Article

Physical, mechanical, and microstructural changes in concretes subjected to slow and fast cooling in a fire situation simulation

Alterações físico, mecânicas e microestruturais em concretos sujeitos a resfriamento lento e rápido em situação de incêndio simulado

Eduardo Pereira
Eveline Manosso Janik Brik
Elias Pereira
Jardiel Matias de Almeida
Marcelo Miranda Farias

Abstract

Concrete, when exposed to high temperatures, has its properties changed, and the recovery processes depend on the intensity of these changes. This paper aimed to evaluate the influence of high temperatures on concrete properties and verify the effects generated in the material when submitted to natural and fast cooling. Three different concrete mixes were exposed to temperatures of 100 °C, 300 ºC, 450 ºC, and 600 ºC, subdivided into slow and fast cooling groups. With the increase in temperature, cracking processes and microstructural alterations intensified, generating reductions in mechanical strength and increases in absorptions. This study has identified that the elastic modulus was the property most affected by these changes. The correlations between the elastic modulus and the other properties were accompanied by increased concrete micro-cracking, water loss, and decomposition of paste phases. Also, it was found an effect of ettringite rehydration during concrete cooling.

Keywords: Fire situations. Elastic modulus. Cracking. Cooling.

[1]**Eduardo Pereira**
[1]Universidade Estadual de Ponta Grossa
Ponta Grossa - PR - Brasil

[2]**Eveline Manosso Janik Brik**
[2]Universidade Estadual de Ponta Grossa
Ponta Grossa - PR - Brasil

[3]**Elias Pereira**
[3]Universidade Estadual de Ponta Grossa
Ponta Grossa - PR - Brasil

[4]**Jadiel Matias de Almeida**
[4]Universidade Estadual de Ponta Grossa
Ponta Grossa - PR - Brasil

[5]**Marcelo Miranda Farias**
[5]Universidade Estadual de Ponta Grossa
Ponta Grossa - PR - Brasil

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Resumo

O concreto quando exposto a elevadas temperaturas tem suas propriedades alteradas e os processos de recuperação são dependentes da intensidade destas modificações. O objetivo deste artigo foi avaliar a influência das altas temperaturas nas propriedades do concreto, em uma faixa na qual a estrutura ainda pode ser recuperada, e a verificação dos efeitos gerados no material quando submetidos a resfriamento natural e resfriamento rápido. Para isto se desenvolveu o programa experimental com três traços de concreto, os quais foram expostos a temperaturas de 100 ºC, 300 ºC, 450 ºC e 600 ºC; subdivididos em grupos de resfriamento lento e rápido. Com a elevação da temperatura, intensificam-se os processos de fissuração e alterações microestruturais, as quais geram redução nas resistências mecânicas e o aumento da absorção. Verificou-se que o módulo de elasticidade foi a propriedade mais afetada por estas alterações. As correlações entre o módulo de elasticidade e as demais propriedades foram acompanhadas pelo aumento da microfissuração do concreto, perda de água e decomposição das fases da pasta, sendo observada posterior reidratação da etringita durante o resfriamento do concreto.

Palavras-chave: *Situações de incêndio. Módulo de elasticidade. Fissuração. Resfriamento.*

Introduction

Concrete, a widely used material in Brazil and worldwide, can be found in constructions of various functionalities and dimensions. It is known that concrete suffers changes in its properties when exposed to high temperatures. Depending on the temperature and exposure time, its use is compromised. Additionally, there is the problem of recovery and use of these structures when subjected to slow and fast cooling conditions, which can change their properties differently.

Most research in this area has focused on controlled situations in the laboratory with natural cooling. Changes in concrete in fire situations can occur in coloration, loss of tensile strength, compressive strength, and elastic modulus, spalling, cracking, and even structure disintegration itself (Costa; Silva, 2002; Georgali, Tsakiridis, 2005; Morales; Campos, Faganello, 2011; Hager, 2013; Battagin, Silveira, 2018). Valente (2014) also highlights the occurrence of other damages, such as surfaces calcination, structural dilatation and shrinkage, and movement of reinforcement due to steel dilatation. Since concrete is a heterogeneous composite, each phase will present a different behavior in the face of thermal actions.

The high temperature effect on cement paste depends on its hydration degree and humidity (Hager, 2013; Battagin; Silveira, 2018; Fernandes *et al*., 2017). When the paste is saturated, its amount of free, capillary, and adsorbed water is higher. In these cases, when the temperature increases, the water under these conditions is lost quickly. If the concrete has low permeability and lower porosity, the moisture exit from its interiors is obstructed, and the concrete may suffer superficial chipping (spalling) due to pressure gradients. This phenomenon is also reported by Fernandes *et al*. (2017) e Komonen and Penttala (2003). Their papers describe that with the increase in temperature up to 100 ºC, a temperature gradient large enough to change the porous structure is formed. According to Heissler *et al*. (2015) and Mehta and Monteiro (2008), the transition zone between paste and aggregate tends to be the most susceptible region of concrete in fire situations. The micro-cracks in these locations comprise a weaker region, which dehydrates easily and is more susceptible to cracking.

From 250 °C onwards, the water between the layers of calcium silicate hydrate (C-S-H), part of the chemically combined water from C-S-H and sulfoaluminate hydrate, will also be lost. It leads to reductions in mechanical strengths. Further cement paste dehydration due to the calcium hydroxide decomposition starts at about 500 °C. When the temperature reaches 600 °C, substantial degradation begins in the concrete because of the removing of hydration water from the cement paste, where the hotter surface layers separate from the inner layers. At 700 ºC, C-S-H decomposes into β-C2S (belite), βCS (wollastonite), and water, resulting in cement paste shrinkage and a substantial reduction in strength. Temperatures around 900 °C are required for complete C-S-H decomposition. Between 1000 ºC and 1200 ºC, concrete undergoes synthesis, and its strength is annulled (Mehta; Monteiro, 2008; Silva, 2015; Caraslindas; Barros, 2004).

