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Effect of cooling method on concrete compressive strength after exposure to high temperatures

Efeito do modo de resfriamento na resistência do concreto após exposição a altas temperaturas

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Abstract

Concrete is the most used construction building in the world due to its versatility, mechanical properties, and low cost and the availability of raw materials for production. Among its properties, its good performance when exposed to high temperatures stands out and is guaranteed by characteristics such as low thermal diffusivity and incombustibility. Although concrete has elevated fire resistance, the mechanical resistance of concrete structures is reduced in fire situations, resulting in structural problems. The effects of the concrete cooling method after exposure to high temperatures on mechanical properties still require studies. In this research, cylindrical specimens were moulded, subjected to temperatures of 200 and 400 °C for a period of 7 hours, and subsequently subjected to two cooling modes: immersion in water and in ambient air. After cooling, the specimens were tested for axial compression and the results compared to the reference specimens cured at 23 °C in a humid chamber. The results demonstrated that heating up to 200 °C did not result in a decrease in resistance regardless of the type of cooling applied; however on heating to 400 °C, there was a reduction of approximately 30% in the resistance, mainly with water cooling.

Keywords: Concrete. Compressive strength. Fire. Cooling.

Resumo

O concreto é o material de construção civil mais utilizado no mundo devido à sua versatilidade, propriedades mecânicas, baixo custo e grande disponibilidade de elementos constituintes. Dentre suas propriedades, destaca-se o bom desempenho quando exposto a elevadas temperaturas, garantido por características como a baixa difusividade térmica e incombustibilidade. Apesar de apresentar boa resistência ao fogo, estruturas de concreto nessas situações têm sua resistência mecânica reduzida em situações de incêndio incorrendo em problemas estruturais. Os efeitos do método de resfriamento do concreto após exposto às elevadas temperaturas nas propriedades mecânicas ainda requer estudos. Nesta pesquisa, corpos de prova cilíndricos foram moldados e submetidos a temperaturas de 200 e 400 °C por um período de 7 horas, sendo posteriormente submetidos a dois modos de resfriamento: imersão em água e ao ar ambiente. Após o resfriamento, os corpos de prova foram ensaiados a compressão axial e os resultados comparados aos corpos de prova de referência curados a 23 °C em câmara úmida. Os resultados demonstraram que o aquecimento até 200 °C não resultou em decréscimo de resistência independentemente do tipo de resfriamento aplicado, entretanto para 400 °C ocorreu redução de aproximadamente 30% da resistência, de forma mais acentuada no resfriamento em água.

Palavras-chave: Concreto. Compressão. Incêndio. Resfriamento.

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Introduction

Concrete is one of the main materials used in civil construction for structural purposes. It is defined as a biphasic cementitious composite constituted by a binder medium in which fine and coarse aggregates are incorporated (MEHTA; MONTEIRO, 2006; NEVILLE; BROOKS, 2010). Its physicochemical and mechanical properties, coupled with the availability of materials at low cost, make concrete the second most consumed product in the world. It is characterized as an incombustible material with low thermal diffusivity, which guarantees satisfactory performance of concrete structures when exposed to fire (FERNANDES *et al*., 2017).

Because it is a non-combustible material that does not emit toxic gases, concrete is superior to materials such as wood and plastics for structural applications in construction. In addition, unlike other materials, the low thermal diffusivity of concrete allows it to maintain a certain strength when exposed to temperatures in the range of 600 to 800 °C , thus allowing rescue operations to be performed within a satisfactory period of time (MEHTA; MONTEIRO, 2006; NEVILLE; BROOKS, 2010).

Figure 1 shows the resistance variation of various materials used in construction as a function of temperature increase.

The Figure 1 demonstrates that all materials exhibit a decrease in strength as the temperature to which they are exposed increases. However, it is observed that although steel has a higher relative strength compared to concrete, up to 600 °C, when used as an isolated element, steel reaches high temperatures much faster than concrete, reducing the time available for rescue in fire situations. Moreover, it is noted that concrete has the shallowest gradient of decreasing resistance in relation to the other materials, thus demonstrating that, although it presents a progressive reduction of its resistance with the temperature increase, the drop in resistance does not occur abruptly as compared to other materials (MEHTA; MONTEIRO, 2006; NEVILLE; BROOKS, 2010; SILVA, 2012).

According to Souza and Moreno (2010), a factor of great influence for the impact on concrete elements subjected to high temperatures is the way in which they are cooled. Sudden cooling, resulting from the use of water directly on the concrete surface, as occurs in fire situations, generates violent temperature gradients in the concrete and as a result, a reduction in the original strength.

