

Experimental analysis of the spalling phenomenon in precast reinforced concrete columns exposed to high temperatures

Análise experimental do fenômeno de deslocamento em pilares de concreto armado pré-fabricados submetidos a elevadas temperaturas



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Abstract

Among the processes that involve the degradation of concrete structures subject to the high temperatures of a fire there is the spalling phenomenon. Its mechanisms are related to the thermal stress of the materials dilatations and pore pressure the process of vaporization of water during heating. The factors that influences in its occurrence are related to concrete properties, structural member characteristics or the exposure conditions, and their parameters are not clearly known yet. This paper aimed to study the influence of three concrete mixtures, four coating thicknesses and two bars diameters of longitudinal reinforcement in the spalling phenomena exposed to ISO 834 fire curve. The characterization of concrete were performed either of the axial compression strength tests, water absorption by capillary and mercury intrusion porosimetry, besides the fire resistance tests in real-scale specimens. It was concluded that the diameter of the bar does not have influence, while the mixture and the concrete cover thickness does. More spalling was recorded for the columns with thicker concrete cover and concrete compressive strength at 61,9 MPa, and although higher strength concrete have less permeability, this characteristic can be balanced with the higher tensile strength of this type of concrete.

Keywords: fire resistance, precast columns, fire, spalling.

Resumo

Dentre os processos que envolvem a degradação das estruturas de concreto submetidas às elevadas temperaturas tem-se o fenômeno de deslocamento, amplamente conhecido como *spalling*. Seus mecanismos estão relacionados às tensões térmicas da dilatação dos materiais e às poropressões do processo de vaporização da água. Dentre os fatores que influenciam em sua ocorrência, destacam-se as propriedades do concreto, características do elemento estrutural e condições de exposição, sendo seus parâmetros ainda não conhecidos claramente. O presente artigo teve como objetivo avaliar a influência que três composições de concreto, quatro espessuras de cobrimento e dois diâmetros de barras da armadura longitudinal exercem no fenômeno de deslocamento em pilares de concreto armado pré-fabricados expostos à curva de aquecimento padrão ISO 834:2014. Para tanto, foram procedidas caracterizações das misturas através de ensaios de resistência à compressão axial, absorção de água por capilaridade e porosimetria por intrusão de mercúrio, além do ensaio de resistência a altas temperaturas em amostras em escala real. Foi possível concluir que o diâmetro da barra não exerce influência sobre o deslocamento, diferentemente da relação água / cimento e da espessura de cobrimento, para os materiais desta pesquisa. Constatou-se maior deslocamento ocorreu nos pilares com maior espessura de cobrimento, com resistência à compressão de 61,9 MPa, sendo que, apesar de concretos de elevada resistência possuírem menor permeabilidade, esta característica pode ser balanceada com maiores valores de resistência à tração.

Palavras-chave: resistência a altas temperaturas, pilares pré-fabricados, incêndio, deslocamento.

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1. Introduction

The spalling phenomenon consists of the loss of surface layers of concrete elements when they are exposed to an elevated heating rate, similar to those of a fire. Its occurrence can be variable and even unpredictable, mild or severe, according to the amount of concrete loss [1]. Phan et al. [2] elucidate that the element undergoes a high thermal gradient between heated exposed side and its cooled core, which can cause the spalling due to the development of thermo-mechanical and hydrothermal stresses.

The thermal expansion of the surface layers of concrete induces compressive stresses due to the imposed restrained conditions, causing indirect tensile stresses with the cooled core [3-4]. According to Anderberg [5], this mechanism can also develop in the corner of the elements, in the matching between two perpendicular surfaces. During heating, some of the moisture present inside the concrete is evaporated to the exterior while some other part migrates to the interior of the element, forming a saturated layer, parallel to the element's surface. The increase of temperature leads to the process of water vaporization, whose volumetric expansion causes pore pressure. [6-7]. When these stresses, caused by mechanical and hydraulic mechanisms, overcome the tensile strength of concrete, the spalling phenomenon occurs. Studies develop by Mindeguia et al. [8] shows that the occurrence of spalling is only possible by a combination of these two mechanisms.

The main consequences of spalling are the direct exposure of the reinforcement to fire and the reduction of the element cross-section, which can lead to the loss of its structural capacity and stability [9]. Several factors contribute to spalling occurrence and the fact that they are interrelated increases the complexity in the definition of the parameters to predict its occurrence. The main factors are related to concrete composition, structural element characteristics and exposure mode. Thus, concrete age and compressive strength, size and type of aggregates, moisture content and permeability, maximum temperature and heating rate, shape and size of cross section,

reinforcement configuration, presence and shape of fibers and load magnitude can influence in its occurrence and magnitude [6,10-11]. Hedayati et al. [11] presents an extensive review about the main studies conducted in the last decades in order to understand the parameters that influence the occurrence of spalling. It was verified that the most of these studies are limited to the evaluation of the influence of different types of loadings on the spalling and how the fiber addition in the concrete mix can contribute to spalling mitigation. As verified in several studies, the application and increase of the loading level in an structure lead to an increase of concrete spalling [12], in the same way that the fiber use increases the tensile strength of the material and the melting of synthetic fibers create pore pressure relief zones [1].

Studies such as Guerrieri and Fragomeni [13] and Miah et al. [12], assessing concrete properties as water/cement ratio (w/c) and the use of mineral admixtures, respectively, evidence an influence over the phenomenon. The lower permeability of high strength concretes limits its capacity to eliminate the expanding moisture during heating process, which results in an increase in internal pore pressure stresses. Ali [14], however, argue that this type of concrete presents higher tensile strength, being able to assimilate these stresses. Thereby, Sanjayan [15] shows that the concrete properties are not the main factors influencing spalling degree.

