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EXPERIMENTAL TESTING ON THE RESIDUAL MECHANICAL PROPERTIES OF ORDINARY CONCRETES AFTER FIRE

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ABSTRACT

Concrete is known to have an enhanced behaviour in fire when comparing with bare steel, however there are some chemical and physical transformations in function of temperature that may compromise this performance. The mechanical and thermal properties of concrete at high temperatures and after fire have changes that have been evaluated in a lot of works around the World, however this is still an open field where a lot of research is needed. This paper summarizes the results of an experimental research to assess the residual mechanical properties of ordinary concretes after fire. It was studied the influence of the fire extinguishing methods, the maximum temperature that the concrete was subjected to and the loading level on the residual mechanical properties of calcareous and granite aggregate concretes. The properties studied were the residual compressive, tensile, splitting and flexural strengths and modulus of elasticity. Four levels of temperature; 20ºC, 300ºC, 500ºC and 700ºC; two loading levels (0.3fcd and 0.7fcd) and two cooling processes (cooling in the air and by water jet) were tested. The results showed that the mechanical properties of concretes are affected by the cooling process (fire extinguishing methods) used beyond the high temperatures and loading levels that were subjected to.

Keywords: concrete; fire; cooling; air; water; strength; spalling.

NOTATION

E_{cT}	Residual modulus of elasticity after being submitted to temperature T
$E_{c20ºC}$	Modulus of elasticity at room temperature
f_c	Compressive strength for cubes
f_{cm}	Mean value of the compressive strength for cubes
$f_{c20ºC}$	Compressive strength at room temperature
f_{cd}	Design value of the compressive strength at room temperature
f_{cT}	Residual compressive strength after being submitted to temperature T
f_{tT}	Residual direct tensile strength after being submitted to temperature T
$f_{t20ºC}$	Direct tensile strength at room temperature
f_{ctT}	Residual tensile splitting strength after being submitted to temperature T

$f_{ct20ºC}$	Tensile splitting strength at room temperature
f_{cfT}	Residual flexural strength after being submitted to temperature T
$f_{cf20ºC}$	Flexural strength at room temperature
C	Cement
W	Water
b	Cross-sectional dimension of specimen
d	Diameter of specimen
h	Height of specimen

INTRODUCTION

The concrete when subjected to fire, followed by a sudden cooling from the fire extinguishing process, may suffer big degradation on mechanical properties. The knowledge of the residual mechanical properties of concrete after fire is essential for evaluating the residual load-bearing capacity of the elements. Several research studies have identified as main parameters that could affect the residual mechanical strength of concrete after fire, the following: type of cement, type and size of aggregates, water / cement ratio, loading level and cooling process. Schneider highlighted the type of aggregates, loading level and cooling process, as the main parameters responsible for concrete cracking (Schneider, 1982).

Abrams assessed, after several research studies, that concrete composed by siliceous aggregates loses higher compression strength than those with calcareous aggregates, although this difference disappears when the temperatures reach 800ºC. The nature of the aggregates is closely linked with the thermal expansion and conductivity coefficient of concrete, because while siliceous concretes have a slight contraction, when subjected to temperatures between 300 and 900ºC, calcareous concretes have an expansion which leads to the appearance of cracking. This can be explained by the higher degree of porosity and coefficient of thermal expansion of the calcareous aggregates. In this sense, the author states that the type of aggregate greatly affects the mechanical strength of concrete in fire and consequently after fire (Abrams, 1983).

The loading level that concrete is subjected to, it is also a parameter that affects the mechanical strength of concrete in fire and after it. Experimental studies carried out by Kodur and Sultan showed that the loading level, when no excessive, has a positive effect on the residual compression strength of concrete because it reduces the degree of cracking. This phenomenon resulted from a densification of the cement matrix of concrete that reduces cracking. This is also valid for the concrete strength after fire (Kodur and Sultan, 1998).

The fire extinguishing method also affects the residual mechanical strength of concrete and consequently the loadbearing capacity of the elements, cooling by water jet is responsible for higher damages in concrete compared with natural extinguishing of fire (Schneider and Nãgele, 1989; Santos et al, 2009).

