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Experimental evaluation of colored HSC column in fire conditions.

C. Britez[1], P. Castro-Borges[2], A. Berto[3], P. Helene[1]

[1]Department of Civil Construction Engineering, Universidade de São Paulo, São Paulo, Brazil. PhD Engenharia.
Email: carlos_britez@terra.com.br
[2]Centro de Investigación y de Estudios Avanzados del IPN Unidad Mérida, Yucatán, México.
[3]IPT. São Paulo, SP, Brasil

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RESUMEN

Ha sido común asociar el concreto de alta resistencia con una mayor susceptibilidad al desprendimiento por explosión (spalling) cuando se le somete a altas temperaturas. Esta duda se debe en parte a los resultados de algunos programas experimentales que se han llevado a cabo en pequeñas probetas de concreto simple sin refuerzo, lo que puede influir sustancialmente en el comportamiento del concreto en situación de incendio. Este artículo presenta un programa experimental en Brasil donde un pilar de concreto armado colorido de alta resistencia (HCAR), con ocho años de edad, fc,8años = 140MPa, árido grueso basáltico, sección cuadrada de 700mm x 700mm, fue ensayado sin carga y con tres lados expuestos al fuego (curva ISO 834) durante 180min (3h). Los resultados demostraron en este caso que el HCAR se mantuvo íntegro y que los pigmentos de óxido de hierro pueden trabajar como excelente termómetro natural, contribuyendo en la evaluación de la estructura después de la simulación de incendio.

Palabras Clave: Concreto de alta resistencia, resistencia al fuego, concreto colorido, pilar sometido al fuego, pigmento de óxido de hierro.

ABSTRACT

In recent times it has been common to associate high-strength concrete with a greater susceptibility to explosive type spalling, when subjected to high temperatures. In part, this doubt is a result of some experimental programs that are carried out on small unreinforced concrete samples (specimens), which could substantially influence the structural concrete behavior in fire conditions. This paper presents an experimental program, carried out in Brazil on a high strength colored reinforced concrete column (HSCC), eight years-old, fc,8years = 140MPa, basalt coarse aggregate, cross section of 700mm x 700mm, tested under no load and with three faces exposed to standard fire curve ISO 834 for 180min (3h). The results demonstrated, in this case, that HSCC maintained integrity under experimental fire and that the iron oxide pigments can work as an excellent natural thermometer, contributing to the evaluation of the structure post-fire simulation.

Keywords: High-strength concrete, fire resistance, colored concrete, column in fire, iron oxide pigment.

Autor de contacto: Carlos Britez

1. INTRODUCTION

Recently, Brazil was recognized internationally by breaking the record of cast-in-place high strength colored concrete, HSCC, which was employed in several columns of the *e-Tower* building in São Paulo City at the southwest region of the Country (Hartmann; Helene, 2003). When *e-Tower* was built in 2002, some replicas of these columns were cast-in-place at the yard of the Escola Politécnica of the University of São Paulo *EPUSP* (Figure 1) to serve as prototypes for future tests regarding mechanical behavior, durability and fire simulation.

Figure 1. (a) e-Tower building, 162m high; (b) HSCC prototype replica, cast at the EPUSP laboratory yard, São Paulo, Brazil

The fact that concrete properties are modified when it is exposed to heat is well consolidated among the technical community (ACI 216R, 1989; Purkiss, 1996; EUROCODE 2 EN 1992-1-2:2004, 2004). Precursor investigations had already shown that concretes, in general, undergone high temperature gradients when exposed to fire and that hot layers at surface have a great tendency to be separated and spall from the cooler interior of body (Abrams, 1971; Neville, 1973).

Nevertheless, this failure by explosive spalling has been observed on inconsistent basis in the case of high strength concretes (Phan, 1996). Notwithstanding the large global progress on technological research of high strength concrete under fire conditions, it still persists the idea, including Brazil, that this structural material has unfavorable behavior when submitted to high temperatures (Ali; O'Connor; Abu-Tair, 2001; Ali, 2002). Several researches (Phan; Carino, 1998; Kodur; Sultan, 1998; Kodur, 2000) in extended experimental programs have been answering this fact, pointing out that the geometry and size of the concrete cross-section, the rebar configuration and steel ratio of the samples (specimens) are fundamental factors that shall be considered for the realistic assessment of the structural concrete performance in fire, mainly when considering the explosive spalling of high strength concrete. Khoury (2000), Morita et al (2002), Kodur (2005) and the *fib* Bulletin n^{r} 38 (2007), observed that factors, such as the geometry, age of the sample (specimens), or the type of coarse aggregate used in the concrete mix, have a significant importance on the behavior of the material in fire conditions and should be duly considered in the analysis of the effective damage of concrete at high temperatures.

2. EXPERIMENTAL PROGRAM

2.1. Prototype column conditions prior to fire test

The prototype column utilized in this experimental study (Britez, 2011) was conceived under the same conditions of the actual *e-Tower* Building concrete columns, using plywood forms, with no especial curing methods, with the same concrete mixture, placing and compacting procedures. It also shall be pointed out that the concrete used to cast the prototypes was supplied by concrete mixer trucks which were deviated from *e-Tower* building site during normal concreting activities. During eight years, the *e-Tower* Building column replicas were exposed to the natural environmental conditions typical of Sao Paulo City [urban and industrial atmosphere, coordinates: 23°32'S / 46°37'W, subtropical *Cfa* climate type according to the universal classification given by *Köppen-Geiger* (Kottek et al, 2006)] with no special care, corrective treatment or surface protection.

