Ultra High Performance Concrete (UHPC) in case of fire

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ABSTRACT
Ultra-high-performance concrete (UHPC) has exceptional mechanical properties at room temperature. However, there are no standardized procedures to characterize UHPC in fire. This is due to the lack of research on the subject, leaving gaps for experimental and numerical studies. This study collects a series of parametric data of UHPC at high temperatures. Thermal diffusivity, thermal conductivity, thermal strain and specific heat as thermal parameters were defined for different temperature ranges. The results were compared with other structural concretes proposed in the literature (NSC, HSC and UHSC). The UHPC exhibited a particular fire behavior. Compared to NSC, HSC and UHSC, the thermal expansion and mechanical parameters of UHPC are less affected in fire, but its thermal conductivity and mass loss are higher. UHPC also has the highest specific heat compared to other concretes. The thermal field of UHPC tends to be higher compared to the other concretes.

Keywords: UHPC, Thermal properties, Structures in fire.

Notation:

CA	Coarse aggregate
FA	Fly ash
HSC	Hight-strength concrete
NSC	Normal-strength concrete
PVA	Polyvinyl acetate
SF	Silica fume
UHPC	Ultra-High-Performance Concrete
UHSC	Ultra-High Strength Concrete
w/b	Water-binder ratio
C_p	Specific heat
k	Thermal conductivity

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INTRODUCTION

Ultra-high-performance concrete (UHPC) is a cementitious concrete with remarkable mechanical properties at room temperature. The specified compressive strength must be at least 120 MPa according to ASTM C1856 (2017) [1]. UHPC has low w/b, high cement content, aggregates, fibers (steel, PVA, glass) and superplasticizer. Its matrix is very dense and has a minimum of interconnected pores, making it an attractive option in chemically aggressive environments.

Buildings are vulnerable to fire. According to Zhu et al. (2021) [2], there is not much research on UHPC at high temperatures. However, UHPC must behave well in fire to be used as a building material. Studies such as Xiong and Liew (2016) [3], Kodur and Khaliq (2011) [4], Li, Qian, and Sun (2004) [5], Poon, Shui, and Lam (2004) [6], Kodur and Sultan (2003) [7], and Shin et al. (2002) [8] already show that high-strength concrete (HCC) does not have the same fire behavior as normal-strength concrete (NSC) due to concrete spalling, as also stated by Ullah et al. (2022) [9] and Akca and Zihnioglu (2013) [10]. According to Liang et al. (2013) [11], spalling occurs more frequently in UHPCs than in NSCs due to their dense structure and limited permeability. Analysis of concrete spalling has been the focus of research that sought to parametrically analyze UHPC under fire conditions [3, 10, 11, 12, 13, 14, 15, 16, 17].

There are no standardized fire design requirements for UHPC structures. Standards such as EN 1992-1.2 (2004) [18], ACI-216 (2014) [19], AS 3600 (2018) [20], NZS 3101-1 (2006) [21], and NBR 15200 (2012) [22] do not provide thermomechanical values for fire design RC structures with compressive strength greater than 100 MPa. There are few studies on this topic, and the fire behavior of UHPC is not well known in the literature. This is a problem in fire design of RC structures. Few studies have attempted to define the thermal properties of UHPC in fire. In this regard, authors such as Ullah et al. (2022) [9] do not suggest any application of UHPC in fire.

There is a discrepancy. Authors such as Du et al. (2021) [23], Willie, Naaman, and Parra-Montessinos (2011) [24], and Habel et al. (2006) [25] believe that UHPC is one of the most promising building materials for the future, but others, including Zhu et al. (2021) [2] and Ullah et al. (2022) [9], question its fire sensitivity. There is a need to do more research on UHPC in fire. According to SFPE (2008) [33], the fire performance of structures depends on the high-temperature properties of their materials.

In contrast, recent UHPC research does not analyze fire behavior. Zhang et al. (2022) [26] studied the mechanical behavior of RC column with UHPC jacket at room temperature; Tian and al. (2022) [27] and Zhou et al. (2023) [28] studied the performance of UHPC under cyclic loading; Zhang et al. (2022) [29] the flexural behavior of UHPC beams; Zhang et al. (2023) [30] the use of UHPC with recycled fine concrete; Li et al. (2023) [31] the mechanical properties of UHPC with different types of cement, Cui et al. (2023) [32] with expansion agents in the concrete mix, among others.