Studies conducted by Ali [14], Kodur [16] and Morita et al. [17], using full-scale samples, demonstrated that several design parameters, such as dimensions and shape of cross-section, presence and configuration of the reinforcement, intensity and mode of loading, influence the spalling phenomenon. Kodur and Raut [18] verified that stirrup configuration and spacing can contribute to the spalling occurrence. Park and Lee (2008) verified an increase in spalling degree with the increase of concrete cover, which can be a critical factor, since most of the standards and codes have as principle the use of the concrete as a thermal insulation to the steel rebars, without considering the occurrence of spalling phenomenon. The objective of this paper was to evaluate the influence of the w/c ratio of concrete mix, the thickness of concrete cover and steel rebar

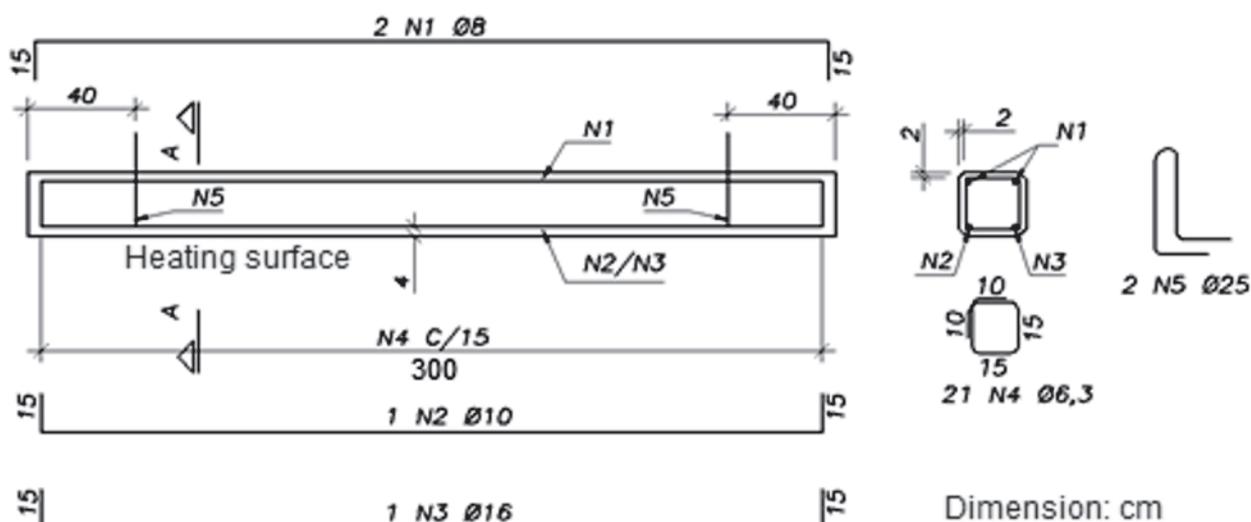


Figure 1
Reinforcement configuration of the columns

Table 1

Mix proportion defined for the environmental exposure classes

Mix	Class of exposure	w/c ratio	Cement consumption (kg/m ³)	Mixture proportioning (unit mass)					
				Cement	Crushed sand	Natural sand	Coarse aggregate 0	Coarse aggregate 1	Water
1	I	0,65	260	1,0	1,19	2,22	1,23	2,88	0,65
2	II	0,60	280	1,00	1,10	2,04	1,15	2,67	0,60
3	IV	0,45	360	1,00	0,91	1,69	1,00	2,33	0,55

diameter on the occurrence of spalling phenomenon. For this purpose, real scale precast concrete columns were evaluated, exposed to the standard ISO 834 fire curve [19]. During fire resistance tests, the temperature variation on the longitudinal bars and on the concrete cover region were registered, as well as the occurrence of noises and water and steam release that could characterize the occurrence of the phenomenon. The results of post-fire analysis were compared to the material properties and the behavior of the elements during its exposure.

2. Experimental program

2.1 Overview of tested samples

The tested samples were representative of reinforced concrete columns

from real-scale buildings, with one side and two corners exposed to fire. Twelve columns were produced, based on the relationship between four concrete cover thickness and three concrete mix composition. The design parameters were adopted based on the criteria established for the different environmental exposure classes described by NBR 6118 [20] and by NBR 12655 [21]. The cast of the columns was carried out in a precast factory, using an automated concrete mixer.

The columns were 300 cm high and ha a square cross-section of 25 cm side. The Figure 1 presents the reinforcement configuration used in all columns, varying the thickness of concrete cover (25 mm, 30 mm, 40 mm and 50 mm), defined to represent each one of the four environmental exposure classes. On the heating exposed side, two longitudinal rebar diameters, commonly used in kind of structural member, were adopted: 10 mm and 16 mm. The longitudinal reinforcement on the non heating