2.2. Concrete Materials

At the beginning of year 2010, before starting the experimental program, cylindrical samples were extracted from the bottom of one of the prototype columns, from a region previously planned for remaining as reference concrete (Figure 2). These samples were tested for compressive strength and presented the characteristic compressive strength of *fc,8years* = 140MPa, higher than compressive strength obtained from test samples cast in 2002, of *fcm,28days* = 125MPa (Hartmann; Helene, 2003). The original dosing of this high strength colored concrete used at both *e-Tower* Building and prototype columns can be seen at Table 1.

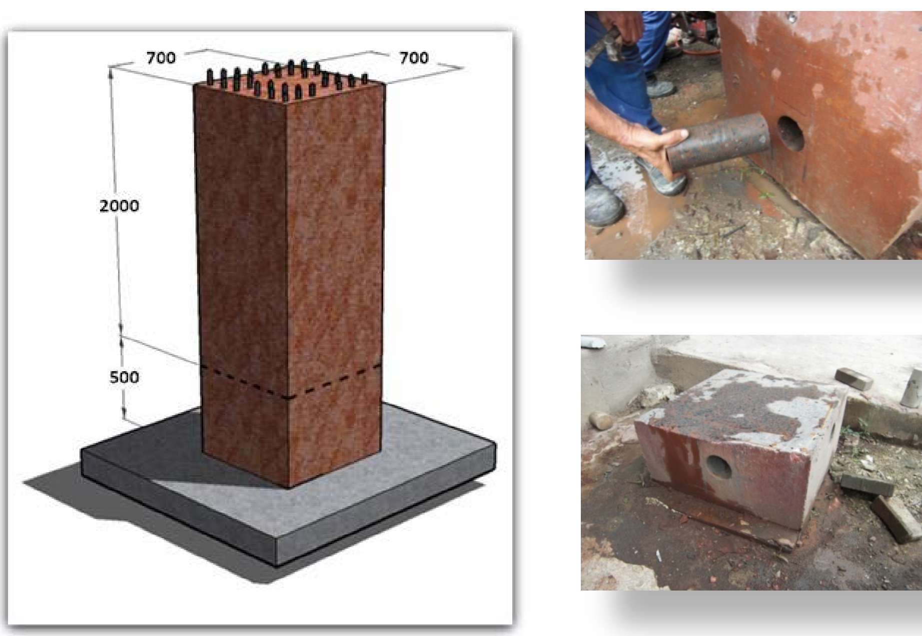


Figure 2. Place at the bottom of the prototype columns where the samples were removed and this lower part of prototype column (remaining), after cutting and extraction. (Note: measures are in mm)

Table 1. High strength colored concrete (HSCC) mix proportions

Materials	Proportion (kg/m³)
Cement (ASTM C 150 Type III + slag)	460 cement + 163 slag
Silica fume or metakaolin (15%)	93
Fine aggregate (quartz)	550
Coarse aggregate (basalt)	1027
Inorganic pigment (iron oxide) (4%)	25
High-range water reducer admixture (1%)	6.2
Cement hydration control admixture (0.5%)	3.2
Water	135

2.3. Cross-section

The prototype cross section was a square, 700mm x 700mm, with no variation all the way up its 2000mm height. The prototype (Figure 3) had a mean concrete rebar cover of 25mm, longitudinal ø = 16mm reinforcing and transversal reinforcement (stirrups), of ø = 8mm each 100mm (in both directions). Reinforcement steel is CA 50 grade (yielding strength f_y = 500MPa).

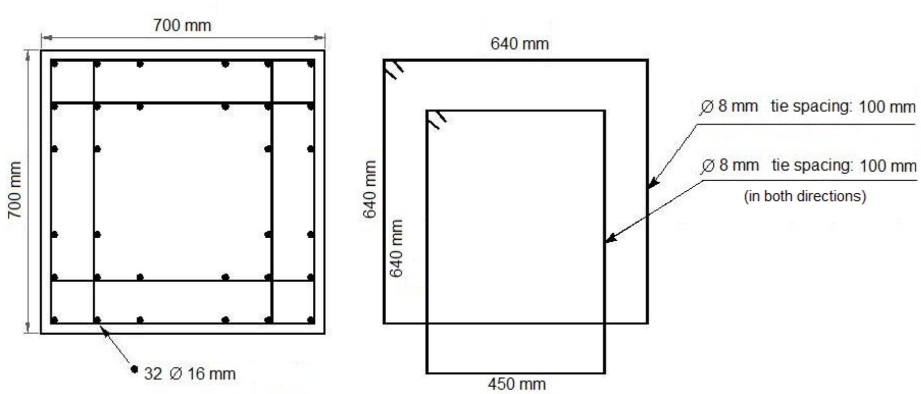


Figure 3. Geometry of the cross-section and reinforcement arrangement of prototype column

2.4. Instrumentation of the prototype column and of the furnace (thermocouples)

Thermocouples embedded inside the prototype column were installed in the region close to the central axis of one of the faces of the column, in four independent lines and with random depths and each line always had four different depths. In all sixteen K-type, ø = 3mm thermocouples were installed with an AISI 316 stainless steel sheath (Figure 4).

The furnace temperature (complying to ISO 834 standard heating curve) was controlled and measured through six K–type thermocouples, maintained at a distance of 150mm of the specimen faces, distributed in strategic points, being two for each face exposed to the fire; positioned at 1/3 and 2/3 of the total height of the prototype column. The K–type thermocouples used for this purpose were of *cromel-alumel*, isolated with ceramic elements and protected by a metal sheath, with 1.2mm diameter cables.

