INFLUENCE OF THE COOLING PROCESS ON THE RESIDUAL MECHANICAL PROPERTIES OF ORDINARY CONCRETES

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Abstract

The concrete structures have usually good behavior in fire. However, when the fire is severe and of long duration the concrete elements may lose partial or totally their load bearing capacity. This phenomenon can be aggravated by the extinction process of the fire used that causes quite always high thermal stresses and cracking in concrete.

With the aim to clarify the effect of the cooling process on the mechanical properties of the concrete a research program was carried out in the University of Coimbra. The concrete specimens were heated up to different temperature levels (300, 500 and 700ºC) and after a period of stabilization they were cooled down. Two processes of cooling were tested, cooling on the air (intending to simulate the natural extinction of the fire) and cooling by water jet (intending to simulate the action of the firemen in fire combat).

During the heating / cooling process the specimens were subjected to a constant compressive load ($0.3f_{cd}$ and $0.7f_{cd}$) in way to simulate the real situation of the concrete when in a structural member. The specimens after the heating / cooling process and at room temperature were then tested in compression, allowing determining the residual compression strength of the concrete.

Keywords: concrete; fire; cooling; air; water; compression; strength

1. INTRODUCTION

The concrete structures have in general good behavior in fire. However, these structures can be affected, in more or less extent, depending the damages in the severity of the fire. The decreasing of the loadbearing capacity of the structural elements depends mainly in the degradation of the mechanical properties of the materials resulting of the fire.

The concrete structures can present after fire such characteristics as the coloration, cracking and spalling, deformation of the elements, buckling of the reinforcement steel and the chemical attack of chlorides resulting of the combustion of plastics.

Another type of damages that happens in general is the cracking. The movements of expansion of the structural elements due to the high temperatures can cause cracks, more or less serious, in the structural elements that being in colder areas provides restraining to the thermal elongation of them. The cracking can also appear locally along the reinforcing bars, as a result of the different coefficient of thermal expansion of the concrete and the steel under the temperature. Another type of cracking results from the different coefficient of thermal expansion of the cement paste and the aggregates. The water used by the firemen in the combat of the fire can also cause serious cracks and spalling in the concrete.

The action of the high temperatures also provokes the decreasing in the compression resistance and elastic modulus of the concrete. These properties depend on parameters as the: type of cement, type of aggregates, the mixture proportions, the age of the concrete, the heating / cooling conditions and the moisture content [7]. From these parameters the type of aggregates, the heating / cooling conditions and the moisture content are the parameters that have more influence in the results.

The knowledge of the mechanical and thermal properties of the concrete at high temperatures is nowadays very complete. However, the same cannot be said for the residual properties after fire and their influence in the loadbearing capacity of the fire damaged elements. The process of extinction of the fire is an aspect that plays an important role on this behavior and must be understood.

In order to contribute for clarifying the influence of the cooling process on the residual mechanical strength of a current concrete after fire a research program was carried out in the Laboratory of Testing Materials and Structures of the University of Coimbra. These tests are part of a bigger experimental program for the determination of the residual resistant capacity of concrete elements after fire. Concrete columns and beams after they be submitted to a heating / cooling process will be tested to rupture and their residual resistance determined.

It is expected that after the compression tests on cylindrical specimens and loadbearing resistance tests on concrete elements, completed by a numerical study on the subject, simplified methods of calculation can be defined for the determination of the residual resistance capacity of concrete elements after fire.

2. EXPERIMENTAL PROGRAM

Several experimental tests were carried out to study the influence of the cooling process on the residual compressive strength of the concrete. Two cooling processes were tested, cooling in the air (that intended to simulate a fire extinct in a natural way) and cooling by water jet (that intended to simulate the action of the fire-fighters in the combat of the fire). The specimens were heated and cooled under loading and tested in compression at room temperature.

2.1. Concrete composition

After a market survey in order to know the most representative concretes used in civil construction works in Portugal, it was chosen the following concrete composition.