The aggregate used in the concrete composition also influences its behavior at high temperatures. During the heating process, the aggregates may dilate in a destructive way to the concrete. The higher the heating degree and the larger the aggregate dimensions, the greater its expansion. This increase in volume due to heating can be observed by the production of "popouts" (Heissler *et al*. 2015).

From a fire protection point of view, the concrete temperature will not rise until all evaporable water has been removed due to the considerable heat of vaporization required for the conversion of water to vapor. The behavior of cement pastes after heating and subsequent cooling is dominated by the moisture absorption from the environment, the absorbed water in the concrete, and the intra-layer water. All waters generate a mechanism for calcium oxide rehydration. Thus, the hydrates formed fill the voids. In general, there is an autogenous recovery of part of the concrete strength after cooling with water.

Due to the changes generated in the concrete microstructure, this study aimed to investigate the interference of high temperatures in the material properties in a temperature range in which the structure can still be recovered. It was also verified the effects generated in the material when submitted to natural cooling (environmental conditions) and fast cooling (where concrete is exposed to contact with water, causing an extreme temperature gradient), as these conditions can affect concrete in different ways.

Materials and methods

In this study, the physical-mechanical behavior of concrete was analyzed with three groups of characteristic compressive strengths (25 MPa, 30 MPa and 35 MPa). The characteristic compressive strengths were defined to represent the most common values civil construction building.

A dosage diagram was prepared to determine the concrete mixes using the IPT/EPUSP method. Both concrete preparation and specimens molding was carried out according to NBR 5738 (ABNT, 2016). Concrete preparation was performed using a concrete mixer. The compaction was performed with a mechanical vibrator, and the cylindrical molds used had a diameter of 10 cm and a height of 20 cm.

In this stage, 360 specimens were made, 120 specimens for each mixture, as shown in Table 1. The specimens with different characteristic compressive strengths (MPa) were named “C25”, “C30”, and “C35”, respectively. They were kept in immersion in water for 28 days for adequate curing. After this age, they were kept at room temperature and protected from the weather until the age of exposure to high temperatures.

The binder used was Portland cement CPII-Z 32, and the results of its physical-chemical characterization are presented in Table 2.

The aggregates were characterized according to NBR 7211 (ABNT, 2019). Tests were performed to determine the bulk specific gravity, apparent specific gravity, and water absorption of coarse aggregate, bulk specific gravity and apparent specific gravity of fine aggregate, water absorption of fine aggregate, unit weight and air-void contents, particle size composition, and determination of material finer than 75 µm sieve by washing. The results are presented in Table 3.

After 120 days of molding, the specimens were exposed to fire in a furnace with LPG gas burners manufactured specifically for this test. The furnace cabinet is made of carbon steel with anticorrosive treatment and electrostatic textured epoxy finish (painting). There is an upper outlet for gas venting. The internal chamber is made of stainless steel. The thermal insulation is made of glass wool, including the doors.

The furnace allowed the concrete to be exposed, not only to high temperatures but also to the fire flames, simulating a fire situation in structural concrete. The contact of the concrete surface directly with the flame is intended to be similar to fire situations. In these cases, the flame reaches only one side of a structural part, generating a temperature gradient in the concrete. This is a pattern in this experiment, which differs from other research. Then, discussions and comparisons with other experiments should consider this factor.

Figure 1 shows the illustrative furnace scheme. Thermocouple sensors were placed inside of it, enabling monitoring and controlling the test temperature. The furnace could heat three specimens simultaneously, and each group was exposed to the desired temperature for 30 minutes, with a heating rate of 0.25 ºC/min (Figure 2). This is a recommendation from RILEM TC 129 (2000), and only the exposure time was adapted.

Table 1 – **Mixes used for concrete preparation**

Concrete Mixes					Cement consumption/ m³
Nº	Cement	Sand	Coarse Aggregate	w/c ratio	
C35	1	1.25	2.25	0.41	595.62
C30	1	2.00	3.00	0.55	442.58
C25	1	2.75	3.75	0.69	352.11

Table 2 – **Requirements of the NBR 16697 standard for cement CP II - F 32**

Physical Test										
Hot Exp.	Beginning of setting time	Ending of setting time	Normal Cons.	Blaine	Retained on		1 day	3 day	7 day	28 day
					# 200	# 325				
Mm	min	min	%	cm²/g	%	%	MPa	MPa	MPa	MPa
0.28	286.25	360.25	28.85	3512	0.65	9.98	12.79	23.85	28.36	34.43

Source: Cement test bulletin, Votorantim Cimentos, May/2020.

Table 3 – **Physical characterization of the aggregates**

Properties	Bulk specific gravity (g/cm³)	Material finer than 75 µm sieve (%)	Fineness Modulus	Water absorption (%)
Fine aggregate	2.63	13.06	1.46	-
Coarse aggregate	4.75	0.50	0.016	0.20

Figure 1 - **Illustrative furnace scheme for fire simulation**

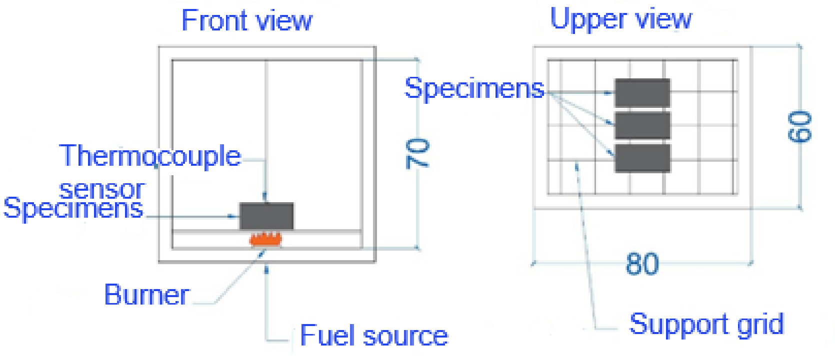
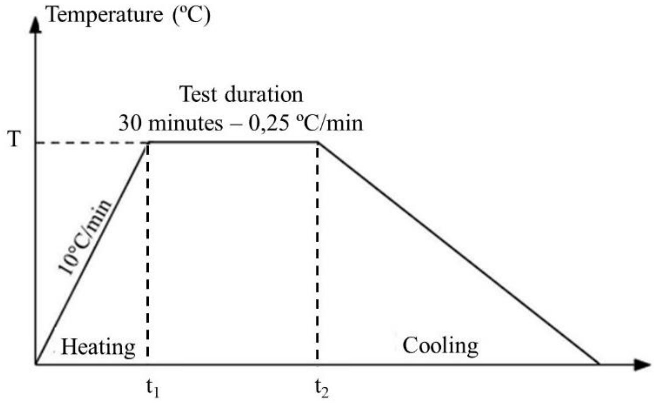