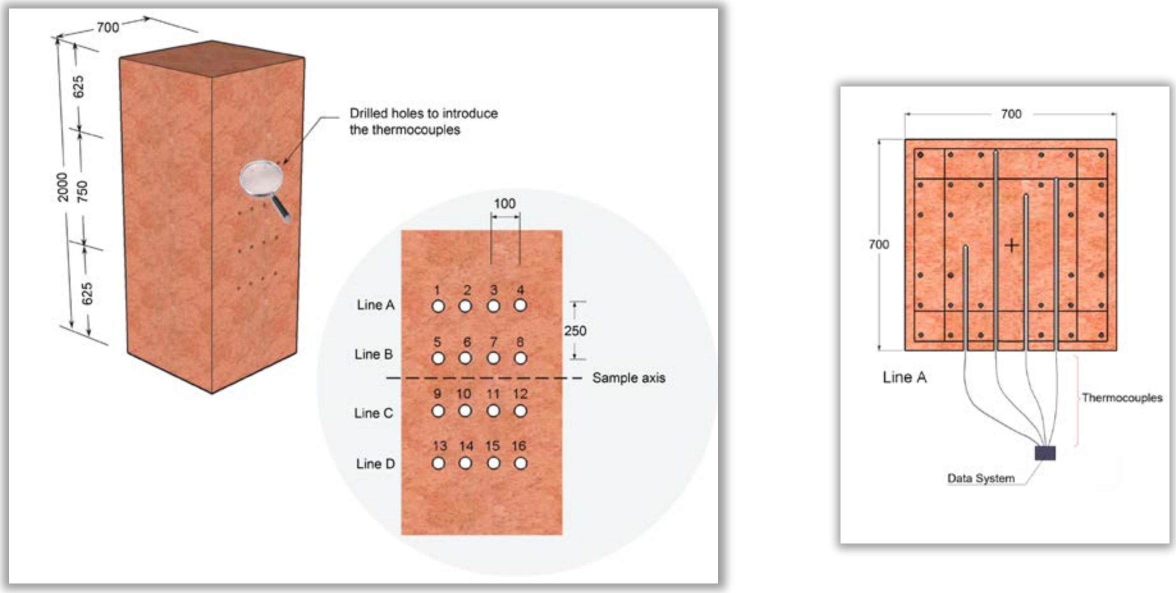


Figure 4. Thermocouples: position and depths (mm) on HSCC prototype-column

2.5. Fire simulation test procedure

The prototype-column with an approximate weight of 2.5ton was cut next to the bottom (Figure 2), leaving a remaining reference specimen of the same column to be tested and later on was rigged and transported to the place where the fire simulation test was to be carried out. The experimental program was developed at the furnace of the Fire Safety Laboratory of the Technological Research Institute (Instituto de Pesquisas Tecnológicas - IPT) of São Paulo State. They have a furnace whose dimensions are compatible with the devised technical program. The furnace that was utilized has five burners for natural gas, located at both lateral walls in a way to avoid any frontal contact between them.

The thermal test programming established that prototype column was to be exposed to fire during 180min (3hr), with a fire test characterized by the standard ISO 834 heating curve, according to Eurocode 2 (EN 1992-1-2:2004, 2004), with International Building Code (International Code Council: ICC, 2009) and with the São Paulo State Fire Hall technical instructions (São Paulo, 2009).

The prototype column was tested without load and with three faces exposed to fire, as a result of the furnace dimensions, which enabled that one of the faces, (where thermocouples were installed), could be kept with free access during the test (Fig. 5). The prototype column was covered with a refractory ceramic fiber blanket “XE” type, density 64kg/m³ at both ends (extremities: bottom and top) to simulate the unidirectional heat propagation during the test. An auxiliary masonry wall was built to close the frontal face of the furnace and two steel hatch windows were installed for any inspection emergency during the test.

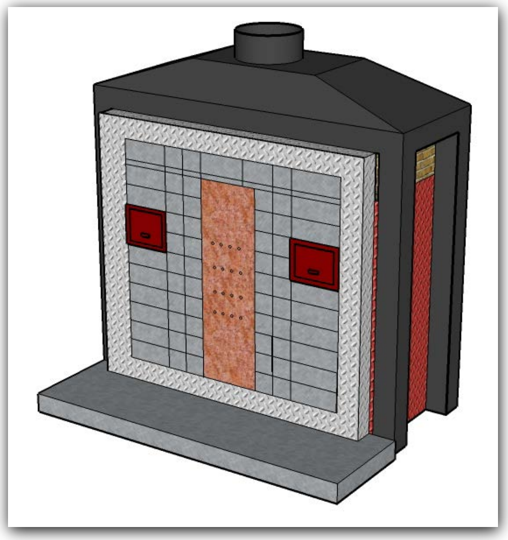
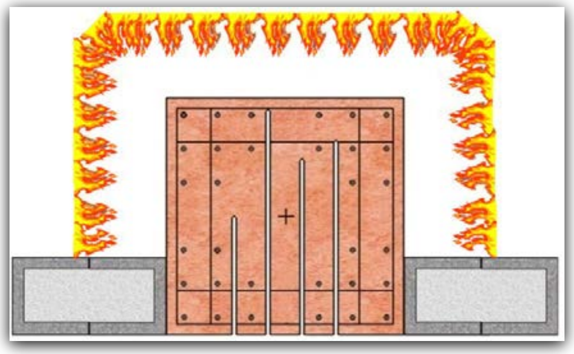



Figure 5. Testing furnace, prototype cross-section and thermocouples placing, and surfaces subjected to direct heating.

