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Original Research

Residual mechanical performance of UHPC with the addition of carbon steel and polypropylene fibers after exposure to 600 °C

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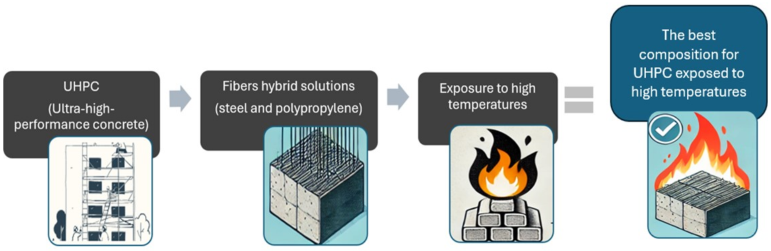

Abstract: Ultra-high-performance concrete (UHPC) is a material that has revolutionized the construction industry due to its versatility of use and the reduction of the cross-sections of structural elements. However, when exposed to high temperatures, UHPC can suffer damage and structural impairment due to the spalling effect. Therefore, the objective of this study is to analyze the influence of the addition of polymeric fibers, associated with steel fibers, to combat the degradation effect at high temperatures characteristic of UHPC. The concretes were molded with the addition of polypropylene fibers, in the percentages of 0.0%, 0.2%, 0.6%, and 1.0%, in a mixture with 75 kg/m³ of steel fibers. The samples were subjected to mechanical compression and flexural tensile tests before and after exposure to a temperature of 600 °C. The results obtained for flexural tensile strength demonstrate that the samples with the addition of 0.2% and 0.6% of PP fibers presented at the first age of the test, an increase of 40.32% and 51.20%, respectively, compared to the composition without the addition of fibers, while the test specimens with 1.0% addition presented a decrease of 17.95%. During exposure to high temperatures, the lower percentage of polypropylene fiber addition was already shown to effectively reduce the chipping effect. In this scenario, the addition of 1.0% PP fibers proved to be the best composition for maintaining the residual mechanical properties of flexural and compressive traction in both proposed curing regimes. With the aid of scanning electron microscopy, it was possible to identify the interaction of the fibers with the cementitious matrix, in addition to analyzing the influence of exposure to high temperatures on UHPC.

Keywords: Concrete, ultra-high-performance, spalling effect, polypropylene fibers.

Introduction

The need for mixtures that enable the design of slimmer structures with high durability has driven research to improve conventional concrete, based on changes to the cement matrix and improvement of the constituent materials, giving rise to UHPC (Ultra High-Performance Concrete). This concrete seeks to increase its homogeneity by excluding coarse aggregates and replacing them with fine aggregates, consisting mainly of cement, pozzolanic ingredients, water, fine aggregate, and others [1, 2]. The reduction in the water/cement ratio, use of superplasticizers, and optimization of grain size led to notable improvements in the resistance properties, rheology of fresh concrete, ductility, and compaction of the material [3, 4]. However, the effect of the superplasticizer depends on the compatibility between the materials used and its insertion can cause air incorporation [5].

Commonly considered agricultural waste, rice husk ash was used as a substitute for active silica, due to its pozzolanic properties and because it is a sustainable addition to UHPC [6–8]. In addition to its high pozzolanic activity, rice husk ash has a high specific area, high silica content, amorphous silica crystallization phase, and porous microstructure [9].

In addition to meeting mechanical strength and durability requirements, fire resistance is an important characteristic that must be taken into consideration when analyzing this type of concrete. Due to exposure to high temperatures, up to 100 ºC, the materials that make up the concrete microstructure are stable, however, the composite structure undergoes physical and chemical changes, which directly impact the properties of the composite [10]. At 300 ºC, the color change of the material can be seen, and, due to the decomposition of hydrated aluminates, at 400 ºC, the portlandite, present in the material, begins to decompose [11]. At 600 ºC, the cracks are deeper, the portlandite is decomposed, and the quartz aggregates crack, resulting from the expansion of approximately 0.8% in their volume. At temperatures close to 800 ºC, widespread cracking of the composite occurs, accompanied by the decomposition of C-S-H (hydrated calcium silicate) and calcite [10].

As it is a heterogeneous material, the behavior of concrete at high temperatures is directly related to the type of aggregate used, strength, and porosity. Conventional concrete is porous enough to allow the evaporation of free water from the mixture when exposed to high temperatures without, as a result, significant spalling phenomena. However, high-performance concretes, due to their higher resistance and low porosity index, make it difficult for water to escape from the interior of the composite, favoring the creation of internal pressures that trigger the spalling effect process [12–14]. The spalling effect is not an intrinsic property of the material but rather is influenced by the mechanical properties, incorporated additives, heating rate, and sample dimensions [15].

The occurrence of the explosive spalling effect was also reported by [16–21] after exposure of UHPC samples to high temperatures, due to evaporation. Water is resisted by the dense cement matrix, forming points of vapor pore pressure that eventually overcome the tensile strength of the concrete, causing the spalling effect. The tensile strength of UHPC is the property most impacted by the origin of pressure due to the formation of vapor inside the pores [22].