Figure 2 **- Schematic of specimens' heating**



These three concrete groups were exposed to five temperature variations (room temperature, 100 ºC, 300 ºC, 450 ºC, and 600 ºC). The concrete used as reference was kept at room temperature, without fire exposure. These temperatures were defined based on characteristic changes in microstructure already reported in the bibliography (Hager, 2013; Battagin; Silveira, 2018; Fernandes *et al*. 2017; Komonen; Penttala, 2003; Heissler, 2015; Mehta, Monteiro, 2008)). The furnace temperature was considered as the temperature reached by the concrete, since it was in direct contact with the flame and during a fire it is not possible to measure the internal temperature of the structural parts.

After exposure to high temperatures, the specimens were cooled. The cooling process was divided into two groups: fast cooling (immersion in water at 20 °C) and slow cooling (room temperature at 20 °C). The rapidly cooled specimens were called "FC" (fast cooling), while those that were cooled gradually were called "SC" (slow cooling). These two groups were analyzed to evaluate the conditions observed in an actual firefight situation (fast cooling) and the conditions observed in laboratories (slow cooling).

After the exposure of the specimens to the different temperatures and cooling processes, the concretes were characterized by compressive strength (ABNT, 2018), tensile strength by diametral compression (ABNT, 2011), absorption (ABNT, 2009), and static elastic modulus tests (ABNT, 2017). The specimens remained in the laboratory for a minimum period of 24 hours for temperature stabilization. This standard was adopted so that all tests were performed with concrete at similar temperatures.

Microscopy images were obtained using a FEG SEM microscope, Tescan, Mira 3, with SE, BSE detectors, and Oxford X-Maxn 50 X-ray analytical microprobe (EDS). For the SEM tests, the surface of the specimens was metallized with gold. X-ray diffraction analysis was used to identify the concrete crystalline phases in a Rigaku Ultima IV diffractometer. The parameters were a 0.02º step, time per step of 1 s, and a scanning range between 5º and 75º (2θ). The test was performed on pressed pellets. Mineral chemical phases were identified by comparison with the International Centre for Diffraction Data (ICDD) standards. The samples analyzed were removed from the face in contact with the flame, fractured, and then sieved for pellets preparation.

The results were statistically treated using spurious elimination considering the standard deviation. Tukey's test was also applied to compare significant differences between the results of the analyses.

Results and discussion

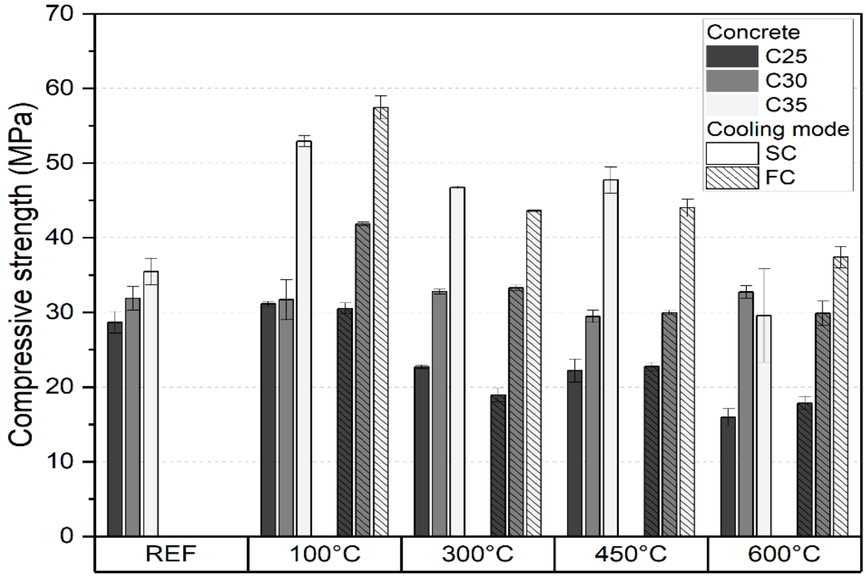
Concrete is a material with good resistance to fire exposure. Its exposure time with no performance loss is satisfactory when compared to other materials. Despite this, the exposure of concrete elements to high temperatures generates changes in their physical, chemical, and mechanical properties. The difficulties faced in describing and predicting the behavior of concrete structures are due to aspects related to the heterogeneity of the medium in question, as concrete is porous, multiphase, and may contain inner fluids in liquid and gas form.

When exposed to extreme conditions, the difficulties in describing and predicting the behavior of concrete structures are even harder, mainly because the material is in constant evolution. Different behaviors are verified after a fire situation, where structures are cooled with water jets or similar, generating a fast-cooling situation. This condition differs from most laboratory experiments, where the samples are cooled slowly. In this investigation, this property was evaluated in both conditions. Figure 3 shows the compressive strength results for both cooling groups.