3. RESULTS AND DISCUSSION

3.1. Column integrity

During the test, spalling effects were mainly observed and analyzed. A series of short pop outs (*popping* type, as per *fib* Bulletin nº 38 classification[18]) began after 3 min indicating surface spalling on the three faces exposed to fire, continuing up to about 40 min of testing. After having opened the furnace (3days after the test, to enable natural air cooling) and the specimen removed, it was verified that the spalling was uniform and just at surface over the three heated sides, characterized by little delaminations, without evidence of significant concrete fragments on the furnace floor (Figure 6).

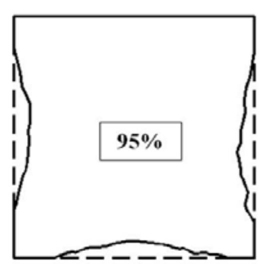



Figure 6. Column integrity and preserved cross section detail, after 180min of standard fire curve.

3.2. Spalling evaluation

In order to quantify the spalling occurrence, depths were measured at 450points over the three column surfaces (150 points per surface, creating a virtual mesh of 200mm x 50mm. Utilizing a precision bubble level, a steel measuring tape and a digital caliper it was found, by visual inspection, that after testing, 95% of the original prototype column section was preserved (geometrical integrity, not mechanical) and that spalling depth varied between 0 and 48mm (maximum value was measured at just one point) with a mean value of 9.3mm referred to the 450 points measured.

It was also observed that the prototype column corners remained geometrically intact (but friable) after 180min of heating. One explanation for the little amount of spalling can be attributed to the combination of several factors, some of them related to the geometry, size, and reinforcement arrangement (Kodur, 2000; Kodur, 2005) and also related to the coarse aggregate (basalt) (Khoury, 2000; *fib* Bulletin n^{r} 38, 2007) and the advanced age of the specimen (Morita, 2001; Morita et al, 2002; *fib* Bulletin n^{r} 38, 2007. This last factor represents very well the actual conditions of most of the existing structures subjected to fire.

3.3. Rebar exposure

It was also investigated the actual extension of exposed perimeter rebars (longitudinal and stirrup reinforcement) after testing. The total area of the exposed longitudinal and transversal rebars amounted to less than 5% of the total rebar area at that region. These measurements were carried out using a steel measuring tape and digital caliper, by visual inspection. It can be observed that notwithstanding the long time that the test lasted, 180min (3hr) and the extended surface spalling, very few reinforcing bars were effectively exposed.

3.4. Temperature distribution in cross section

During the 180min (3hr) fire test, six thermocouples monitored the ISO 384 standard curve evolution inside the furnace and other sixteen thermocouples monitored heat propagation inside the prototype column (embedded). Heat propagation (Figure 7) at column interior was uniform according to the depth of the thermocouples. It is possible to observe (Figure 8) that at 180min the thermocouples positioned at the rebar cover depth (25mm from the surface) did not registered temperatures higher than 600°C although inside the furnace, temperature was about 1100°C. In this case, the low heat diffusion and the consequent high thermal gradient could be attributed to the coarse aggregate type (basalt), which has favorable thermal properties when exposed to heat (*fib* Bulletin n^{r} 38, 2007).

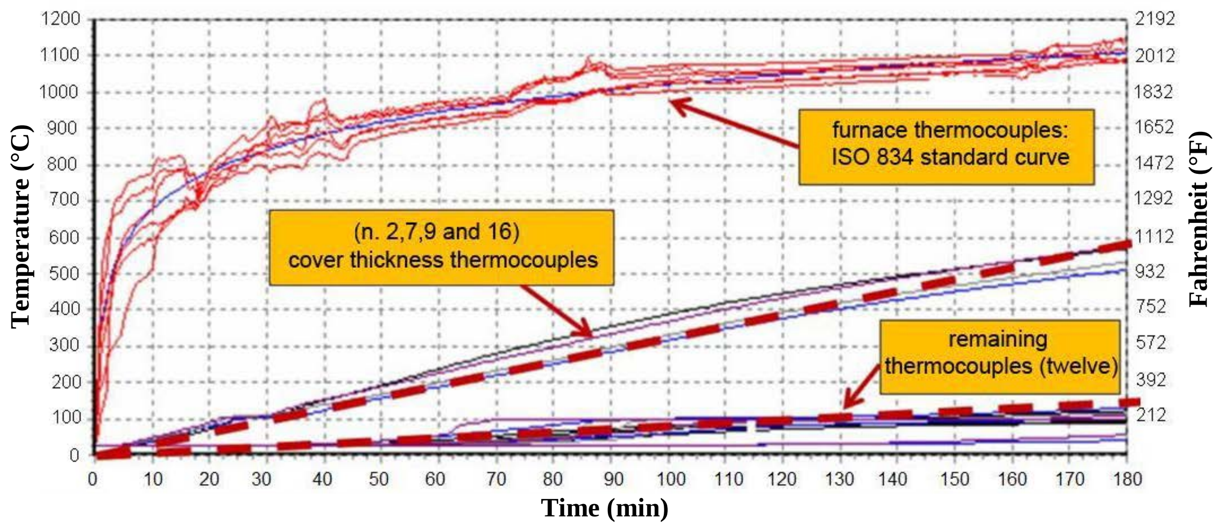


Figure 7. Temperature history in furnace (fire standard ISO 834) and inside the HSCC specimen.