Kodur et al. (2020) [37] investigated the thermal properties of UHPC. Conductivity, specific heat, mass loss, and expansion were investigated by the authors. The literature review recommended by Zhu et al. (2021) [2] proved to be the only study that suggested thermal parameters for UHPC in different temperature ranges. The UHPC studied by Kodur et al. (2020) with fc value between 164 and 178 MPa contains SF, silica sand, PP and steel fibers, slag and coarse aggregates (CA). Yang et al. (2019) [38] already show that CA reduces the thermal field of UHPC, i.e., UHPC without CA has a much larger temperature gradient than UHPC with CA. The UHPC in this study does not contain CA, but PVA fibers and a 750-day curing of the concrete, which makes this study a precedent. UHPC without CA has not yet been evaluated in the literature.

In this study, the thermal properties of UHPC without CA were determined. Conductivity, diffusivity, specific heat and thermal elongation were determined as thermal properties. Equations, diagrams, and tables for the use of these parameters in fire design of structures were presented to fill a gap in standard procedures.

METHODS

The methods used to characterize UHPC in each temperature range are shown. The materials used to build the UHPC are shown below.

MATERIALS

The cement used was a high-initial resistance type that contained fewer chemical cement additions. It is a Portland cement used in Brazil classified as CP-V ARI by NBR 16697 [39]. Silica fume (88.5% silicon contained) and fly ash (50.0% of silicon content) were used with, respectively, specific gravity of 350 kg/m³ and 210 kg/m³. Silica fume acts as a microfiller. It also reacts with calcium hydroxide, thus increasing the final strength.

A natural quartz sand with 260 kg/m³ was incorporated. It is a river sand that received a washing process to eliminate impurities. The steel fiber had a length of 25 mm and a diameter of 0.75 mm, with a tensile strength of 1100 MPa and a modulus of elasticity of 210 GPa. The PVA (polyvinyl acetate) fiber had a length of 12 mm and 0.04 mm in diameter, tensile strength of 1600 MPa and modulus of elasticity of 41 GPa. Superplasticizing additive based on polycarboxylates was incorporated to improve the workability of the concrete. The UHPC production and mix was made according to Christ et al. (2022) [40] method.

The concrete mix is presented in Table 1.

Table 1 – Concrete mix

Material	Unit content (kg/m³)	Ratios of concrete mix
Cement	488	1.00
Silica fume	268	0.55
Fly ash	235	0.48
Natural sand (fine aggregate)	1025	2.10
Steel fiber	120	0.25
PVA fiber	6	0.02
Chemical additive	17.6	0.03
Water	178	0.36

The average compression strength of the concrete at 28, 150 and 750 days were 108.0, 146.4 and 162.4 MPa, respectively. The elastic modulus was 41.4, 44.0 and 46.1 GPa at, respectively, 28, 150 and 750 days. These results were obtained by testing a concrete cylinder with a dimension of 150x300 mm (diameter x length) made according to ASTM C470 [41]. The concrete compressive strength testing was obtained according to ASTM C39 [42] and the elastic modulus in accordance to ASTM C469 (2014) [43] procedures. The concrete samples are produced in accordance to ASTM C31 [44] and ASTM C192 [45].

THERMAL PROPERTIES DEFINITIONS

The thermal diffusivity, specific heat, thermal conductivity and thermal elongation data were determined as shown below.

Diffusivity

The thermal diffusivity of UHPC was obtained according to the Flash Method proposed by ASTM E1461 [39]. The method is used to measure values of thermal diffusivity of a wide range of solid materials. The results were obtained by testing a concrete cylinder with a dimension of 12.7x2.5 mm (diameter x thickness) in accordance to ASTM E1461-13 [46] prescriptions. The UHPC specimens were heating to 100, 200, 300, 400, 500 and 600°C. The test equipment used was a thermal diffusivity analyzer (TDA) with a temperature range from -125°C to 500°C, a thermal diffusivity measurement ranges from 0.01mm²/s to 1000mm²/s and a thermal conductivity range from 0.1W/mK to 2000W/mK..