At this point, it is worth mentioning that a significant portion of the studies analyse the variation of compressive strength of concrete under natural cooling conditions (concrete after exposure is progressively cooled only by contact with the environment), indicating the need for studies comparing the different types of cooling.

One of the works that presents a comparison between the effects of natural and sudden cooling on concrete strength was developed by Morales, Campos and Faganello (2011), where concrete specimens were exposed to temperatures of 300 °C and after natural cooling its resistance decreased 5% and after sudden cooling decreased almost 30%.

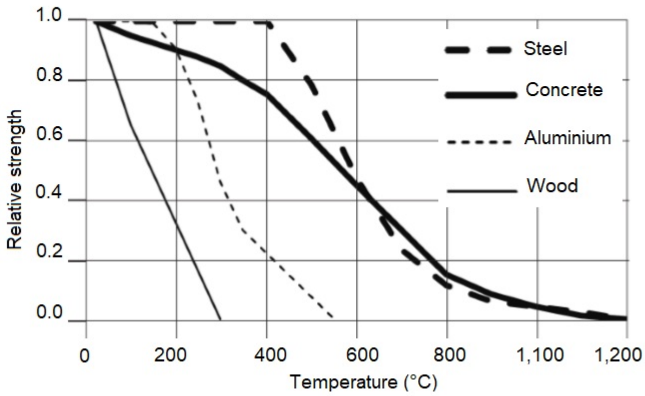
Lorenzon (2014) evaluated concrete specimens exposed to temperatures of 300, 500, and 800 °C during 30 to 90 minutes periods and subsequently subjected to natural cooling and sudden cooling. The results indicated that considering natural cooling and 60 minutes' exposure to high temperatures, the decreases in concrete strength were 30% (300 °C), 43% (500 °C), and almost 100% (800 °C). With respect to sudden cooling, lower values of residual compressive strength were observed compared to natural cooling with values of the order of 7.5%.

Souza and Moreno (2010) used cylindrical specimens of 10 x 20 cm (diameter x height) to evaluate the effect of exposure to temperatures of 300, 600, and 900 °C on the compressive strength under natural cooling and sudden cooling. The results obtained by the authors are presented in Table 1, where it is possible to observe a significant reduction in the mechanical properties of concrete after 600 °C. It is noteworthy that at 900 °C the specimens showed intense cracking, to the point that it was not possible to manipulate the specimens for compression testing.

Maanser, Benouis, and Ferhoune (2018) analysed the mechanical properties of concretes with different additions and additives exposed to temperatures of 20, 105, and 300 °C. The authors observed that all concrete specimens presented a reduction of compressive strength when the temperature was increased, and this reduction varied according to the additive used. Anyway, it was found that the greatest strength reduction occurred in concrete produced with 2% air entraining additive.

Ehrenbring *et al*. (2017) evaluated the residual compressive strength of reinforced concrete hollow core slabs after a real fire situation. The objective of the authors was to identify which interventions would be needed for

Figure 1 – Variation of material strength when exposed to high temperature.



Source: Silva (2012).

Table 1 – Concrete compressive strength considering different cooling methods.

Temperature	Natural air cooling		Sudden cooling	
	Compressive strength (MPa)	Percentage residual	Compressive strength (MPa)	Percentage residual
23 °C	30.45	100%	30.45	100%
300 °C	26.80	88%	24.66	81%
600 °C	26.19	86%	22.23	73%
900 °C	2.44	8%	0.00	0%

Source: Souza and Moreno (2010).

rehabilitation of the structure. Based on visual analysis, X-ray diffractometry, and X-ray fluorescence spectroscopy assays, the authors observed that the structure had been exposed to a temperature close to 700 °C but could not stipulate the exposure time. The fire that hit the bottom of the slab caused a significant reduction in compressive strength only in the 10- and 20-mm layers, which had residual compressive strengths of 30 and 75% respectively. The authors also pointed out that for layers above the 20-mm layers, the loss of strength was negligible, since the maximum temperatures reached were below 100 °C, demonstrating that despite the high temperature of the medium, internally the concrete did not suffer large variations.

Botte and Caspeele (2017) analysed the effects of two cooling methods on the mechanical properties of concrete. In the first method, water was sprayed during 5 minutes on the surface of concrete specimens after exposure to high temperatures; the second method consisted of immersing the specimens in water at 20 °C for the same period after exposure to high temperatures. The exposure temperatures and time were defined as 20 °C (reference), 175 °C, 350 °C, and 600 °C, all for 900 minutes (15 hours), and then the cooling method were performed.