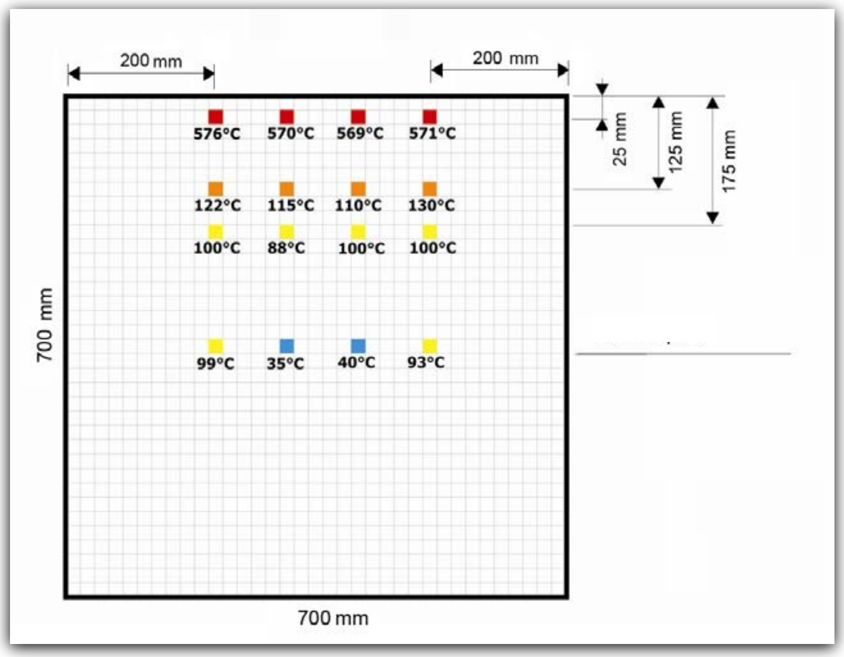


Figure 8. Cross section temperature map in the specimen at 180min of the standard fire curve.

3.5. Colorimetric index (inorganic pigmentation by iron oxide)

Due to the use of inorganic pigmentation with iron oxide, which was added to the high strength colored concrete mix (4% in cement weight), it was possible to evaluate qualitatively the column prototype region which was damaged by the exposure to heat during 180min (3hr).

In this case, principally due to the geometry and the size of the transversal size of the column, as well as the conditions of the experiment (slightly reducing atmosphere and a long exposure time to fire), it was verified that at least a depth of 55mm of the specimen showed a darker or black coloration at the central part of the sides and also that color alteration was not so evident at the column surface and at some depth of the corners (Fig. 9), where color was less dark and a more faded (orange hue).

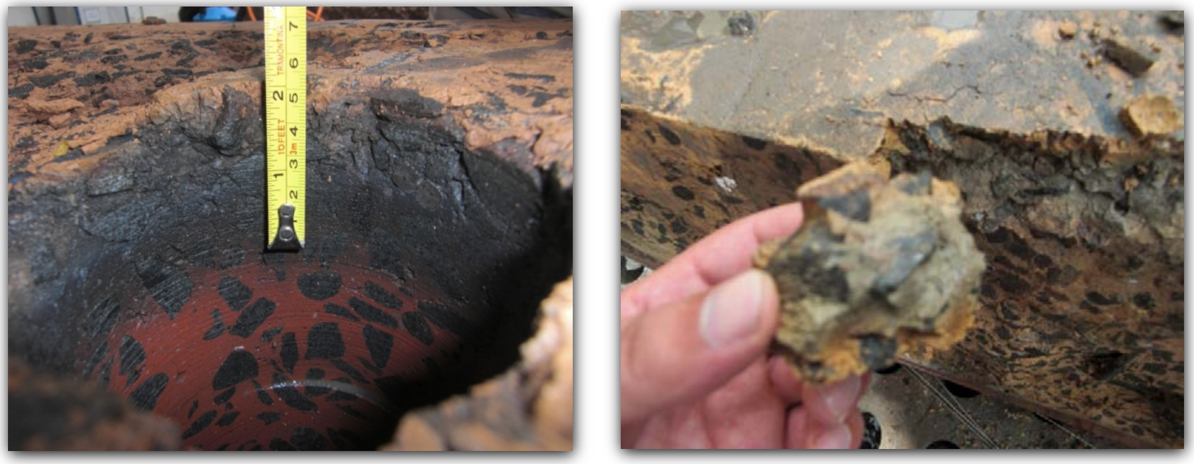
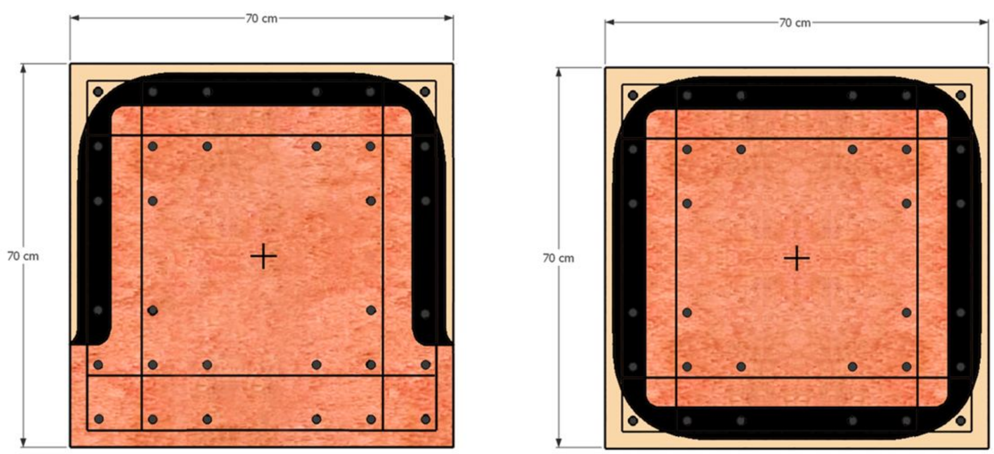


Figure 9. Colorimetric index prototype column.