The results indicate that the behavior of the material, when heated, is related to cement consumption and concrete mixes. It can be seen that the initial heating at 100 ºC tends to increase the strength of the concrete the higher the cement consumption. This effect is not significant in the lower-consumption mixes (352 kg/m³). From this temperature onwards, the compressive strength decreases as the temperature at which the concrete is exposed increases. This behavior was also found in the research by (Xu *et al*., 2001), which justifies the result by the fact that the water lost in this condition is the concrete's free water, which leads to greater Van der Waals forces as a result of the cement gel layers coming closer together. It has also been shown that, in concretes with higher cement consumption, the available water content is lower due to the smaller porosities, which tends to generate lower internal pressures and consequently less cracking (Savva; Manita; Sideris, 2005; Xu *et al*., 2001).The results also allowed identifying that the increase in temperature between 300 ºC and 450 ºC led the compressive strength to have a slight decrease.

This phenomenon is also described by Hager (2013), Dias *et al.* (2020) and Kim, Yun and Park (2013). According to authors, this decrease is due to the resistance of concrete to water vapor flow caused by the high temperature. As a result, the internal autoclave condition arises in the cement paste and results in additional hydration of the anhydrous cement grains (Savva; Manita; Sideris, 2005). The most expressive values of strength loss are from the concretes exposed to 600 ºC. This decrease in strength can be explained mainly by the onset of micro-cracking (Xu *et al.* 2001).

Figure 3 **- Compressive strength of concretes (C25, C30, and C35) subjected to different temperatures and cooling conditions (Slow - SC and Fast - FC)**



For samples exposed to 600 ºC, the compressive strength decreased compared to the 100 ºC temperature samples. On average, there was a reduction in compressive strength when analyzing all the mixes and types of cooling. This was attributed to concrete dehydration, where the calcium silicate hydrate decomposition, the main hydrate of the microstructure, begins (Xu *et al.* 2001). Also, it is attributed to the intensification of micro-cracking within the matrix and the losing of part of water in cement gel, causing surface cracking (Souza; Moreno Junior, 2010).

It should be noted that the losses in compressive strength, compared to the concretes that were not heated, were significant only for concretes produced with the lowest cement consumption. For concretes made with 442 kg/m³ and 595 kg/m³, the final strengths after heating to 600 ºC are equivalent to the concretes that were not submitted to fire.

It was also verified that, after the first effect at 100 ºC, the temperature increasing leads to a decrease in concrete compressive strength, regardless of the type of cooling and the cement consumption. This was evidenced by the correlations (R^2 = 84.95) between the results in both cooling. Dias *et al*. (2020) also did not identify a significant influence on the changes in compressive strength concerning the cooling method. In the tensile strength (Figure 4), the behavior was similar. After the increase to 100 ºC, there was a tendency for tensile strength decrease as the exposure temperature increased.

It was found that in both cooling processes and the three mixtures, the tensile strength is more affected at a temperature of 600 ºC. Above 500 ºC, there is dehydration of both layers of calcium silicate hydrates (C-S-H) and calcium hydroxides ($Ca(OH)_2$), which reduces tensile strength. Other changes, such as weakening of the transition zone between paste and aggregate, decomposition, and aggregate differential expansion, also contribute to the more accelerated degradation of concrete (Kodur; Khaliq, 2011).

Although the concretes under analysis are of different types, it is evident that the loss of tensile strength is more intense than the loss of compressive strength. This is because micro and macro cracks are produced due to the incompatibility of the thermal expansion of the materials within the concrete. The micro-cracks were evident in the samples exposed above 450 ºC, which showed a greater tendency to disintegrate and separate the coarse aggregate from the rest of the paste, indicating that the transition zone had been affected. This was based on the visual analyses shown in Figure 5 and Figure 6 during the preparation of samples for SEM analysis. In these regions, it was difficult to obtain a smooth cut in the sample without disaggregating the cement paste with the coarse aggregate, and this effect was associated with more attenuated embrittlement in the transition zone.