The authors observed a higher reduction of strength due to sudden immersion cooling compared to the spray cooling method. At 175 °C, the samples submitted to immersion cooling presented approximately 65% residual compressive strength, while the samples submitted to the spray presented approximately 85% residual compressive strength. At 350 °C the residual compressive strengths were 45 and 55% for the specimens submitted to water immersion and spray cooling, respectively, and at 600 °C the authors observed that the difference caused by the type of cooling in the residual compressive strength tended to disappear, so that the compressive strength found for immersion-cooled samples was 20% and the resistance for spray-cooled samples was about 25%.

Using construction materials usually employed in western Paraná state for concrete production, in this study cylindrical specimens were moulded and subjected to temperatures of 23 °C (reference), 200 °C, and 400 °C for a period of 7 hours, then subjected to sudden cooling and natural cooling, and then tested for compression to evaluate the effects of the cooling methods on the compressive strength of concrete after exposure to high temperatures.

Experimental programme

Thirty concrete specimens of 5 x 10 cm (diameter x height) were moulded using Portland cement CP II Z [similar to ASTM Type I (MP)] with specific mass equal to 3.09 g/cm^3, determined according to ABNT NM 23 (ABNT, 2001), quartz sand with specific mass equal to 2.65 g/cm^3 and fineness modulus equal to 1.85, determined according to ABNT NM 52 (ABNT, 2009) and ABNT NM 248 (ABNT, 2003), respectively, and basaltic coarse aggregate with a maximum characteristic dimension equal to 9.52 mm and specific mass equal to 2.90 g/cm^3, determined according to ABNT NM 53 (ABNT, 2003) and ABNT NM 248 (ABNT, 2003), respectively. Using these materials, concrete was proportionated using the Brazilian Portland Cement Association Method (ABNT, 1983) resulting in mass proportions (kg/kg) of 1:1.49:2.12:0.50 (cement: fine aggregate: coarse aggregate: water), with slump equal to 95 mm, according to NM 67 (ABNT, 1998).

To evaluate the effect of cooling method on concrete compressive strength, Table 2 presents the sample groups, the exposure temperature, and the cooling method. Six samples of each group were moulded; samples from group A were considered as reference and were not exposed to high temperatures. Samples from groups B and C were exposed to 200 °C and then cooled naturally in air and suddenly submerged in water, respectively, while samples from groups D and E were exposed to 400 °C and the same cooling processes were used.

All concrete samples were cured during 28 days in a humid chamber. Since the direct exposure of the specimens to high temperatures could lead to rapid evaporation of water present in the concrete pores and, consequently, to abrupt ruptures during the heating process, the samples were dried during 24 hours at 105 °C. After the drying process, samples from groups B, C, D, and E were exposed to temperatures of 200 and 400 °C during 7 hours in a muffle furnace and then submitted to different cooling methods.

Samples in the natural cooling group were removed from the furnace and placed on the workbench in the laboratory at a temperature of 20 °C and air humidity of 85%). Samples in the sudden cooling group were removed from the furnace, immediately submerged in water at a temperature of 20 °C for 1 minute (Figure 2), and then placed on the workbench until stabilization at ambient temperature.

After cooling, the specimens were subjected to the compression test as prescribed by NBR 5739 (ABNT, 2007), using a universal test machine with a capacity of 200 tons. The compressive strength values obtained were compared to the values of the specimens of the reference group (Group A).

Results analysis

Firstly, it was observed that the sudden cooling reduced the temperature of the specimens to values close to 70 °C for all cases, regardless of the temperature to which the specimen was exposed (200 or 400 °C), giving a significant temperature gradient of 130 °C in the case of the group C specimens and 330 °C in the case of the group E specimens.

Another important point observed in the test is the physical appearance of the specimens after exposure to high temperatures. The specimens heated to 400 °C presented a lighter coloration, greater superficial cracking in relation to the reference specimens, and a slight crumbling to the touch, thus providing an indication of the beginning of chemical decomposition of the cementitious matrix.

Table 3 presents the strength results obtained after performing the compression tests. The drying process of samples during 24 hours at 105 °C aimed to avoid cracking of samples when exposed to high temperatures and, as a consequence, samples that were kept at 23 °C presented compressive strength higher than 50 MPa, which can be attributed to the absence of water in concrete pores. When concrete is saturated, water in concrete pores generates internal stresses during the compression test and reduces the compressive strength.

A progressive strength reduction was observed as the temperature to which the specimens were exposed increased, with the largest decrease in strength occurring when the specimens were subjected to temperatures between 200 and 400 °C; the average reduction in resistance was from 6% at 200 °C to 30% at 400 °C.