Schemes of actual and hypothetical transversal section colors after the fire simulation test can be observed in Figure 10. Colors were produced by the existence and chemical reduction reactions of the synthetic iron oxide inorganic pigment (Fe_2O_3) promoted by the heat. At Figure 9(b) a hypothetical schematic drawing of the transversal section, admits by inference a symmetrical damage of the column at four sides, not taking into account the parts that were sided by masonry (see Figure 5).



(a) actual condition ***(b) hypothetical condition***

Figure 10. Schemes of actual and hypothetical cross-section colors after the fire simulation test

3.6. Residual mechanical properties of concrete

Several cores were extracted orthogonally from the transversal section, and these extractions were done in regions coinciding with the different depth of the thermocouples, excepting thermocouples located at rebar cover region mean depth (25mm), where the compressive strength was negligible (friable concrete). Core sample extractions were performed by the IPT

Construction Materials Laboratory Team with an electrical core drilling machine, model HCCB 6 *Hydrostress* made by *Tyrolit do Brasil*. Compressive strength tests were performed on a *Mohr* & *Federhaff – AG* hydraulic press, with a 200tf capacity and a precision of 100kgf.
The results obtained showed that the dark (black) region do not have a significant mechanical strength (it can be considered negligible: friable concrete) and that the region where the reddish original color was preserved (immediately after the dark color, at a 55mm distance from the external face, measured orthogonally) maintained residual mechanical strength very similar to that of the column central portion, i.e., the original mechanical resistance (prior to fire simulation, f_{ck} = 140MPa). Color scheme of Fig. 11 shows a good correlation (Fig. 12) with precursor investigation done by Anderberg (1978b) *apud* Purkiss (1996), commonly known as the "500ºC Method" (exclusion of peripheral portion that reached temperatures about 500ºC or higher, by admitting a significant reduction of mechanical strengths in these regions).

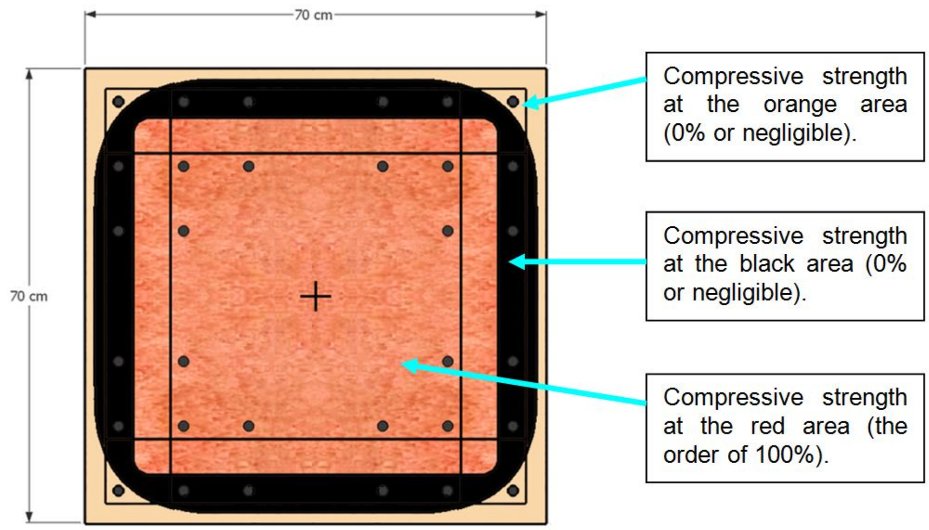


Figure 11. Concrete residual mechanical properties, post-fire simulation.

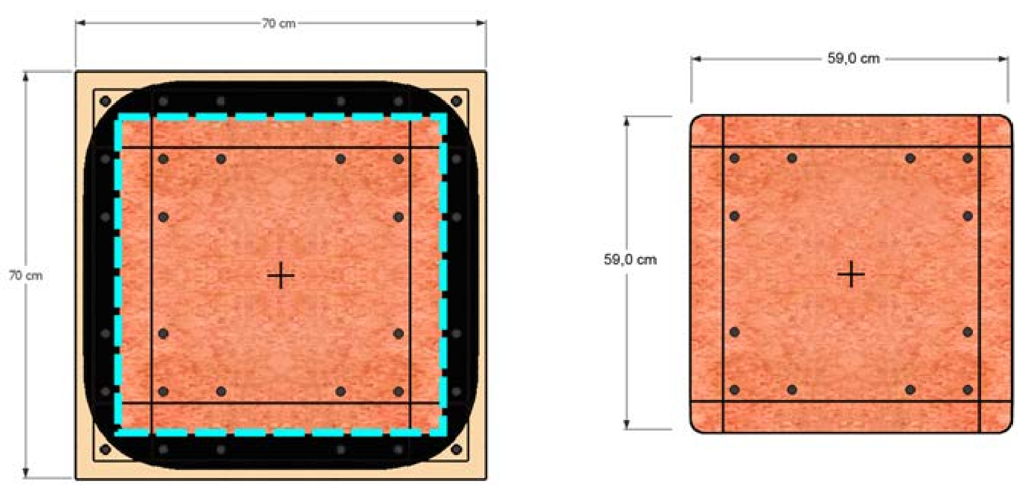


Figure 12. Virtual cross-section reduction due to the residual compressive strength post-fire simulation (hypothetical condition).

