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The effect of high temperatures on concrete compression strength, tensile strength and deformation modulus

Efeito de altas temperaturas na resistência à compressão, resistência à tração e módulo de deformação do concreto

A. A. A. DE SOUZA [a]
ambrosio@fec.unicamp.br

A. L. MORENO JR [b]
almoreno@fec.unicamp.br

Abstract

This paper has as a goal to present the results of experimental investigations on the behavior of concrete when submitted to high temperatures. A concrete of common utilization in our region, with cement and usual aggregates mixed in usual proportions (mix), was submitted to temperatures of 300ºC, 600ºC and 900ºC, in order to assess probable variations in its compression strength, tensile strength and deformation module. The effect of rapidly cooling concrete, usual in fire fighting, was assessed; a few test bodies submitted to high temperatures were rapidly cooled and others were slowly cooled (to room temperature). The probable recovery of the mechanical properties under investigation following concrete rehydration – after a possible reduction from the effects of the high temperatures applied – was also assessed; test bodies were submitted to high temperatures and cooled slowly; a few were immersed in water and others were wrapped up in plastic film and then evaluated in relation to the researched properties for concrete ages of 28, 56, 112 and 224 days after slow cooling. Upon finishing this work, important results on the effect of high temperatures on concrete mechanical properties were obtained, thus providing a major contribution for the recovery design of structures that had been subject to fire.

Keywords: concrete, fire, mechanical propeties.

Resumo

Este trabalho teve como objetivo a investigação experimental do comportamento do concreto quando submetido a elevadas temperaturas. Um concreto de utilização comum em nossa região, com cimento e agregados usuais, misturados em proporções também usuais (traço), foi submetido a temperaturas de 300 °C, 600°C e 900 °C , de maneira a se avaliar prováveis alterações na resistência à compressão, na resistência à tração e no módulo de deformação deste concreto. O efeito do resfriamento rápido do concreto, usual em intervenções de combate a incêndios, foi avaliado; alguns dos corpos-de-prova submetidos às altas temperaturas estipuladas foram resfriados rapidamente e outros foram resfriados lentamente (ao ambiente). A recuperação provável das propriedades mecânicas analisadas, com a reidratação do concreto – com possível redução após o efeito das altas temperaturas aplicadas - também foi avaliada; corpos-de-prova submetidos às altas temperaturas estipuladas e resfriados lentamente, foram parte imersos em água e parte envoltos em filme plástico e a seguir, cada parte correspondente foi avaliada, em relação às propriedades do concreto pesquisadas, para as idades do concreto de 28, 56, 112 e 224 dias após o resfriamento lento. Ao final deste trabalho, importantes resultados sobre o efeito de altas temperaturas nas propriedades mecânicas do concreto puderam ser obtidos; contribuindo, em muito, para o estabelecimento de parâmetros para o projeto de recuperação de estruturas submetidas ao efeito do fogo.

Palavras-chave: concreto, altas temperaturas, propriedades mecânicas, reidratação.

[a] *Doutoranda, Departamento de Estruturas, Faculdade de Engenharia Civil, Arquitetura e Urbanismo, UNICAMP, ambrosio@fec.unicamp.br , Rua Saturnino de Brito, 135, Cidade Universitária Zeferino Vaz, Barão Geraldo, Campinas, SP, Brasil, cep: 13083 - 852;*

[b] *Professor Doutor , Departamento de Estruturas, Faculdade de Engenharia Civil, Arquitetura e Urbanismo, UNICAMP, almoreno@fec.unicamp.br , Rua Saturnino de Brito, 135, Cidade Universitária Zeferino Vaz, Barão Geraldo, Campinas, SP, Brasil, cep: 13083 - 852;*

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1. Introduction

Damages caused by a fire on a concrete structure can be observed from simple discolored spots or tarnish produced by smoke to the structural element complete destruction as a result from the loss of its mechanical strength.
The effects of fire, as well as its intensity and extension, are directly connected to the capacity a building has to resist or not to the development of a fire. Unfortunately, there is no absolute safety against fires and, therefore, several preventive measures are used with the intent of reducing risks.
Currently, little is known about the behavior of reinforced concrete structures under fire. This lack of information is a result from existing difficulties for testing in actual life scale. Most known data are the result from tests in laboratories, performed on isolated elements of a building and from the experience arising from buildings that were involuntarily submitted to fires.
This work presents results from the experimental assessment of the effect of high temperatures on mechanical properties of concrete and has as a main goal to contribute to establish design parameters for the recovery of structures that were submitted to fire.