Castillo and Durrani found also in their studies that the appearance of cracking is more prone in case of sudden cooling and this is responsible for damages reducing the mechanical strength of concrete. The authors observed a continuous degradation of the concrete with the temperature from 100 to 600ºC, being the concrete strength for temperatures higher than this almost zero (Castillo and Durrani, 1990).

The spalling is another phenomenon that occurs in concrete structures subjected to high temperatures. The high temperatures associated to the loading level, shape and thickness of the element, type of concrete and aggregates used, are responsible for this phenomenon (Harmathy, 1995). The result is a reduction of the residual load-bearing capacity of the elements.

There are other parameters, reported by other authors, that may lead to spalling in concrete, as for example the: low porosity associated to a low permeability, sudden increasing of temperature with huge thermal gradients in the element, high humidity responsible for increasing the water vapour pressure in concrete pores and thermal stresses in the direction parallel to the heated surface (Hertz, 1984; Bazant and Kaplan, 1996; Hertz, 2003).

The use of adjuvants and additives that may reduce the concrete porosity, of lightweight aggregates of high porosity that typically contain high water contents, low water/cement ratio, among others, are also factors that may lead to concrete spalling (Zhukov, 1980, Schneider, 1982; Hager, 2004). Spalling can be explained as a phenomenon that results from the interaction of chemical, thermal, mechanical and hydro factors, associated with concrete microstructural changes caused by the high temperatures (Anderberg, 1997; Bazant, 1997).

As stated in several studies, concrete suffers significantly losses in mechanical strength due to the high temperatures experienced in fire, the loading level and the fire extinguishing method used. In order to clarify the influence of these parameters it was developed an experimental study at the Laboratory of Testing Materials and Structures of the University of Coimbra, on assessing the residual mechanical properties of ordinary concretes (calcareous and granite aggregate concretes) after fire. The properties studied were the residual compressive, tensile (direct and splitting), flexural strength and modulus of elasticity. The influence of these properties on concrete cracking and spalling are also briefly analysed.

EXPERIMENTAL STUDY

Concrete composition and specimens

As they are the most used in civil construction in Portugal, calcareous and granite aggregate concretes were studied in this research work. The type and size of aggregates used in compositions are presented in Table 1.

Table 1 Type and size of aggregates

Aggregate type		**Aggregate size**
Course	crushed stone 1 (B1)	12.7mm
	crushed stone 2 (B2)	19.1mm
Fine	fine sand (A1)	< 4mm
	coarse sand (A2)	

In concrete compositions was used Portland Cement CEM II/A-L 42.5R. Table 2 presents some information about this cement in terms of chemical composition and mechanical properties.

The concrete compositions are presented in Table 3.

The superplasticizer (SP) was the Sikament® 195R that had the function of reducing the water needs and increasing concrete workability.

Table 2 Some properties of Portland cement CEM II/A-L 42.5R

Chemical composition			**Mechanical properties**		
Element	SO_3	Cl	**Compressive strength**	Age - 2 days	Age - 28 days
%	≤ 4	≤ 0.10	**MPa**	≥ 20	≥ 42.5 and ≤ 62.5

Table 3 Composition of calcareous aggregate (CC) and granite aggregate (GC) concretes per m^3

Concrete composition	**CEM (Kg)**	**Water (dm^3)**	**SP (dm^3)**	**A1 (Kg)**	**A2 (Kg)**	**B1 (Kg)**	**B2 (Kg)**	**W/C**
CC	300	166	3.30	364	495	505	377	0.56
GC	320	165	3.20	310	511	617	459	0.52

In Table 4 are presented the compression strength and resistance class of the tested concretes according to EN 206-1 (2007). The specimens were cured in the ambient conditions of the Laboratory (around 20ºC and 60% of relative humidity).