Figure 4 - **Results of tensile strength by diametral compression**

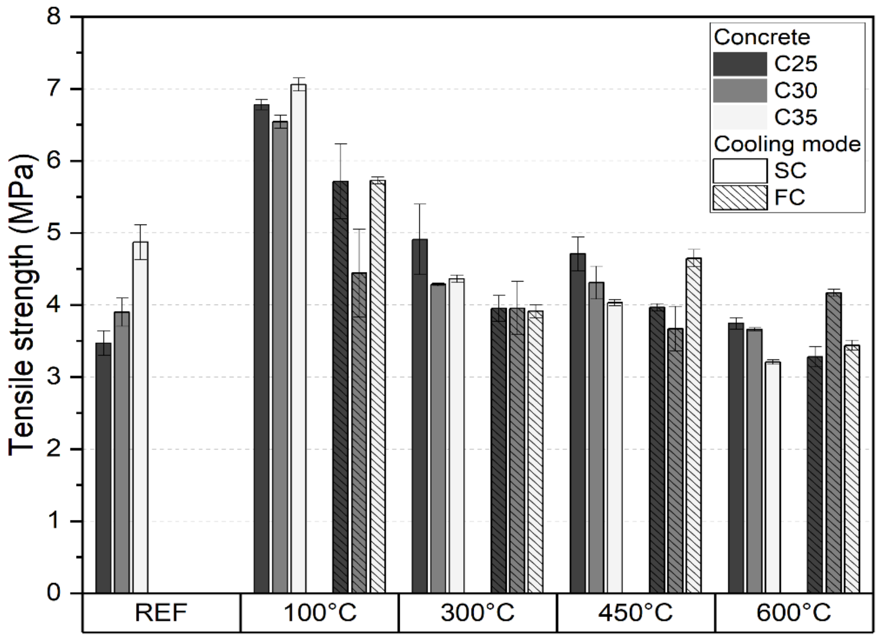


Figure 5 **- Comparative fragility of specimens after heating**

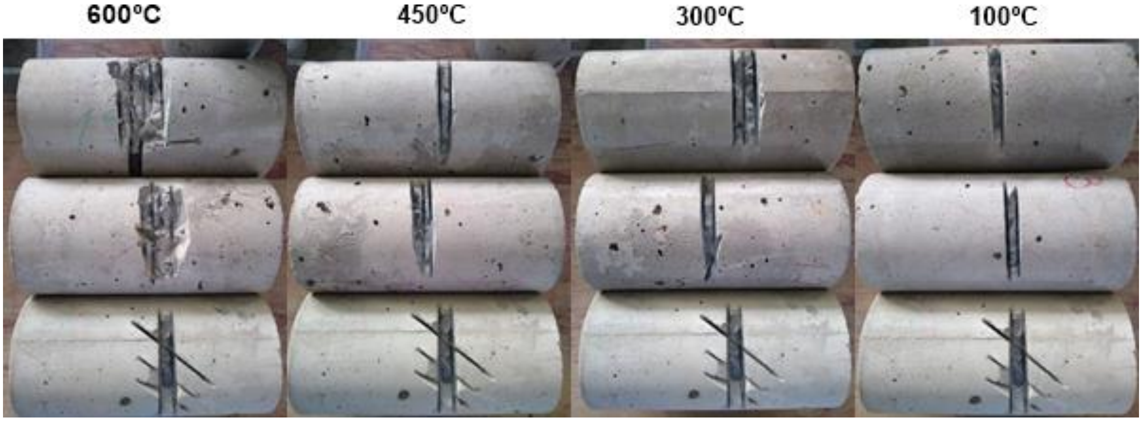


Figure 6 **- Concrete embrittlement: emphasis on the transition zone between paste and aggregate in C35 concrete heated to 600 degrees and slowly cooled**

Kodur and Khaliq (2011) define that the decrease in the concrete tensile strength (with temperature change) can be attributed to the weak concrete microstructure in the usual strength range, which allows the formation of initial microcracks. At 300 ºC, concrete loses approximately 20% of its initial tensile strength, and above 300ºC, the concrete tensile strength is further reduced. Carette, Painter and Malhotra (1982) complemented this analysis on the concrete tensile strength in their study of concrete in a temperature range of 75 ºC to 600 ºC through the residual strength technique. The authors reported a 65 to 70% reduction in tensile strength at 600 ºC. They concluded that the water/cement ratio and the aggregate type have a significant influence on the concrete tensile strength. In this study, it was also possible to identify a tensile strength loss near 600 ºC. Yet, it was not as significant as that observed by the authors. It was also found that the mixtures with a higher water/cement ratio were more affected by this mechanical property.

Because of these microstructural changes and concrete cracking, the absorption increases as the temperature at which the concrete is exposed rises (Figure 7), regardless of the mixtures and the cooling type. This increase is more significant in the slow-cooling group, where absorption increases between 22% and 31% for temperatures of 450 ºC and 600 ºC, respectively. In the fast-cooling group, absorption increased by approximately 7% and 14% for temperatures of 450 ºC and 600 ºC, respectively.

This increase in absorption was expected, as described by Fernandes *et al*. (2017). The slow cooling has the highest rate of absorption increase because these concretes had no contact with water after heating and could not rehydrate. It can be seen (Figure 8) that the correlation between compressive strength and absorption was significant when the samples were abruptly cooled. In addition, it can also be seen that the absorption increase is more significant in the concrete richer in cement (concrete C35).

The micrographs obtained by SEM also indicate the increase in concrete cracking with temperature increase (Figure 9). At room temperature, no cracks are found. However, rising temperature leads to an increase in the amount of cracks and their thickness. In these images it is still possible to verify that, for the fast cooling, the cracks are more evident and are present in greater amount. For both types of cooling, the cracks are larger for the highest temperatures (450 °C and 600 °C).

Figure 7 - **Absorption of concretes subjected to different temperatures and cooling conditions**