The use of steel fibers concomitantly with polypropylene (PP) fibers can bring benefits to UHPC, since PP fibers prevent fragmentation phenomena caused by fire, while steel fibers give the material a certain resistance to residual flexion, even when exposed to high temperatures [23]. The authors emphasize that, with the addition of fibers, they obtained an improvement in the post-cracking resistance in flexion; however, the uniaxial compression resistance did not suffer significant changes due to the action of fire, and the axial tensile resistance suffered gradual damage according to exposure to temperature rise, resembling conventional concrete.

Due to the low melting temperature, the addition of polypropylene fibers with a smaller diameter but with a longer length proved to be more effective in reducing the probability of the spalling effect occurring, by creating, after disintegration, a larger network of internal microchannels. which make it possible to relieve the internal pressure of the concrete [17]. Other synthetic fibers, such as: aramid fibers (AR), polyester fibers (POL), polyamide fibers (NY), and aramid pulp fibers (AP), were added to UHPC in studies conducted [24], aiming to minimize aggressiveness and occurrence of the spalling effect, however, they did not prove to be as efficient as PP fibers.

Polypropylene fibers have a low melting point, between 140 and 170 ºC, and therefore, when they volatilize, they are absorbed by the cement matrix, generating a network of small voids [25]. The micro-channels generated are responsible for dissipating vapor pressure, thus reducing internal tensile stresses and the propensity for explosive spalling [26]. When exposing the fibers to heat, at 170.5 ºC, there is a change from solid to liquid phase, which starts to be absorbed by the concrete. At 399.5 ºC, evaporation occurs, and finally, at 442.9 ºC, there is complete disintegration of the fiber. Polypropylene fibers, when exposed to high temperatures, melt, helping to release water through the pores [27].

In this context, we intend to analyze the influence of adding polypropylene fibers, in percentages of 0.0%, 0.2%, 0.6%, and 1.0%, in ultra-high-performance concrete following the guidelines [28, 29], with a fixed consumption of carbon steel fibers of 75 kg. /m³, and remaining close to the range indicated by the bibliography [30–32], compared to compression and traction in flexion at early ages. Likewise, identify the residual mechanical properties of the specimens after exposure to a temperature of 600 °C after 28 days, and with the aid of SEM (Scanning Electron Microscopy). This seeks to identify the effect of fiber hybridization with the UHPC matrix when exposed to high temperatures.

Experimental Section

Materials

High initial strength Portland cement, CP V-ARI, was used, as it is a cement with a high clinker content and provides high initial strength to the concrete, with an apparent specific mass between 0.9 and 1.2 g/cm³ and absolute specific mass between 2.8 and 3.2 g/cm³. The natural sand used has a specific mass of 2604 g/cm³, a fineness modulus of 2.21, and a maximum dimension of 2.36 mm [33–35]. The granulometric curve and its continuous distribution are shown in Figure 1.

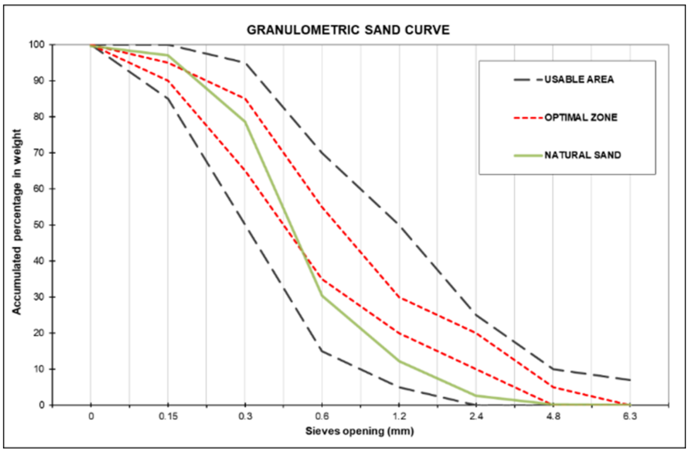

Figure 1. Aggregate particle size curve.

Considering that the cement particles pass through the #150 mm sieve, quartz powder #320 mm mesh was used to ensure better packaging of the mixture by filling voids. It has a specific weight of 2.65 g/cm³ and a melting point of around 1720 ºC. Rice husk silica was used, an industrial component obtained through the controlled combustion of rice husk. Its properties are presented in Table 1.

Table 1. Rice husk silica properties.

Physical and chemical properties	Results
Fire loss (%)	< 5
Moisture (%)	< 3
pH	Between 8 and 10
Specific mass (g/cm³)	2.16
Residue in sieve # 325 (%)	< 5
Content of SiO_2 (%)	> 90
CTAB Assay (m²/g)	10 to 12
Specific surface (m²/g)	15 to 20

The additive used was a third-generation superplasticizer, with high-performance characteristics from the Sika® ViscoCrete®-100 HE brand, which meets regulatory requirements [36]. The chemical base of the additive is a polycarboxylate solution in an aqueous medium, with a density of 1.09 ± 0.02 kg/L and a pH of 5.0 ± 1.0. The metallic fibers used are carbon steel, belonging to class A1 [37], in a wavy shape with dimensions of 12.5 mm in length and a diameter equal to 0.50 mm (shape factor to 0.04), with tensile strength greater than 1,150 MPa and elasticity of 210,000 MPa. The properties of the polypropylene fibers used are described in Table 2.

