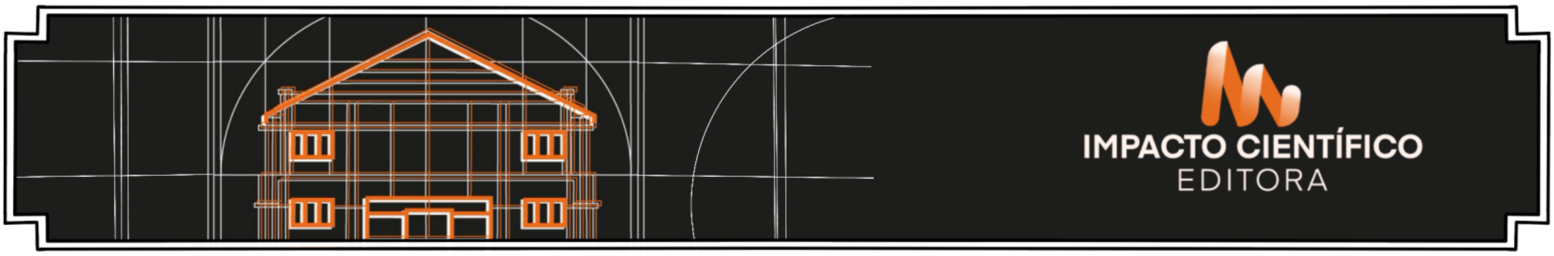

FIBER-REINFORCED CONCRETE IN A FIRE SITUATION

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ABSTRACT

Fires pose a significant threat to structures, and can cause collapses due to the physical, chemical, and mechanical transformations in reinforced concrete. In Brazil, standards such as ABNT NBR 15575 and NBR 14432 regulate fire safety, requiring that the project contemplate fire resistance (TRF). The case of the Wilton Paes de Almeida building, which collapsed in 2018, exemplifies the severe damage of a poorly controlled fire. The addition of fibers to concrete is a standout measure to improve performance at high temperatures, especially against peeling. Fire resistance is evaluated by the time that an element maintains stability, tightness and thermal insulation under standardized conditions.

Keywords: Fire resistance. Reinforced concrete.

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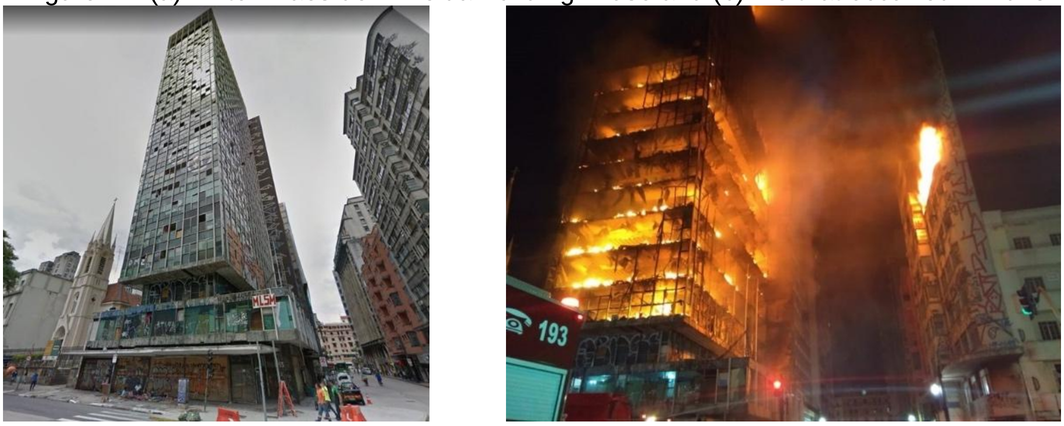
CONTEXT

Fires are one of the most destructive agents of structures, and can lead to the collapse of the building. The heating of the elements promotes a set of physical, chemical and mechanical transformations, culminating in changes – sometimes significant – in their safety, stability and carrying capacity. Therefore, the possibility of a fire occurring in a structure must be admitted in the design stage, and the set of regulatory standards that are intended for this must be met.

In Brazil, the fire safety of construction systems is required by the performance standard, ABNT NBR 15575, in addition to regulatory standards, such as NBR 5628 (ABNT, 2022), NBR 14432 (ABNT, 2001), NBR 14323 (ABNT, 2013) and NBR 15200 (ABNT, 2024), among others. There are also state regulations for fire departments.

Disasters can be remembered and serve as a learning experience. The Figure 1the exhibition is the Wilton Paes de Almeida building, built between 1961 and 1968 in the city of São Paulo, which had 24 floors and 11,083 m² of built area. This building collapsed on 05/01/2018, due to the fire that started on the 5th floor, which quickly spread to adjacent rooms and floors. The intensity of the fire was so expressive that it damaged the neighboring building, by thermal radiation, as can be seen in the Figure 1b.

Figure 1 – (a) Wilton Paes de Almeida Building in use and (b) fire that occurred in 2018



(a) (b)

Source: g1.globo.com

The structure of the Wilton Paes de Almeida building was in reinforced concrete. The exposure of conventional concretes to high temperatures triggers a series of phenomena that directly influence their performance. Characteristics such as element moisture, heating rate, part dimensions, and structural staticness are influential factors. In the search for measures that aim to preserve the performance of concrete under high temperatures, the addition of fibers in concrete is highlighted, and is applied to specific conditions.

