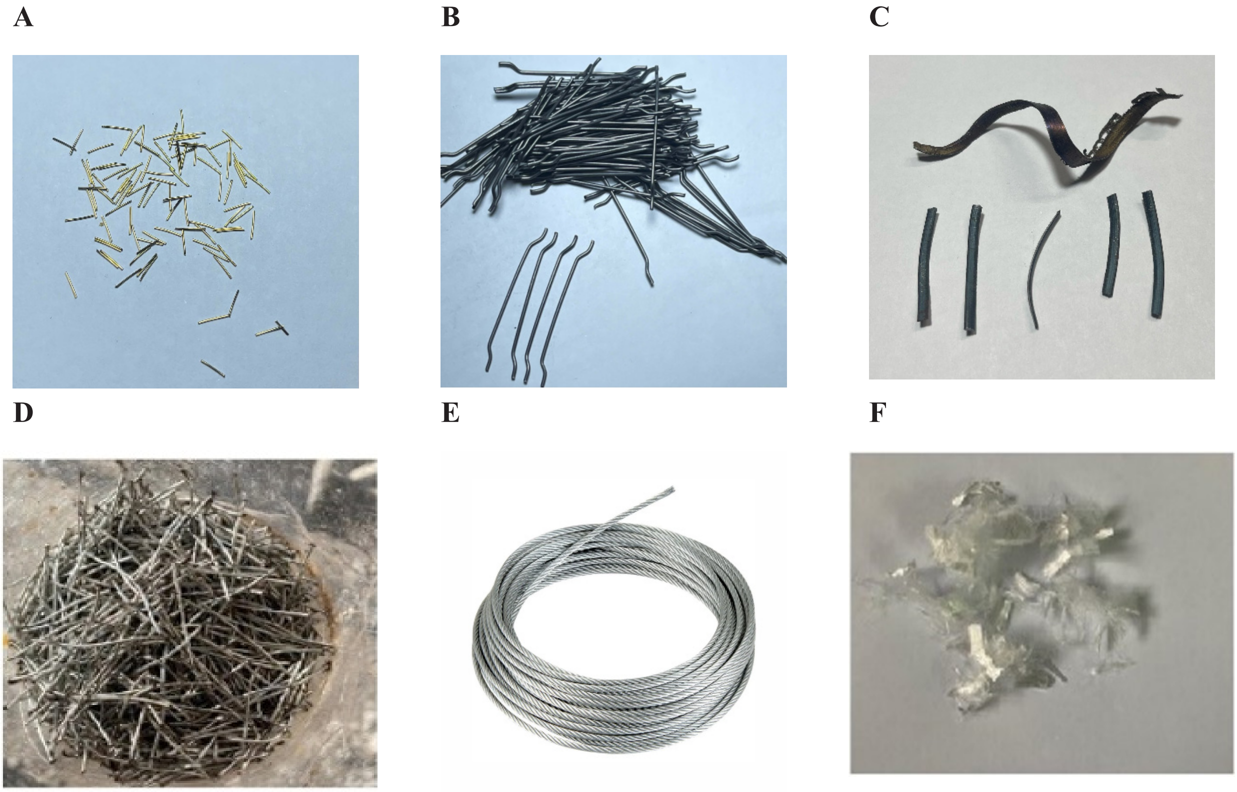

Figure 1. Fibers used in this study. (**a**) Dramix fibers (**b**) hooked steel fibers (**c**) fibers recycled from lathing waste (**d**) steel fibers recycled from car tire waste (**e**) Tow cable used for fiber extraction. (**f**) Polypropylene fibers.