Table 2. Properties of polypropylene microfibers.

Physical and chemical properties	Value
Diameter	0.018 mm
Length	12 mm
Shape factor (d/l)	0.0015
Specific weight	0.91 g/cm³
Melting temperature	160 ºC
Ignition temperature	365 °C
Tensile strength	300 MPa
Young Modulus	3000 MPa

Production and curing samples

For the analysis, samples were designed in a prismatic format, with dimensions of 4 x 4 x 16 cm, with a mass ratio of 1:0.2:0.3:1.20, (cement, rice husk silica, quartz powder, fine aggregate), maintaining a fixed consumption of 75 kg/m³ of carbon steel fibers, according to proposed ranges [30–32]. The variation in the percentage of addition of polypropylene fibers was 0.0%, 0.2%, 0.6%, and 1.0%, over the cement mass, according to the percentages proposed by [28, 29]. Table 3 presents the mass quantity of materials used, with the mix without the addition of polypropylene fibers being taken as a reference, and the others identified according to the variation in the percentage of addition of polypropylene fibers.

In total, 48 samples were molded, 12 for each UHPC composition, using a planetary mixer. Preparing the mixtures took around 12 minutes, following the pattern of pre-mixing dry materials (cement, quartz powder, rice husk silica, and fine aggregate), at low speed; insertion of 90% of the water in the mixture; dilution of an initial content of 1.0% of superplasticizing additive in the remaining 10% of water in the mixture, for after insertion into the concrete; placement of the remainder of the superplasticizing additive; and, finally, introduction of metallic and polypropylene fibers. After demolding, all specimens were placed in submerged curing, at a temperature of approximately 20°C, until completing a period of 7 and 28 days.

Tests in the hardened state

Pilot study

A pilot study was carried out on four UHPC samples, without the addition of polypropylene fibers, which underwent submerged curing for up to 21 days and, subsequently, 7 days in ambient curing. Arranged in an oven, with an initial temperature of 0ºC with an average variation of 21°C/min, where, upon reaching a temperature of 526°C, the beginning of the spalling effect was observed, with explosions lasting up to 633°C. The explosions were noticed over approximately twelve minutes, where there was complete degradation of the samples. Aiming to analyze the mechanical residual properties, four other samples were subjected to drying in an oven for 24 hours at a temperature of 105°C before being placed in the oven. Likewise, the procedure followed was the same as described above; however, up to the exposure temperature of 700°C, no explosion or evidence of a spalling effect was observed. The test was interrupted at this temperature, and the samples only showed small cracks.

Figure 2 shows the effects of exposure to high temperatures on samples that were subjected to ambient curing and shows the specimens that underwent oven drying.

Table 3. Total quantity of materials per cubic meter.

Mix ID	C (kg)	RHS (kg)	QP (kg)	S (kg)	Water (kg)	W/C	SF (kg)	PF*		SP* (%)
								(kg)	(%)	
0.0-PP	827.04	165.4	248.1	992.5	272.9	0.33	75	----	0.0	3.36
0.2-PP	827.04	165.4	248.1	992.5	272.9	0.33	75	1.65	0.2	3.36
0.6-PP	827.04	165.4	248.1	992.5	272.9	0.33	75	4.96	0.6	3.36
1.0-PP	827.04	165.4	248.1	992.5	272.9	0.33	75	8.27	1.0	3.36

C: cement; RHS: rice husk silica; QP: quartz powder; S: fine aggregate; SF: steel fibers; PF: polypropylene fibers; SP: superplasticizer additive;
* Consumption of cement mass.

Figure 2. Pilot study samples.

Microscopy (MEV-FEG) and Spectroscopy (EDS)

The SEM-FEG analysis was carried out at the Central Microscopy Laboratory (LCMIC) of the University of Caxias do Sul (UCS) using a Tescan scanning electron microscope - model FEG Mira 3 (Czech Republic), on eight samples with dimensions of 1 x 1 x 0.5 cm (width x length x height) taken from specimens of composition 0.0-PP and 1.0- PP before and after exposure to high temperatures, to enable the analysis of the interface between the cement matrix and the fibers and the effects of adding polypropylene fibers against the occurrence of the spalling effect.

The specimens were left in a desiccator with moisture-absorbing material for five days. They were then fixed to a metal sample holder with conductive carbon-based double-sided tape. All samples were subjected to carbon deposition on their surface using the graphite rod pyrolysis technique. Carbon serves as an electrically conductive material and, like gold, is the recommended material for coating ceramic materials for analysis by scanning electron microscopy.

Exposure to high temperatures

The samples were exposed to high temperatures in an electric oven, from the Brasimet brand, type KOE 40/25/65, with a voltage of 380 V, heating current frequency of 60 Hz, and power of 18 kW. Based on the results obtained from the pilot study, the high-temperature exposure test was conducted at a maximum temperature of 600ºC with an average heating rate of 20.27 °C/min. The heating curves varied in the test of each UHPC composition because they were carried out on different days, with the heating of the equipment being hampered by the external temperature and ambient humidity. Figure 3 shows the heating curves obtained during the exposure test to high temperatures.