2. Effects of high temperatures on the concrete

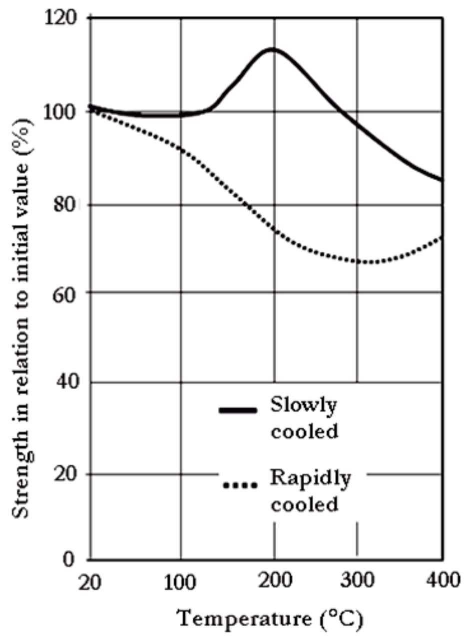
2.1 Mechanical properties of concrete

Compression strength, tensile strength and longitudinal deformation modulus are mechanical properties that have their values reduced when the concrete is submitted to high temperatures.
According to Paulon [1], when concrete is submitted to temperatures up to 150°C, its strength is not altered, but for higher temperatures tensile strength begins to decrease. This loss in strength can reach 70% for temperatures close to 600ºC due to gel dehydration and the increase of micro-cracking, Table [1].
Compression strength does not significantly change up to about 300°C. However, at this temperature and above, a significant reduction begins, with a loss around 20% according to Almeida [2]. Tests performed by Galleto & Meneguini [3], confirming Almeida

Tabela 1 – Effect of high temperature of the elastic modulus of concrete (Paulon (1))

Temperature (°C)	Residual elastic modulus (%)
25	100
100	75
200	68
300	48
400	35
500	33
600	9

Figura 1 – Effect of rapid cooling on the compression strength of concrete (Cànovas (7))



[2], have shown that conventional concrete heated to 300°C and slowly cooled had a 24% loss in compression strength in relation to its original, unheated strength.
The reduction in compression strength of concrete submitted to 600°C is approximately 50%, according to Petrucci [4]. Neville [5] justifies this reduction with the occurrence of a progressive degradation of concrete submitted to this temperature. Cracking intensifies in joints, in imperfectly compacted areas or, in the case of reinforced concrete, on the planes of steel rods, which, after being exposed begin to conduct heat and accelerate the harmful effect of the high temperature on the concrete.
Working with cylindrical test bodies, 10 cm diameter x 20 cm height, heated to 300°C, cooled both slowly and rapidly, Galleto & Meneguini [3] obtained reductions, respectively, of 4% and 21% only on the longitudinal deformation modulus in relation to test bodies that had not been submitted to high temperatures. These results significantly differ from results shown in Table [1].
There is a great difference between the results obtained by the various researchers on this matter. Malhotra [6] justifies this difference as a result from factors such as: differences in acting stresses and humidity conditions of concrete while in the heating process, differences in the exposure time to high temperatures, differences in physical and mechanical properties of aggregates, to mention a few.
A factor that has a major influence on the effect of high temperature on concrete mechanical properties is the cooling speed. The utilization of water in a fire, for instance, is similar to quenching, causing a great strength reduction as a result from intense temperature gradients created in the concrete, Figure [1].
It is important to note that part of the decrease in mechanical properties as a result from heating can be recovered with concrete re-

hydration. According to Canovas [7], if the concrete temperature is not higher than 500°C, it can be subject to rehydration later, which can help in recovering up to 90% of its initial strength after one year.
Therefore, one can not generalize results obtained by the various researchers. One should take into account all factors pointed out by each of them in order to have a correct interpretation of the various results.