The concrete composition was composed by Portland cement (CEM) type II/A-L 42,5R (chemical composition: $SO_3 \leq 4\%$ and Cl ≤ 0.10%; compression strength: 2 days - 20MPa and 28 days - 42.5MPa), superplasticizer (SP) SIKA (Sikament® 195R) and four types of aggregates: fine sand (A1), coarse aggregate (A2), crushed stone 1 (B1) with the maximum size of 12.7 mm and crushed stone 2 (B2) with the maximum size of 19.1 mm.

Table 1. Concrete composition per m^3

CEM [Kg]	A1 [Kg]	A2 [Kg]	B1 [Kg]	B2 [Kg]	SP [%CEM]	W/C
300	364	495	505	377	1.33	0.56

In Table 2 is presented the compressive resistance class of the concrete according to NP EN 2006-1 [3].

Table 2. Compressive resistance class of the concrete

fc (MPa)	fc_m (MPa)	fc_k (MPa)	Resistance class	0.7 fc_d (kN)	0.3 fc_d (kN)
57.9 56.2 57.3	57.1	56.1	C45/55	93.4	40.0

2.2.Specimens

The evaluation of compressive strength of concrete was carried out in cylindrical specimens of 75mm in diameter and 225mm in height, with a ratio of height/diameter of 3.

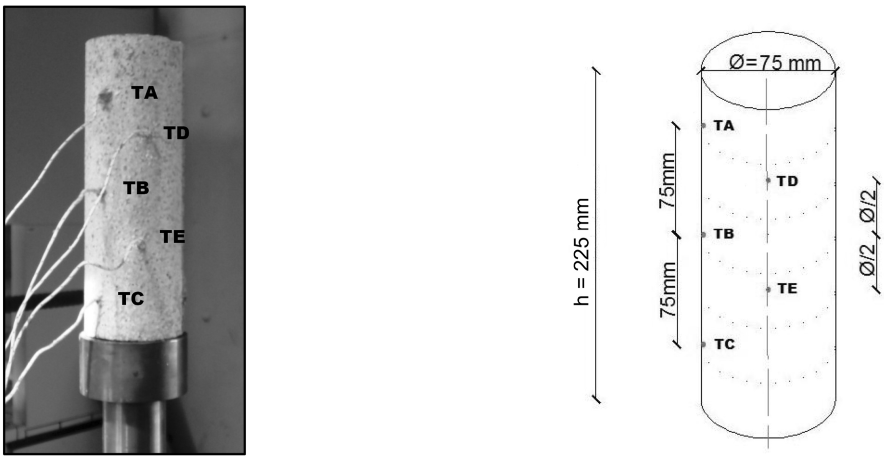

Figure 1. Specimens and location of thermocouples.

The specimens were provided with five thermocouples type K in order to register the evolution of temperature inside the concrete. The location of the thermocouples in the specimens was based on the recommendations of RILEM's TC – 200 HTC [5] (Figure 1).

2.3. Test procedure

Two different test systems were used to simulate the cooling processes usually used in reality. The cooling in the air (intending to simulate the natural extinction of the fire) and cooling by water jet (intending to simulate the action of the firemen in fire combat).

2.3.1. Cooling in the air

The test system was composed by an universal tensile / compression machine Servosis with load capacity up to 600kN, a cylindrical oven with a heating chamber of 90 mm in diameter and 300 mm in height, maximum temperature of 1200^{o}C and a data acquisition system TML. In tests were registered forces, displacements, specimens and oven temperatures (Figure 2).

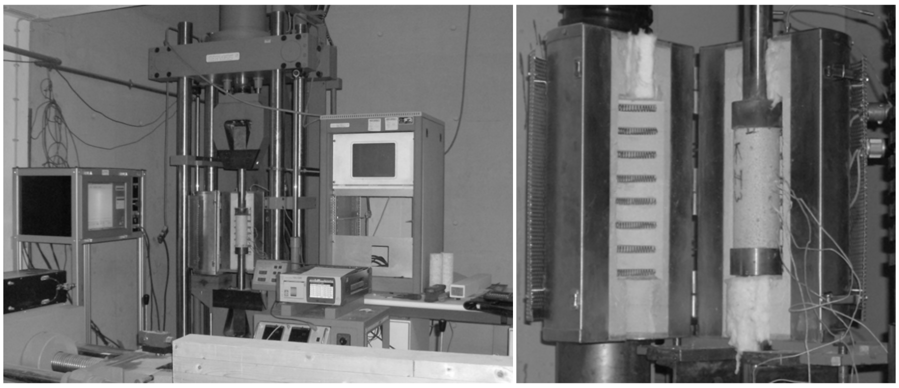

Figure 2. Test set-up - cooling in the air.