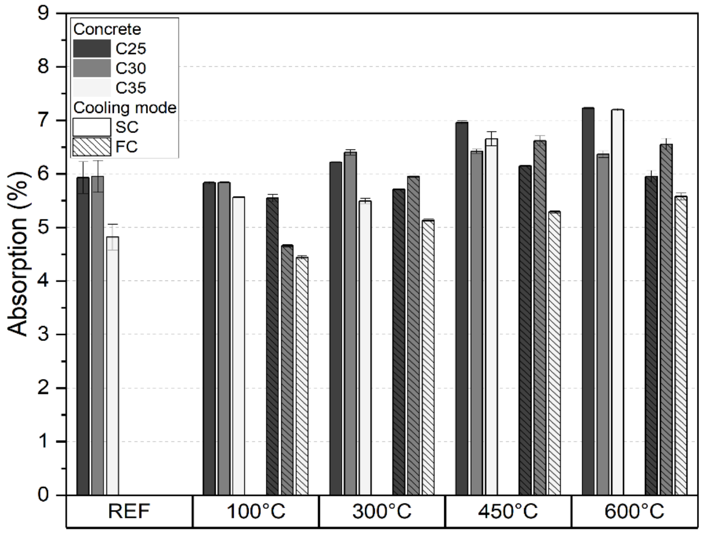


Figure 8 - **Correlation between compressive strength and absorption**

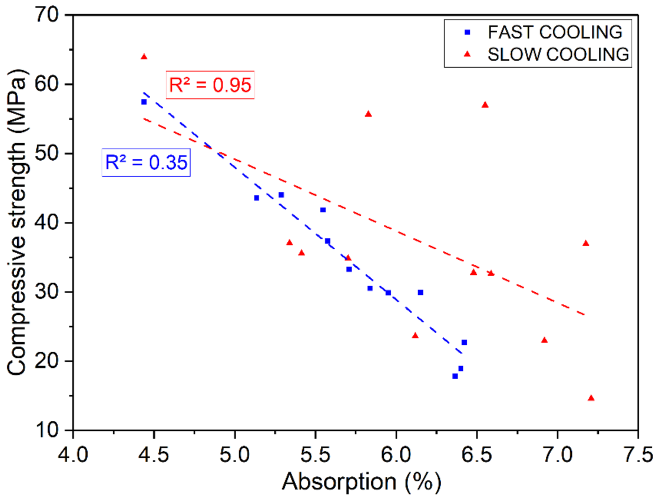
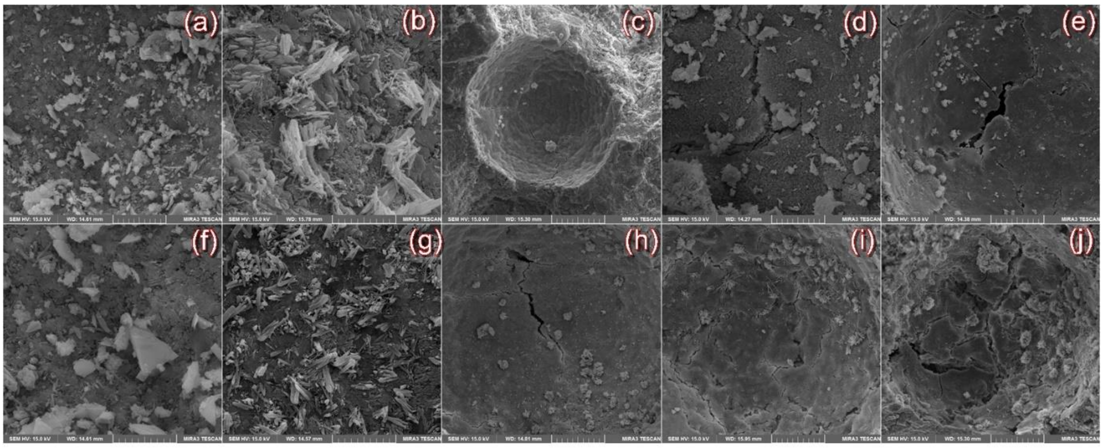


Figure 9 - **SEM micrographs indicating crack progression as a function of temperature for C25 concretes**



Note: *(a) REF x 5Kv; (b) C25-SC - 100 ºC x 12Kv; (c) C25-SC - 300 ºC x 1Kv; (d) C25-SC - 450 ºC x 5Kv; (e) C25-SC - 600 ºC x 1Kv; (f) REF x 12Kv; (g) C25-FC - 100 ºC x 12Kv; (h) C25-FC - 300 ºC x 1Kv; (i) C25-FC - 450 ºC x 1Kv; (j) C25-FC - 600 ºC x 1Kv.

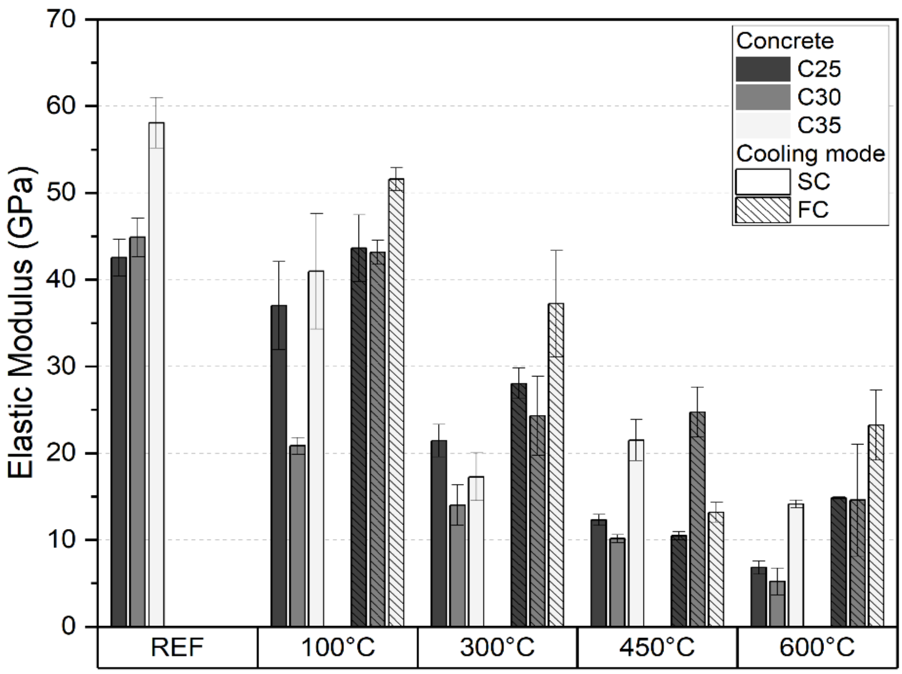
The increase in absorption is induced by the evaporation of free, capillary and chemically combined water, which occurs more intensely up to 300 ºC. From 450 ºC onwards, the pores increase in quantity and size due to the dehydration of the cement's hydrated products and the nucleation of small pores, giving rise to larger pores and, consequently, a more significant increase in the void ratio after 450 ºC (Silva, 2015). In addition to water loss, microcracks also occur, which explains the increase in absorption, where microcracks, mainly due to the thermal incompatibility of the hardened cement paste and aggregate, increase porosity and decrease strength. According to Vodak *et al*. (2004), this process occurs throughout the entire temperature range. The author also mentions that the additional "mini hydration" is mainly caused by water molecules with relatively high kinetic energies released at temperatures above 250 °C. This phenomenon leads to an increase in strength and a decrease in porosity. Because of these phenomena, there are significant changes in the modulus of elasticity of the concrete, and this hypothesis could be an explanation for the results observed in Figure 10.

There is a significant reduction in the elastic modulus with increasing exposure temperature, regardless of the cooling condition. Another relevant point is that the decreases were constant at 100 ºC, unlike the other properties analyzed. Overall, the most significant reduction begins at 300 ºC. In the C30 and C35 mixtures, where the percentage of mortar paste is higher, it is noticed a recovery in the elastic modulus value when the temperature reaches 600 ºC (in the fast cooled group) and when the temperature reaches 450 ºC (in the slow cooled group). Dias *et al*. (2020) and Souza e Moreno Junior (2010) also describe similar results.

The results available in the literature are quite variable due to different concrete compositions and test conditions, as observed by Kodur (2014). Despite this, the curves of compressive strength and elastic modulus, as a function of exposure temperature, indicate a tendency to decrease with increasing temperature. Also, fewer degradations occur when the exposure time to high temperatures is shorter. This study also shows that regardless of the mix design used, the reduction in the elastic modulus is significant and should be considered for analysis of concrete exposed to high temperatures.