The proper design, dosing and execution of reinforced concrete structures for normal stress conditions do not guarantee that, in the event of a fire, the system will meet adequate functionality and safety requirements. Regardless of whether the element is composed of reinforced concrete and/or reinforced with fibers, designing and building these structures considering the possibility of a fire, despite being a relatively recent criterion in Brazil, especially compared to other countries, is mandatory.

Next, the main aspects related to the performance of fiber-reinforced concrete were addressed.

INTRODUCTION TO THE STUDY

The analysis of the performance of structural or sealing elements in a fire situation is carried out in terms of their fire resistance. It is a criterion that is defined by the time in which a given element fulfills the functions of (I) structural stability, (II) tightness to hot gases and smoke and (III) thermal insulation, during exposure to a pre-defined heating program, such as the fire curve standardized by ISO 834 (ISO, 2014).

This standardized curve is recognized by NBR 14432 (ABNT, 2001), EN 1991-1-2 (EN, 2004), AS 1530-4 (AS, 1994) e CAN/ULC-04 (ULC, 2014) for building fires. Countries that do not follow ISO 834 adopt similar curves, such as ASTM E-119, but with little variation in the temperature of each interval, a fact that allows a standardization of procedure. There are other fire curves, specific for unconventional cases, such as hydrocarbons and tunnels. There are also curves that aim to feed fire dynamics models, for architectural analysis and active and passive devices. However, it is not within the scope of this chapter to detail them.

The unit of measurement of fire resistance is temporal, defined in minutes. The longer the time in which a certain element meets the three requirements, during exposure to the standardized temperature curve, the longer its fire resistance time (TRF). This is the criterion adopted in projects and laboratory analyses.

Buildings of greater height or risk of fire have higher requirements for required fire resistance time (TRRF) in their elements, which often overlap with the requirements for normal exposure conditions (ambient temperature). In general, a structure or vertical closure system designed with a longer fire resistance time promotes greater safety for users, because, in addition to preventing premature collapse during the fire, it confines the flames and prevents them from spreading to neighboring rooms.

In Brazil, the TRRF can be extracted from NBR 14432 or regional legislation, as presented in the

Table 1, valid for residential buildings, proposed by Technical Instruction No. 08 of 2018 of the Fire Department of the State of São Paulo. The height of the building establishes its class which, combined with the specificity of its use, defines the TRRF, in minutes. It is up to the technical manager to design systems with a time equal to or greater than this. It should be noted that the height in reference is the one counted from the surface of the ground floor, intended for the escape, to the highest habitable slab of the building. Therefore, the TRRF must be less than or equal to the TRF of the elements and construction systems. That is:

$$\mathbf{TRRF \leq TRF}$$

Table 1 – TRRF in residential buildings (in minutes)

Building height from ground level							
P1 Class h≤6m	P2 Class 6<h≤12m	P3 Class 12<h≤23m	P4 Class 23<h≤30m	P5 Class 30<h≤80m	P6 Class 80<h≤120m	P7 Class 120<h≤150m	P7 Class 150<h≤250m
30	30	60	90	120	120	150	180

Source: prepared based on NBR 14432 (ABNT, 2001a) and IT08 (CBMESP, 2018).

In this chapter, the aspects related to the elements built in fiber-reinforced concrete (CRF) when exposed to high temperatures were discussed, and the factors that influence the fire resistance of these pieces. A comparison was also made with project requirements of national and foreign standards.

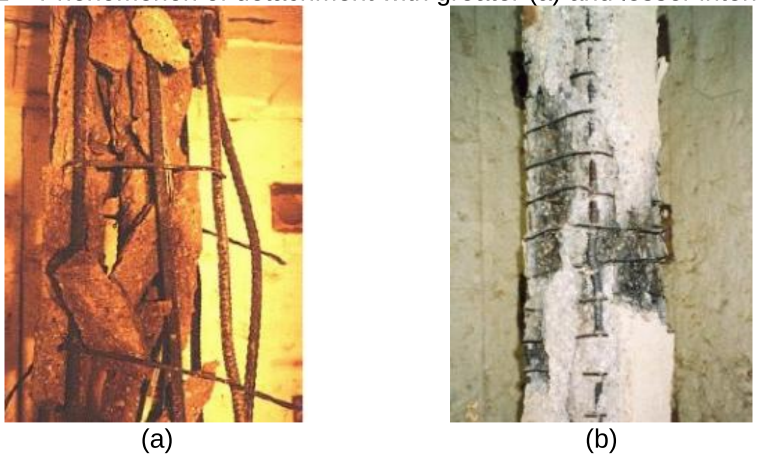
Next, some phenomena that influence the performance of these elements at high temperatures are presented, with emphasis on the phenomenon of detachment, which justifies the technical feasibility of adopting fibers in certain situations.

THE SPALLING PHENOMENON

In most cases, concrete elements have reasonable fire performance, under normal use and environmental conditions. The slender sections of these elements help to preserve **thermal insulation** and **watertightness** criteria for a few minutes of exposure to high temperatures. As for the requirement of **structural stability**, the thermal properties of the concrete and the protection that it provides to the reinforcements, combined with the monolithism inherent to these systems, are sufficient for the fire resistance to be met during some interval. It is noted that there is some intrinsic fire resistance to these structures, in greater or lesser magnitude, depending on some factors and design criteria admitted for the ambient temperature.