The test procedure was adopted according to the RILEM TC – 200 HTC recommendations [5]. The specimen was first loaded at a load level of $0.3f_{cd}$ or $0.7f_{cd,}$ being f_{cd} the design value of the compression strength of the concrete at room temperature. The load was kept constant during the heating / cooling process. When the load level was reached, the specimen was heated at a heating rate of 3ºC/min, until the desired level of temperature. Various levels of maximum temperature were used (300, 500 and 700°C). The level of temperature was reached when the average temperatures on the three specimen thermocouples of the surface match the temperature of the furnace. The maximum axial temperature differences between any of the three surface temperature readings could not exceed 1°C at 20°C, 5°C at 100°C and 20°C at 700°C. The specimen was then kept at that temperature for an hour to stabilize. After this the oven was opened and the specimen cooled in the air. When the temperature in the specimen match again the room temperature (approximately 20^{o}C) the compression test was carried out. The load was increased at a rate of 0.25 kN/s up to rupture of the specimen.

2.3.2. Cooling by water jet

The test system was similar to the previous one with some differences resulting to the type of cooling process in use (figure 3). After the specimen reached the necessary temperature level, the oven was open, pushed to the rear side, and the specimen was then cooled down by jets of water (figure 3). The specimen by this process cooled down very fast. The water flow was around 3.9 x 10^{-4} m^3/s and the pressure 3.5 x 10^5 Pa.

Figure 3. Test set-up - cooling by water jet.

2.4. Results

2.4.1. Evolution of temperatures in the specimens

Figure 4 shows the evolution of temperatures in the thermocouples of the specimen for the series of 500ºC, cooling in the air. The heating phase lasted around 2,8 hours and the cooling down phase around 4 hours.

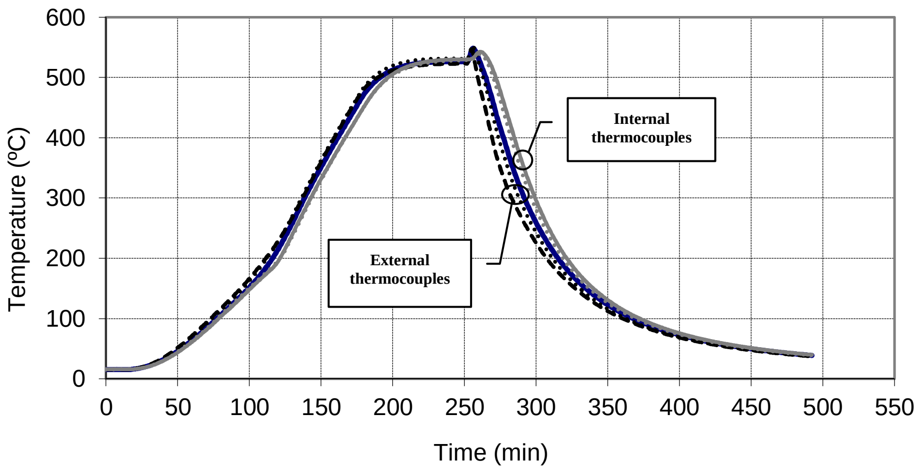

Figure 4. Evolution of temperatures on the specimen – series of 500ºC - cooling in the air.

In the heating phase, no big differences in the temperatures registered in the thermocouples, were observed. The temperatures became even closer in the stabilization period. In the cooling down phase the thermocouples of the surface of the specimen registered a higher decrease on the temperatures than the inner ones, as expected.

Figure 5 shows the evolution of temperatures in the thermocouples of the specimen for the series of 500ºC, cooling by water jet. The cooling down phase was shorter in this case and lasted around 10min (aprox. 50ºC/min).