Almost no transient influence occurs during concrete cooling after temperature exposure. A reasonable assumption for the concrete behavior under cooling is that the elastic modulus is fixed according to the correspondent's previous maximum temperature. Besides that, thermal stresses can be significantly irreversible under cooling conditions (Ulrich, 1988). Also, the cooling condition does not have a considerable influence on elastic modulus because, in both cooling conditions, this property loss is significant. The correlation between elastic modulus and absorption (Figure 11) is also significant and should be mentioned. According to Mehta and Monteiro (2008) and Heissler *et al*. (2015), the elastic modulus is influenced by removal of hydration water from cement paste, portlandite dehydration, C-S-H decomposition, and the micro-cracks in the transition zone.

Figure 10 - **Elastic modulus of concrete subjected to different temperatures and cooling conditions**



This correlation between absorption and elastic modulus shows the microcracking in concrete exposed to high temperatures, which allows an increase in absorption and a decrease in elastic modulus. Xu *et al*. (2001), Handoo, Argawal and Argawal (2002) and Lim and Modal (2015) reinforce in their studies that microcracking is the primary cause of deterioration when concretes are exposed to high temperatures, reporting that microcracking starts around $Ca(OH)_2$ crystals and then around unhydrated cement particles. $Ca(OH)_2$ decomposes after exposure above 400 °C to 600 °C, and the rehydration of the dissociated $Ca(OH)_2$ becomes a detrimental cracking cause (accompanied by a 44% volume increase). The XRD results (Figure 12) indicate portlandite at all temperatures, probably a rehydration process result.

Figure 11 - **Correlation between immersion absorption and elastic modulus**

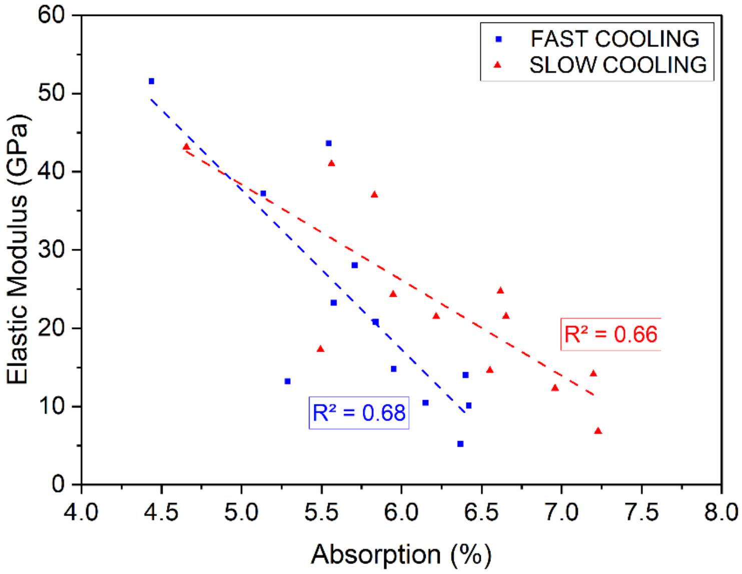
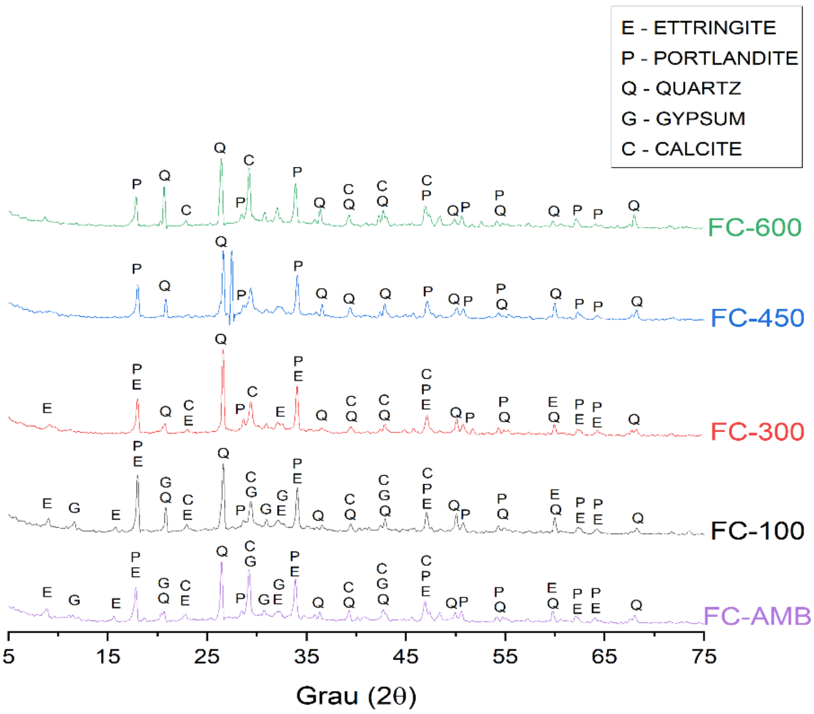


Figure 12 - **X-ray diffraction characterization of C35 concrete at different exposure temperatures and fast cooling**



Based on XRD results, from 300 ºC on, no more gypsum and ettringite crystals are identified. In a heating situation, this result is expected since their decomposition range does not exceed 200 ºC (Menezes *et al*., 2020; Song *et al.*, 2018; Ferreira, 2019). However, micrograph analyses show ettringite crystals in all samples (300 °C, 450 °C, and 600 °C), according to Figure 13. This phenomenon is attributed to the ettringite rehydration process generated after the cooling process. No phases were assigned to other peaks, especially those between 32 and 33º (2θ), since, in XRD analysis, a crystal can only be identified if a standard series of crystal peaks is present.