By performing a variance analysis using the statistical program R, the data presented at Table 4 were obtained, indicating that there is a statistical difference in compressive strength between some treatments. Therefore, a Tukey-Kramer multiple comparison test was performed, resulting in a mean significant difference value equal to 4.48 MPa.

Table 2 – Identification, exposure temperature, and cooling methods.

Sample identification	Temperature °C	Cooling method
A	23	-
B	200	Natural
C	200	Sudden
D	400	Natural
E	400	Sudden

Source: The authors.

Figure 2 – Sudden cooling procedure: (a) water immersion (b) cooling time measurement.

Source: The authors.

Table 3 – Compressive strength according to temperature and cooling method.

Temperature	Cooling method	Sample compressive strength (MPa)								Reduction (%)
		CP1	CP2	CP3	CP4	CP5	CP6	Mean	Standard deviation	
23 °C	-	60.40	54.95	52.74	62.80	57.78	57.86	57.75^a	3.30	-
200 °C	Natural	57.27	56.69	57.47	58.72	56.93	57.90	57.50^a	0.73	0.43
	Sudden	60.40	58.21	55.16	52.99	50.93	47.92	54.27^a	4.63	6.02
400 °C	Natural	43.57	42.81	42.63	42.02	41.53	41.66	42.37^b	0.78	26.63
	Sudden	41.18	40.72	40.62	40.11	40.11	39.44	40.36^b	0.61	30.11

Source: The authors.

Table 4 – Variance analysis results.

Source of variation	SS	df	MS	F	P-value	F crit
Between groups	1707.753	4	426.9382	59.28231	2.15E-12	2.75871
Within groups	180.0445	25	7.20178			

Source: The authors.

Table 3 presents the mean compressive strength, where the same letters indicate the treatments with statistically equal means, proving that there was a significant reduction in resistance when the samples were exposed to a temperature of 400 °C, similar to results presented by Morales, Campos and Faganello (2011).

The reason for this type of behaviour corroborates the statements about the beginning of a process of decomposition of the cementitious matrix. At 100 °C, the beginning of the evaporation of free water present in the pores of the concrete occurs and the hydrated chemical composites start the dehydration process and thus the stream pressure in the concrete pores rises. However, at 400 °C, beyond the water evaporation, a process of decomposition of the cement matrix begins, mainly from calcium hydroxide (CaOH2) (ROJAS; CINCOTTO, 2013). At temperatures higher than 500 °C, thermal gradients between aggregates and cementitious matrix potentiate the opening of cracks, accelerating the process of degradation and loss of strength (CAETANO *et al*., 2019; LI *et al*., 2019; MOGHADAM; IZADIFARD, 2019).

Although the mean values of compressive strength presented a greater reduction when samples were submitted to sudden cooling compared to natural cooling, there was no statistical difference for samples submitted to the same temperature. In general, under natural or sudden cooling after exposure to a temperature of 200 °C (Groups B and C), the decrease in compressive strength was not significant in relation to the reference group (group A), showing that at this temperature, even with the evaporation of the capillary water present in the concrete pores, its resistance capacity was little affected. On the other hand, at 400 °C, due to the decomposition of the cementitious matrix, the damages produced were significant, with reductions that reached 30% in relation to the reference group. These data corroborate previous studies (SOUZA; MORENO, 2010; LORENZON, 2014; EHRENBRING *et al*., 2017; BOTTE; CASPEELE, 2010), whose authors also observed a significant decrease in strength only when the concrete exposure temperature exceeded 200 °C.

Conclusions

The present work analysed the effects of different cooling methods (natural and sudden) after concrete exposure to high temperatures. The results corroborate the literature data and the main conclusions are described below:

• A temperature rise leads to physical and chemical modifications of the concrete, where it is possible to observe changes in color and cracking. Moreover, it was observed in this study that at temperatures up to 400 °C a process of crumbling of concrete began as a result of the decomposition of the cementitious matrix.

• The effects of concrete exposure to high temperatures impact its mechanical properties, especially when there is a process of decomposition of the cementitious matrix. In this case, regardless of the cooling method, the exposure of the concrete to a temperature of 200 °C generated a slight variation of the mechanical properties, since at this temperature there is only a loss of the capillary water present in the concrete pores. On the other hand, the exposure temperature of 400 °C leads to decomposition of the cementitious matrix and consequently a significant reduction of the mechanical properties of the concrete.

• When exposed to 400 °C and sudden cooling, the concrete compressive strength decreases by approximately 30%.

• From the perspective of cooling, it was observed that concretes subjected to sudden cooling had lower values of compressive strength compared to naturally cooled concretes, but this variation can be considered statistically insignificant.

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