However, the phenomenon of detachment or chipping, called in the international literature as *spalling* (some authors still prefer to use the term in Brazil), can compromise the integrity of the concrete, exposing the reinforcements to heat, inducing excessive plastic deformations, reducing the structural capacity of the section and compromising the stability of the element. The Figure 2 shows the phenomenon of detachment in reinforced concrete pillars (KODUR, 2005), with different intensities.

Figure 2 – Phenomenon of detachment with greater (a) and lesser intensity (b)



(a) (b)

Source: Kodur (2005)

From a thermohydraulic and thermomechanical nature, detachment is a phenomenon that promotes the detachment of the surface layers of the concrete elements, when exposed to high temperatures. The origin of this process lies in the free water inside the concrete which, when heated, changes phase and creates vapor pressures that, if not dissipated, accumulate inside the piece.

Difficult and complex to predict, it is a semi-destructive mechanism, which can originate in:

a) non-uniform temperature distribution in the section;
b) amount of evaporable water from concrete, free water, which manifests itself with small or large and sudden release of energy.

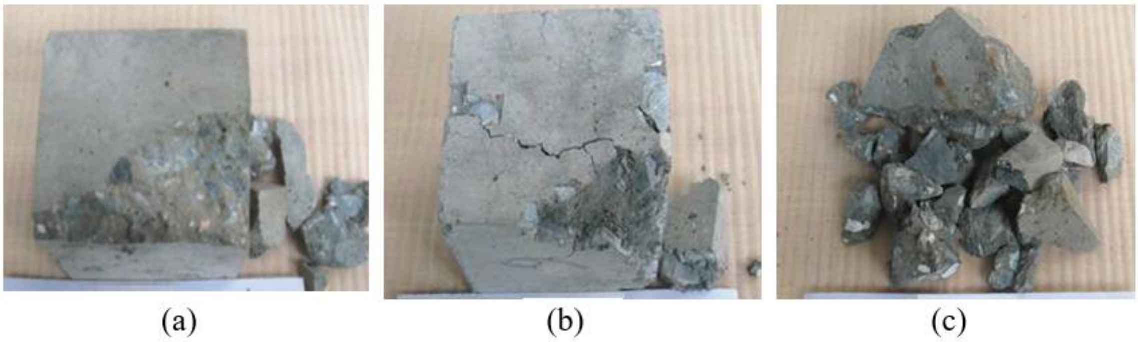
The first (a), of low intensity, promotes a superficial fragmentation of the element, while in the second (b), more intense, there is the detachment, which can be explosive, of layers of concrete. In the vast majority of cases, the phenomenon is restricted to the region where the reinforcement is covered, the unarmed portion of the section. The main consequence, in addition to the direct or indirect exposure of the reinforcements to heat, elements that are more sensitive to temperature, is the reduction of the cross-section of the element and/or the loss of structural stability.

The accumulation of vapor pressure in the section, added to the cracks produced by the stresses caused by thermomechanical mechanisms, forms ideal conditions for detachment. It should be noted that concrete fragmentation occurs only when its tensile strength is overcome by vapor pressure. This fact may be due to the reduction of the strength of the concrete by temperature. The cracks formed by the thermomechanical mechanism, by weakening the concrete, work as a trigger for the pore-pressure to induce detachment.

Some authors claim that this mechanism does not depend on the state of tension of the part, coming from the external loading, which is not a consensus. The binding conditions are more influential than the acting load, especially in terms of thermal expansion restriction. Studies produced on a full scale have shown that the elements most susceptible to chipping are the pillars and slabs, which have a higher degree of restriction to thermal expansion, in addition to a greater area exposed to high temperatures.

Factors such as surface heating rate, free water and concrete porosity contribute to the analysis of the causes of the phenomenon, which does not necessarily develop in all concrete. Humidity has a direct influence on the behavior of the element under high temperatures, as shown by the Figure 3. As a consequence of the phenomenon, there is the exposure of the reinforcements to intense heat, the reduction of the cross-section, loss of thermal insulation and impact on the resistive capacity of the element.

Figure 3 – Concrete exposed to high temperatures for moisture of (a) 75%, (b) 88% and (c) 100%



Source: Peng *et al.* (2013)

The use of fibers plays an important role in mitigating this phenomenon. This is the greatest contribution of the incorporation of reinforcements in concrete pieces susceptible to the action of a fire.

Each type of booster has a certain volatilization temperature. The phenomenon of detachment occurs when the surface layers of the concrete reach temperatures between 200 and 250ºC. Therefore, it is essential that the incorporated fiber has a volatilization below this temperature so that it creates steam escape paths and acts to mitigate the phenomenon. The fibers that best fit this characteristic are polypropylene and nylon.