3.7. Residual mechanical properties of steel (rebars)

In all, four rebar samples were manually extracted, with usable lengths of 60cm (for each steel rebar sample), by surface chipping with hammer, flat chisel, bull point chisel and a cutting disc for steel. Two of them were extracted from the corners region (longitudinal) and two from the side region (stirrups). For comparison purposes, another rebar was extracted from the region opposite to the fire (protected by masonry), which was identified as “reference sample”. Tensile tests were performed on extracted rebars with a universal testing machine, type 03 (M.U.E. 03) at IPT Mechanical and Structural equipment Laboratory (LEME). The testing machine was made by *Alfred J. Amsler & Co.*

As per the test results obtained, it was possible to observe that the corner longitudinal rebars (ø 16mm), after a slow cooling at room temperature, underwent a reduction of about 25% of their mean tensile strength, if compared to reference samples. At the central part of the sides, (transversal rebars, ø 8mm), a quite lesser reduction of about 10% was observed. The results obtained show a good correlation with other experimental works (Suprenant, 1983; Cabrita Neves; Rodrigues; Loureiro, 1996; Purkiss, 1996), which unanimously point to the fact that residual properties of steel submitted to temperatures above approximately 550ºC undergo irreversible losses and that above 700ºC these losses become higher, and they can reach 30% or even more. Reaserchers (Cabrita Neves; Rodrigues; Loureiro, 1996) also remarked that the lesser the rebar diameter, the lesser the strength reduction. Strength reduction is higher for bigger diameter rebars and, principally, when they are cooled at room temperature. Color scheme at Figure 13 indicates the extraction locations, comparing them with the temperature estimates and the rebar tensile strength reduction.

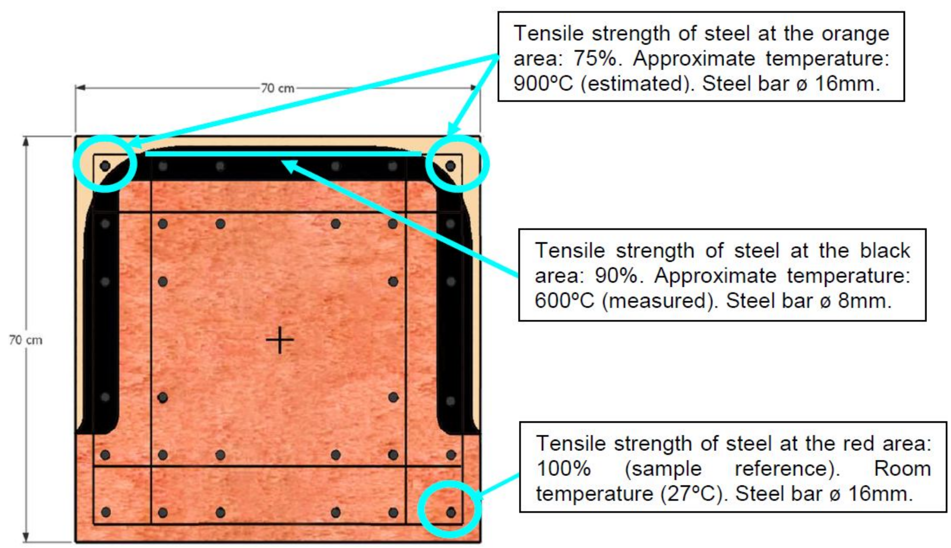


Figure 13. Steel residual mechanical properties, post-fire simulation.

3.8. Mineralogical characterization and thermal analysis

Mineralogical characterization was done by X-ray diffraction and thermal analysis by DTA-TGA (Differential Thermal Analysis and Thermo Gravimetric Analysis) on four samples extracted from strategic regions of the tested prototype column (after fire simulation), and also on another sample extracted from the column remaining (reference specimen). These tests were developed by the Mineralogical Laboratory team of the Brazilian *Portland* Cement Association (ABCP) on *Rigaku model D/max-1000* and *Rigaku model TAS 100*, respectively.

From the obtained results, it was observed a similar mineralogical composition of reddish colored samples (before and after fire simulation). In this case, X-ray diffraction enabled to infer that the sample which was exposed to fire (which preserved the original red color) maintained the same properties, including mechanical strength, of the original column. In the case of the black-colored sample (central part of the side exposed to fire), it was possible to verify the existence of magnetite (Fe_3O_4), substituting hematite (Fe_2O_3), produced by the iron oxide reduction chemical reaction, which was probably provoked by a slightly reducing atmosphere inside the furnace (characterized by incomplete combustion of natural gas), by high temperatures and by the total time that the fire simulation lasted. The orange-colored samples (at corners and central part of column sides) were remarked by their different mineralogy, having new-produced synthetics, similar to minerals *akermanite* and *wollastonite*. The existence of these synthetic compounds, produced by sintering in regions more exposed to fire (orange color) may indicate the occurrence of temperatures above 900ºC, which are necessary to produce these anhydrous minerals from hydrated compounds (Jacob, 1976; Rosenqvist, 2004). In these samples it can also be verified the existence of magnetite (Fe_3O_4), which substitutes hematite (Fe_2O_3).
On the other hand, it was seen that thermal analysis potentially contributed to indicate concrete degradation extents, which was more evident by verifying the mass loss of the samples. It was possible to verify that samples located at peripheral regions of the prototype column had less significant mass losses related to regions that maintained the original red color. At dark (black) regions it was found a total mass loss of about 6% and at orange regions (corners) a total mass loss of only 0.67%. The *portlandite* contents also underwent significant reductions in these regions, being null at corner region samples (orange color) and 3% at dark regions. As a comparison basis, the sample extracted from the region that maintained the red color had a total mass loss of about 12% and a portlandite content of about 9%, which indicates the existence of compounds that are still hydrated at these regions (Figure 14).