Table 4 Compression strength and resistance class of tested concretes

Concrete type	**fc (MPa)**	**fc_m (MPa)**	**Resistance class**
CC	45.4 43.8 43.0	44.05	C30/37
GC	40.6 39.4 40.7	40.23	C30/37

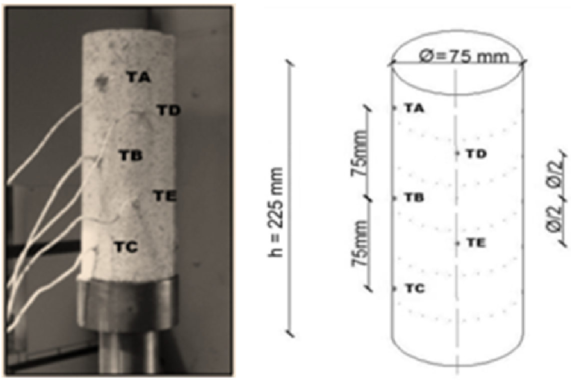

Fig. 1 Specimens for the compressive and direct tensile strength tests and location of thermocouples

The assessment of the residual compressive strength and direct tensile strength of concrete was carried out on cylindrical specimens of 75mm diameter and 225mm height, that corresponded to a height/diameter ratio of 3:1. The specimens were provided with five thermocouples type K in order to register the temperatures inside the concrete. The location of thermocouples in the specimens was based on the recommendations of RILEM TC 200 (2005) (Fig. 1).

The specimens for the residual tensile splitting strength and modulus of elasticity tests were cylinders of 150mm diameter and 300mm in height (Fig. 2) (EN 12390-6, 2003; RILEM TC 129 MHT, 2004). They were provided with embedded type K thermocouples for temperature measurements. In the cylinders for the modulus of elasticity tests, three strain gauges TML type PFL-30-11, were applied, in orthogonal sides of the specimen.

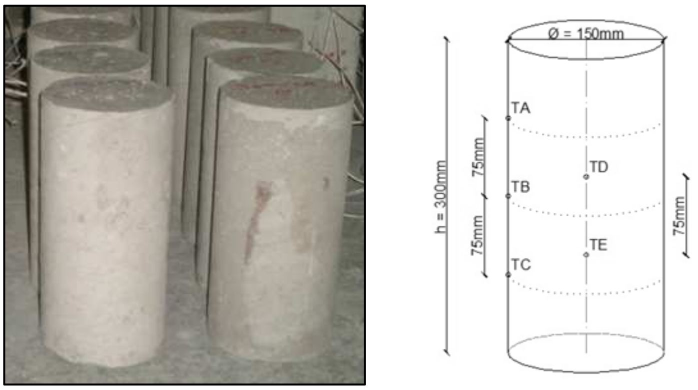

Fig. 2 Specimens for the tensile splitting tests and location of thermocouples

The specimens for residual flexural strength tests were of prismatic shape with 150mm x 150mm x 600mm (EN 12390-5, 2009) (Fig. 3). They were provided with embedded type K thermocouples for temperature measurements.

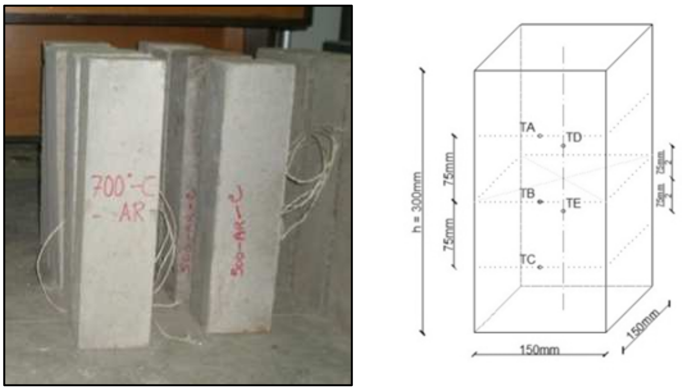

Fig. 3 Specimens for the flexural strength tests and location of thermocouples

Test Plan

This experimental research was carried out in four steps: the first was concerned to the compression strength, the second to the tensile strength (direct and splitting), the third to the flexural strength and the fourth to the modulus of elasticity tests. All tests were carried out after a heating and cooling process. The characteristics of the specimens tested are summarised in Table 5. Three tests as a minimum were developed for each combination of parameters.