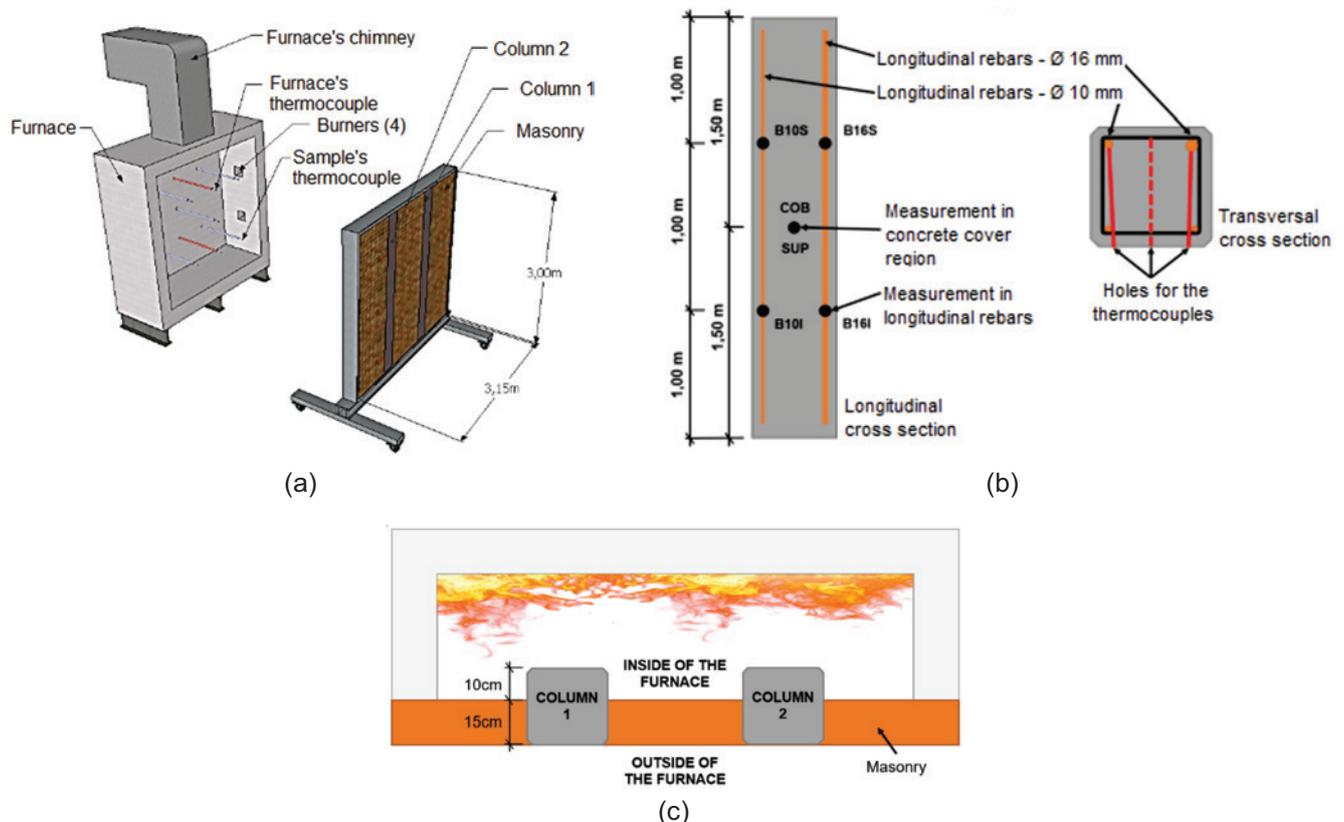


Figure 2

(a) 3D scheme of system installation in the vertical furnace, (b) thermocouple location and (c) system plan scheme

exposed side consists of two rebars with 8 mm diameter. The stirrups, made up of 6,3 mm diameter bars and spaced every 15 cm, were bend- ed with 90° ties. All the reinforcements consisted of CA-50 steel.

Three mix proportions were used in concrete columns productions, with a 52% mortar ratio and slump fixed in 100 mm, with the use of a polycarboxylate based superplasticizer. The mix were determined by the IBRACON dosage method [22], setting w/c ratio and cement consumption according to the specified by three environmental exposure classes. Table 1 presents mix proportions of each composition.

The cement used was the CPV-ARI, based on its small amount of additions and high early strength, which is desirable for the lifting of columns at early ages in the precast industry. The coarse aggregates used are from basalt origin, extracted from the city of Bento Gonçalves/RS, are divided in two particle size zones: 0,15/6,3 e 2,4/19. The material from 0,15/6,3 zone presents fineness modulus of 5,17 and maximum diameter of 9,5 mm, while the material from 2,4/19 zone presents fineness modulus of 6,77 and maximum diameter of 19 mm. The materials were employed in proportions of 30% and 70%, respectively.

Two types of fine aggregates were used, identified as natural sand and crushed sand. The natural sand have quartz origin, coming from Rio Jacuí/RS, have a fineness modulus of 2,14 and a maximum diameter of 2,4 mm. The crushed basalt, resulted from the crushing of basalt rocks from the city of Bento Gonçalves/RS, have a fineness modulus of 2,44 and a maximum diameter of 2,4 mm. The materials were employed in proportions of 65% and 35%, respectively.

2.2 Fire resistance tests

The columns were transported from the precast factory to the laboratory where the fire resistance tests were conducted. It was used a vertical furnace heated by four liquefied petroleum gas burners located on the side walls of the interior furnace chamber, which has 2,5 m high, 2,5 m wide and 1,0 m long. The furnace is controlled by differential pressure, with a total heating power of 65,4 kcal/h, with 396 kcal/h in the lower part and 258 kcal/h in the upper part, programed to perform an automatic heating according to the fire curve for buildings described by ISO 834 [19] standard, expressed in Equation 1.

$$T = 345 \times \log_{10}(8t + 1) + 20 \quad (1)$$

Where t is time, in minutes, and T is medium temperature of the fur-

nace, in °C. All the tests lasted 240 minutes and the maximum temperature reached inside the furnace was, approximately, 1153 °C.

The developed system for the test consists in two columns embedded in a masonry wall on a steel structure attachable to the vertical furnace, in a way that one side and two corners (or 45% of his cross-section) were exposed to high temperatures. Figure 2 presents a schematic diagram of the system developed to the columns evaluation. Due to test system limitations, the samples were tested without loading, limiting their evaluation only to spalling phenomenon.