While the aforementioned methods have demonstrated promising results in laboratory settings, their implementation on an industrial scale may be cost-prohibitive. In contrast, UHPC is often produced through trial and error, with mixing, pouring, and vibration techniques that are similar to those used for conventional concretes. The only significant difference is the increased mixing time required, where dry ingredients are typically mixed for 10 minutes before the addition of water and superplasticizer, followed by an additional 5 to 10 minutes of mixing. Once the desired workability and viscosity are achieved, fibers may be incorporated as needed. When mixing concrete containing fibers of varied sizes, it is essential to follow a specific order: first, the smaller fibers are added to the mix, followed by the larger fibers. After the mixing process is completed, the concrete specimens are placed in a mold and kept in ambient temperature conditions with relative humidity maintained at 65 ± 5% for a period of 24 hours. Following this initial curing period, the specimens are demolded and placed in a water tank at a temperature of 23 °C for further curing. The weight ratios used in this study are given in **Table 2**. After mixing, the concretes were poured into three layers and tamped with a piston weighing 3.15 kg. Care was taken to avoid drying out the specimens prior to testing. **Table 2** provides the weight ratios used for each concrete mixture in this study.

Table 2. Mix proportions.

UHPC	Cement	Microsilica	Fine siliceous sands	Fibers	water	Superplasticizer
Containing fibers F1, F2, R1, R2, R3, R4	35.1%	7.89%	42.9%	3.28%	10.11%	0.72%
Containing Polypropylene Fibers (PP)	36.25%	8.16%	44.34%	0.063%	10.44%	0.74%
Without Fiber (NF)	36.3%	8.3%	44.2%	0%	10.45%	0.75%

3. Test method

The mechanical and durability tests were carried out after a curing period of 28 days. All the test results for this study are obtained from the mean of three identical specimens.

3.1 Assessment of the compressive strength

ASTM C39-04a has been followed to determine the compressive strength of samples. Tests were on 100 × 100 × 100 mm cubic specimens at the age of 28 days.

3.2 Assessment of the tensile strength

To ascertain the modulus of rupture, a third-point loading test method was implemented, utilizing specimens measuring 500 × 150 × 150 in dimension. The span length between the supporting points of the test apparatus was fixed at 500 mm. The test procedure was carried out in accordance with the specifications outlined in ASTM C78-02. Prior to testing, the samples were stored in compliance with ASTM C192-02 until they reached the desired curing age of 28 days.

3.3 Assessment of the heating

The purpose of this study is to determine the effects of temperature changes on UHPC. It should be noted that, to date, no unique test method has been followed by all researchers for mechanical measurements of concrete under high temperatures, although some fire curves have been recommended for the heating [48,49]. In this study, a furnace was used to heat the concrete samples. In addition to control concretes (concretes that have not been subjected to any temperature change), two different regimes have been used to heat the concrete samples. In the first regime (abbreviated as 250), the temperature of samples is raised from the room temperature to 250 °C at an average rate of 3 °C /min, and then this temperature is maintained for 1 hour. In the second regime (abbreviated as 800) which was performed on another group of samples, the temperature was raised from the room temperature to 800 °C at an average rate of 3 °C /min and then this temperature was maintained for 1 hour. In addition, two different regimes have been used to reduce the temperature. In the first regime (abbreviated as -W) the heated samples are immediately placed in a 100-liter bath of water at a temperature of 20 degrees. In the second regime (abbreviated as -A) the heated samples were cooled in air. For example, the abbreviation 800-A means that the sample is heated to 800 °C and then cooled in air.

3.4 Assessment of the ultrasonic test

To ensure a standardized approach to measuring the ultrasonic pulse velocity, ASTM C597-16 was adopted as the reference standard for this study. A portable device capable of generating pulses in the range of 50 to 54 Hz was employed to measure the velocity of the samples that had been previously subjected to thermal heating at 28 days of age, utilizing specimens with a dimension of 100 × 100 × 100 mm.

