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Effect of Moisture Content on the Behavior of High Strength Concrete at High Temperatures

Efeito do Teor de Umidade no Comportamento do Concreto de Alta Resistência em Altas Temperaturas

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ABSTRACT

In this paper, an experimental program was carried out to investigate the residual mechanical properties of high strength concrete and normal strength concrete, and how moisture content and temperature affect the spalling process. Three mixtures with water-cementitious material ratios, from 0.25 to 0.50, and with different saturation levels were heated in an electric furnace to elevated temperatures, from 200°C to 600°C. After heating, the specimens were cooled down to room temperature and then tested for compression and tensile strength. The results showed that high moisture content induces the spalling process and reduces considerably the mechanical properties of high strength concrete, mainly at temperatures above 400°C.

Keywords: high temperature, fire, concrete, moisture, spalling.

RESUMO

Neste trabalho, foi realizado um programa experimental para investigar as propriedades mecânicas residuais dos concretos de alta resistência e de resistência normal, além de como o teor de umidade e a temperatura afetam o desplacamento explosivo. Três misturas com relação água-materiais cimentícios, de 0,25 à 0,50, e com diferentes níveis de saturação foram aquecidas em forno elétrico à temperaturas elevadas, de 200°C à 600°C. Após o aquecimento, as amostras foram resfriadas à temperatura ambiente e depois ensaiadas quanto à resistência à compressão e à tração. Os resultados mostraram que altos teores de umidade induzem o desplacamento explosivo e reduzem consideravelmente as propriedades mecânicas do concreto de alta resistência, principalmente em temperaturas acima de 400°C.

Palavras-chave: altas temperaturas, fogo, concreto, umidade, desplacamento explosive.

1. INTRODUCTION

In recent years, the construction industry has shown significant interest in the use of High Strength Concrete (HSC), whereas it offers significant economic and architectural advantages over the Normal Strength Concrete (NSC), among being suited for special construction requiring high durability [1]. These advances result from improvements in the material internal microstructure given by several factors, such as: modifications in the mixture composition, water-reduction admixtures, the use of superplasticizers, optimization of grain size distribution, the use of particles with pozzolanic activity, fibers addition, etc. [2-3]. However, in cases where HSC is exposed to fire attack, the refinement of the pore structure seems to contribute negatively to its fire resistance, rendering the material more susceptible to explosive spalling.

Explosive spalling is considered a concrete catastrophic failure, that generally occurs during the early

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stages of fire, when concrete reaches temperatures up to 300ºC [4]. The material explosively brakes into pieces, often without advance notice [5]. This phenomenon is strongly related to the initial pore saturation and moisture migration in concrete. When the temperature increases, the free water in the pores will expand, while increasing the saturated vapor pressure. The continuous expansion of water, together with the moisture migration, frequently leads to a physical saturation of the pores. Further heating will then generate additional strains in the pores and can lead to cracking and hydraulic fracture of the solid skeleton [6]. A review of the literature indicates that explosive spalling is a result of a combination of two effects: the build-up of pore pressure by vaporization and moisture transport and thermal stresses and external loads in concrete [3, 7-10].

It is a consensus that there is a number of factors that influences the explosive concrete spalling such as moisture content, porosity, strength, type of aggregate, heating rate, applied loads, constraints and others. The interaction among these different factors and how they influence each other are not completely understood and can cause differences on the results [7]. According with [11], these differences can be attributed to the non-homegeneity of concrete which gives each concrete specimen a unique material structure with unique voids and moisture distribution.

HSC particularly is more susceptible to this phenomenon because of the low porosity/permeability and high percentage of initial pore saturation/moisture content [5-7, 12-15].

Data from specific studies show this dependency. Fire tests conducted in concrete slabs with various moisture contents and different classes of concrete showed that moisture content has a dominant influence on spalling frequency for concrete strengths greater than 60 MPa [16]. A similar research was conducted by [17] in a series of fire damage degree tests in concrete slabs with 90% of moisture content. The results showed the cover loss of concrete due to spalling and consequently the exposition of aggregates to fire. [18] reported that a lower w/b at the beginning of mixing and/or a higher moisture content at the time when concrete is exposed to high temperature is prone to induce spalling of concrete as a result of the increased pore vapor pressure.