During the test, temperature measurements in the sample were made and noises that could characterize the occurrence of spalling were monitored, mainly the explosive type. In order to simulate the actual cooling phase of a fire, the furnace was turned off and the sample was cooled at room temperature [23]. Temperature measurement were performed using type K 8 AWG thermocouples, with 3,26 diameter, and maximum admissible temperature of 1260°C. Before the casting of concrete, thermocouples were installed near to the longitudinal steel rebars where it was desired to analyze the temperature. The location of these points followed the requirements of JIS A1304 [27], with two measuring points in the middle third of each longitudinal rebar and one in the geometric center of the column, at the concrete cover region (Figure 2).

2.3 Post-fire evaluation of the columns

The evaluation of columns post fire resistance tests occurred through visual observations and determination of cross-section loss. Through visual observation, it was possible to identify the occurred spalling types, as well as changes in concrete surface. The cross-section loss was determined by measuring the spalled area every 10 cm in height, using a setsquare and a caliper, verifying the depth of frontal and side spalling on each corner.

3. Results

3.1 Characterization of produced concrete

During the column's production phase, concrete cylindrical specimens were casted to material's characterize. Compressive strength, mercury intrusion porosimetry and capillary water absorption tests were made. Figure 3 presents the relation between

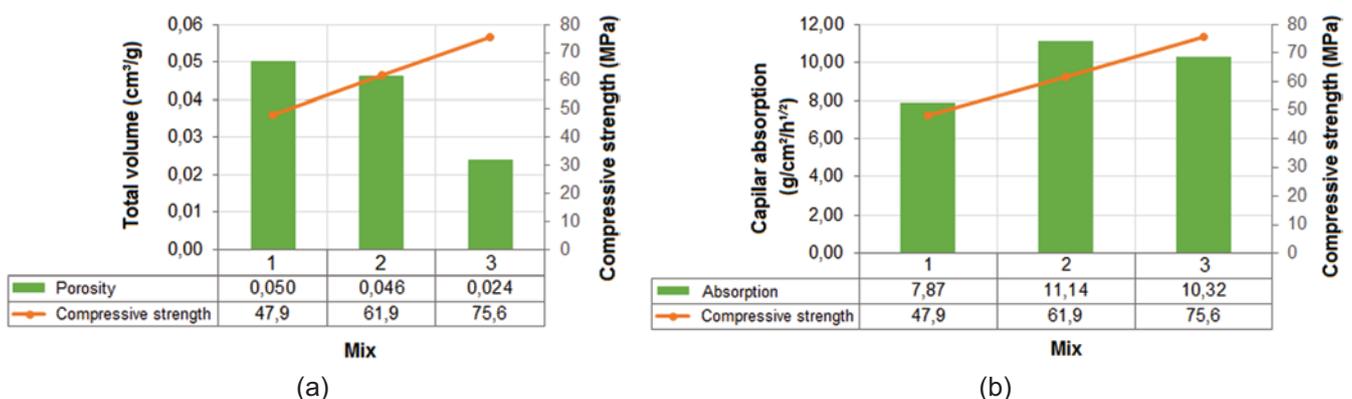


Figure 3

Relation of compressive strength with (a) total porosity and (b) capillary absorption rate

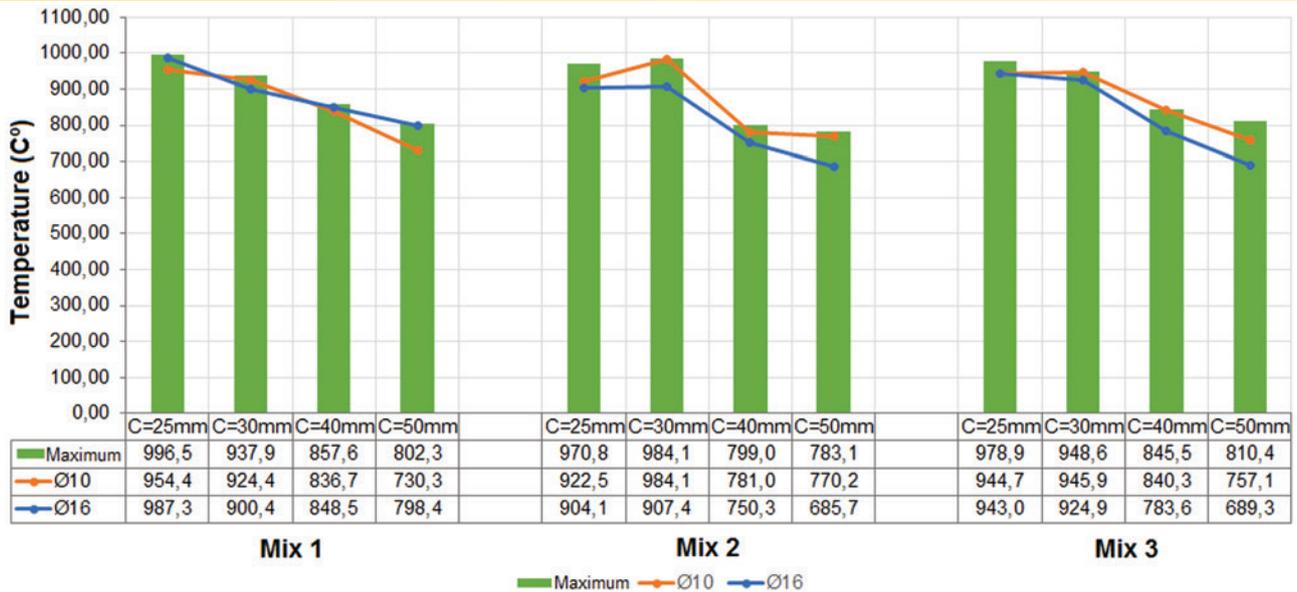


Figure 4 Maximum temperatures reached

compressive strength results with the capillary absorption rate and total porosity obtained in the characterization tests. For the comparative analysis of the results, potential compressive strength values were used, being 47,9 MPa, 61,9 MPa and 75,6 MPa, representative of mix 1, 2 and 3, respectively.