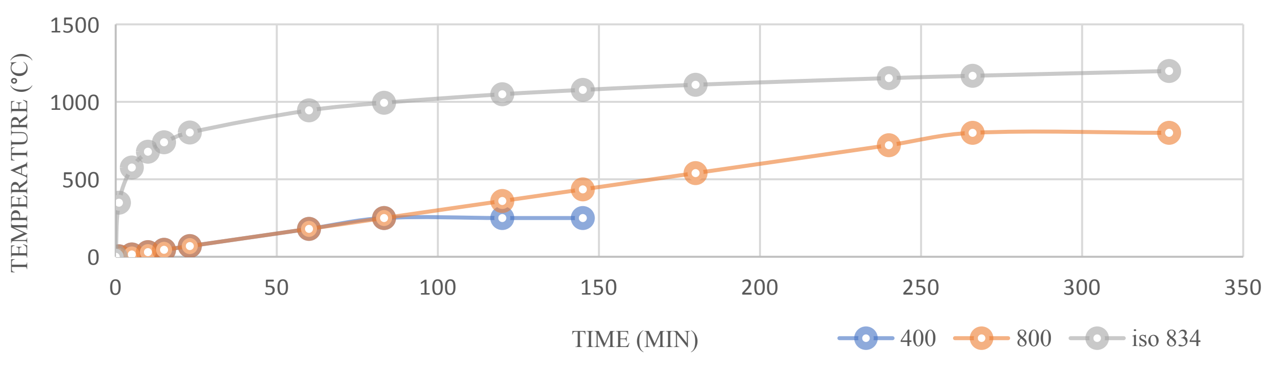

Figure 2. Graph of temperature over time.

4. Results and discussion

All the test results for this study are obtained from the mean of three identical specimens.

4.1 Compressive strength tests

Figure 3 shows the compressive strength of concrete made with different fibers at the age of 28 days. Each data point has an average strength of 3 cubic samples with dimensions of 100 × 100 × 100 mm. The relative residual compressive strengths of concrete (with respect to unheated concretes) are plotted in **Figure 4**. It should be noted that a spalling-type failure was observed in most 800-W samples (samples that were heated to 800 °C and then cooled in water).

As can be seen, the unheated concrete containing the Dramix steel fibers (F1) has the highest compressive strength with a final stress of 120.2 MPa. The unheated concrete made with hooked steel fibers (F2), recycled from lathing industry (R1), recycled from car tires (R2), recycled from tow cable (R3) and polypropylene fibers (pp) had 81.4, 87.3, 86.7, 87.5, and 88.3% of this resistance, respectively.

As shown in **Figure 4**, the 800-W samples have the greatest strength loss. Samples containing Dramix steel fibers, hooked steel fibers, recycled from lathing industry, recycled from car tires, recycled from tow cable and polypropylene fibers show 86, 90, 88, 87,87 and 91 percent strength loss respectively in comparison with the unheated samples made with the same fibers. It can be concluded that, at this thermal regime, the strength loss ratio for all concretes made with steel fibers is roughly the same; although concretes with standard steel fibers have higher initial strength.

Figure 3 also indicates that at 250 ºC, the samples with polypropylene fibers demonstrate a different behavior. While a strength loss is observed in concretes containing steel fibers, a slight increase in the compressive strength is noticed in the concretes containing polypropylene fibers. A similar phenomenon can be seen in other studies. Where, a slight increase in the compressive strength has been reported in the concretes containing polypropylene fibers, at 200 °C [50]. The cause of this situation has been attributed to the decrease in moisture and increase in Van der Waals forces at the contact surfaces of cement gel and fibers [50].