3. Experimental assessment of concrete when submitted to high temperatures

3.1 Featuring tests of materials

Concrete test bodies, 10 cm in diameter and 20 cm high, were prepared with usual cement and aggregates, also mixed in usual proportions.
The mix used assured a decrease of 15 cm, obtained in compliance with standard NBR NM 67 - Determination of consistency by the reduction of truncated cone (slump test) [8]. The proportion of materials in weight, was 1:3:3 (cement, sand, stone 1) and the water/cement ratio was 0,6.
The cement used was CPII-32 and the sand used in concrete was a medium sand, shown in Table [2], as per specifications in standard NBR 7211/05 [9].
Concrete was prepared according to specifications in NBR 12821 – Preparation of concrete in the laboratory [10] and test bodies were molded according to NBR 5738 – Molding and curing cylindrical or prismatic concrete test bodies [11].

3.2 Main tests - Proceeding

For each temperature under analysis, 300°C, 600°C and 900°C, 66 concrete test bodies were molded and prepared. Specimens were tested in order to assess the effect of temperature on compression strength, tensile strength and longitudinal deformation modulus.
Three months after the preparation, and after the gain in compression strength was stabilized, 6 test bodies were tested in order to assess the previously mentioned mechanical properties. Of the 6 test bodies, 3 were submitted to a compression test and

Tabela 2 – Results of fine aggregate featuring test

Wire screens mesh (mm)	Retained material (g)	Retained percentages (in weight)	
		Individual	Accumulated
76	0	0	0
64	0	0	0
50	0	0	0
38	0	0	0
25	0	0	0
19	0	0	0
12.5	0	0	0
9.5	0	0	0
6.3	55.1	4.44	4.44
4.8	22.2	1.79	6.23
2.4	135.4	10.92	17.15
1.2	259.7	20.95	38.10
0.6	285	22.98	61.08
0.3	221.3	17.85	78.93
0.15	220.8	17.81	96.74
Fundo	40.4	3.26	-
Total	**1239.9**	**100**	**302.67**

Maximum Diameter = 6.3 mm   Finess Modulus = 2.98

Tabela 3 – Results of coarse aggregate featuring test

Wire screens mesh (mm)	Retained material (g)	Retained percentages (in weight)	
		Individual	Accumulated
76	0	0	0
64	0	0	0
50	0	0	0
38	0	0	0
25	0	0	0
19	0	0	0
12.5	3086.0	60.5	60.5
9.5	1074.0	21.05	81.55
6.3	618.9	12.14	93.69
4.8	139.5	2.73	96.42
2.4	182.6	3.58	-
Total	**5101**	**100**	**332.16**

Maximum Diameter = 19 mm   Finess Modulus = 1.80

the other 3 to a tension test. In 2 test bodies submitted to the compression test, the concrete longitudinal deformation modulus was also determined.
Each group of 6 test bodies was submitted to the above mentioned temperatures, 300ºC, 600ºC and 900ºC. Heating was gradual, at a rate of 15°C/min, starting from a temperature of 25ºC (fixed as room temperature) for all test bodies.
Upon reaching the final temperature, the test bodies remained at that temperature for approximately 2 hours. In the end of this period, 6 of them were rapidly cooled, by immerging them in running water.
After this rapid cooling, bodies were tested to compression and tension, so that results obtained could be compared with those for unheated concrete.
The 54 remaining test bodies were slowly cooled. After the stipulated temperature was reached, test bodies remained inside an oven and the temperature was gradually reduced, at a rate of 1ºC/min, until reaching room temperature. After slow cooling, 6 test bodies were withdrawn from the oven and tested, and results were compared to those obtained for unheated test bodies and for those submitted to rapid cooling.
Of the remaining 48 test bodies, 24 were immersed in water and 24 were wrapped up in plastic film.
Of each group of these 24 test bodies, 6 were assessed in relation to the mechanical properties of interest on the 7th day, 6 more on the 26th day, 6 more on the 56th day and 6 test bodies more on the 112th day.
The comparison of results between the 2 groups (Group 1: Test bodies immersed in water and Group 2: Test bodies wrapped up in plastic film) provided an assessment of rehydrating concrete after it is submitted to high temperatures.