Rehydration is a relevant factor when the durability of the structure is being analyzed. Ettringite loses water and decomposes with increasing temperature. After cooling, the ettringite can form again by rehydration. Lima (2005) and Almeida (2017) also describe this rehydration process. It causes expansions, which eventually contribute to the appearance of cracks in concrete. Another configuration verified is that this secondary ettringite presents an irregular crystalline arrangement. It indicates that the rehydration process does not allow a homogeneous and orderly crystallization and may occupy spaces of cracks generated during heating. It may also explain the increases in compressive and tensile strengths at lower temperatures and higher cement consumption. Souza and Moreno Junior (2010) studied the rehydration of concrete exposed to high temperatures and observed that concrete exposed to air, i.e., rehydration process at ambient, reached indexes close to those obtained for specimens immersed in water (with a difference of 10% less). It corroborates with the conclusions of this study, in which concrete remained at room temperature after the heating processes.

Conclusions

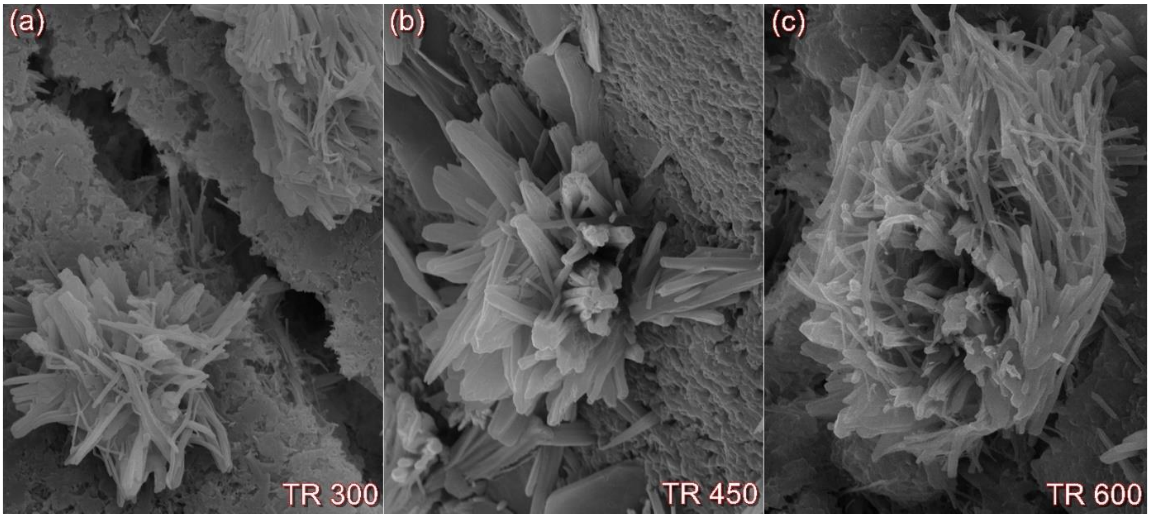
This research made it possible to evaluate the changes in concrete with different cement consumption and water/cement ratio when exposed to different temperatures, as well as slow and fast cooling conditions. The most significant results were found in concrete exposed to 600 ºC.

Tensile strength was more sensitive to variations in heating temperature. In both cooling conditions and in all three types of concrete, tensile strength was also more affected at 600 ºC. The results show that the type of cooling does not influence the decrease in tensile strength.

The increase in absorption was induced by the intensification of cracking processes, which were greater in the samples not exposed to water after heating.

No significant transient influences were identified during the cooling of the concrete after exposure to temperature. It is believed that the behavior of concrete under cooling is fixed according to the corresponding previous maximum temperature and that thermal stresses may be irreversible under cooling conditions.

Figure 13 **- FEG micrographs indicating ettringite crystals from the rehydration process in C35 concrete at different temperatures**



Regardless of the concrete mix and cooling, the modulus of elasticity of concrete is affected by exposure to high temperatures, and as the exposure temperature increases, the elastic modulus decreases. There is also a significant correlation between the loss of the modulus of elasticity, compressive strength, and absorption. The reduction in the modulus of elasticity is more significant than the reduction in compressive strength.

Although there were no significant reductions in compressive and tensile strength compared to concrete in natural conditions, the modulus of elasticity was significantly affected by the increase in temperature, indicating that this property needs to be assessed after accidents to guarantee the stability of concrete structures in service after recovery.

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Eduardo Pereira
Writing – review & editing, Conceptualization, Methodology, Formal analysis.

Departamento de Engenharia Civil | Programa de Pós-Graduação em Engenharia e Ciência de Materiais | Universidade Estadual de Ponta Grossa | Av. General Carlos Cavalcanti, 4748, Uvaranas, Bloco E | Ponta Grossa – PR – Brasil | CEP 84030-900 | Tel.: (42) 3220-3074 | E-mail: eduardopereira@uepg.br

Eveline Manosso Janik Brik
Writing – original draft, Writing – review & editing, Credit, Formal analysis.

Programa de Pós-Graduação em Engenharia e Ciência de Materiais | Universidade Estadual de Ponta Grossa | E-mail: eveline.brik@gmail.com

Elias Pereira
Conceptualization, Methodology, Formal analysis.

Departamento de Engenharia Civil | Universidade Estadual de Ponta Grossa | Av. General Carlos Cavalcanti, 4748, Uvaranas | Ponta Grossa – PR – Brasil | CEP 84030-900 | E-mail: elpereira@uepg.br

Jadiel Matias de Almeida
Methodology, Credit, Formal analysis.

Programa de Pós-Graduação em Engenharia e Ciência de Materiais | Universidade Estadual de Ponta Grossa | E-mail: jadielmatias@gmail.com

Marcelo Miranda Farias
Methodology, Credit, Formal analysis, Writing – review & editing.

Programa de Pós-Graduação em Engenharia e Ciência de Materiais | Universidade Estadual de Ponta Grossa | E-mail: mirandafariasmarcelo@gmail.com

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Av. Osvaldo Aranha, 99 - 3º andar, Centro
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CEP 90035-190
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