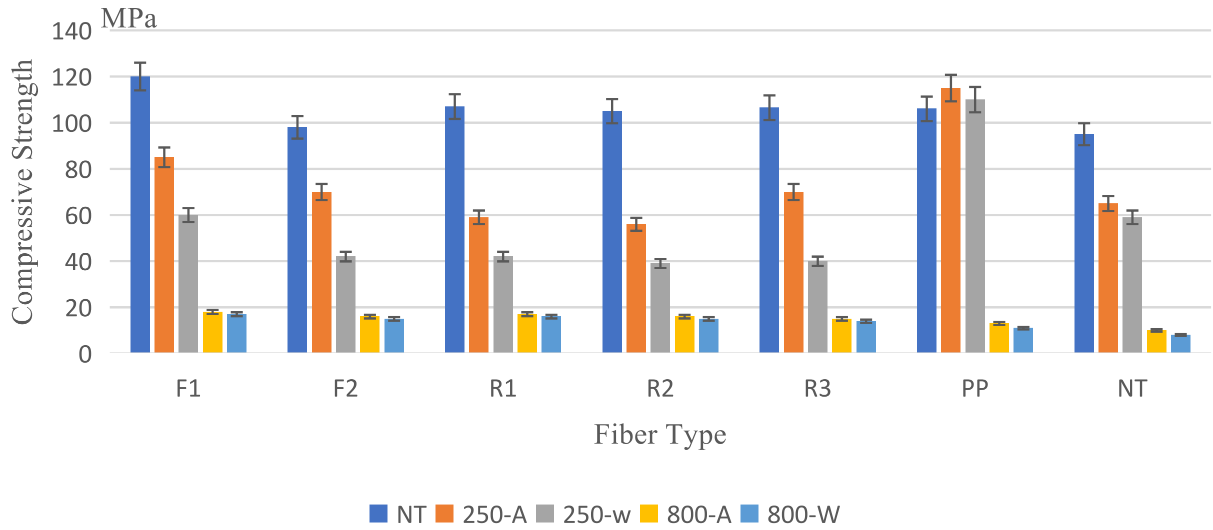

Figure 3. Compressive strength of UHPC with different fibers under different thermal regimes. NTS: Unheated. 250-A: heated to 250 ° C and cooled in the air. 250-W: heated to 250 ° C and cooled in water. 800-A: heated to 800 ° C and cooled in the air. 800-W: heated to 800 ° C and cooled in water.