The results of the mercury intrusion porosimetry tests showed a reduction in porosity with the increase of compressive strength. However, the capillary absorption rate of mix 1 was lower than mix 2 and 3, which shows a lower connectivity between the concrete pores when compared to the others.

3.2 Fire resistance tests

From temperature measurement it was possible to determine the maximum temperature reached during the test in the concrete cover, as well as the maximum average temperature reached in each rebar (Figure 4). Although these values did not represent the spalling occurrence moment, they were adopted for the comparative analysis of the results because they remained under the same conditions throughout the test.

It was verified that the concrete cover has influence at the reached temperature reached in the steel rebars and in the concrete cover region. For the columns with a concrete cover thickness of 25 mm, the maximum temperature registered is between 970,8 °C and

996,5 °C, while for the columns with a concrete cover thickness of 50 mm, the maximum temperature registered is between 783,1 °C and 810,4 °C. This is due to the thermal insulation provided by concrete, where it can be observed that the increase in concrete cover thickness by 25 mm can reduce the temperature reached in longitudinal rebar by up to 194,2 °C.

Regarding the influence of concrete composition on the temperature distribution, it was not possible to identify relation between the studied mixes and the recorded temperature values. Although the 10 mm diameter rebars showed, in most cases, higher temperature values than the 16 mm, it was not possible to find relations between rebar diameter and the reached temperatures. This variability in the results may be linked to concrete spalling that can lead to a temperature distribution that did not represent the whole structure.

From the temperature records through the test, it was possible to verify that all samples presents a period in which the temperature remains constant, around 100 °C. According to Mehta and Monteiro [24], the concrete temperature increases only after the full evaporation of all free water in concrete, which happens approximately at 100 °C. Thus, by means of the recorded temperatures it was possible to determine the necessary time to reach 100 °C in each measured point (Figure 5a) and the time at which the registers remained at this temperature (Figure 5b), because they

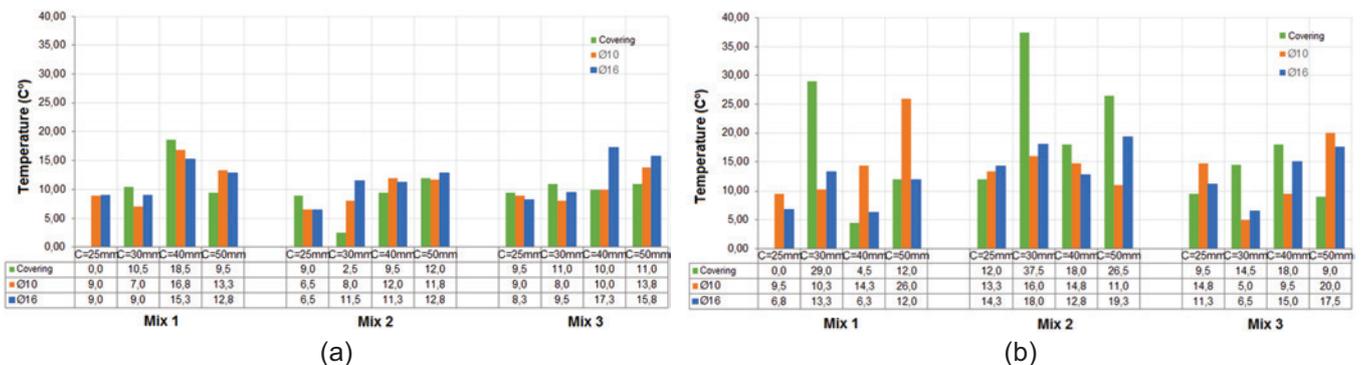


Figure 5 Period (a) to reach 100°C and (b) stay at 100°C

represent the necessary time to evaporate all the concrete water. It should be noted that this information might be important to characterize the water transport in the columns, a factor influencing the occurrence of concrete spalling.

It was verified that there is a tendency to increase in time to the measurement point reach the temperature of 100 °C with the increase of concrete cover thickness. This can also be explained by the thermal delay provided by concrete to the rebars, where the spalling occurrence may have influenced the recorded data. It is possible to notice a trend to increase in the period at the 100 °C with the increase of concrete cover thickness and compressive strength of concrete mix used, corroborating with the already presented fact that the concrete acts like a thermal protection to the reinforcement.

During the fire resistance tests, different behavior was observed among the samples, mainly regarding the release of water by the columns and the noises that could characterize the concrete spalling inside the furnace. As the tests were performed on every two columns, the qualitative analysis did not allow to distinguish the columns of their occurrence. The duration of these events did not exceed 35 minutes of the test and were accom-

panied by water and steam release by the surface not exposed to high temperatures.

3.3 Post-fire evaluation

The aspect of the 12 columns after the tests is shown in Figure 6. It is possible to verify that the occurrence of concrete spalling occurred predominantly at the columns corners and in some points reached all the exposed cross-section or the exposure of the rebars. This kind of spalling is classified by FIB [10] as “corner spalling” and occurs from thermal stresses in element [5]. It was observed that the color and the visual aspect at the concrete surface were similar in all columns, with the appearance of small black dots randomly distributed at the surface, due to the used crushed sand. The basalt aggregates showed, in their magnitude, vitreous aspect with a smoother and darker surface appearance (Figure 7).

