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EXPERIMENTAL RESEARCH ON THE RESIDUAL MECHANICAL PROPERTIES OF AN ORDINARY CONCRETES AFTER FIRE



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ABSTRACT

This paper summarizes the results of an experimental research to assess the residual mechanical properties of an ordinary concrete after fire. It was studied the influence of the cooling process, 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; 20, 300, 500 and 700°C; two loading levels (0.3f and 0.7f_{cd}) and two cooling processes (cooling in the air and by water jet) were tested. The high temperatures attained and the sudden cooling down process on the concrete showed a negative effect on its residual mechanical properties. This effect was more notorious on the residual compression strength than in the other mechanical properties.

Keywords: concrete, fire, cooling process, strength, spalling.

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1. 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 [1].

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 800°C. The nature of the aggregates is closely linked with the thermal elongation and conductivity of concrete, because while siliceous concretes have a slight contraction, when subjected to temperatures between 300 and 900°C, calcareous concretes have an expansion which leads to the appearance of cracking. This can be explained by the higher degree of porosity and thermal elongation of the calcareous aggregates. In this sense, the author states that the type of aggregate greatly affects the mechanical strength of concrete at high temperatures and consequently after cooling down [2].

The loading level that the 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 [3].

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 [4, 5, 6].

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 compression strength of concrete. The authors observed a continuous degradation of the concrete with the temperature from 100 to 600°C, being the compression strength of concrete for temperatures higher than this almost zero [7].

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. The result is a reduction of the residual load-bearing capacity of the elements [8, 9, 10, 11].

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.

2. EXPERIMENTAL STUDY

2.1 Concrete composition and specimens

As they are the most used in civil construction in Portugal, calcareous (CC) and granite (GC) aggregate concretes were studied in this research work. In concrete compositions was used Portland Cement CEM II/A-L 42.5R. The concrete compositions are presented in Table 1. The superplasticizer (SP) was the Sikament® 195R that had the function of reducing the water needs and increasing concrete workability.

Table 1: Composition of calcareous aggregate (CC) and granite aggregate (GC) concretes (m³)

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

Table 2: Compression strength and resistance class of tested concretes

Concrete type	f_c (MPa)	f_{c_m} (MPa)	Resistance class
CC	45.4	44.05	C30/37
	43.8		
	43.0		
GC	40.6	40.23	C30/37
	39.4		
	40.7		

In Table 2 are presented the compression strength and resistance class of the tested concretes according to EN 206-1 (2007) [12]. The specimens were cured in the ambient conditions of the Laboratory (around 20°C and 60% of relative humidity).

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) [13] (Figure 1).

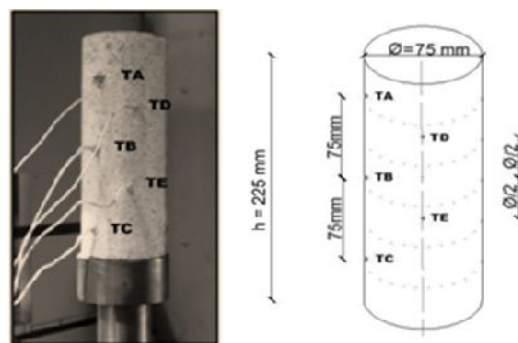


Figure 1: Specimens for the compressive and direct tensile strength tests and location of thermocouples

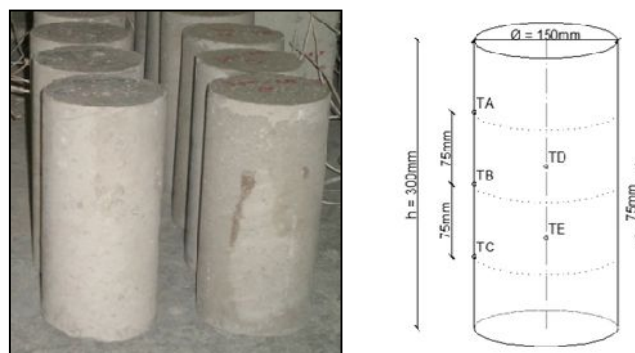


Figure 2: Specimens for the splitting tensile tests and location of thermocouples

The specimens for the residual splitting tensile strength and modulus of elasticity tests were cylinders of 150mm diameter and 300mm in height (Figure 2) [14, 15]. 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.