FIBERS PARTICULARITIES DURING WARM-UP

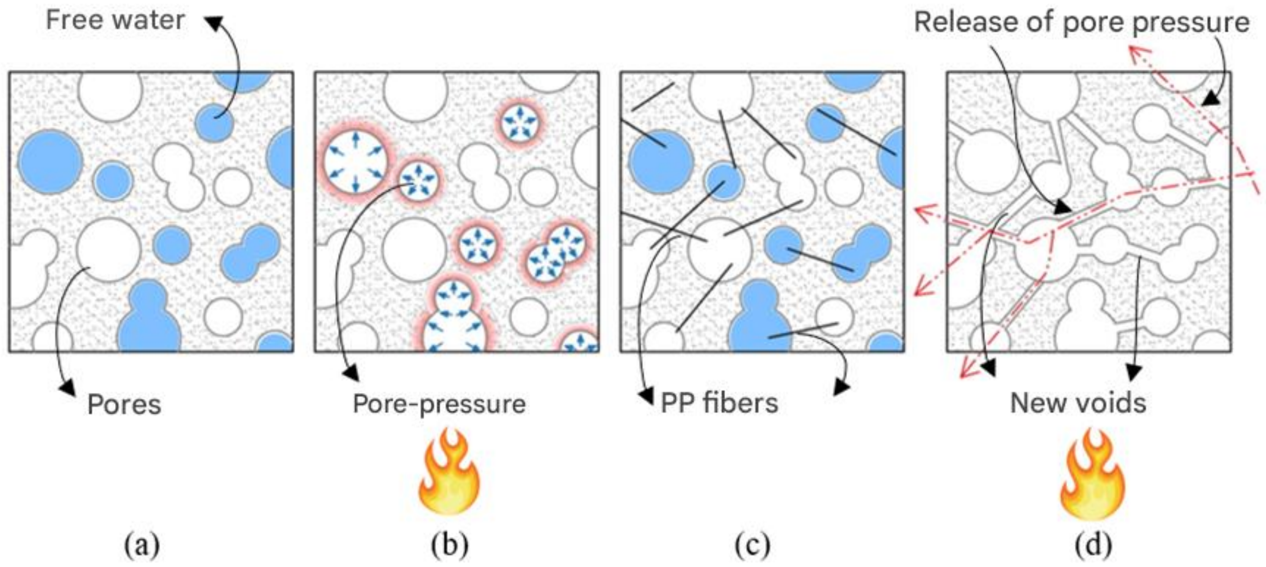
The subsequent items analyze the performance of concretes with the addition of polypropylene, nylon, and steel fibers.

POLYPROPYLENE FIBRES:

Polypropylene fibers act to mitigate the phenomenon of detachment in concrete pieces, especially those with low curing age, high internal humidity, and/or in concretes of high mechanical strength, with low porosity. The heating of polypropylene fibers results in their volatilization, creating voids in the cementitious paste, allowing the internal moisture to escape, reducing the pore-pressure of the concrete. The polypropylene fibers volatilize in the range of 170ºC, creating microchannels, functioning as escape valves for the formed pore-pressure, relieving the state of internal tension and reducing the susceptibility to detachment.

The justification for the incorporation of PP fibers in conventional concrete, susceptible to fire, is shown in the Figure 4.

Figure 4 – Concrete (a) conventional, with reduced pore interconnectivity, (b) heated, (c) with PP fibers and (d) heated with vapor release