It should be noted that, although the interface between aggregate and cement paste was considered the most weak phase of concrete in several situations, including its behavior in elevated temperatures, it was verified that the spalling occurred inside the aggregates. The observed behavior is similar to that presented

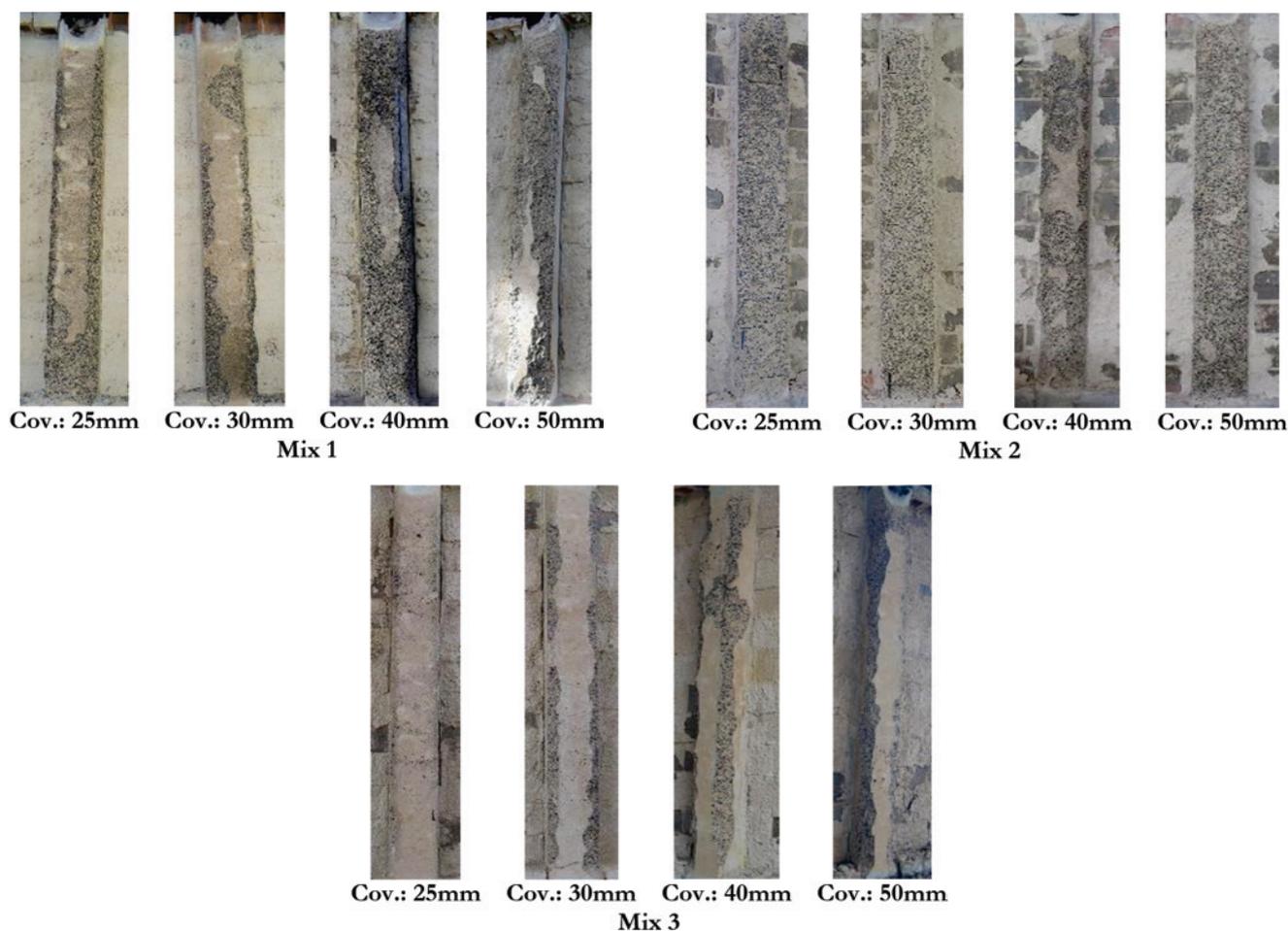


Figure 6
Aspect of columns after fire resistance tests

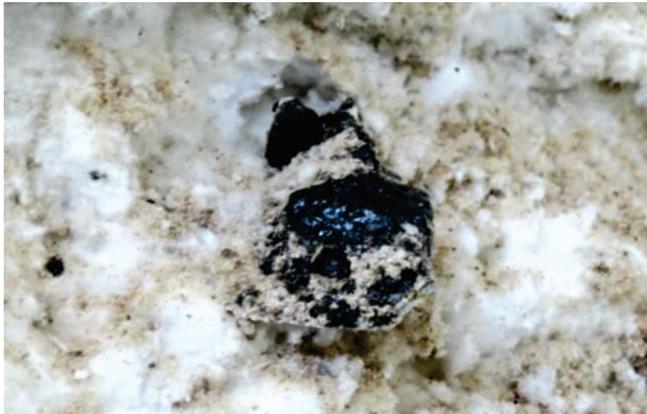


Figure 7
Final aspect of a piece of concrete fixed at internal coating of the furnace

by Hager [25], where the development of thermal stresses by the aggregates expansion and shrinkage of the surrounding cement paste causes the appearance of cracks, which can lead to the spalling phenomenon.

After the tests, an inspection was realized inside the furnace, where it was possible to verify the presence of concrete pieces fixed in the inner side of the furnace (Figure 7). This register, along with the noises during the tests, can be used to characterize the occurrence of explosive spalling phenomenon.

Figure 8 presents a summary of results obtained in the determination of average cross-section reduction by spalling in the columns. It is observed that there is a direct relation between average cross-section loss with the increase of concrete cover thickness. These results agreed with those presented by Morita et al. [17], who report that the increase of concrete cover thickness implies in the increase of concrete spalling.