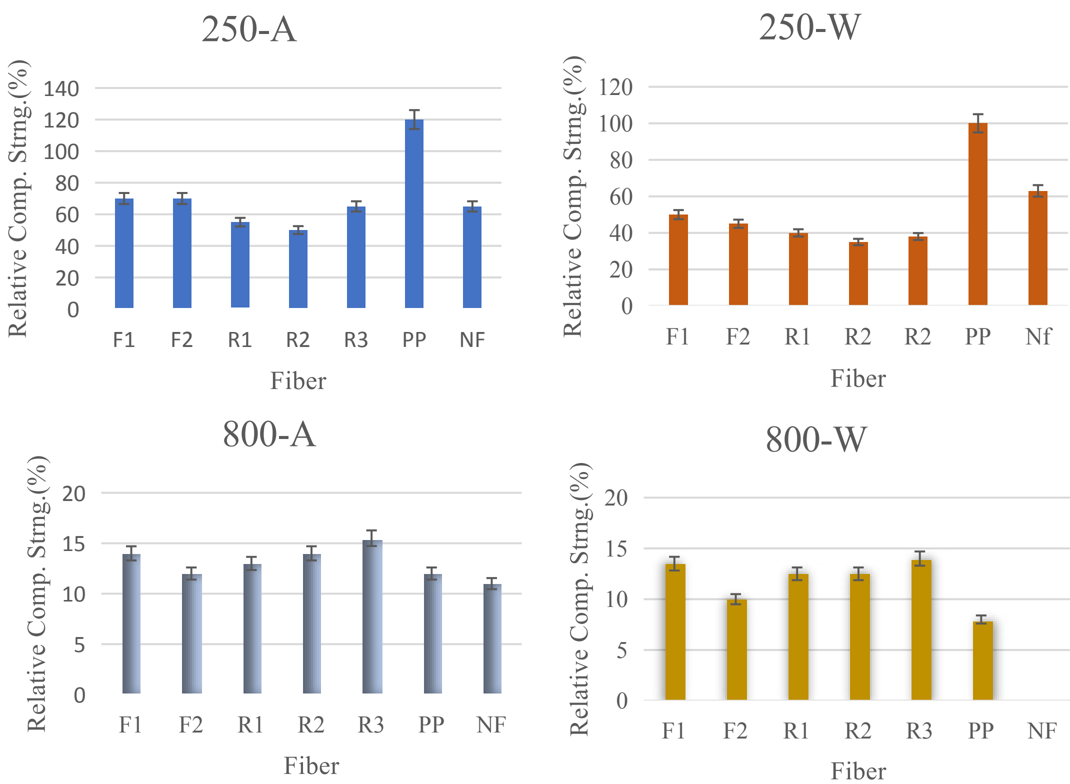

Figure 4. Relative residual compressive strength of UHPC under different thermal regimes.

4.2 Tensile strength tests

Figure 5 provides a visual comparison of the tensile strength in bending for the UHPC samples reinforced with various fibers, tested at 28 days of age. Notably, the samples containing Dramix steel fibers (F1) displayed the highest tensile strength (16.93 MPa). In comparison, the samples reinforced with hooked steel fibers (F2), recycled lathing fiber (R1), recycled steel fibers from car tires (R2), recycled steel fibers from tow cable (R3), and polypropylene fibers (PP) exhibited tensile strengths that were approximately 85.2%, 89.7%, 88.2%, 86. **Figure 6** shows the relative tensile to compressive strength ratio (in percentage) for different samples. It is observed that the concretes with steel fibers that have been heated to 250 degrees often have a higher relative strength ratio. But the decline of this ratio is evident at higher temperatures. And in **Figure 7**, the relationship between compressive and tensile strength is shown.

4.3 Ultrasonic pulse velocity test

This test was performed on unheated samples and 800-W specimens. A comparison between ultrasonic pulse velocities of concrete made of different fibers is shown in **Figure 7**. In general, no significant sensitivity to fiber type is observed. However, a noteworthy relationship has been observed between the ultrasonic pulse velocity before heating, and the strength loss at 800 degrees for the concrete samples with steel fibers. These are shown in **Figures 9 and 10** (together with 95% confidence lines). The abscissa of **Figure 8** shows the ultrasonic pulse velocity of unheated samples (no distinction is made between steel fibers), the ordinate shows the compressive strength loss of samples after 800° C heating. Figure 10 shows a similar graph for the tensile strength loss. Please note that the data associated with the samples with polypropylene fibers or samples which were made without fibers are not included in these graphs. These graphs were drawn only between the data for concrete containing steel fibers. Also, please note that these trends are observed only between specimens heated to 800° C. As can be seen, samples with higher ultrasonic wave velocities experience a greater strength loss after heating.