According to the thermal diffusivity (α) results and with the density in fire (ρ) it is possible to obtain the specific heat (C_p) and thermal conductivity (k) according to Equation (1).

$$\alpha = k/\rho.C_p \qquad (1)$$

Specific heat

According to the thermal diffusivity results and according to Equation 1, the specific heat values were defined for the same temperature ranges as in section 2.2.1.

Conductivity

According to the results of thermal diffusivity and Equation 1, the thermal conductivity values were defined for the same temperature ranges as in section 2.2.1.

CORRELATION WITH THE STANDARD PROCEDURES AND REFERENCES

The results (data available in this research) were compared with those proposed by the references. When possible, the data were compared with normal-strength (NSC), high-strength (HSC), ultra-high-strength (UHSC) and, when available, ultra-high-performance (UHPC) concrete similar to this research. Graphs were proposed with the UHPC results of this research. From these, new equations were extracted.

REMARKS FOR TESTING UHPC IN HIGH TEMPERATURES

The first fire tests with UHPC test specimens were evaluated at 28 and 150 days after their construction. However, in these ages, there was explosive spalling of the concrete. In the first case, there was spalling when the specimen was heated to around 100°C. In the second case, when heated to 300°C. After 700 days, the specimens showed no more concrete spalling when heated to 800°C. This justifies carrying out the tests with 750 days.

The low porosity of UHPC prevents internal dissipation of water vapor produced during heating. It is necessary that fire tests be carried out on aged concrete. Due to the high mechanical strength of UHPC, the amount of internal water vapor is high and the concrete spalling is explosive. These results are in agreement with Zhu et al. (2021) [2] and Ullah et al. (2022) [9], who showed that UHPC is more susceptible to spalling in fire than NSC. However, it is important to highlight that the spalling decreases with age, as the internal humidity of the concrete tends to reduce with age, as shown by Manica et al. (2020) [50] and in accordance the previous results of this research.

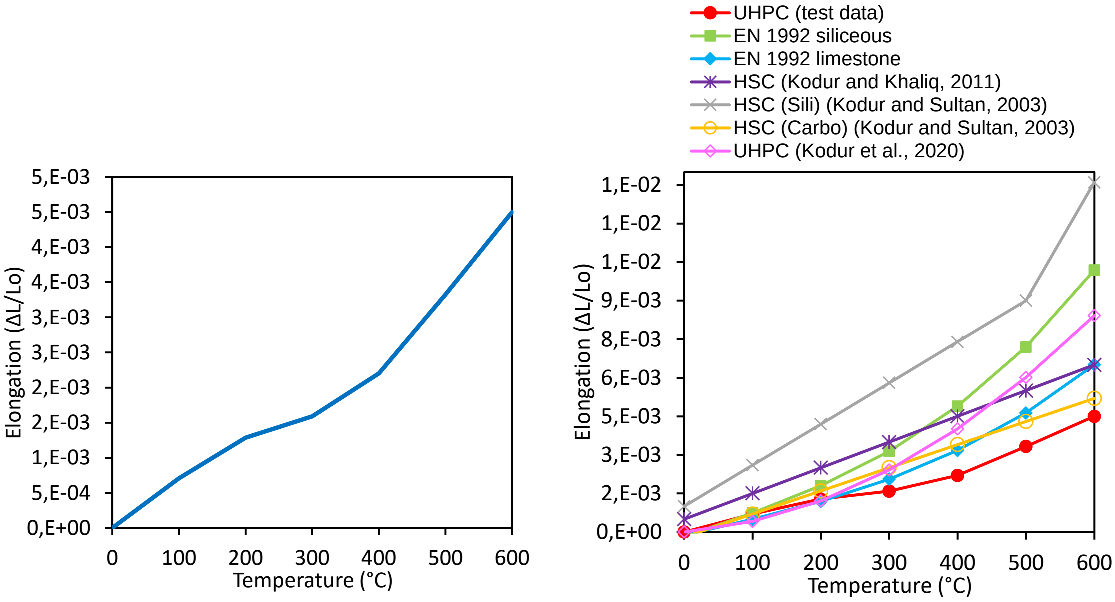
RESULTS AND DISCUSSION

The results of this research are presented.