Figure 9 shows the relation between compressive strength and average cross-section loss. It can be noted that column made from mix 1,

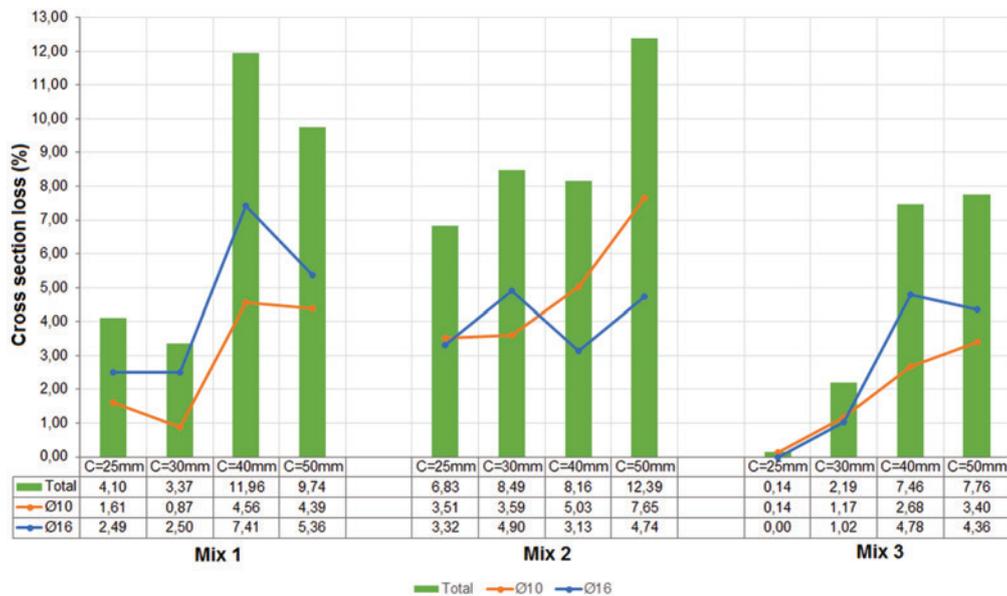


Figure 8
Average cross-section loss

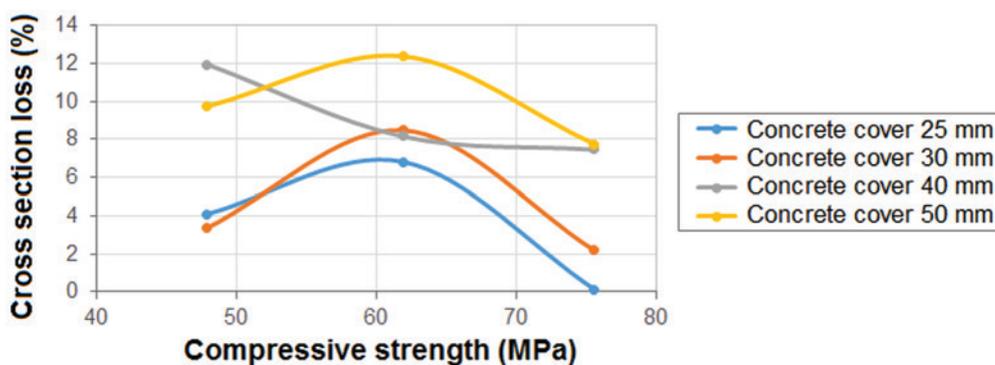


Figure 9
Influence of compressive strength on spalling

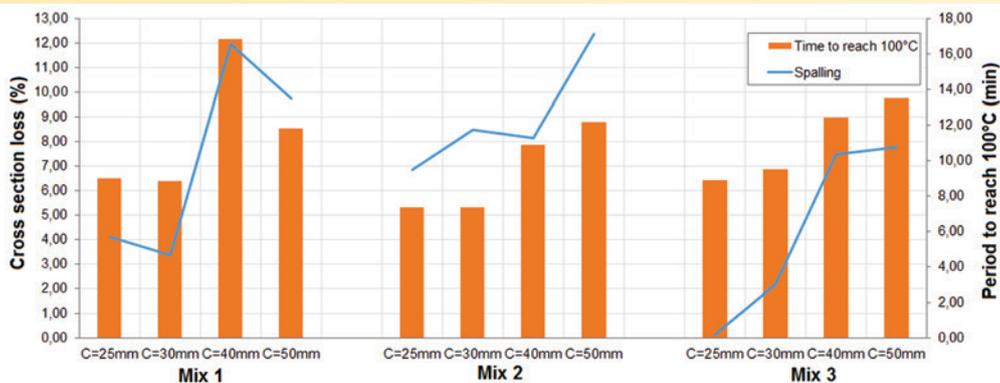


Figure 10

Relation between spalling and the necessary time to reach the temperature of 100°C

with concrete cover of 40 mm, differentiated from the other columns made from other mixes. In general, the degree of spalling occurrence can be predicted by a curve where there are critical values of compressive strength, according to the used concrete cover thickness. It is noted that there is a tendency in the increase of spalling with the increase in concrete compressive strength up to values of 60,0 MPa, when the trend is reversed and spalling degree begins to decrease.

The lower degree of spalling in concrete with compressive strength values lower than 60,0 MPa can be explained by the fact that these concretes are more permeable and have a lower tensile strength, reducing the pore pressure and being more fragile. On the other hand, the lower degree of spalling in concrete with compressive strength higher than 60,0 MPa due to higher tensile strength of these and, therefore, may be able to absorb stresses that promote the concrete spalling, also verified by Ali [26]. Therefore, it can be said that, for studied conditions, there is a maximum point for the occurrence of concrete spalling, in this case in the concrete columns with compressive strength in the order of 60,0 MPa, and before and after, the phenomenon is smoothed.