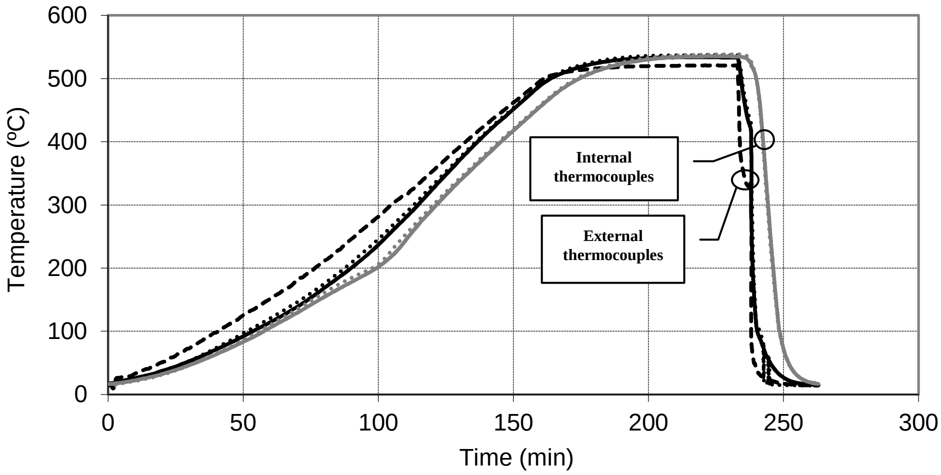

Figure 5. Evolution of temperatures on the specimen – series of 500ºC - cooling by water jet.

In the heating phase one of the surface thermocouples presented a faster increase of the temperature then the others, this could happen due to a wrong location of the thermocouple.

2.4.2. Residual compression strength

Figure 6 presents the variation of the residual compression strength of the concrete in function of the maximum temperature for the case of cooling in the air. In the figure it can be observed a decrease on the residual compression strength of the concrete in function of the maximum temperature. This decrease is similar for both load levels up to 300ºC, after which the specimens loaded with 0.3*fcd* showed a higher reduction in the residual compression strength. It can be concluded that the loading of 0.7*fcd* has a beneficial effect, reducing the loose of residual compressive strength in function of the maximum temperature experienced by the concrete.

At 300^{o}C there was a reduction of 15% in the residual compressive strength of the concrete for both load levels. At 500^{o}C the reduction was approximately 45% for the 0.3*fcd* and 30% for the 0.7*fcd* load level. For 600^{o}C all specimens collapsed during the period of stabilization of temperature and the residual compressive strength was considered null.

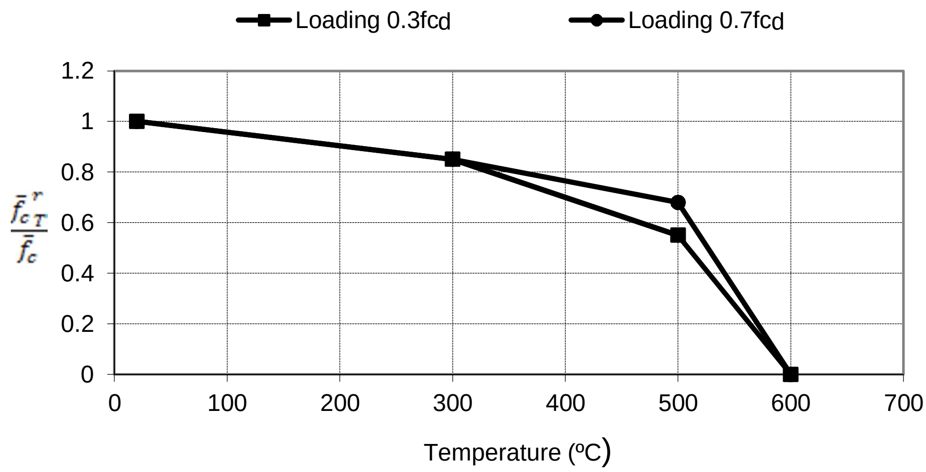

Figure 6. Residual compression strength of the concrete in function of the maximum temperature - cooling in the air.