4. Experimental results

Tables that follow show results obtained for compression strength, tensile strength and longitudinal deformation modulus for concrete that was heated, heated and rapidly cooled, heated and slowly cooled, slowly cooled and wrapped up in plastic film, and slowly cooled and immersed in water.
Table 4.1 shows results that will be taken as the “comparison standard” (100%) for the evaluation of the decrease in mechanical strength of concrete when submitted to the stipulated temperatures. All results shown in Tables [4], [5], [6], [7], [8], [9], [10] and [11] are referenced to the standard values.
Due to micro-cracking resulting from rapid cooling, all test bodies

Tabela 4 – Propriedades Mecânicas do Concreto sem Aquecimento

Resistência à compressão (MPa)	Resistência à tração (MPa)	Módulo de Elasticidade (GPa)
30.45	2.73	2.75

submitted to 900° broke; therefore, it was not possible to perform tests to determine compression strength, tensile strength and deformation modulus in this condition.
Values shown in the following tables, related to the 300°C and 600°C, were obtained from a research work of Doro [12].

5. Assessment of results

The experimental results for the reduction of compressive strength and elastic modulus were compared to the reduction curve of these properties shown in the NBR 15200 (ABNT, 2004) in Figure

Tabela 5 – Mechanical properties of heated and slowly cooled concrete

Compression Strength (MPa)		Tensile Strength (MPa)		Deformation Modulus (MPa)	
Standard	100%	Standard	100%	Standard	100%
300°C	88%	300°C	79%	300°C	50%
600°C	86%	600°C	60%	600°C	30%
900°C	8%	900°C	2%	900°C	3%

Tabela 6 – Mechanical properties of heated and rapidly cooled concrete

Compression Strength (MPa)		Tensile Strength (MPa)		Deformation Modulus (MPa)	
Standard	100%	Standard	100%	Standard	100%
300°C	81%	300°C	63%	300°C	41%
600°C	73%	600°C	61%	600°C	19%
900°C	0%	900°C	0%	900°C	0%

Tabela 7 – Strength of heated, slowly cooled and wrapped up in plastic film concrete

Compression Strength (MPa)	7 days	28 days	56 days	112 days
300°C	82%	82%	77%	81%
600°C	51%	60%	63%	51%
900°C	9%	10%	10%	11%

Tabela 8 – Compression strength of heated, slowly cooled and immersed in water concrete

Compression Strength (MPa)	7 days	28 days	56 days	112 days
300°C	74%	84%	94%	93%
600°C	55%	72%	85%	85%
900°C	38%	40%	38%	46%

Tabela 9 – Tensile strength of heated, slowly cooled and wrapped in plastic film concrete

Compression Strength (MPa)	7 days	28 days	56 days	112 days
300°C	71%	67%	69%	69%
600°C	51%	57%	64%	61%
900°C	6%	8%	8%	9%

Tabela 10 – Tensile strength of heated, slowly cooled and immersed in water concrete

Compression Strength (MPa)	7 days	28 days	56 days	112 days
300°C	74%	81%	98%	98%
600°C	51%	75%	92%	94%
900°C	31%	37%	46%	50%

Tabela 11 – Deformation modulus of heated, slowly cooled and wrapped up in plastic film concrete

Compression Strength (MPa)	7 days	28 days	56 days	112 days
300°C	54%	50%	45%	53%
600°C	28%	20%	14%	13%
900°C	3%	3%	3%	3%

Tabela 12 – Deformation modulus of heated, slowly cooled and immersed in water concrete

Compression Strength (MPa)	7 days	28 days	56 days	112 days
300°C	60%	69%	88%	90%
600°C	65%	56%	81%	82%
900°C	3%	4%	7%	7%