Table 5 Test Plan

Residual test	**Specimen shape and size (m)**	**Loading level**	**Temperature (ºC)**
compression strength	cylinders, d=75:h=200	$0.3f_{cd}$	20, 300, 500, 700
		$0.7f_{cd}$	20, 300, 500, 700
direct tensile strength	cylinders, d=75: h=200	-	20, 300, 500, 700
splitting strength	cylinders, d=150: h=300	-	20, 300, 500, 700
bending strength	prisms, b=150: h=600	-	20, 300, 500, 700
modulus of elasticity	cylinders, d=150: h=300	-	20, 300, 500, 700

Test set-up and procedure

The experimental set-up for the residual compression strength tests were composed by a universal tensile/compression machine of 600kN and a tubular furnace attached on it (Fig. 4a). Two cooling processes were in this case tested: cooling in the air (simulating a fire extinguished in a natural way) and the cooling by water jet (simulating the action of fire men with water extinguishing of fire) (Fig. 4 b and c).

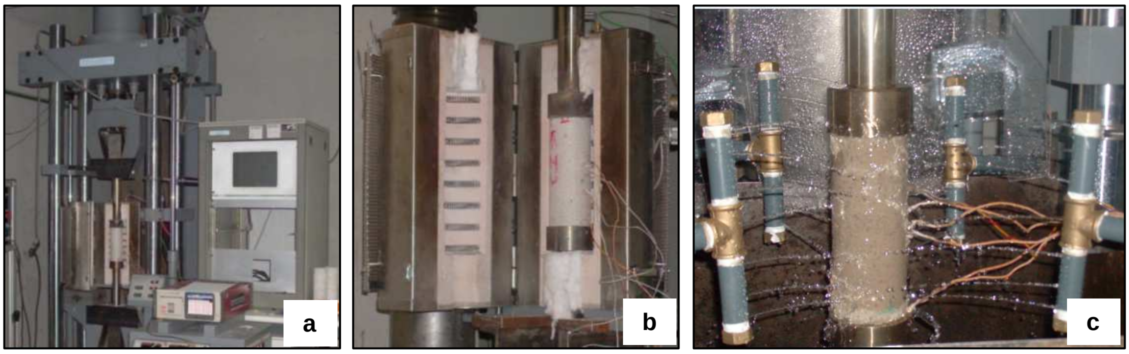

Fig. 4 Residual compression strength. a) Test set-up. b) Cooling in the air. c) Cooling by water jet

The specimens were subjected, during the entire test, to a constant compressive loading equal to a percentage of the design value of the compression strength of the concrete at room temperature ($0.3f_{cd}$ and $0.7f_{cd}$). This load tried to simulate the conditions when concrete is in real structures.

The specimens were the heated up at a rate of 3ºC/min up to the desired level of temperature. The temperature was considered achieved when the average temperatures on the three superficial thermocouples match the temperature of the furnace. The maximum axial temperature differences between the three superficial temperature readings could not exceed 1ºC at 20ºC, 5ºC at 100ºC and 20ºC at 700ºC. The specimens were then kept at that temperature for an hour to stabilize. After this the specimens were cooled down in the air (Fig. 4b) or by water jet (Fig. 4c) to ambient temperature. When the temperature reached again the ambient temperature (more or less 20ºC) the compressive tests were carried out. The test procedure was adopted according to the RILEM TC 200 HTC recommendations (RILEM TC 200 HTC, 2005). The compressive test was carried out being the loading increased at a loading rate of 0.25kN/s up to rupture of the specimen.

For the residual tensile strength of concrete two types of tests were carried out: direct tensile and tensile splitting tests. In both type of tests the specimens were first heated up, at a heating rate of 3ºC/min, up to the desired levels of temperature. The same procedure of the last tests was used for the stabilization of temperatures in the specimens. After this the specimens were cooled down in the air or by water jet, simulating the two cooling processes in study. When the temperature of the specimens reached again the ambient temperature, the residual tensile strength test was carried out.

The residual direct tensile tests were carried out in a universal tensile/compression machine of 200 kN. A tensile loading was applied directly to the specimen, at a loading rate of 0.25kN/s, up to the rupture of the specimen (Fig. 5).