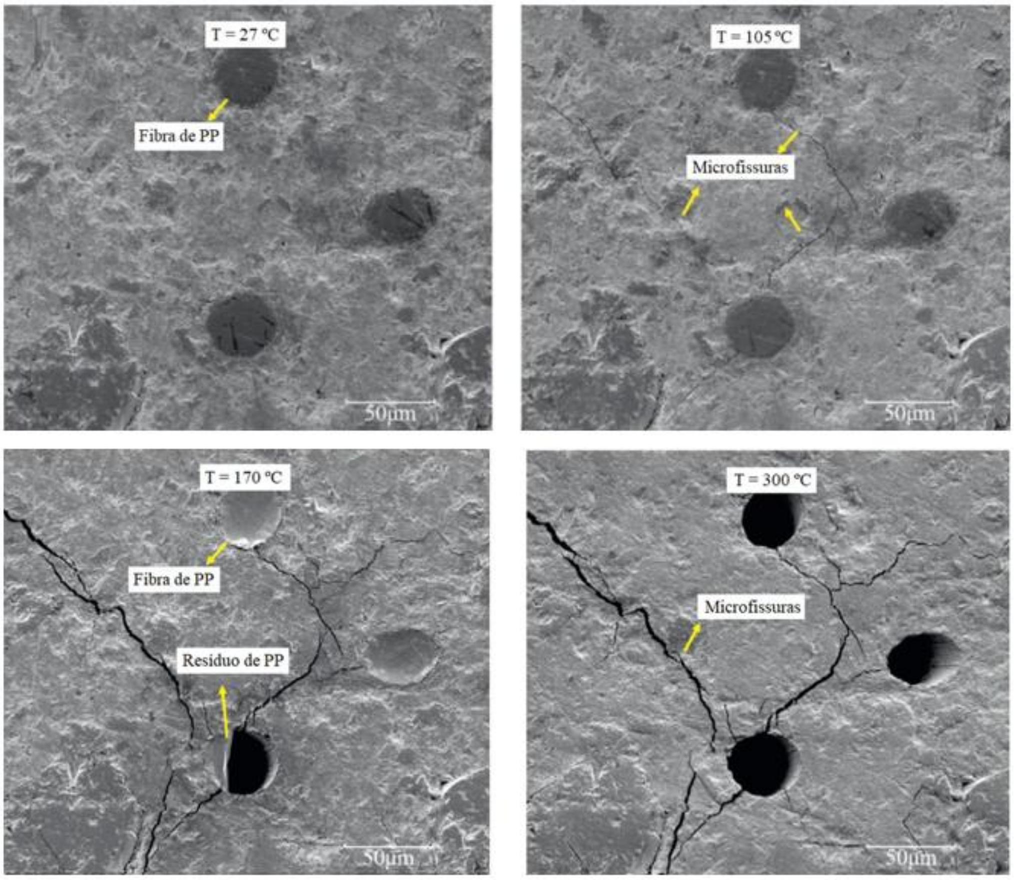


Source: the authors

Figure 4 shows that in cases where concretes have high strength, such as high-strength (CAD) and ultra-high-strength (CUAD), permeability is generally reduced, with low pore interconnectivity (Figure 4a), which can promote a build-up of pore-pressure in the elements, because the vapor pressure is not dissipated to the outside of the part (Figure 4b). The incorporation of polypropylene fibres (Figure 4c), even if low permeability is preserved, it volatilizes – partially or totally – when heating the concrete, allowing the release of water vapor (Figure 4d) by the formation of interconnected voids, creating paths for the relief of vapor pressure. Thus, tensions that weaken the part are not generated.

In a study by Ding *et al.* (2016), with the addition of polypropylene fibers, it was possible to reduce the pore-pressure by up to 49.5%. The formation of voids caused by the volatilization of the fibers can be observed in the Figure 5, where the heating of the fibers in the cementitious matrix is shown, between temperatures of 27ºC and 350ºC, as well as the cracks formed in the periphery of the fiber.

Figure 5 – Polypropylene fibre reinforced concrete under various temperatures



Source: Zhang, Dasari and Tan (2018)

Fibers of small length and diameter, when disintegrating, do not create an interconnectivity capable of dissipating vapor tensions. Kalifa *et al.* (2000) suggest that the length and diameter should be at least 19 mm and 40 µm, respectively, for polypropylene fibers to be effective. When applied to usual concrete, these reinforcements can be classified as polymeric microfibers.

The volatilization of polypropylene fibers promotes the loss of strength in structures if used at high levels. If, on the physical side, the volatilization of the fibers and the formation of pores helps to minimize detachment, on the mechanical side this porosity can harm the element. However, this reduction can be disregarded for low levels, which are usually used for this purpose.

However, it should be noted that the effect of detachment is not so common in fires that occur in existing buildings, being more noticeable in experimental works with small samples and high internal humidity. Reinforced concrete structures exposed to fires tend to have a high curing period, a higher maturation of the part and, therefore, a lower internal free water content. This scenario is ideal for detachment to occur less intensely in conventional structures.

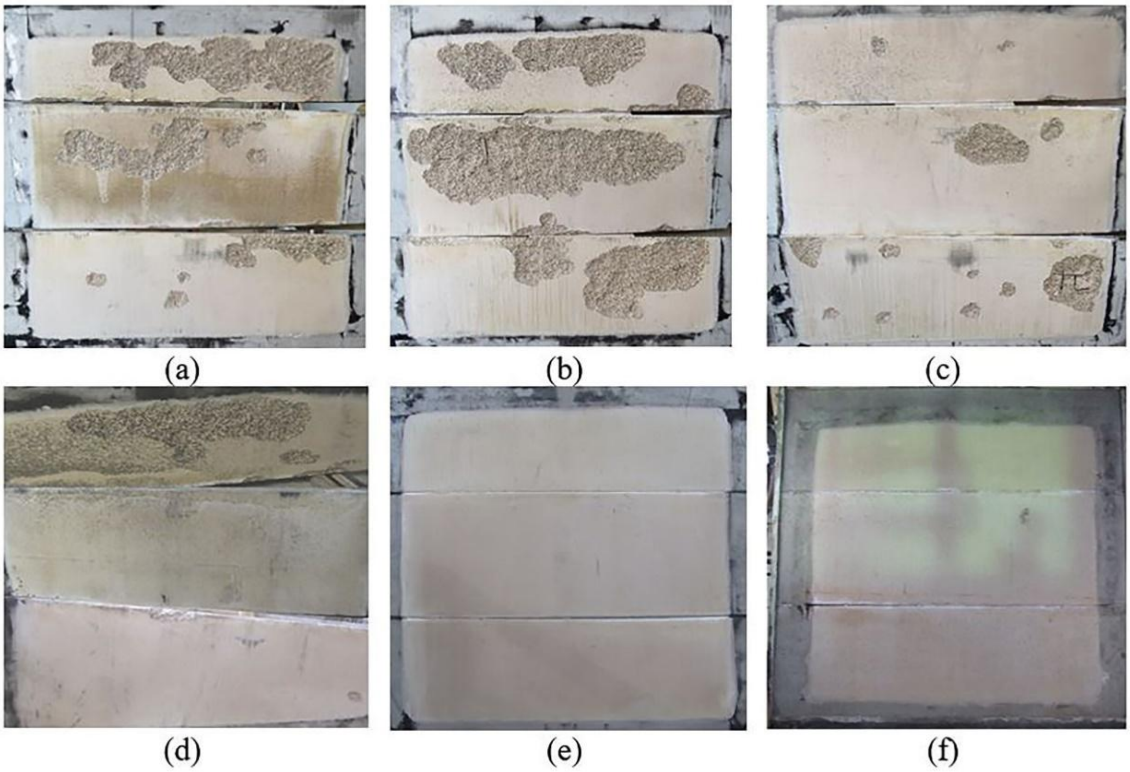
Some experimental work shows this. The Figure 6 shows two plates exposed to two hours of the standard heating curve. The plate without the addition of fibers showed detachment after 20 minutes of exposure to flames, while the one with 1000 g/m^3 of fibers did not show detachment. The tests were carried out at a young age, when the plates had high internal humidity, not consistent with the practice of real fires.