It can be found an estimation of a level of moisture content under which spalling is unlikely to occur in [19]. The recommended value is 3% by weight. However, according with [20], a potencial problem with the fixed 3% moisture limit is that other factors are excluded, such as the type of aggregate, porosity, permeability and amount of cement in the mix rate. These factors can reduce the precision in the setting of this type of limit. In fact, [21] reported that HSC mixes without fibers, with moisture content by weight from 3,8% to 5,2%, did not show spalling during ISO 834 fire. However siliceous-calcareous concretes exhibited crater formed spalling on cylinder surface and all concretes cylinders with 60 kg/m^3 of silica fume (SF) showed severe explosive spalling with a max surface loss of 27% in the same moisture content conditions.

The addition of polypropylene (PP) fibers into HSC is a remarkable measure for preventing spalling [22-24]. [19] recommends to include more than 2 kg/m^3 of polypropylene fibers to prevent spalling in HSC, however the size of the fibers is not specified on the document. According with [25-27], PP fibers increase the permeability of concrete in consequence of melting at 170 ºC, contributing to the creation of a network more permeable than the matrix, allowing the outward migration of gas and resulting in the reduction of pore pressure. Also [18] explains that due to the melting and ignition of polypropylene, which is randomly distributed in concrete at a relatively low temperature, the left pores radiate out to form microcracks, connecting the existing capillary pores to provide channels for the scaping of water vapor.

High temperatures also affect the mechanical properties of HSC due to irreversible physical and chemical changes that happen in the material during the heating process [28,29]. Also, it was observed that the degree of deterioration in the properties was considerably worse if moisture was retained in the concrete during heating. Hence, the influence of heat exposure on the properties is critically dependent on the moisture content of concrete. However, there is a lack of information in the literature about the effect of moisture content on the properties of concrete at high temperatures. Data from [30] showed that the compressive strength is reduced substantially if moisture is kept inside the test sample. According with [31], there is a relationship between compressive strength and initial pore saturation after heating. A slight reduction in compressive strength was observed as the initial pore saturation increases, i.e., concrete specimens with higher moisture leads to a slightly lower strength. The authors attributed the strength loss to internal pressure effects in the pores. A similar analysis was performed by [32]. The results showed that the strength loss was higher in saturated samples (40%) than dried samples (15%) in the 150°C e 250°C range. [33] investigated the influence of temperature, water content, specimen size, strength grade and temperature profiles on the mechanical properties of normal-strength concrete (NSC) and high-strength concrete (HSC) after high temperature. The compressive strength of concrete after it was heated to 800°C was tested in three levels of water content: specimens heated to constant weight until 105°C before fire, ordinary specimens and specimens immerged into water for 48h before fire. The results showed that different water content brings about different concrete compressive strength after high temperature. A slight reduction in compressive strength, independent of the grade of concrete, occurred in the specimens immerged into water for 48h before fire. However, the authors concluded that the effect of water content on the compressive strength after 800°C was not remarkable.

In this paper, cylindrical specimens of three strength grades were submitted to high temperatures to investigate the effects of initial saturation and temperature on the residual mechanical properties of high strength concrete (HSC) and normal strength concrete (NSC), as well as to establish a relationship between compressive strength, saturation level and temperature associated with spalling occurrence.

2. MATERIALS AND METHODS

2.1 Materials

Portland cement used was equivalent to ASTM type V. Commercial silica fume was used as cementitious material. Crushed siliceous and natural river sand were used as coarse and fine aggregates, with nominal sizes of 19.0 mm and 4.8 mm, respectively. For HSC specimens, a superplasticizer was used to achieve the required workability of concrete.

2.2 Mix Proportions

The study has been performed on 3 mixtures: two of High Strength Concrete (HSC) and one of Normal Strength Concrete (NSC). The mix proportions and the related 28-day concrete compressive strength are summarized in Table 1.

Table 1: Mix design for the normal-strength and high-performance concrete (kg/m^3).

Concrete mix	Batch quantities (kg/m^3)		
	NSC	HSC-1	HSC-2
Ordinary Portland cement	367	493	520
Silica fume	-	49	52
Coarse aggregate (19.0 mm)	1083	1118	1136
Sand (4.8 mm)	716	634	628
Water	183.5	150	140
Superplasticizer	-	2.46	4.27
$f_{c28days}$ (MPa)	43.2	77.8	85.8

2.3 Curing and Sample Preparation

The specimens were demolded 24 hours after casting and placed in a water tank at room temperature at least for 28 days. At this age, 3 samples of each concrete mix batch were removed from the tank and their saturated weights were determined. Afterwards, the samples were placed in a furnace and dried at 105°C until a constant dry weight was reached. Dry and saturated weights were used as reference data for the determination of the saturation levels in the concrete specimens. Three different saturation percentages were selected for this study: 75%, 90% and 100%. During the drying process of the specimens reaching the saturation degree of 75% and 90%, the 100% saturated samples were maintained in the water tank, so that all the samples were tested with the same age (90 days). When the specimens reached the targeted saturation levels, they were sealed in metallic packages and placed in a climatic chamber to retain the saturation level until the heating test was carried out.