THERMAL ELONGATION

Table 1 and Figure 1 a show the thermal elongation ($\Delta L/L_o$) results of UHPC for different temperature ranges. Figure 1b shows the comparison of these results with references.

Figure 1 – Thermal elongation at high temperatures



(a) UHPC (test data)

(b) UHPC (test data) and references

Table 1 – Thermal elongation: correlation between UHPC and references

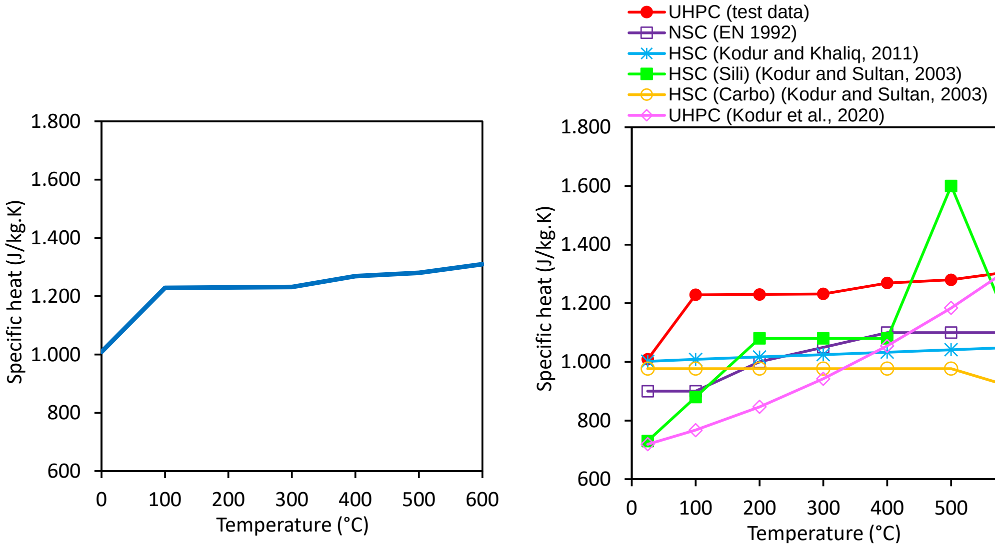
Temperature (°C)	Thermal elongation $\Delta L/L_o$ (x10^{-3})						
	UHPC Test Data	EN 1992 NSC (Sili) (C20/50)	EN 1992 NSC (Lime) (C20/50)	HSC (Kodur and Khaliq,2011)	HSC - Sili (Kodur and Sultan,2003)	HSC - Carbo (Kodur and Sultan,2003)	UHPC (Kodur et al., 2020)
	(a)	(b)	(c)	(d)	(e)	(f)	(g)
25	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	0.71	0.74	0.50	1.50	2.60	0.70	0.41
200	1.28	1.80	1.19	2.50	4.20	1.60	1.21
300	1.59	3.14	2.06	3.50	5.80	2.50	2.41
400	2.20	4.89	3.18	4.50	7.40	3.40	4.01
500	3.33	7.20	4.63	5.50	9.00	4.30	6.01
600	4.50	10.2	6.50	6.50	13.6	5.20	8.41

UHPC (Table 1a) has positive thermal elongation when exposed to high temperatures, as with other concretes (Table 1b-g). The UHPC of this research had the lowest $\Delta L/L_o$ value in relation to the others. Up to 100°C thermal elongation can be related to the loss of humidity (free water) in the concrete. Between 200 and 300°C, it can be related to the loss of adsorbed water from hydrated cement compounds and aggregates. Between 300 and 500°C, values may be associated with $C_a(OH)_2$ and CaO dehydration, as reported by Laneyrie et al. (2016) [16]. The lower expansion of UHPC (Table 1a) in relation to the other concretes (Table 1b to f) shows the influence of the coarse aggregate in this aspect. In relation to the UHPC tested by Kodur et al. (2020) [37], in addition to the aggregate, also the experimental procedure (see section 2).