Figure 6 – Effect of delamination on fiberless concrete

Source: Schüttleworth (2001)

Tests carried out on full-scale elements with conventional concrete, with compressive strength of 50 MPa, showed that, at advanced ages (up to 830 days), the phenomenon of detachment did not occur, making it unnecessary to incorporate polypropylene fibers for this purpose. In Figure 7 It is possible to note that the phenomenon occurred at ages up to 56 days, and was not observed in the plates tested at 84 and 830 days, greater than 2 years of cure.

Figure 7 - Plates tested at (a) 7, (b) 14, (c) 28, (d) 56, (e) 84 and (d) 830 days



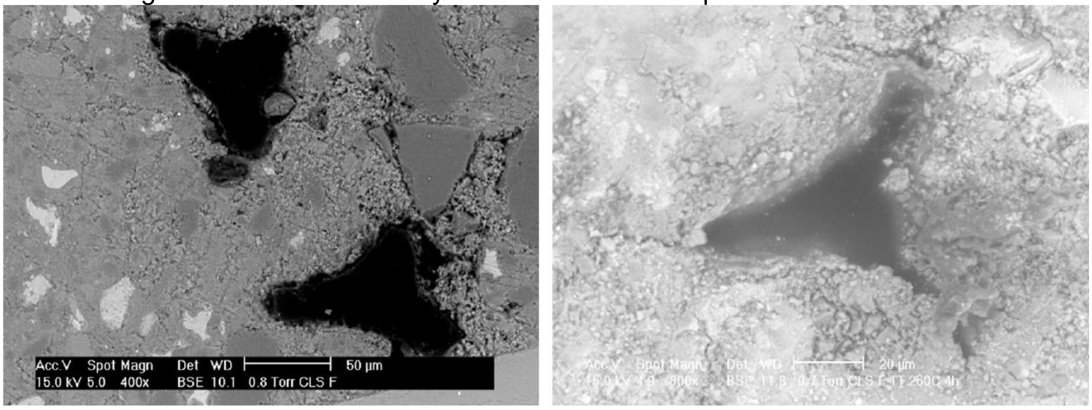
Source: itt Performance collection (Unisinos)

Therefore, understanding the behavior of fiber-reinforced elements in a fire situation is important to seek correct definitions in design.

NYLON FIBERS:

Nylon fibers have a similar function to polypropylene: to create pore-pressure dissipation pathways through the volatilization of the fibers, as shown in the Figure 8. The main differences between the fibers are that the dimensions of the nylon fibers are reduced and the melting temperature is higher, close to 250ºC. The addition of these fibers does not present significant variations in the mechanical characteristics of the concrete and results in a decrease in the specific heat of the material.

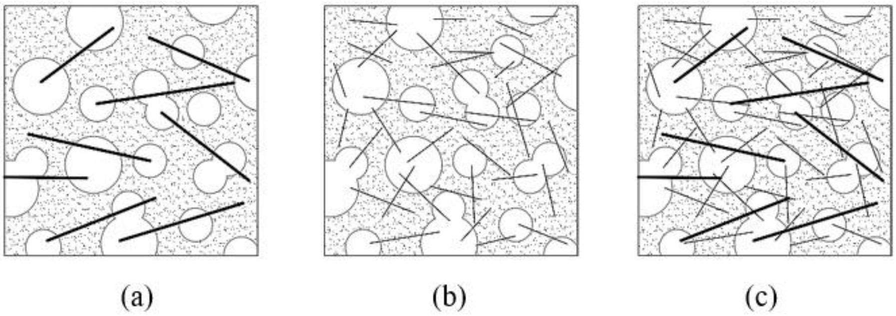
Figure 8 – Concrete with nylon fibers at room temperature and at 250 ºC



Source: Ozger *et al*. (2013)

Because they have a reduced diameter compared to polypropylene fibers, nylon fibers are less prone to the formation of lumps and, therefore, tend to mix more homogeneously in the cementitious matrix. Due to this, it was noted that it is possible to avoid the phenomenon of detachment with a lower fiber content, as they tend to be more dispersed in the matrix. This optimum content is in the order of 0.04%, while the minimum proportion of polypropylene fibres is 0.1% (HAN *et al.*, 2012). The Figure 9 shows that, with nylon fibers, there is a greater tendency for greater connectivity between the pores than polypropylene fibers. This leads to a greater potential for vapor dissipation and thus mitigation of detachment. It is also possible to hybridize the fibers, using both simultaneously.

Figure 9 – Fibers of (a) polypropylene, (b) nylon and (c) hybridization



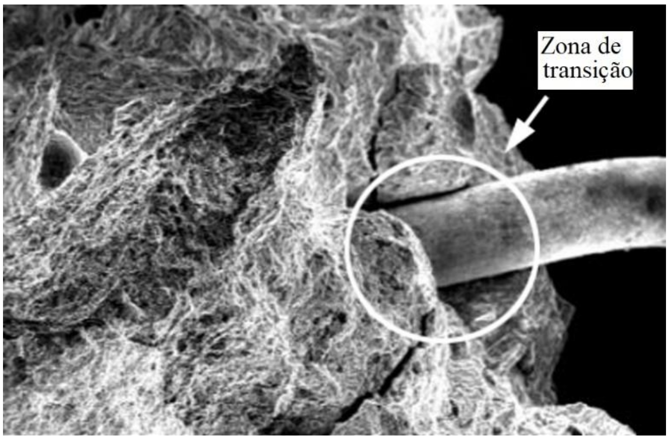
Source: the author

STEEL FIBERS:

By controlling the formation of cracks and increasing the ductility of the part, the metal fiber prevents the detachment of concrete damaged by heating. This causes the detachment, if it exists, to occur later and be of the explosive type, with aggressive detachment of layers. In terms of fire performance, this is the most striking contribution of the incorporation of metal fibers into concrete: mitigating the consequences of detachment, without attacking the phenomenon at its source.