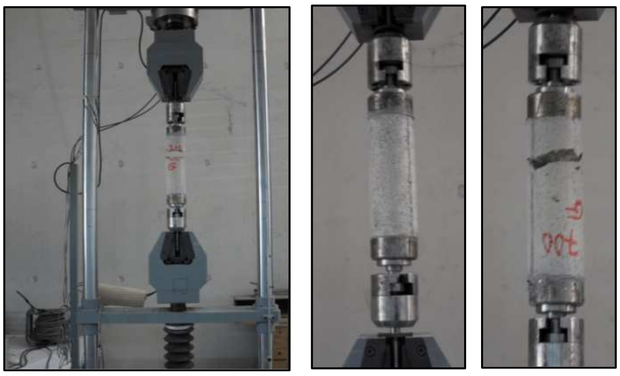

Fig. 5 Test set-up – residual direct tensile strength tests

A set of pull-rods was specially fabricated for the direct tensile tests (Fig. 6).

Fig. 6 Pull rods for the direct tensile tests

The residual tensile splitting tests were carried out according to EN 12390-6 (2003). The specimens were tested under diametrical compression, in an universal testing machine of 600kN, being the load applied continuously and without shock, at a constant loading rate, in the range of 0.04 to 0.06 MPa/s, until rupture (Fig. 7).

In the residual flexural strength tests of concrete the heating and cooling was similar to the tensile tests. The bending tests were carried out in an universal tensile / compression machine of 600kN, using a special set of supports for three-point bending tests (Fig. 8). The load was increased at a loading rate of 0.05MPa/s, up to the rupture of the specimen, according EN 12390-5 (2009).

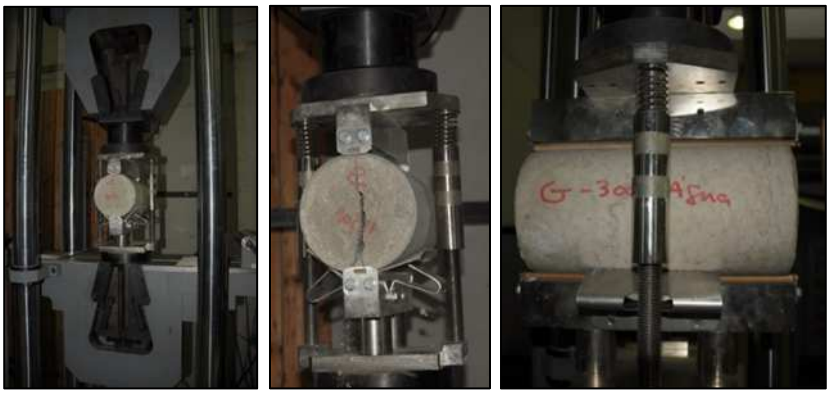

Fig. 7 Test set-up – residual tensile splitting strength tests

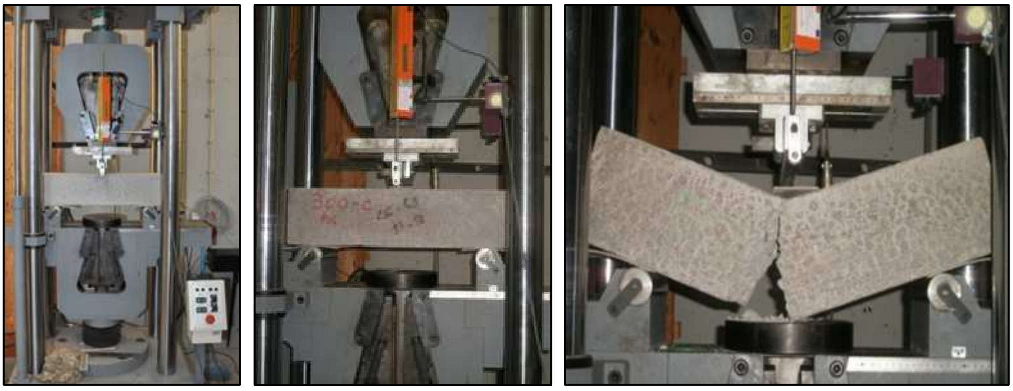

Fig. 8 Test set-up – residual flexural strength tests

In the residual modulus of elasticity tests, after the heating/cooling process, that was similar to the last tests, the specimens were then subjected to cyclic loading, between the loading levels of 0.5MPa and $f_{c20^{\circ}C}/3$, according the RILEM TC 129 MHT (2004) recommendations. In these tests were registered the strains measured in the strain gauges. The universal tensile/compression machine of 600kN was once more used for this porpoise (Fig. 9).