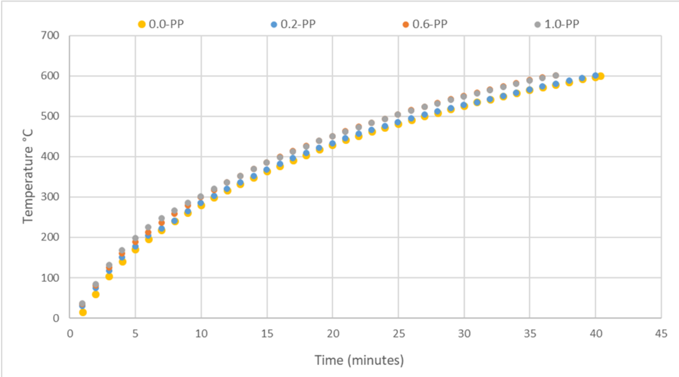

Figure 3. Heating curves.

After results were obtained from the pilot test, to carry out the exposure test to high temperatures, at 28 days of age, two curing regimes were proposed where two samples were taken from the submerged cure to the environment seven days before the test and, two other samples, were subjected to curing in an oven at 60ºC for 48 hours before exposure to the oven, to eliminate the free water present without, however, damaging the polypropylene fibers.

Tensile strength in bending and compression

Mechanical tensile strength tests in flexion and compression at 7 and 28 days were based on the Brazilian standard [38], this limited due to existing laboratory infrastructure. The specimens were kept in submerged curing at a temperature of 20 ºC until the age at which the tests were carried out. The analysis of residual mechanical properties was carried out immediately after exposing the samples to high temperatures, following the guidelines [38].

Results and Discussion

Microscopy (MEV-FEG) and Spectroscopy (EDS)

Figure 4 shows the SEM-FEG of the samples before their exposure to high temperatures for the samples without and with the addition of polymeric fibers.

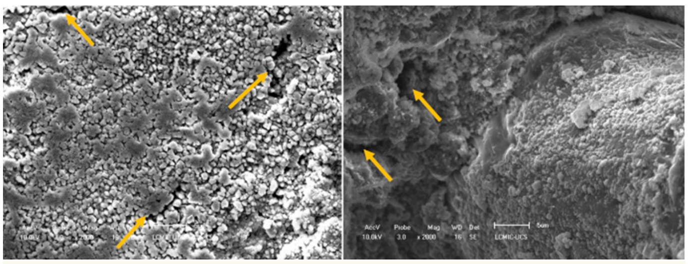

Figure 4. MEV-FEG with a magnitude of 2000x. without exposure to high temperatures: (a) 0.0-PP; (b) 1.0-PP.

Figure 4 demonstrates a dense structure with a small number of voids in both samples, which indicates a suitable granular packing for UHPC. The densified matrix of UHPC is also highlighted by [39], in addition to exhibiting an intertwined structure surrounded by the C-S-H gel.

Figure 5 shows the microstructure of UHPC 0.0-PP and 1.0-PP before exposure to high temperatures and the EDS of the samples.

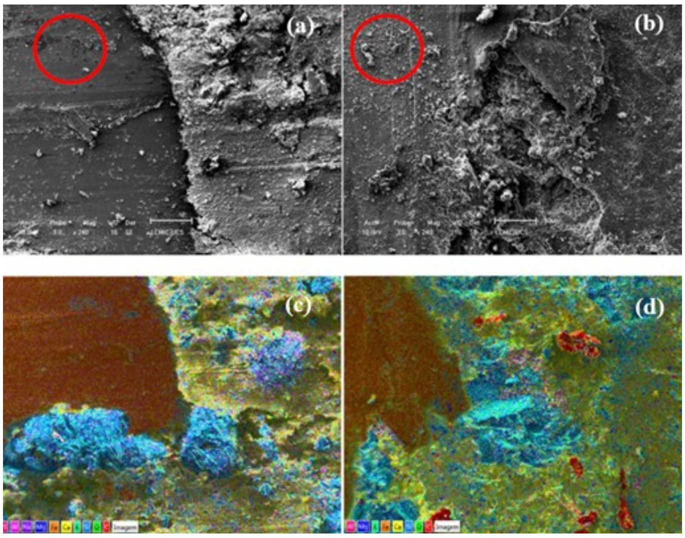

Figure 5. MEV-FEG with a magnitude of 240x. without exposure to high temperatures: (a) 0.0-PP; (b) 1.0-PP. EDS with a magnitude of 240x. without exposure to high temperatures: (c) 0.0-PP; (d) 1.0-PP.

Through the spectra obtained by EDS analysis, the locations demarcated by red circles (a) and (b) showed a large amount of iron, linked to the presence of carbon steel fibers in this region. Due to the nature of the aggregates, silica is the chemical element most present in the specimens. The region highlighted in the 0.0-PP sample in Figure 5(a) presents a discontinuity between the steel fiber and the cementitious matrix, linked to several reasons, one of which is the smooth surface of the steel fiber [40].