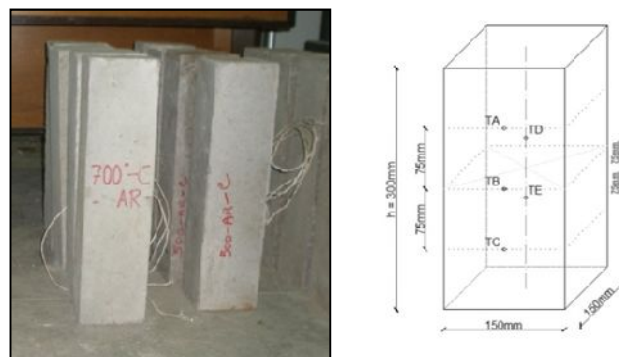


Figure 3: Specimens for the flexural strength tests and location of thermocouples

The specimens for the residual flexural strength tests were of prismatic shape with 150mm x 150mm x 600mm [16] (Figure 3). They were provided with embedded type K thermocouples for temperature measurements.

2.2 Test set-up and procedure

The experimental set-up for the residual compression strength tests were composed by an universal tensile/compression machine of 600kN and a tubular furnace attached on it (Figure 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 firemen in extinguishing a fire with water) (Figure 4 b and c).

The specimens were subjected, during the heating and cooling down process, to a constant compressive loading equal to a percentage of the design value of the compression strength of the concrete at room temperature (0.3 and $0.7f_{cd}$). This load tried to simulate the conditions when concrete is in real structures. The specimens were heated at a rate of $3^{\circ}\text{C}/\text{min}$ up to the desired level of temperature. After this they were cooled down in the air (Figure 4b) or by water jet (Figure 4c) to ambient temperature. When the temperature reached again the ambient temperature (more or less 20°C) the compressive tests were carried out. The test procedure was adopted according to the RILEM TC 200 HTC recommendations [13]. The compressive

test was carried out being the loading increased at a loading rate of 0.25kN/s up to rupture of the specimen.

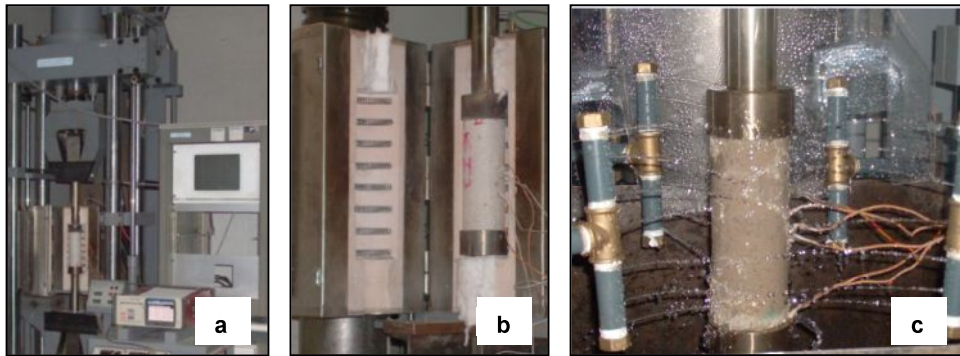


Figure 4: Residual compression strength tests. a) Test set-up. b) Cooling in the air. c) Cooling by water jet

For the residual tensile strength of concrete two types of tests were carried out: direct tensile and splitting tensile tests. In both type of tests the specimens were also first heated up, at a heating rate of 3°C/min, up to the desired levels of temperature. The residual direct tensile tests were carried out in an 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 (Figure 5).

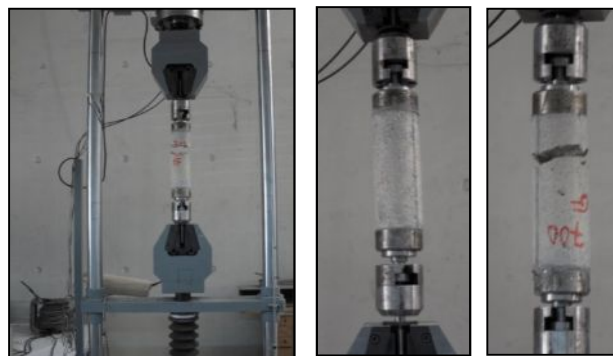


Figure 5: Test set-up – residual direct tensile strength tests

The residual splitting tensile tests were carried out according to EN 12390-6 (2003) [14]. 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 (Figure 6).