Due to the high melting point presented by steel fibers, they are not expected to melt under fire situations, which compromises pressure dissipation. However, cracks are formed in the interface zone between the fiber and the matrix, as Figure 10. This results in better dissipation of internal pressures, but with less intensity when compared to the addition of polypropylene fibers. In a study conducted by Ding *et al.* (2016), the addition of metallic fibers promoted a decrease of up to 15.8% in pore-pressure.

Figure 10 – Cracks in the transition zone between steel fiber and cementitious matrix



Source: Ding *et al*. (2016)

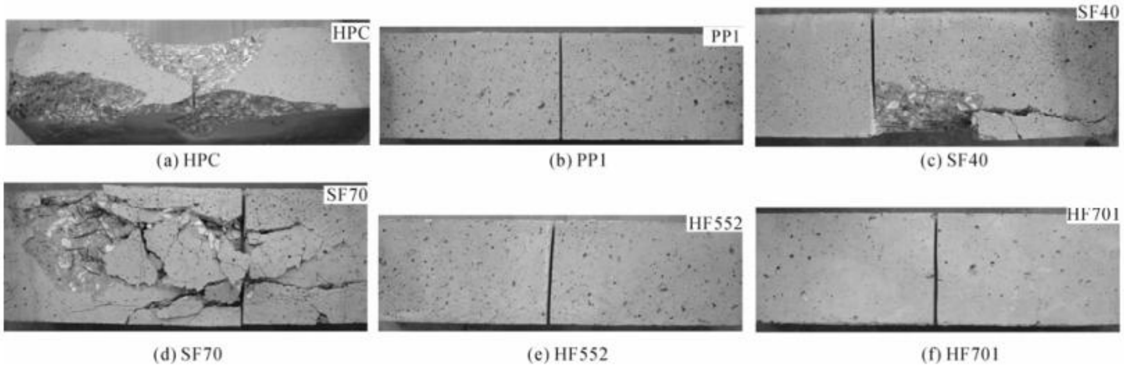
Metallic fiber preserves the fire performance of concrete structures until the moment it loses its ability to resist tensile stresses, as a result of the action of heat.

Steel is an excellent conductor of heat. This causes the increase in fiber content to generate a more intense heating of the cross-section and thus a reduction in the strength of the concrete. On the other hand, the greater heating of the internal layers of the section reduces the thermal gradient, acting indirectly on the attenuation of the detachment.

The fibers act predominantly after the nucleation of cracks in the concrete, changing the brittle behavior to pseudo-ductile. With the increase in fiber content, concrete has a tendency to increase detachment. This is due to the fact that, in the absence of *micro-spalling* in the first cracks, vapour tensions accumulate in excess in the concrete covering layer, increasing the accumulated energy and, therefore, the susceptibility or intensity of detachment.

In the study conducted by Dong *et al.* (2008), it was possible to compare the effects of the use of polypropylene fibers, steel fibers and these together (hybrids) on the fire resistance of high-strength reinforced concrete beams, above 55 MPa. The tests showed that the configuration of the part with the use of fiber hybridization is interesting under high temperatures, mitigating detachment and preserving the mechanical characteristics of the part. In the case of the samples designed with the isolated addition of polypropylene and steel fibers, they showed a loss of residual compressive strength of up to 85% and 54%, respectively, while the hybrid samples showed a residual loss of 39%. The Figure 11 presents the final characteristic of the beams (a) without addition, (b) polypropylene (1 kg/m³), (c) metal fibers (40 kg/m³), (d) metal fibers (70 kg/m³), (e) and (f) hybrid.

Figure 11 – Final appearance after exposure to a temperature of 1000°C



(a) HPC (b) PP1 (c) SF40

(d) SF70 (e) HF552 (f) HF701

Source: Dong *et al*. (2008)

The images reinforce that metallic fibers, if used in isolation, may not attenuate the effect of detachment. In theory, they only postpone the occurrence of the phenomenon – which starts to occur more intensely – and must be replaced or combined with polypropylene ones for efficiency to be achieved. The metal fibers incorporate a higher tensile strength of the concrete, causing the peeling resistance to increase. Because these fibers do not promote water vapor dissipation, or promote it to a lesser extent, the increase in tensile strength causes the deflation to occur with a higher accumulated vapor pressure, making the damage greater and the effect with a more explosive character, having seen the greater energy released.

Polypropylene and steel fibers improve the behavior of structures in fire situations in the initial moments of exposure to high temperatures. Polypropylene fibers control concrete fragmentation, while metal fibers provide a ductility to the matrix after cracking under high temperatures.