In Figure 6, SEM-FEG images of the 1.0-PP samples are presented, after their exposure to high temperatures, highlighting the presence of metallic fibers in the UHPC.

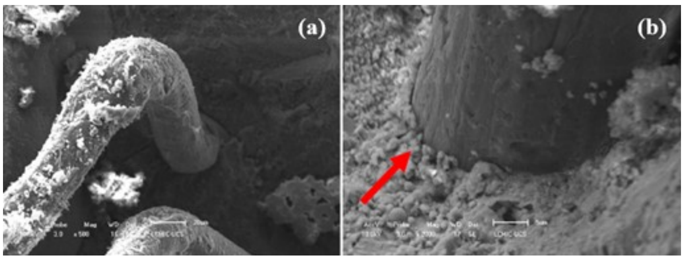

Figure 6. MEV-FEG with a magnitude of 500x. after exposure to high temperatures: (a) 1.0-PP. MEV-FEG with a magnitude of 2000x. after exposure to high temperatures (b) 1.0-PP.

Observing the images in Figure 6 (a) and (b), it is possible to observe that the dense matrix remains after exposure to high temperatures, which may be due to the use of polypropylene fibers, which may have helped to dissipate tensions caused by the increase in temperature. This effect stands out due to the strong fiber-matrix interaction, also observed by [41, 42].

Figure 7 shows the microstructure of UHPC 0.0-PP and 1.0-PP after exposure to high temperatures and the EDS of the samples.

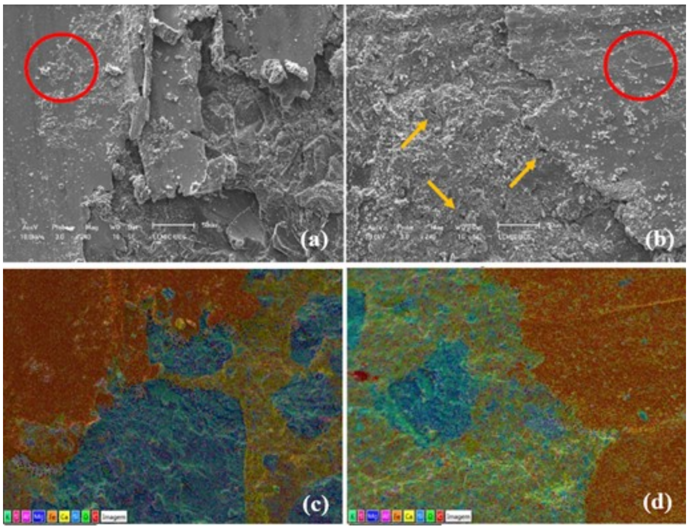

Figure 7. MEV-FEG with a magnitude of 240x. after exposure to high temperatures: (a) 0.0-PP; (b) 1.0-PP. EDS with a magnitude of 240x. after exposure to high temperatures: (c) 0.0-PP; (d) 1.0-PP.

In the same way as in the samples before exposure to high temperatures, the regions demarcated with the red circle showed a high concentration of iron, when analyzing the spectrum of the specimens, showing the presence of carbon steel fibers. The regions indicated in Figure 7(b), by yellow arrows, showed small voids linked to the composite formulation itself or due to the melting of the polypropylene fibers. Voids arising from the melting of PP fibers in UHPC samples when exposed to high temperatures have been reported [12, 24, 43].

The PP fibers melted at 167 °C, and the microchannels generated decreased concentration due to the release of vapor pressure, thus increasing the strength of the UHPC. Considering that the steel fibers remain closely linked to the matrix, large cracks do not develop. The decomposition of C-H and C-S-H hydrates at 400 to 500 °C makes the structure of UHPC weaker and more porous. From this exposure temperature, the cracks become more relevant, and the resistance begins to decrease; the interface between steel fiber and cement becomes weaker, and the crack width increases [41]. On a larger visualization scale, Figure 8 shows the same 1.0-PP sample.

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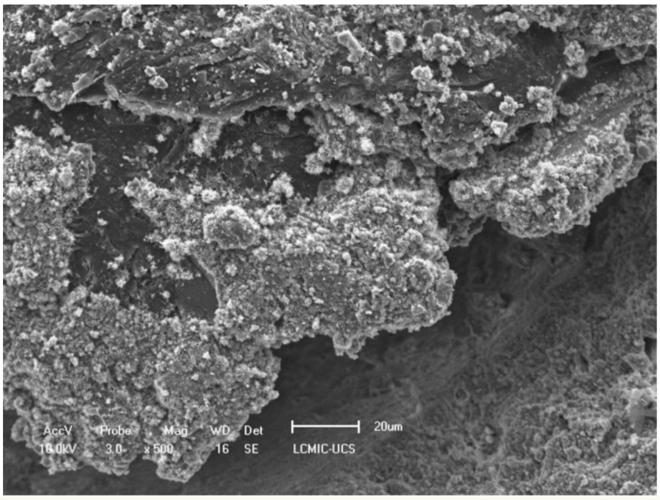

Figure 8. MEV-FEG with a magnitude of 500x. after exposure to high temperatures 1.0-PP.