Figure 7 presents the variation of the residual compression strength of the concrete in function of the maximum temperature for the case of cooling by water jet.

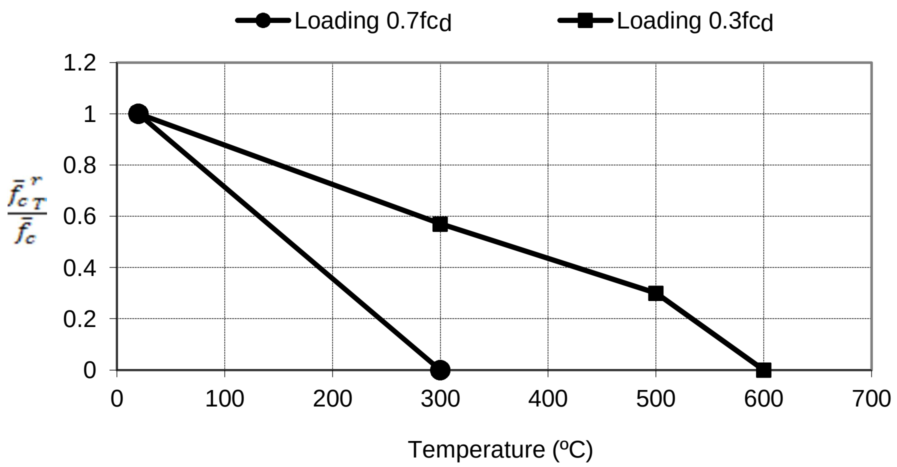

Figure 7. Residual compression strength of the concrete in function of the maximum temperature - cooling by water jet.

In figure 7 the reduction in the residual compressive strength in function of the temperature, are more pronounced than the case of cooling in the air. All the specimens subjected to the load level of 0.7*fcd* collapsed during the cooling phase. For the case of the load level of 0.3*fcd* the concrete presented a reduction of around 40% for 300ºC, 70% for 500ºC and a null value for 600ºC on the residual compression strength.

In the case of cooling by water jet it can be concluded the higher is the loading the higher is the decreasing on the residual compression strength.

In figure 8 is made a comparison of the influence cooling processes in the residual compression strength of the concrete for specimens loaded with $0.3f_{cd}$. In this graph it can be observed that the cooling by water jet is more prejudicial than the cooling in the air.

An interesting aspect is this concrete presents some compression strength for 500ºC, being the value null at 600ºC for both cooling processes.

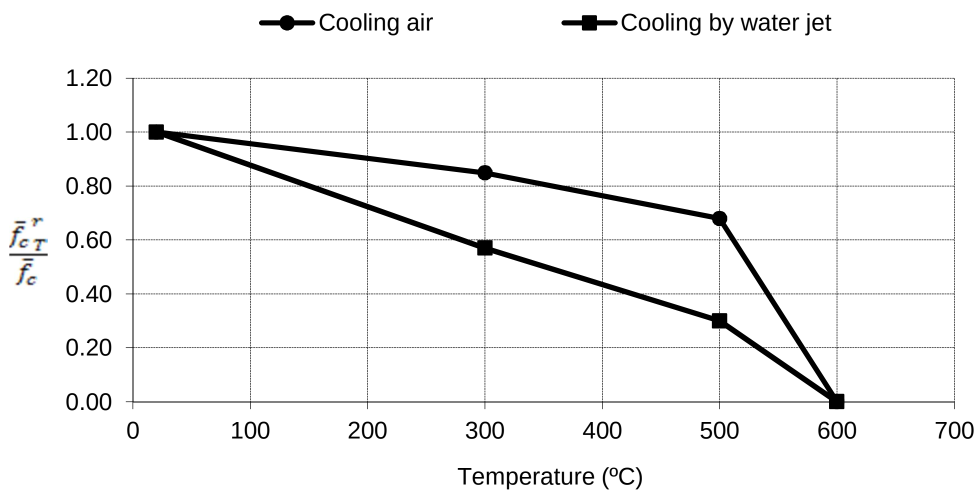

Figure 8. Residual compression strength of the concrete in function of the maximum temperature - load level of $0.3f_{cd}$ – comparison of cooling processes.