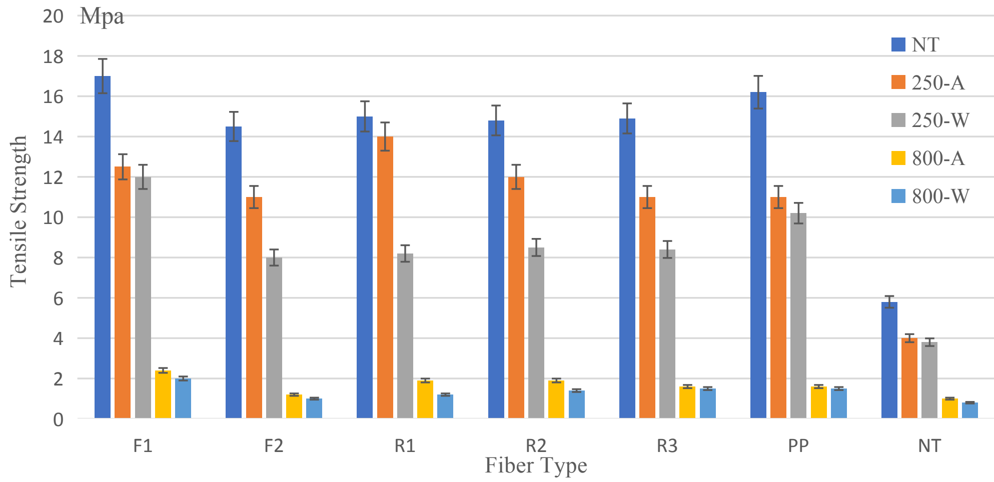

Figure 5. Tensile strength of UHPC with different fibers under different thermal regimes.

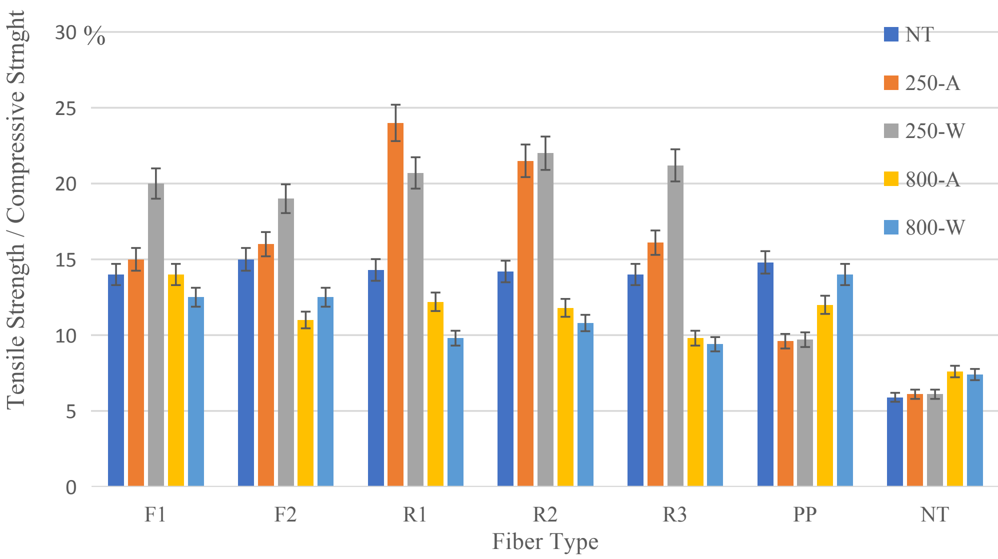

Figure 6. Tensile to compressive strength ratio for UHPC with different fibers under different thermal regimes.

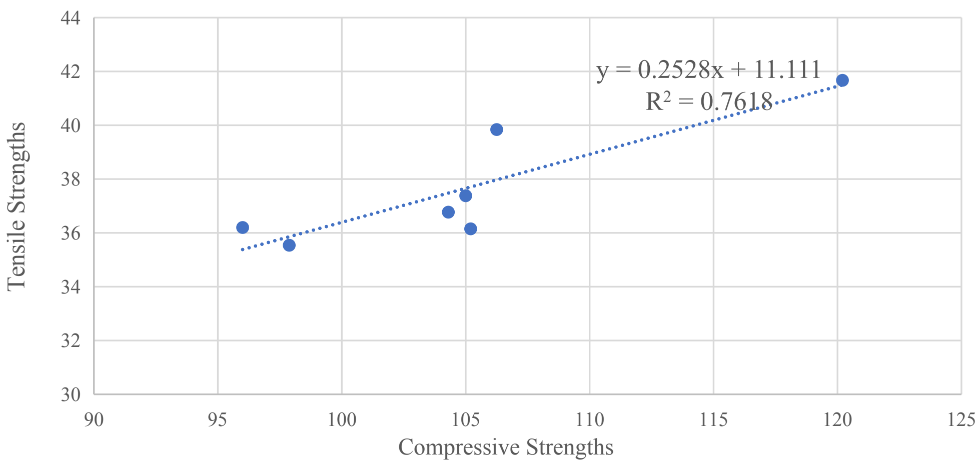

Figure 7. The relationship between compressive and tensile strengths.