Specific heat

Figure 2a and Table 2 show the specific heat results of UHPC in different temperature ranges. Figure 2b shows the comparison of these results with references.

Figure 2 – Thermal elongation at high temperatures



(a) UHPC (test data)

(b) UHPC (test data) and references

Table 2 – Thermal elongation: correlation between UHPC and references

Temperature (°C)	Specific heat (J/kg.K)						
	UHPC Test Data	NSC EN 1992 (C20/50)	NSC (Shin et al., 2002)	HSC (Kodur and Khaliq, 2011)	UHPC (Kodur et al., 2020)	HSC - Sili (Kodur and Sultan,2003)	HSC - Carbo (Kodur and Sultan,2003)
	(a)	(b)	(c)	(d)	(e)	(f)	(g)
25	1009	900	1104	1000	720	730	977
100	1229	900	-	1008	767	880	977
200	1230	1000	-	1016	846	1080	977
300	1232	1050	-	1025	942	1080	977
400	1269	1100	-	1033	1055	1080	977
500	1280	1100	1354	1041	1184	1600	977
600	1310	1100	-	1050	1330	1080	911

Specific heat changes with temperature due to chemical and physical changes that occur in cement past and aggregates when in heating. According to fib Bulletin 38 (2007) [55] and Kodur et al. (2020) [37], specific heat around 100°C increases because of evaporation of moisture present in the form of free water (Figure 2). Between 100°C–300°C, specific heat increases further due to the evaporation of moisture present in the remaining free water, in addition to the adsorbed and bonded water. In 300-500°C range, the C_p value remains almost constant because of the counteracting effects of decrease in moisture due to complete evaporation of free water and the increase in humidity due to $Ca(OH)_2$ decomposition. There is a small increase in C_p after this temperature due to the release of moisture from the decomposition of the C─S─H gel and significant deterioration of the microstructure within the concrete.

In the case of the UHPC, Figure 2a and Table 2a show that at 25°C its specific heat is 1009 J/kg.k. This means that the amount of energy required to increase the temperature of 1 kg of UHPC by 1K is 1009 J. At the same temperature, these values are similar to those presented by Shin et al.

(2002) [8] for NSC, by Kodur and Khaliq (2011) [4] for HSC and Kodur and Sultan (2003) [7] by HSC with carbonate aggregate. however, the UHPC value at 25°C (Table 2a) was lower than those reported by EN 1992 for the NSC (Table 2b), for the UHPC evaluated by Kodur et al. (2020) [27] (Table 2e), and also for HSC with siliceous aggregates proposed by Kodur and Sultan (2003) [7] (Table 2f).

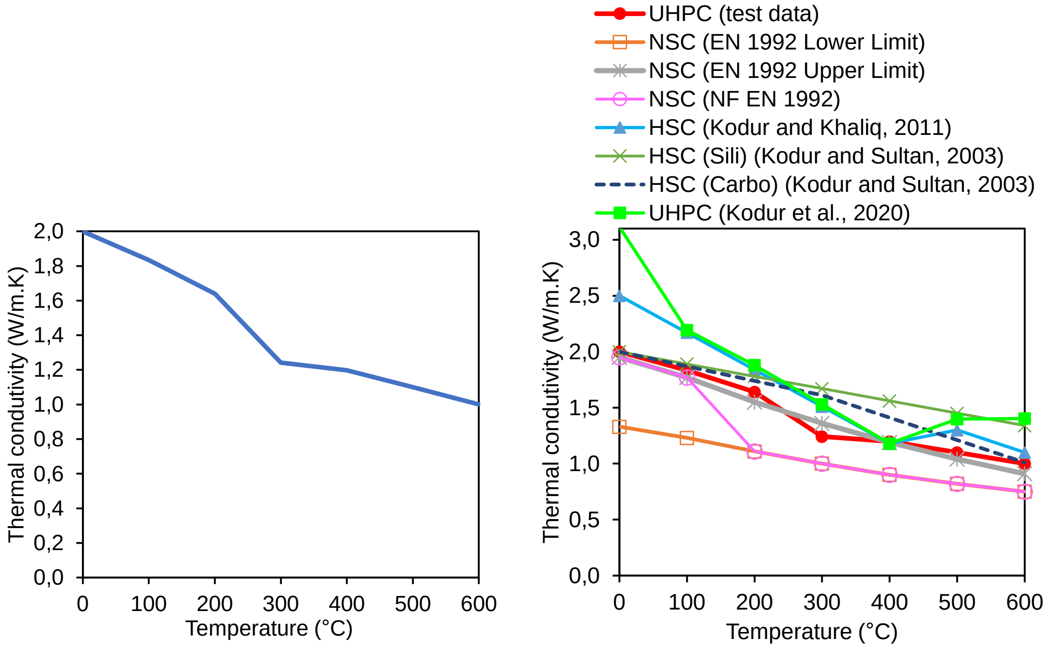
According to Figure 2a and Table 2a, at 100°C, the C_p of the UHPC tested increased to 1229 J/kg.K. At the end of the tests (600°C) the value was 1310 J/kg.K. For the equations proposed in section 5, the value of the specific heat in the range from 100 to 600°C was defined as the average of the C_p readings in this temperature range (i.e., 1270 J/kg.K). This is a practical simplification of fire design since there is variability between the results, according to Table 2.