2.4 Heating Regime

A total number of 56 groups of three cylindrical specimens were heated in an electric furnace up to 200°C, 400°C and 600°C (target temperatures). The furnace temperature was set by a digital temperature controller connected to the furnace power supply, with temperature feedback from a thermocouple located in the furnace. The specimens were heated without pre-load until reaching the target temperature and maintained until a thermal steady state was achieved (2 hours). After exposure, the furnace was switched off and the specimens were allowed to cool down for 24 hours inside the furnace. Then, the specimens were removed from the furnace and allowed to cool naturally to room temperature. The results were compared with reference values at room temperature (unheated concrete specimens).

3. RESULTS AND DISCUSSION

3.1 Residual Compressive Strength

The effects of moisture content on the compressive strength of high strength concretes at elevated temperatures are shown in Figure 1. At 200°C, a small improvement occurred in the residual strength, which varies from 3 to 12%. This is consistent with what has been observed by others investigations [34-36]. In [34], the recovery of strength in unstressed specimens occurred between 200 and 300ºC and it was attributed to the general stiffening of the cement gel or to the increase in surface forces between gel particles due to the removal of adsorbed moisture. In [37], it was suggested that the strength increase could be a slow process of hydration stimulated by the temperature. Finally, [38] emphasized that the increase of strength can be happening because the concrete was exposed to high temperatures at an early age. On the other hand, within the 200-400°C range, the strength loss was markedly different between the HSC grades. While HSC-1 samples lost strength above 400°C, HSC-2 samples still experienced a strength increase for the saturation levels of 75% and 90%. In the literature, this behavior has only been observed in stressed tests [13-15, 34] and may be related to the higher intrinsic strength of HSC-2 or to the fact that the confined water retards the material thermal degradation. At 600°C, HSC specimens showed a reduction in compressive strength. [39] reported that the strength loss at the this temperature is attributed to decomposition of calcium hydroxide between 450 and 500°C. Besides, saturated samples showed the lower residual strength due to the occurrence of spalling in 50% of the HSC saturated samples, affecting considerably their compressive strength. Finally, it can be noted a relationship between compressive strength, saturation level and spalling frequency at 600°C. The probability of spalling on HSC increases as the saturation level and compressive strength of the material also increases.

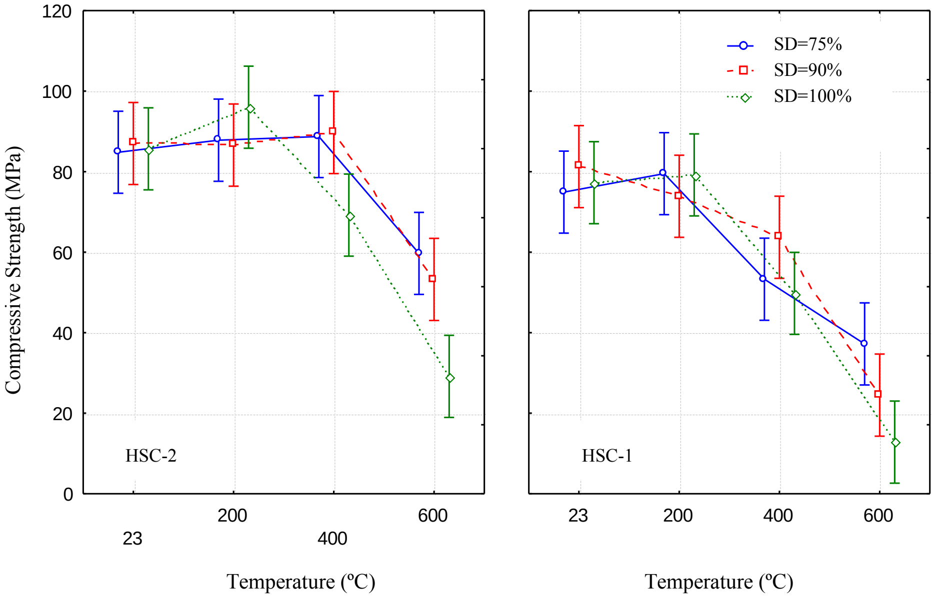

Figure 1: Influence of Saturation Degree (SD) on compression strength of HSC at elevated temperatures.