With the application shown in Figure 8, it is possible to observe a large amount of cement hydration crystals. This effect is enhanced by the exposure temperature, thus justifying the increase in resistance obtained, mainly to compression.

Tensile strength in bending

The flexural tensile strength values obtained for each composition are represented in Figure 9.

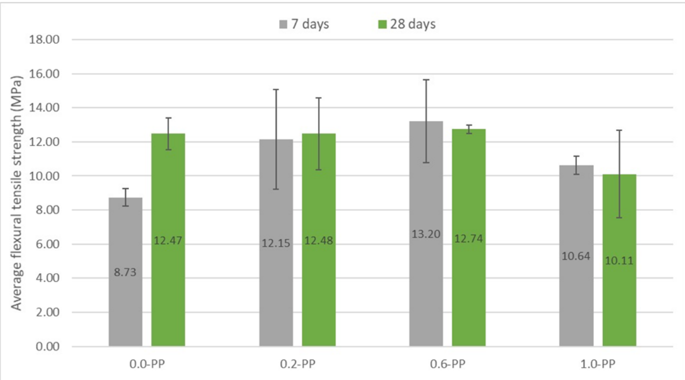

Figure 9. Flexural tensile strength test results.

After 7 days, UHPC, containing 0.6-PP showed greater resistance than the 0.0-PP mix, achieving a growth of approximately 33.86%. After 28 days, the 0.6-PP composition again proved to be the best mixture, obtaining an approximate increase of 20.64% about 1.0-PP, which is the composition with the lowest flexural tensile strength.

The higher the polypropylene fiber content, the decreased the tensile strength of the samples; the addition of 1% resulted in a greater dispersion of the test results, which can be observed by the standard deviation presented. In general, the addition of polypropylene fibers can lead to a reduction in the mechanical properties of reinforced concretes at different temperatures investigated [44].

The influence of the addition of steel fibers in cylindrical UHPC specimens, after 28 days, had an increase of 48% in tensile strength in specimens with the addition of 1% of 16 mm long steel fibers, about the control trait without the addition of fibers. At the same age of analysis, at a dosage of 6%, the resistance was approximately 4 times higher than in concrete without addition [45].

The influence of the addition of polypropylene microfibers on flexural tensile strength was observed, where the higher the added fiber content, the more effective the resistance growth. Fiber consumption was set at 1, 2, and 3 kg/m³, obtaining, after 7 days, an increase of 7.34%, 10.84%, and 9.27% respectively. At 28 days, the increases in tensile strength were 3.13%, 9.70%, and 10.86% [46].

Compressive strength

The obtained compressive strength values are presented in Figure 10.

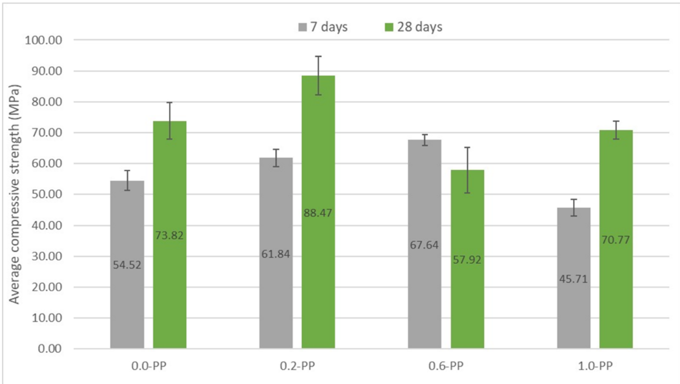

Figure 10. Compressive strength test results.

Among the samples with the addition of polypropylene fibers, after 7 days, the 0.6-PP composition showed a higher resistance index, which, compared to the control mix, achieved an increase of approximately 19.40%. After 28 days, the 0.2-PP sample proved to be the best mixture, obtaining an approximate growth of 16.55% about the 0.0-PP. As the content of PP fiber addition increased, a decrease in resistance was observed in the samples. The reduction in compressive strength of the specimens containing propylene fibers may be associated with the increase in porosity in the fiber-matrix transition zone [47]. In UHPC samples, with the addition of PP fibers, the compressive strength also increased by around 5%, compared to samples without the addition [48].

The addition of polypropylene microfibers generates a more dispersed microstructure, with less homogeneity, greater porosity, larger pores, and fewer interconnected fibers, which justifies the reduction in mechanical properties (tensile strength and compressive strength) with their addition [44].

Flexural tensile strength after exposure to high temperatures

The values obtained for residual flexural tensile strength, at 28 days, for each UHPC composition, after exposure to high temperatures, are represented in Figure 11.