The ultrasonic pulse velocity is an indicator of the density of concrete and the closure of its pores. As mentioned in the introduction, the mechanical strength of UHPC under high temperatures correlates to the volume and the degree of closure of concrete pores. Studies by other researchers have shown that the closure of the pores can further increase the trapped water vapor pressure at high temperatures, which in turn produces very large tensile strains in the concrete [26,27]. Experimental results of the present study can mean that the ultrasonic pulse velocity before heating (which is a measure of concrete density) is also a measure for predicting the strength of concrete after the heat shock. However, due to the limited number of experiments performed by the authors, this issue can be considered more comprehensively in future research for a definite conclusion.

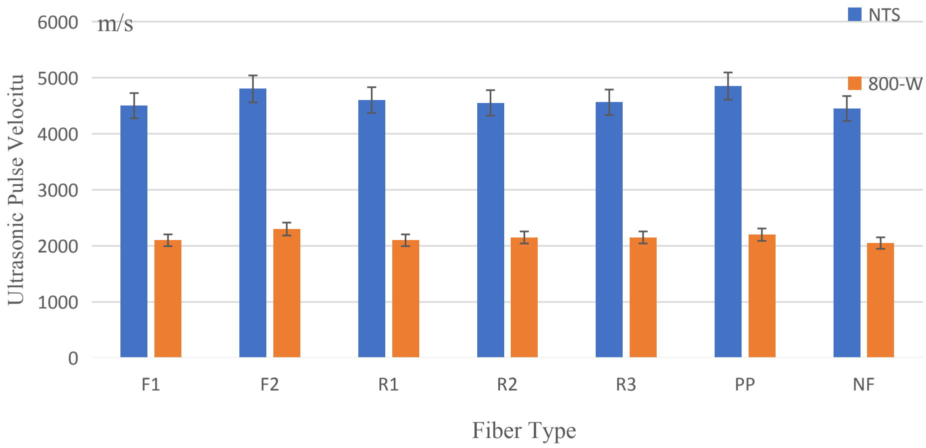

Figure 8. Ultrasonic wave velocity in high-strength concrete with different fibers.

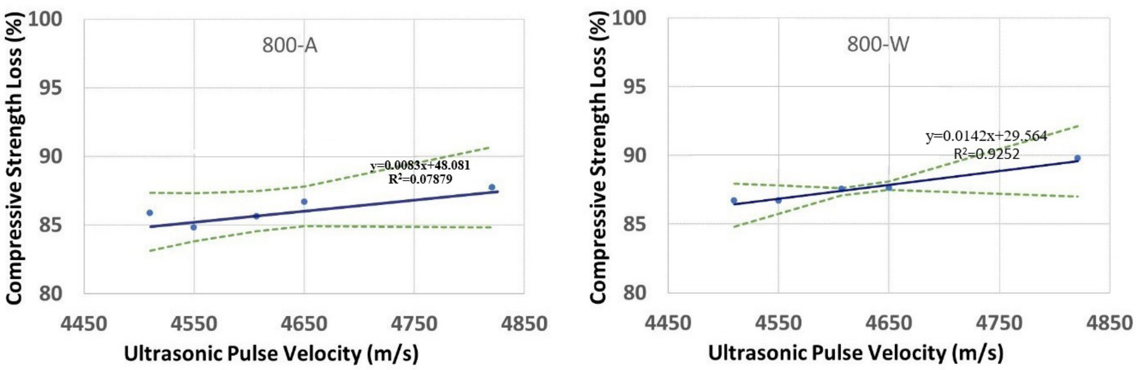

Figure 9. Compressive strength loss of concrete at 800 degrees and ultrasonic pulse velocity (before heating).