Figure 6: Test set-up – residual splitting tensile strength tests

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 (Figure 7). The load was increased at a loading rate of 0.05MPa/s, up to the rupture of the specimen, according to EN 12390-5 (2009) [16].



Figure 7: 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 $f_{c20^{\circ}\text{C}}/3$, according to the RILEM TC 129 MHT (2004) recommendations [15]. 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 purpose (Figure 8).



Figure 8: Test set-up – residual modulus of elasticity tests

3. RESULTS

Figures 9 to 14 present the variation of the residual mechanical properties of the CC and GC concretes tested.

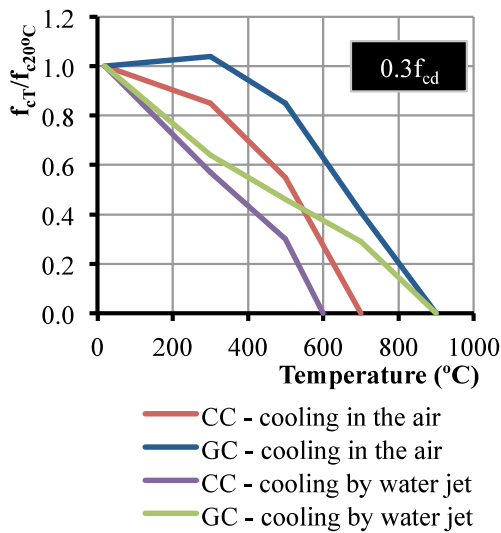


Figure 9: Residual compression strength - 0.3f_{cd} - cooling in the air and by water jet - calcareous (CC) and granite concrete (GC)

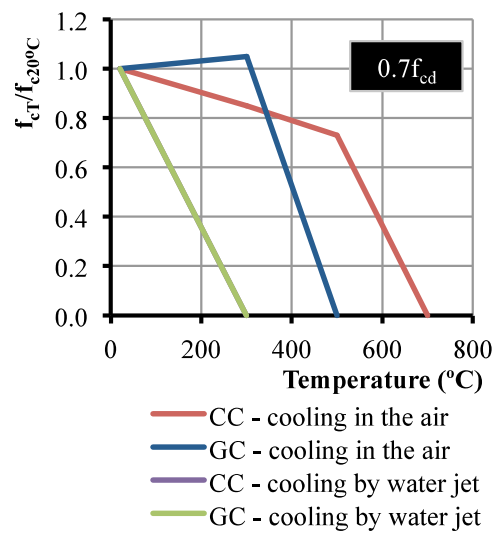


Figure 10: Residual compression strength - 0.7f_{cd} - cooling in the air and by water jet - calcareous (CC) and granite concrete (GC)

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 (Figure 9). At 700°C , 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 was 100%, for both cooling processes.

For the loading level of $0.7f_{cd}$, cooling in the air, temperatures under 300°C , the GC presented higher residual compression strength than the CC. However, for temperatures above 300°C , the opposite was observed. The GC at 500°C presented a null value while the CC still presents around 70% of its compression strength at ambient temperature (Figure 10).

In Figures 11 and 12, 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 (Figure 11). 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 500°C the process inverted being the cooling in air more prejudicial.