Since spalling of NSC samples under heating was not noticed (even for saturated specimens), the strength results are only compared with HSC saturated specimens, as shown in Figure 2. By comparison, it has been found that the compressive strength in NSC diminishes gradually with the increase of temperature, while in HSC samples the strength loss is more pronounced only within the 400-600°C range. The reduction factors for compressive strength of NSC and HSC are given in Table 2.

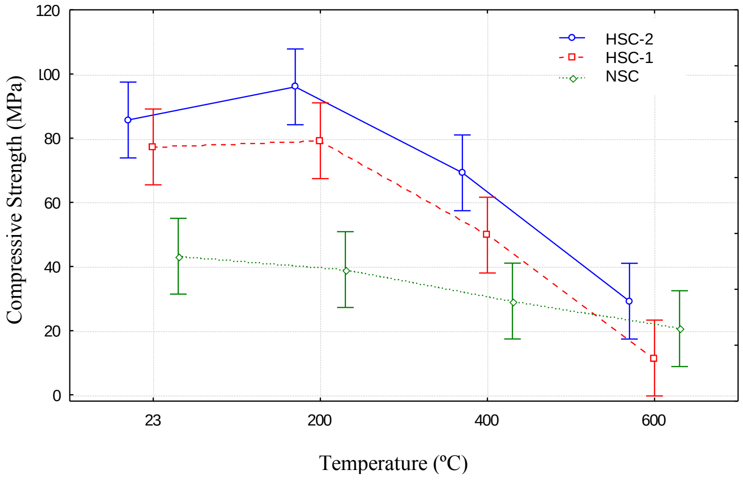

Figure 2: Influence of temperature on compressive strength of NSC and HSC specimens at the saturation condition.

Table 2: Reduction factors for compressive strength of NSC and HSC saturated samples.

Temperature (°C)	$k_{c,\theta} = f_{c,\theta}/f_{c,23°C}$		
	NSC	HSC-1	HSC-2
23	1,00	1,00	1,00
200	0,90	1,03	1,12
400	0,68	0,64	0,81
600	0,48	0,17	0,34

3.2 Residual Tensile Strength

The experimental results concerning the effects of moisture content and temperature on HSC tensile strength are shown in Figure 3. Both HSC grades have similar behavior for all the saturation levels. At first, at 200°C, it seems that the saturated samples have retained more strength than the unsaturated specimens. This may be due to the evaporation of free water, which retards the thermal deterioration of the material. However, within the 200-400°C range, the strength reduction of saturated samples is higher than unsaturated specimens. This might happen because of the lower strength loss of saturated samples between 23°C and 200°C. At last, at 600°C, the water content presents a significant role in concrete tensile strength, where saturated samples showed the lower residual strength due to 50% of the samples suffered spalling, affecting drastically the tensile behavior of HSC. [40] reported that at this level of temperature the severe strength loss is attributed not only to the decomposition of the hydration products but also the thermal incompatibility between aggregates and cement paste. For HSC, [33] observed that the dense structure induces thermal stress that results in many microcracks and even a few macrocracks. Besides, the decomposition of $Ca(OH)_2$ and other components also induce the appearance of cracks.