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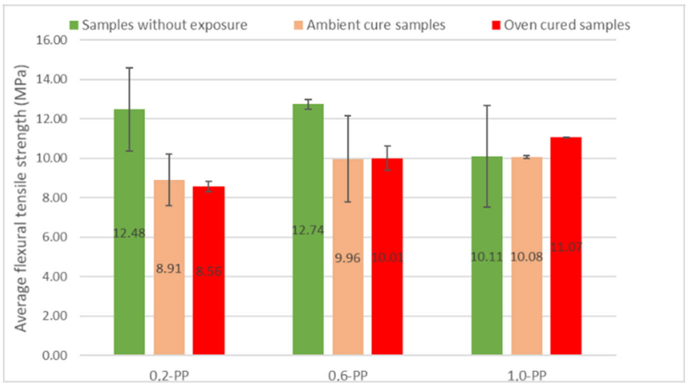

Figure 11. Average flexural tensile strength before and after exposure to high temperatures.

During exposure to high temperatures of the 0.0-PP composition, spalling may have begun at temperatures of around 253 °C, explosions lasting until 600 °C, when the test was terminated. All samples, whether subjected to oven or environmental curing, almost completely disintegrated, and, therefore, it was not possible to obtain resistance values.

All samples, with the incorporation of polypropylene fibers, showed an increase in voids after being subjected to high temperatures, possibly caused by the melting of polypropylene fibers and resulting from water evaporation. Figures 12 (a) and (b) firstly show the 1.0-PP samples subjected to ambient curing and those cured in an oven. Faced with the color change, the specimens went from dark gray to light gray [49].

Figure 12. Specimens with 1.0-PP after exposure to high temperatures: (a) environment-cured; (b) oven-cured specimen.

In comparison to the pilot test carried out, drying in an oven at 60°C was not sufficient to prevent the occurrence of the spalling effect in samples of the reference mix subjected to this curing regime, due to the failure to eliminate moisture. The samples in ambient curing had the same behavior as in the pilot test, almost completely disintegrating. CAD (high-performance concrete) samples, without the incorporation of polypropylene fibers, resulted in extremely rapid deterioration, intensified by the occurrence of the spalling effect [46].

Steel fiber reinforced concrete, after being exposed to temperatures close to 300 °C, tends to exhibit microcracking along the steel fiber/matrix interface. These cracks are radial, less than 10 μm wide, and occur due to thermal incompatibility between the fiber and the matrix, which weakens the fiber/matrix bond and significantly reduces flexural performance [50].

After exposure to high temperatures, the 0.2-PP samples showed a reduction in resistance of approximately 28.61% and 31.41%, respectively, after ambient curing and in an oven at 60 °C. The 0.6-PP composition resulted in a decrease in strength of approximately 21.82% in the ambient curing regime and 21.43% after oven drying. A slight decrease was noticed in 1.0-PP, where, in ambient curing, there was an approximate variation of 0.30%; however, unlike the oven-dried samples, they showed an average increase of 8.67%.

After exposing UHPC specimens, with the hybridization of PP and steel fibers, to temperatures of 100 °C to 800 °C, the tensile strength is directly affected by the increase in temperature, due to the appearance of microcracks internal to the cement matrix. At 300 °C, an increase in resistance is observed, this effect being attributed to the cement hydration reaction and the enhancement of the pozzolanic effect. Concomitant to this, the pores left by the fusion of PP fibers can contribute to alleviating damage to the concrete. With the increase in exposure temperature, tensile strength suffers a drastic drop, linked to the continuous appearance of internal cracks in the concrete and chemical changes in its composition, which, at 800 °C, present around 10% of the initial strength of samples at room temperature [51]. Furthermore, the inclusion of hybrid fibers (steel and polypropylene) resulted in a remarkable restoration of the mechanical capacity of the concrete [52].

The proposed control mix [51] contained an additional percentage equal to 2.0% of steel fibers, however, they obtained better performance with the hybridization of polypropylene fibers at a content equal to 0.15%, due to the tensile strength of this material provides the concrete with an additional gain in tensile strength. The results obtained with fiber hybridization demonstrate that the additional percentage of 1.0% polypropylene fibers remained more stable.

When investigating UHPC with hybrid fibers (steel and polypropylene), it was observed that the PP fibers (1%) melted completely, and the steel fibers became brittle, with an oxidation layer, reducing their ability to puncture. The UHPC matrix showed a reduction in the content of alite, portlandite, and dolomite [53].

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Compressive strength after exposure to high temperatures

The values obtained for residual compressive strength, at 28 days, for each UHPC composition, after exposure to high temperatures, are represented in Figure 13. Due to the complete disintegration of the 0.0-PP mixture, it was not possible to obtain data for analysis.

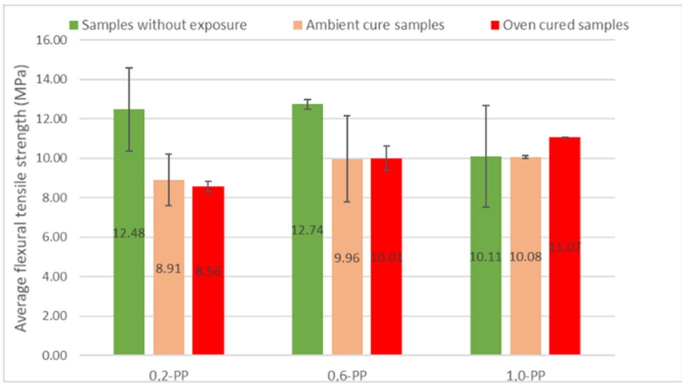

Figure 13. Average compressive strength before and after exposure to high temperatures.