Fig. 9 Test set-up – residual modulus of elasticity tests

RESULTS

Table 6 resumes the values of the residual mechanical properties of the calcareous aggregate (CC) and granite aggregate (GC) concretes studied.

Furthermore, Figs. 10 to 15 present the variation of the residual mechanical properties of the CC and GC concretes tested.

In the residual compression tests, for the loading level of $0.3f_{cd}$, both CC and GC experienced a reduction on the residual compression strength as function of temperature (Fig. 10). At 700ºC, for example, for the GC, the reduction was about 60%, for cooling in the air, and about 70%, for cooling by water jet, and for the CC, the reduction was100%, for both cooling processes.

Table 6 Reduction factors for the residual mechanical properties of the tested concretes

			Cooling in the air					**Cooling by water jet**				
		Temperature (ºC)	**20**	**300**	**500**	**700**	**900**	**20**	**300**	**500**	**700**	**900**
CC	**Retained compressive strength (%)**	**$0.3f_{cd}$**	100	85.00	55.00	0	-	100	57.00	30.00	0	-
		$0.7f_{cd}$	100	85.00	73.00	0	-	100	0	-	-	-
	Retained direct tensile strength (%)		100	55.00	5.00	1.00	-	100	9.00	8.50	8.00	-
	Retained splitting tensile strength (%)		100	63.47	29.56	9.13	-	100	61.01	30.04	12.18	-
	Retained bending strength (%)		100	61.99	21.78	3.57	-	100	36.78	21.33	4.26	-
	Retained modulus of elasticity (%)		100	28.00	11.00	6.00	-	100	18.00	7.00	3.00	-
GC	**Retained compressive strength (%)**	**$0.3f_{cd}$**	100	104.00	85.00	41.00	0	100	64.00	46.00	29.00	0
		$0.7f_{cd}$	100	105.00	0	-	-	100	0	-	-	-
	Retained direct tensile strength (%)		100	65.00	24.00	8.00	-	100	54.00	29.00	23.00	-
	Retained splitting tensile strength (%)		100	78.55	-	-	-	100	59.77	-	-	-
	Retained bending strength (%)		100	81.85	-	-	-	100	50.60	-	-	-
	Retained modulus of elasticity (%)		100	68.00	-	-	-	100	37.00	-	-	-

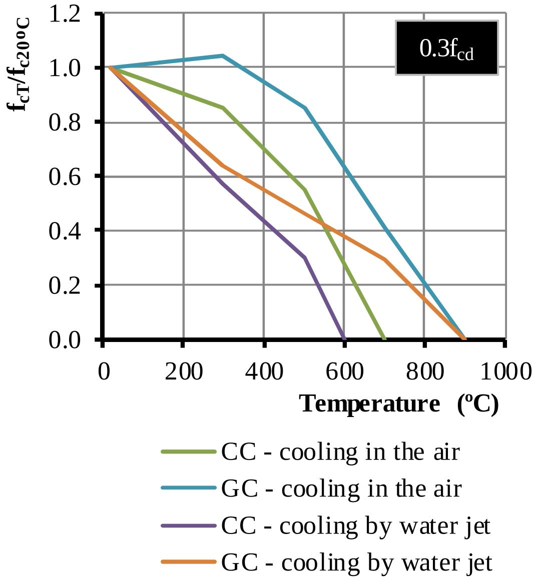

Fig. 10 Residual compression strength - $0.3f_{cd}$ - cooling in the air and by water jet - calcareous (CC) and granite concrete (GC)

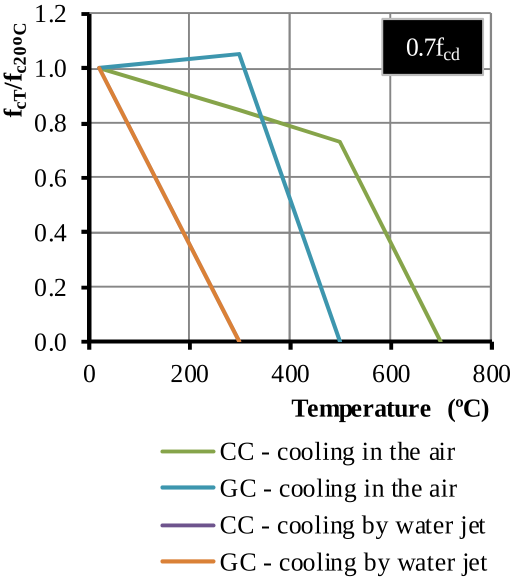

Fig. 11 Residual compression strength - $0.7f_{cd}$ - cooling in the air and by water jet and granite concrete (GC)