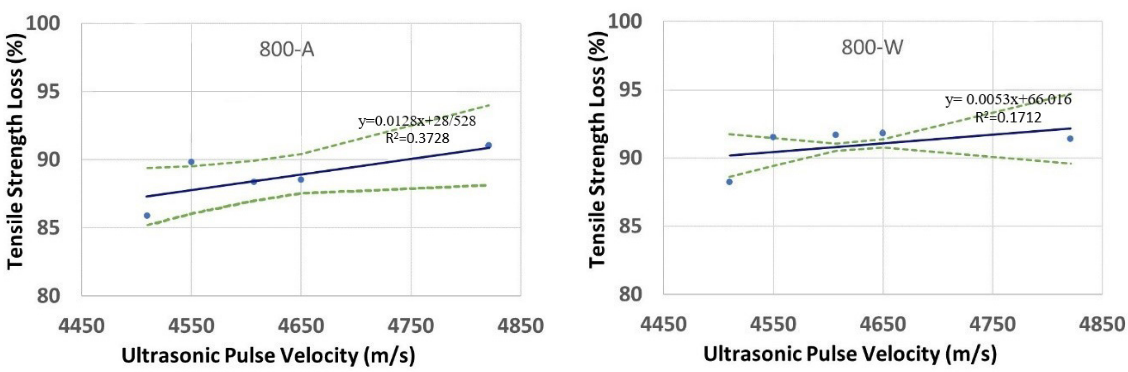

Figure 10. Tensile strength loss of concrete at 800 degrees and ultrasonic pulse velocity (before heating).

4.4 Water absorption tests (sorptivity)

The results of this experiment do not show a significant difference in the water absorption of unheated concrete made from different fibers. The average water absorption was 0.16% (4 g) after 48 hours. The results of this experiment show that the water absorption test may not be reliable in predicting the behavior of concrete after heating.

5. Conclusion

In this study, examined the effects of various fibers on the compressive strength, tensile strength, ultrasonic pulse velocity, and water absorption of UHPC, both prior to and after thermal heating. To further elucidate the behavior of UHPC under thermal conditions, six different types of fibers were incorporated into the mix design, with the resulting specimens subjected to four different thermal regimes, including a control group that was maintained at room temperature.

The results of the compressive strength tests revealed a notable difference in performance between UHPC with standard steel fibers and those containing polypropylene fibers. While the initial strength of UHPC with steel fibers was higher, the strength loss ratios after thermal exposure were similar for all concretes containing steel fibers. In contrast, concrete made with polypropylene fibers demonstrated a unique behavior, with a slight increase in compressive strength observed after exposure to 250 °C and subsequent cooling in water.

The tensile strength of UHPC with F1 steel fibers was significantly reduced after being subjected to an 800°C heat shock and subsequent cooling, highlighting the destructive effects of high temperature on this type of concrete. Furthermore, the concretes with steel fibers that were heated to 250°C often exhibited a higher tensile strength to compressive strength ratio, indicating that the stress transfer mechanisms under tensile loading may be affected differently by thermal exposure compared to compressive loading.

A noteworthy finding in this study was the observation of a correlation between the ultrasonic pulse velocity of unheated samples and the strength loss at 800 degrees. The experiments demonstrated that samples with higher initial ultrasonic pulse velocity values tended to experience greater strength loss after thermal exposure. While the limited number of experiments in this study limits definitive conclusions, the potential relationship between ultrasonic pulse velocity and thermal performance is an intriguing avenue for future research.

Author Contributions

The amount of participation of the authors in writing this article is 35% for Mr. Seyed Hossein Ghasemzadeh Mousavinejad, 35% for Arash Radman and 35% for Sepher ghorbani Gilkalaye.

Conflict of Interest

The authors declare that there are no conflicts interest in this manuscript.

Data Availability Statement

Data are openly available in a repository.

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