It was observed that the spalling were mostly between the first 5 and 20 minutes of testing, as well as the beginning of water release by the external surface of the columns, highlighting the preponderance of pore pressure. In general, during this period, the temperature inside the furnace is between 500 °C and 750 °C and the temperature measured in the thermocouples located in concrete cover is at 100 °C, i.e., during the process of evaporation of the water present inside the concrete. Thus, it is possible that the registered spalling occurred due to the development of hydrothermal mechanism. Figure 9 presents the relation between average cross-section loss and the mean period at the temperature of 100 °C in each column.

It is verified a relationship between average cross-section loss and

period at the temperature of 100 °C with the increase of concrete cover thickness for each mix, although this is not linear. It was not possible to identify such relation between the analyzed mixes, and the columns of mix 3 presented the highest values of period at the temperature of 100 °C and, at the same time, the lowest values of average cross-section loss. In addition, the occurrence of spalling can lead to a reduction in the time of water evaporation, since it allows its mitigation to the external environment more quickly. Therefore, it is possible that, for the cases where there was greater spalling than the period at the temperature of 100 °C, spalling occurred due to the predominance of hydrothermal mechanism.

Phan et al. [2] states that the temperature of concrete at the depth where there are occurrence of spalling is 220 °C to 280 °C, usually in the concrete cover zone. As in most cases of this paper, the spalling did not reach the reinforcement, which was at the temperature of 100 °C at the moment where the noises were recorded, it is probable that the temperature near the surface of the elements had higher values, or near the spalling occurrence temperature aforementioned, according to Phan et al. [2]. Figure 10 presents the relation between average cross-section loss and average maximum temperature.

It is also observed that, even in the maximum spalling occurrence for the columns of the same mix with highest concrete cover thickness, there was a reduction in the maximum temperature values reached in the rebars. Thus, it is possible that although spalling cause the reduction in concrete cover thickness during exposure, this phenomenon did not significantly interfere in the maximum temperature values recorded in the longitudinal rebar.

4. Conclusion

With respect to the temperature records in the longitudinal rebars,

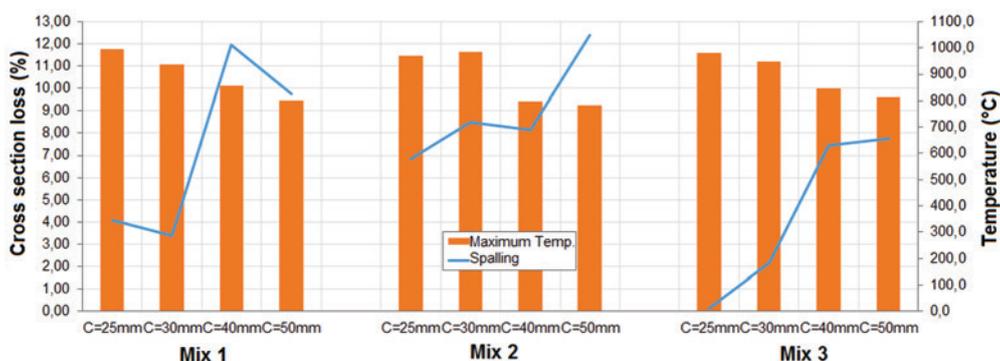


Figure 11

Relation between spalling and maximum temperature

it was possible to note a preponderance of the influence of cover thickness in these records, as well as for the analysis of average maximum temperature values recorded at the rebars, where the mix and the rebar diameter did not show any influence on the analyzed conditions. It was also verified that the cover thickness is the main variable that influences the time required to reach the temperature of 100 °C, while the w/c ratio is the only one that affects the time of stay at the temperature of 100 °C.

Because the noises were registered qualitatively, it did not allow to identify its relationship with the study variables. However, it was verified that, for the most part, these occurred between 5 min and 20 min after the beginning of the exposure, when the temperature inside the furnace was between 500°C and 750°C and the temperature in the columns was of 100°C, i.e., during the process of evaporation of water present inside the concrete. After the fire resistance tests, it was verified the occurrence of spalling was predominantly at columns corners and, in some cases, reached the entire exposed cross-section. It was also verified the occurrence of other types of spalling, such as aggregate and post-cooling, according to the literature classification previously presented. Furnace inspection after the test revealed pieces of concrete fixed in its internal coating, which characterizes its occurrence in an explosive type.

It was verified that both the concrete mix and the cover thickness influence the occurrence of spalling phenomenon, with preponderance of the former. By verifying the influence of concrete properties it was observed the tendency to increase the average cross section loss with the increase of the concrete compressive strength up to 60,0 MPa, when this trend is reversed. The lower degree of spalling in the columns with compressive strength lower than 60,0 MPa can be explained by the higher porosity and permeability of these concretes, which allows the relief of the pressures caused by water vaporization, while columns with concrete compressive strength greater than 60,0 MPa presents greater tensile strength, capable of absorbing the stresses.

In general, it is possible to conclude that the occurrence of spalling phenomenon is not only related to the intrinsic properties of concrete, being that the cover thickness also has influence in such phenomenon. Through the analysis performed in the columns during and after fire resistance tests, it can be affirmed that even in the occurrence of spalling, in no case was verified the possibility of collapse of the structural element. The direct exposure of the reinforcement to the high temperatures, in turn, could have caused damages related to the loss of mechanical strength, which could be better evidenced by the presence of loading, variable not addresses in this study.

Although this study contributes to the understanding of spalling phenomenon occurrence, other variables may influence its occurrence, as it can be seen in bibliography. Therefore, it is suggested that future work evaluate the influence of aggregate type used in the concrete composition and the application of loading on samples during the tests to allow the determination of its fire resistance.

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