FIBER BLANKETS ADHERED WITH POLYMERS FOR REINFORCEMENT OF STRUCTURES

The use of polymer-bonded fibers to reinforce structures in the event of fire has grown in recent years, especially in the last two decades. Also called fiber-reinforced polymer, it is a composite made up of fibers – the most frequent are carbon, glass or aramid – and polymer matrix, usually epoxy adhesive. Although there are still few rules on this reinforcement, we can cite ACI 440.2R (ACI, 2017) and fib Bulletin 14 (FIB, 2001) that deal with the subject.

When looking to reinforce a structure, you can use blankets with carbon fibers, for example, which have excellent performance at room temperature. However, the adhesion of the blankets is through epoxy adhesives, which degrade at relatively low temperatures, in the order of 50ºC, changing the resistant capacity of the reinforced piece. At high temperatures, the resins undergo phase exchange, producing a reduction in the bearing capacity of the reinforcement.

Carbon fibers themselves, at temperatures of around 125ºC, suffer from a decrease in tensile strength, in the order of 40 to 50%. For temperatures in the range of 200ºC, the reduction can reach 90%. These results vary, given the configurations of the composite, such as orientation and amount of fibers, in addition to the chemical composition of the matrix.

In this way, it becomes essential to passively protect the structural element reinforced with fiber blankets adhered with polymer, enabling the delay of the action of high temperatures on the part. Protection can be achieved through the use of plasterboard or calcium silicate boards, for example, with varying thicknesses and number of boards, depending on the TRF sought. Also, protection can be given with engineered mortar reinforced with fibers.

FIBER-REINFORCED ENGINEERED MORTAR

The most frequent use of fiber-reinforced mortars occurs in buildings structured in steel. These structures are, depending on some scenarios and design circumstances, more sensitive to high temperatures than reinforced concrete structures. This requires that the structural design incorporate passive protections into the metal profiles, in order to mitigate the effect of the fire. One of the most economically viable and well-accepted alternatives in the market is the blasting of mortar reinforced with polypropylene fibers, as shown in the Figure 12.

Figure 12 – Steel structure covered with fiber-reinforced mortar.

Source: www.thebalancesmb.com/

Figure 13 – Metal profile blasting

Source: www.archiproducts.com

It should be noted that the activity must be done in the assembled structure, as Figure 13, aiming to preserve the full protection of the parts – including in the connection region – and avoid impacts and detachments from localized mechanical efforts during the profile transport stage.

The use of these mortars aims to create a watertight barrier without detachment, which is the reason for the incorporation of the fiber, during exposure to the heat of the profiles. This layer slows down the heating of the elements, lowering the average temperature, preserving its mechanical properties for longer periods. Generally, the critical analysis of the efficiency of this solution is done through laboratory tests, with instrumentation of the steel profiles, monitoring the development of temperature through exposure to the standardized temperature curve.

SOME NORMATIVE DESIGN GUIDELINES

Design verification procedures at high temperatures can be divided into three classes. The first involves relatively simple and straightforward procedures, usually tabulated, found in most technical standards. These criteria are based on prescriptions based on important research works, offering designers, for example, minimum prescribed dimensions, requiring, in some cases, little knowledge of the subject for compliance. The second class admits the strength of the structure based on analytical procedures for calculating at room temperature, allowing the reduction of the strength of the heated elements. The third, more refined class involves the heating curve, the transfer of heat to the structure, and its response to high temperatures. The first class is prescriptive, and the last two are based on performance.

Design criteria only exist when you have a mastery of the material's performance under the necessary conditions. Regarding the design of conventional reinforced concrete structures, there are standards that guide the verification of structures against fire by different procedures. In addition to experimental methods, which are costly and used under very specific conditions, there are numerical propositions for calculating the TRF of structural elements. However, the use of fibers is recommended only from the perspective of detachment, and there is no absolute convergence between the standards under this criterion. It is known that, in order to increase the TRF, the reinforcements must be protected by the concrete of the covering layer. However, in this sense, studies from the past decade showed that, in the existence of high thickness of covering, the intensity of the peeling increased, generating concern from some regulations. Some more recent studies show that other variables prevail.

The tabular methods proposed in NBR 15200 (ABNT, 2012) are inspired by structural Eurocodes (EN, 2004). The Eurocode proposes empirical recommendations to mitigate the phenomenon of chipping, such as the incorporation of polypropylene fibers or sacrificial bars in coatings greater than 40mm. Standards such as CEB *Bulletin* nº208 (CEB, 1991), BS 8110-2 (BSI, 1985), AS 3600 (AS, 2009), NZS 3101 (NZS, 2006) e IS 456 (IS, 2000) they also use tabulated methods of structural verification that refer to the covering of reinforcement to increase the TRF, but none suggests the use of fibers to mitigate detachment.

A IS 456 (IS, 2000) It recommends special measures for horizontal elements, in cases where the covering exceeds 40mm for beams and 35mm for slabs, such as the use of sacrificial bars. NZS 3101 (NZS, 2006) it only mentions that the tabulated analysis covers of the TRF must be observed together with those practiced in durability, not setting measures to preserve the elements of the detachment in high thicknesses. The AS 3600 (AS, 2009) cites not being prepared to mitigate the chipping mechanism, recommending the use of BS 8110-2 (BSI, 1985). The approach to this phenomenon by BS 8110-2 (BSI, 1985) It is made for concretes with covering thicknesses greater than 40 mm, where the use of paints, sacrificial bars or light aggregates is recommended to mitigate the phenomenon. These standards do not admit the strength of concrete as a determining factor for detachment. The use of fiber is not mentioned.

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