Figure 9 presents a comparison of the influence cooling processes in the residual compression strength of the concrete for the case of the load level of $0.7f_{cd}$.

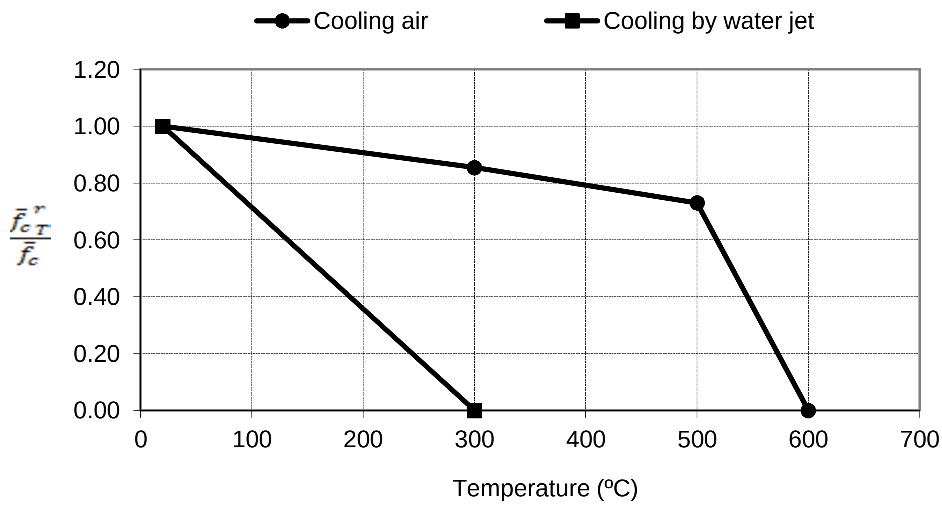

Figure 7. Residual compression strength of the concrete in function of the maximum temperature - load level of $0.7f_{cd}$ – comparison of cooling processes.

Considering the results achieved, the compressive residual strength of concrete is adversely affected by using the cooling by water jet. For the case of 0.7$f_{cd,}$ at 300ºC a difference of 85% in the residual compression strength is registered.

From these results it can be concluded the higher the load level the higher the influence of the cooling process.

3. CONCLUSIONS

These tests allowed concluding that the cooling process has a great influence in the reduction of the compression strength of the ordinary concretes. The faster is the cooling process the higher is the reduction in the compression of the concrete. The firemen in the fire extinction works, use great amount of water that affects largely the concrete resistance compromising the loadbearing capacity of the elements. The cracking of the concrete increases considerably due to the sudden cooling originated by the water. If the process of extinction of the fires was done in a natural way in the air, it would be better for future use of the concrete structure.

It can also be verified that the load level has a beneficial effect decreasing the reduction of the compression strength of the concrete in the case of cooling in the air and a prejudicial effect in the case of cooling by water. In the case of cooling in the air, the loading, when no excessive, reduces some cracking that happens in the concrete, mainly during the cooling phase. In the case of cooling by water jet as higher the load level, higher is the reduction of the compression strength of the concrete.

These tests will be followed in the very near future by a large series of compression tests for determining the compression strength of the ordinary concrete at intermediate levels of temperature during the cooling phase.

The performance of similar study on the residual mechanical properties of concretes reinforced with polypropylene fibers is also of extreme interest. This type of fibers, when subjected to high temperatures, volatilize and create pathways for the releasing of the water vapour generated into the concrete in case of fire. These pathways are good in the spalling control however can reduce the concrete strength after fire.

NOTATION

fc – Compressive strength of the concrete at room temperature for cubes.

fc_m – Mean value of the compressive strength of the concrete at room temperature for cubes.

fc_k – Characteristic value of the compressive strength of the concrete at room temperature for cubes.

fc_d – Design value of the compressive strength of the concrete at room temperature for cubes.

$\bar{f}_{cT}^{r}$ – Mean value of the residual compressive strength of the concrete for cylinders.

$\bar{f}_c$ – Mean value of the compressive strength of the concrete at room temperature for the cylinders.

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