For the loading level of 0.7$f_{cd,}$ cooling in the air, temperatures under 300ºC, the GC presented higher residual compression strength then the CC. However, for temperatures above 300ºC, the opposite was observed. The GC at 500ºC presented a null value while the CC still presents around 70% of its compression strength at ambient temperature.

From Figures 10 and 11 it is notorious that this CC is more affected by the heating than the GC and the cooling process by water jet affects greatly the residual compression strength of the concretes. All the specimens of CC cooled by water jet collapsed during the cooling down process and it was impossible to carry out the compressive test at room temperature.

In Figs. 12 and 13, it is observed that the residual tensile strength of the concretes decreases with the temperature as in the compressive strength. The GC, comparing to the CC, showed once more a better behaviour in respecting to the residual direct tensile strength (Fig. 12). The cooling process by water jet affected more this mechanical property than the cooling in the air, however something interesting is observed on the results that for temperatures higher than 500ºC the process inverted being the cooling in air more prejudicial.

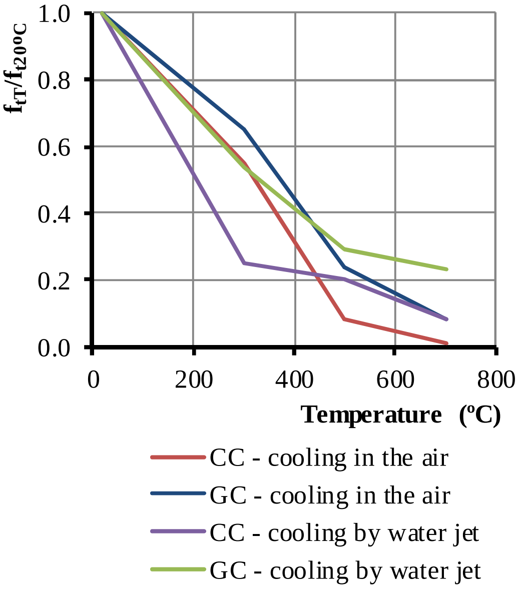

Fig. 12 Residual direct tensile strength – cooling in the air and by water jet - calcareous (CC) and granite concrete (GC)

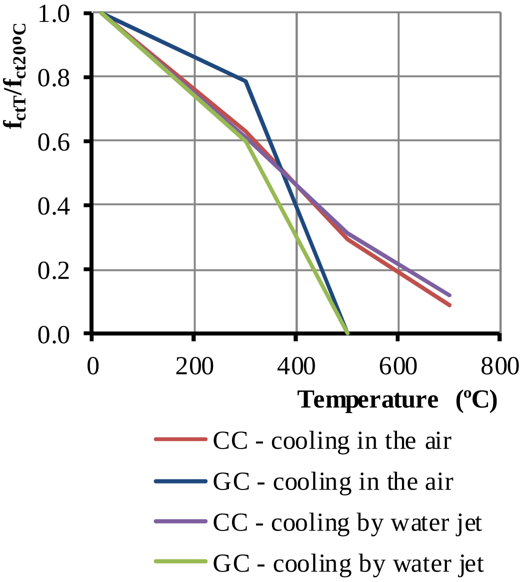

Fig. 13 Residual tensile splitting strength – cooling in the air and by water jet - calcareous (CC) and granite concrete (GC)

In the residual tensile splitting tests (Fig. 13) it was verified that up to around 300 ºC, both concretes showed a similar behaviour. After this temperature the GC was the most affected by the temperature. Another interesting result of these tests is that for every concrete the behavior of the one slowly cooled in air was similar to the one sharply cooled by water jet.

Comparing Figure 12 with Figure 13 the tensile strength determined by direct tensile was smaller than the one determined by tensile splitting. These results confirm the ones found by other researchers but still is an open field of research for explaining this phenomenon.