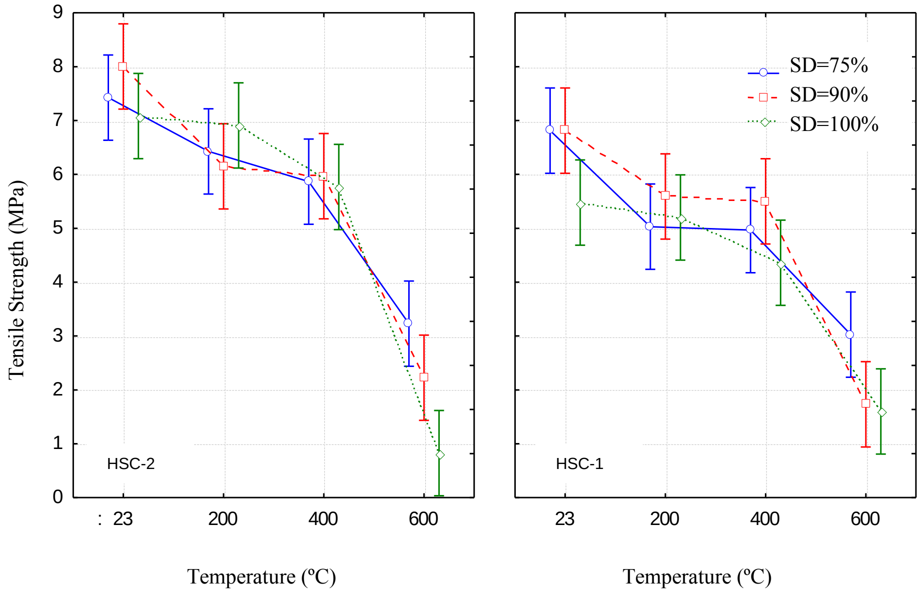

Figure 3: Influence of Saturation Degree (SD) on tensile strength of HSC at elevated temperatures.

By comparison, Figure 4 shows the tensile behavior of HSC and NSC at high temperatures for saturated specimens. Again, NSC and HSC behave differently at high temperatures. The tensile strength in NSC diminishes linearly with the increase of temperature. However, HSC maintains a higher percentage value of residual strength up to 400°C, followed by a sharp reduction at 600°C. The reduction factors for tensile strength of NSC and HSC are given in Table 3.

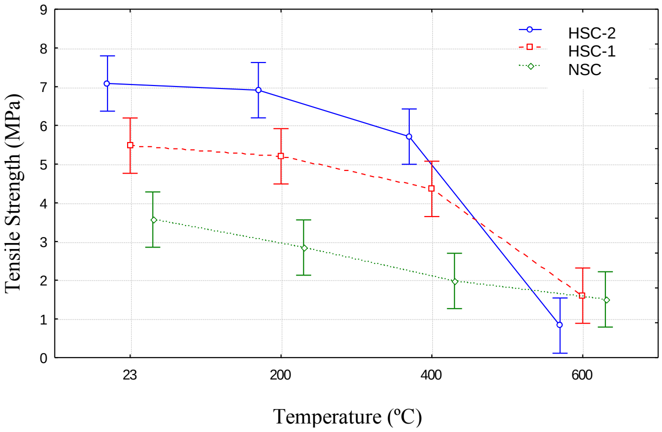

Figure 4: Influence of temperature on tensile strength of NSC and HSC specimens at the saturation condition.

Table 3: Reduction factors for tensile strength of NSC and HSC saturated samples.

Temperature (°C)	$k_{t,\theta} = f_{t,\theta}/f_{t,23°C}$		
	NSC	HSC-1	HSC-2
23	1,00	1,00	1,00
200	0,80	0,95	0,98
400	0,55	0,79	0,81
600	0,42	0,29	0,12

Table 4 shows that the influence of temperature on tensile strength is more pronounced than the compressive strength. The results were obtained considering the average of all the saturation degrees (75%, 90% and 100%). According with [41], this behavior might be related to the occurrence of many micro- or macrocracks in the specimens, due to thermal incompatibility within the heated concrete. Tensile strength seems to be more sensitive to such cracks than the compressive strength. In conformity to [42], tensile strength reduction is a result mainly related to the thermal composition and/or the stability of the formed hydrates, which act as the main binders between the concrete constituents.

Table 4: Comparison between reduction factors for compressive and tensile strength of HSC.

Temperature (°C)	$k_{c,\theta} = f_{c,\theta}/f_{c,23°C}$	$k_{t,\theta} = f_{t,\theta}/f_{t,23°C}$
23	1,00	1,00
200	1,03	0,85
400	0,84	0,77
600	0,46	0,35

4. CONCLUSIONS

In this study, the effects of moisture content on the residual properties of different concrete grades exposed to high temperatures were investigated. The results assessment provides interesting conclusions:

- Normal strength concretes and high strength concretes behave differently when exposed to high temperatures. In NSC, the reduction of mechanical properties happens gradually with the increase of temperature, while in HSC a considerable loss of strength starts from 400°C;

- The saturation level affects considerably the residual strength of high strength concretes at elevated temperatures, mainly in the 400-600°C range, due to damages caused by chemical and physical changes in the microstructure, together with the spalling process;

- The strength reduction on tensile strength is higher than compressive strength since tensile strength is more susceptible to the development of cracks with the increase of temperature;

- Explosive spalling did not occur in the NSC specimens, even for saturated samples. This behavior can be attributed to the connectivity of pores which can allow the water vapor to escape, avoiding vapor pressure build-up in the pores. However, in the HSC specimens, the spalling frequency is mainly associated to the saturation level and the compressive strength of the material. As the moisture content in concretes with low porosity/permeability increases, the probability of spalling occurrence also increases.

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