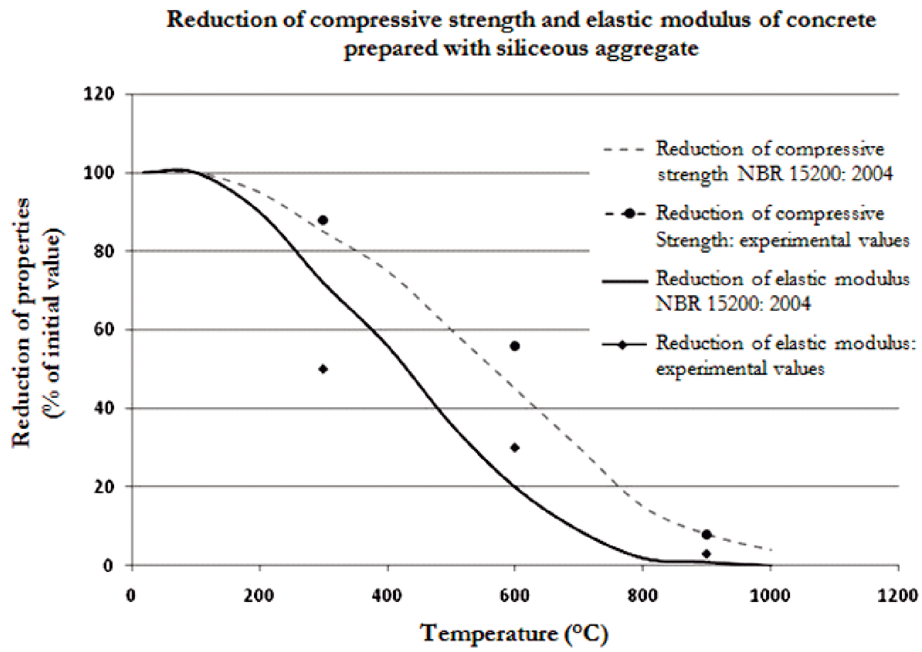
[2]. Experimental values for the compressive strength are close to the NBR curve ones. There was a significant difference only for the maximum heating temperature exceeding 600°C, but it presented smaller reduction than the Standardized one.

Relating to the elastic modulus, the differences between experimental values and the Standardized ones were observed for the maximum temperatures of 300°C and 600°C,with larger reduction and smaller reduction respectively.

Results shown in the above Figures [3], [4] and [5] evidence a significant decrease in compression strength that starts at 600°C, which practically becomes zero at temperatures close to 900°C. This result, in a greater or smaller reduction degree, was already expected, from data comprised in previous studies on the subject. At the temperature of 600ºC, concrete loses not only free water but also the water contained in the gel, thus causing a high level of surface cracking. Aggregates expand, then resulting internal stresses that reduce compression strength.

It is also observed that test bodies that were immersed in water recover part of their initial compression strength with time, with rehydration. Such rehydration increases as the temperature the con-

Figura 2 – Experimental values of compressive strength and elastic modulus reduction of concrete prepared with siliceous aggregate and from NBR 15200: 2004



crete was submitted to decreases. This recovery reached values between 40% and 90% for concretes rehydrated during 112 days, with the lowest values relating to a higher heating temperature.

In relation to tensile strength, a greater loss can be observed when comparing to compression strength, when the decrease in strength was more pronounced. This fact was also expected, having as a basis micro-cracking of concrete, which causes a more significant loss in tensile strength.

However, it is worth noting that the recovery in tensile strength with rehydration was greater than that observed for compression strength. In this case, the recovery reached values between 50% and 95%, and similarly to the case of compression strength, lower values related to higher temperatures.

In relation to the deformation modulus, it is worth noting that for temperatures around 600ºC, the deformation modulus was reduced of 20% of its original value, reaching zero for temperatures around 900ºC. Once rehydrated, concrete recovered almost 80% of the initial deformation modulus for temperatures below 600ºC.