The residual flexural strength reduced also in function of the temperature being the cooling process by water jet more prejudice in this mechanical property (Fig. 14). The GC presented once more the worst results. The GC presented a resistance null at 500ºC however the CC maintains some resistance by some more time showing a null value for temperatures of 700ºC.

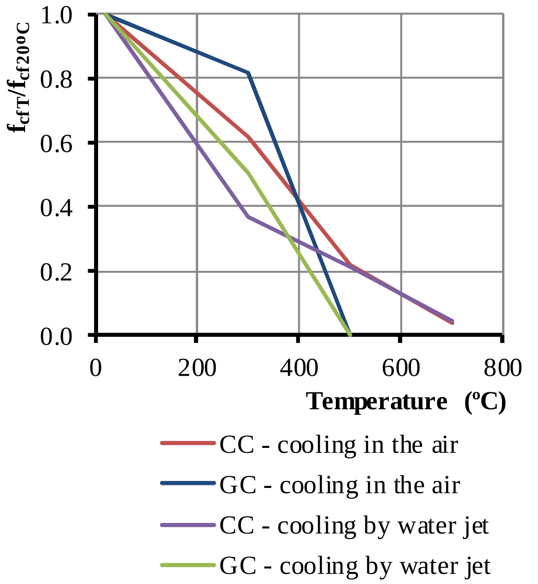

Fig. 14 Residual flexural strength – cooling in the air and by water jet - calcareous (CC) and granite concrete (GC)

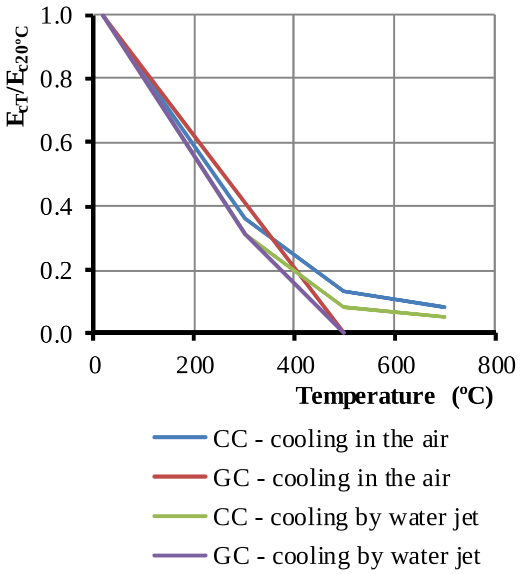

Fig. 15 Residual modulus of elasticity – cooling in the air and by water jet - calcareous (CC) and granite concrete (GC)

The residual modulus of elasticity decreased sharply with the temperature (Fig. 15). In this mechanical property it is not notorious the influence of one cooling process in relation to the other. The GC presented a null of modulus of elasticity for temperatures of 500ºC, while in the calcareous aggregate concrete this value only applies for temperatures of 700ºC.

CONCLUSIONS

The following conclusions may be drawn from the present study:

- The cooling process influenced very much on the residual compression strength of the concretes after heating and cooling. In the case of cooling by water jet, whatever was the loading level and the temperature reached, the CC presented a worst behaviour when compared with the GC. However this is not true for the case of cooling in the air, because for loading levels of $0.7f_{cd}$ and temperatures above 400ºC, the CC regained its performance when compared with the GC.
- The loading level, if not too excessive, interferes positively on the residual compression strength of concrete. The loss of residual compression strength is not so strong if concrete is loaded. This loading denies the occurrence of internal cracking in the concrete due to the heating/cooling process. These experimental tests showed that higher the loading level higher the influence of cooling process in reducing the residual compression strength of concrete, mainly in the case of cooling by water jet.
- The residual tensile strength of concrete decreased also with the temperature. The CC was more affected than the GC.

- The residual flexural strength was not different from the other mechanical properties; it has reduced in function of the maximum temperature that the concrete was subjected to. This phenomenon was more marked for cooling by water jet. The GC was in this case more affected.
- Independently of the aggregate type of concrete and cooling process used, the residual modulus of elasticity shows a sharply decrease with temperature.

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