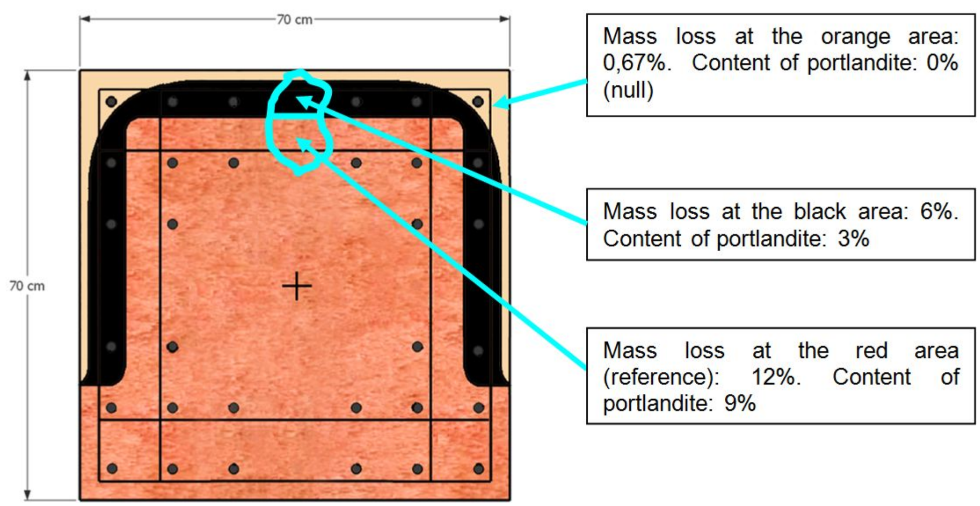


Figure 14. Mass loss and content of portlandite identified post-fire simulation.

4. CONCLUSIONS

1. The specimen dimensions, the cross section and the rebar arrangement and reinforcement ratio of the prototype column seem to have decisively and positively influenced the thermal performance and the high strength colored concrete behavior under fire exposure;

2. It should be observed that in this experimental program, just as an example, three cylindrical (100mm x 200m unreinforced concrete specimens and with the same age and mix concrete, were placed inside the furnace, which were in general disintegrated (see Figure 15) after 180min (3hr) of fire testing. Thus, it is recommended that small unreinforced concrete specimens not be utilized to evaluate spalling. Although they are useful for evaluating thermal concrete properties at different temperatures, they are not recommended to evaluate spalling of structural concrete members, as they may underestimate, in some cases, the high strength concrete performance in fire situations;

Figure 15. Small cylindrical unreinforced HSCC specimens partially disintegrated after fire testing; they had been placed together with the large prototype column.

3. The type of the coarse aggregate should also have contributed to the good thermal behavior of the high strength concrete. Coarse aggregates with greater thermal stability, as basalt can lead to more satisfactory results, since other parameters as geometry, cross section size, age of concrete, rebar arrangement and reinforcement ratio, are properly considered. It is observed that high strength concrete shall be classified not only by mechanical compressive strength, but also by the aggregate type, mainly when dealing with concrete in fire conditions;

4. The high strength concrete prototype column showed a good performance when exposed to 180min (3hr) of fire test, having preserved its geometric integrity, with 95% of the cross-section area preserved (only 5% of effective reducing due to spalling) and exposing only 5% of the total perimeter rebars steel (longitudinal and stirrups) area exposed, demonstrating that in this case, the use of polypropylene fibers is not be necessary;

5. In this thermal experimental program, the specimen age was favorable. The concrete is a changeable material with time-dependent physical-chemical hydration reactions of Portland cement; and from the fire resistance standpoint, it does not have the sufficient maturity for a large experimental program at its first months of age. Thus it is recommended that concrete

structural elements in fire simulation experiments shall be carried on specimens with a minimal age of one year, with maturity, moisture content and the hydration degree more compatible with most existing concrete buildings under use;

6. The use of inorganic pigmentation in concrete mix design can be considered an important qualitative index, and partially quantitative, of the depth of the damage produced to the specimens by exposing it to fire in experiments. For this reason, it can be proposed that the addition of inorganic iron oxide pigment (Fe_2O_3) be commonly used in laboratory experimental programs dealing with reinforced concrete structural members in general (normal and high strength). Independently of compressive strength tests performed on extracted cores, it would be possible to infer, just by the colorimetric index, that the structural member practically did not underwent significant changes in its mechanical properties, in he places where the original reddish color was maintained;

7. In the case of the residual compressive strength of concrete exposed to fire, it can be noted an excellent correlation with temperatures measured by thermocouples, and temperatures also have a good correlation with pigment color changes. The prototype column had a good performance when exposed 180min (3h) to fire, having preserved (mechanical integrity) its mechanical strengths in a transversal section of approximately 59cm *x* 59cm where the red color was maintained;

8. In a general way, the reduction of reinforcing steel residual mechanical strengths is directly proportional to the temperature and to the rebar diameter. Furthermore, reduction is still more evident (increased) if the specimen cooling at ambient temperature (air cooling);

9. The use of mineralogical characterization tests and thermal analysis can potentially contribute to evaluating structures that underwent intense heat exposure during a fire, provided a correct interpretation of results be done, mainly regarding water contamination of extracted samples. It was possible to detect a differentiated mineralogy along with an abrupt mass loss, related to the most degraded concrete portions, located at peripheral regions of the prototype column transversal section. It shall be pointed out that these degraded regions coincide with colorimetric indexes and, consequently, with highest temperatures.

5. ACKNOWLEDGEMENTS

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