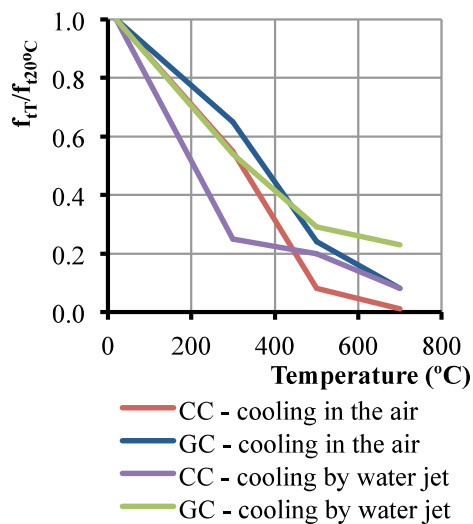


Figure 11: Residual direct tensile strength – cooling in the air and by water jet - calcareous (CC) and granite concrete (GC)

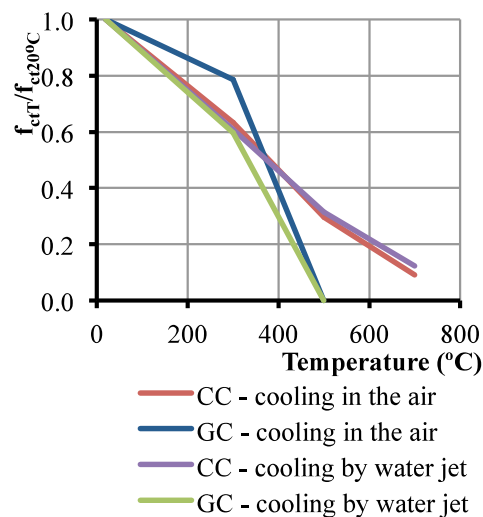


Figure 12: Residual tensile splitting strength – cooling in the air and by water jet - calcareous (CC) and granite concrete (GC)

In the residual tensile splitting tests (Figure 12) it was verified that up to around 300 °C, 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 11 with Figure 12 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 (Figure 13). The GC presented once more the worst results. The GC presented a resistance null at 500°C however the CC maintains some resistance by some more time showing a null value for temperatures of 700°C.

The residual modulus of elasticity decreased sharply with the temperature (Figure 14). In this mechanical property it is not notorious the influence of one cooling process in relation to the other. The GC presented a null value of modulus of elasticity for temperatures of 500°C, while for the calcareous aggregate concrete this value only occurred for temperatures of 700°C.

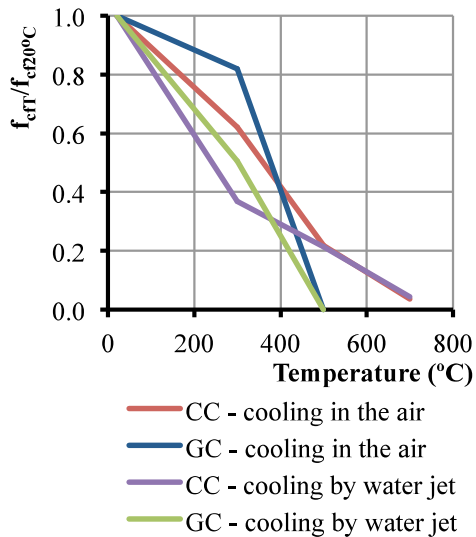


Figure 13: Residual flexural strength – cooling in the air and by water jet - calcareous (CC) and granite concrete (GC)

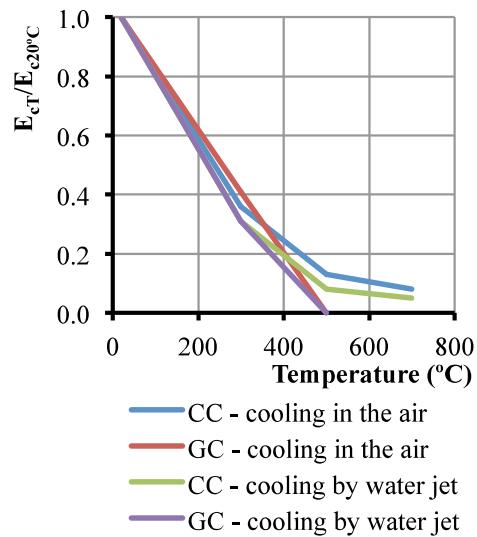


Figure 14: Residual modulus of elasticity – cooling in the air and by water jet - calcareous (CC) and granite concrete (GC)

4. CONCLUSIONS

The following conclusions may be drawn from the present research study:

- The cooling process influenced very much 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 400°C , the CC has a better performance behaviour 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 down 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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