Figura 3 – Recovery of the compression strength of heated concrete after rehydration

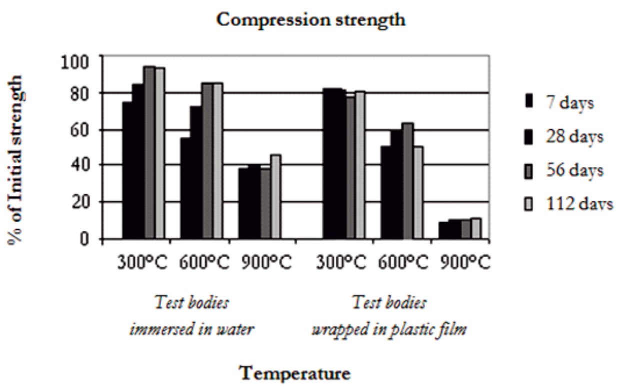


Figura 4 – Recovery of the tensile strength of heated concrete after rehydration

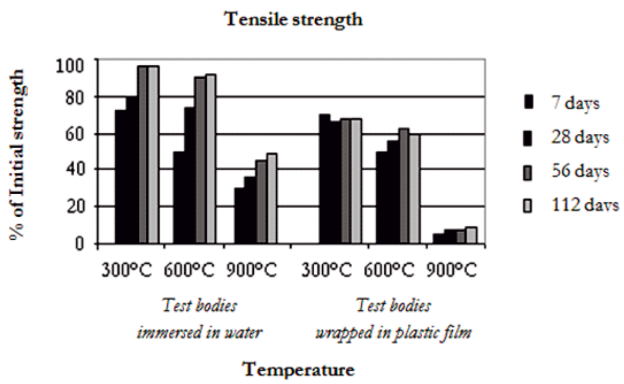
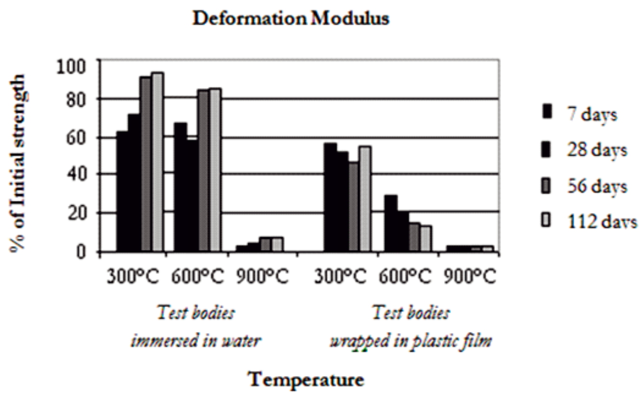


Figura 5 – Recovery of the elastic modulus of heated concrete after rehydration



6. Conclusions

This study can contribute for better understanding the effect of high temperatures on concrete mechanical properties and, eventually, contribute for establishing parameters for designing the recovery of structures that were submitted to fire.

It was observed that concrete, when submitted to temperatures close to 900ºC, its mechanical properties, either to tension or compression, can reach values close to zero.

In relation to the reduction of the longitudinal deformation modulus with heating, which significantly interferes with the vertical displacement of a structural element, we could observe values close to zero for temperatures lower than 900ºC.

It was also observed that rehydration after heating can contribute for recovering a significant portion of a concrete initial mechanical strength, either to compression, tension of deformation modulus.

Similarly, it was also observed that such recovery is inversely proportional to the temperature the concrete was submitted to, that is, the greater the temperature, the smaller the recovery rate (or rehydration) of concrete.

Results that must be evidenced are those related to the rehydration of concrete. Even when test bodies were submitted to 900ºC, the material was rehydrated, with a recovery of up to 60% of their initial mechanical strength.

Another interesting result was the recovery speed of mechanical properties with rehydration. It was observed that, when concrete was heated and then rehydrated, the recovery in compression strength was relatively fast, reaching levels close to the maximum observed recovery rate already on the 56th day after beginning rehydration.

All results obtained are coherent, if compared to previous studies. However, it should be noted that there are many variables involved in the problem and any change in these variables can result in significant differences between results attained by other researchers. Among these variables, one can point out concrete humidity, water/cement ratio, aggregate type, cement type, size of the test body, exposure time to temperature, rate of temperature increase and cooling rate.

It is also important to point out that results obtained in this work, added to those obtained in previous researches on this subject, can help in forecasting the degree of decay a structure or structural element can reach after a fire. This aspect is of utmost importance in designing for the recovery or reinforcements of such structure or structural element.

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