In Figure 13, as well as in Figures 9, 10, and 11, it can be observed that the fiber content directly influences the mechanical properties of the composites.

The 1.0-PP composition achieved a higher percentage of residual compressive strength growth compared to the other samples subjected to ambient curing; on the other hand, the 0.6 -PP showed the smallest increase. Analyzing the oven curing process, 0.6-PP showed a higher rate of resistance growth, whereas 0.2-PP samples had the lowest performance. Comparing the two curing regimes, all samples subjected to oven curing showed greater growth in compressive strength, by accelerating the hydration reactions of the cement paste during the curing process.

The increase in resistance due to exposure to high temperatures was linked to the hydration of the anhydrous phases due to the migration of water in the pores, which leads to the formation of hydrates with better binding properties [54]. Thus, the increase in mechanical properties is probably due to the combined effects of greater cement hydration and a contribution from the reactions of pozzolanic materials [55].

At 200 °C, UHPC samples with the addition of 0.1, 0.5, and 1.0% polypropylene fibers showed higher compressive strength values compared to room temperature. Such growth in resistance is due to the hydration of the cement paste by the evaporation of free water in the mixture, thus generating a greater Van der Waals force, which brings the cement gel layers closer together. At 400 °C, they observed a drastic increase in compressive strength [56]. According to [57], this phenomenon is mainly attributed to the subsequent hydration process, with hydration catalysed through unreacted cementitious products, in the presence of steam escaping under the effect of autoclaving, formed in the pastes.

In line with other studies indicating that the presence of hybrid fibers (steel and polypropylene) has demonstrated significant restoration in the mechanical capacity of these concretes, the use of hybrid fiber reinforcement effectively reduced the loss of residual compressive strength [52].

Below 300 ºC, the high-temperature effect increased the compressive strength of UHPC, due to the samples undergoing a process equivalent to high-temperature curing. The moisture in the sample evaporates, but due to the dense matrix, it ends up taking longer, and, as a result, it continues to hydrate the cement particles to improve compressive strength. As the exposure temperature increased to 400°C, the residual compressive strength fell drastically, due to the internal damage caused by the high temperature being greater than the increase in compressive strength caused by hydration [51].

Conclusions

Regarding flexural tensile strength, the samples with hybridization of carbon steel and polypropylene fibers performed better compared to the 0.0-PP composition, due to the combination of the resistance of the PP fibers with the concrete. The composition that achieved the best results was 0.2-PP, however, as the PP fiber content was increased to 1.0%, the flexural tensile performance of the samples decreased due to the increase in voids within the cement matrix.

Among the samples with hybridization of PP and carbon steel fibers, the results obtained under compression showed atypical behavior over the ages for the sample with the addition of PP fibers in percentages of 0.6%. The mixture with 0.2% polypropylene fibers achieved an increase in resistance over the ages, surpassing the values of the control composition, proving to be the best percentage of addition.

Faced with the occurrence of the explosive chipping effect, only the 0.0-PP composition suffered damage of great magnitude, both in the samples subjected to the ambient curing regime and in an oven at 60°C. In comparison to the pilot test carried out, in which the samples were cured in an oven at a temperature of 105°C, it can be concluded that the spalling effect is directly related to the presence of excess water in the mixture, where the proposed curing in the greenhouse, was not enough to eliminate the moisture present.

The proposed minimum percentage of 0.2% addition of PP fibers proved to be effective in minimizing the probability of the spalling effect occurring in both proposed curing regimes. At high temperatures, the fibers melt and, as a result, internal micro channels form in the samples, thus reducing the internal pressure of the cement matrix, resulting from the evaporation of the free moisture present.

All UHPC samples with added polypropylene fibers showed increased compressive strength after exposure to high temperatures. Specimens subjected to oven curing at 60 °C for 48 hours demonstrated better performance, considering that temperature can accelerate the cement hydration process, which can also be observed by scanning electron microscopy (SEM), and therefore may contribute to the strength of the samples, with those with a higher PP fiber content showing the best results. However, complementary tests are suggested in future work.

Finally, a promising field of research is observed, seeking to understand the effects of hybridization of polymeric and metallic fibers, as well as the use of rice husk ash in high-strength concrete, providing the opportunity to create more efficient concrete with alternative materials to natural raw materials. The greater resistance to high temperatures (effect of the use of polymeric fibers), without altering the mechanical performance (effect observed with the use of metallic fibers), and, similarly, the use of rice husk ash as an active substitute for silica, guarantee the utilization of this residue, resulting from the burning of rice husks, for the benefit of the concrete structure, maintaining the pozzolanic reactions of the mixture. For future work, it is also important to delve deeper into the rheological effects of these mixtures, as well as the alteration of toughness generated by the hybridization of fibers and their proportion relative to the total volume of concrete.

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Authors Contribution

R.A. Roman: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft; M. Poletto: Investigation, Writing; review and editing, Visualization; V. Cecconello: Conceptualization, Methodology, Validation, Investigation, Resources, Writing; review and editing, Supervision. All authors have approved the final version of the manuscript.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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