In the temperature range 100-600°C, the same interpretation and comparison made at 25°C between researches is preserved (Table 2a-g). However, the research of Kodur et al. (2020) [37] for UHPC (Table 2e) and Kodur and Sultan (2003) [7] (Table 2f) for HSC, which at initial temperatures (i.e., 25 °C) did not converge with the UHPC of this research, tends to converge at the end of analysis. Normally the UHPC of this research (Table 2a) has a specific heat relatively higher in relation to the others concretes. It can be attributed to the lower permeability and dense microstructure of UHPC that requires more heat for evaporation of water.

Conductivity

Figure 3a plots the thermal conductivity of UHPC for various temperature ranges. Figure 3b and Table 3 show the comparison of these results with bibliography.

Figure 3 – Thermal elongation at high temperatures



(a) UHPC (test data) (b) UHPC (test data) and references

Table 3 – Thermal conductivity: correlation between UHPC and references

Temperature (°C)	Thermal conductivity (W/m.K)								
	UHPC Test Data	NSC EN 1992 (lower limit)	NSC EN 1992 (Upper limit)	NSC NF EN 1992	NSC (Shin et al., 2002)	HSC (Kodur Khaliq, 2011)	UHPC (Kodur et al., 2020)	HSC - Sili (Kodur and Sultan,2003)	HSC - Carbo (Kodur and Sultan,2003)
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)
25	2.00	1.33	1.95	1.95	2.19	2.42	3.11	1.97	1.97
100	1.83	1.23	1.77	1.77	-	2.17	2.19	1.89	1.87
200	1.64	1.11	1.55	1.11	-	1.84	1.88	1.78	1.74
300	1.24	1.00	1.36	1.00	-	1.51	1.53	1.67	1.61
400	1.20	0.90	1.19	0.90	-	1.18	1.18	1.56	1.41
500	1.10	0.82	1.04	0.82	1.28	1.30	1.40	1.45	1.21
600	1.00	0.75	0.91	0.75	-	1.10	1.40	1.34	1.00

Thermal conductivity variation in concrete with temperature is governed by the change in moisture levels in fire. Concrete moisture decreases with increasing temperature and therefore thermal conductivity decreases at high temperatures. At temperatures above 100°C, free water starts to evaporate, sometimes causing spalling. When the concrete temperature reaches about 300°C, the adsorbed water from the calcium silicate hydrate (C━S━H) gel and a part of the chemically bound water begin to evaporate. The concrete temperature further to 400°C causes decomposition of $C_a(OH)_2$, converting it into C_aO and H_2O, increasing the moisture content of concrete. Further increase in temperature beyond 500°C leads to decomposition of C—S—H and further deterioration of concrete and aggregate.

According to Figure 3b and Table 3, it can be seen that the UHPC in this research (Table 3a) are, respectively, 50.4%, 2.6% and 2.6% higher in relation to the NSC proposed by EN 1992-1.2 [18] (Table 3b and c) and NF EN 1992 [53] (Table 3d). Research by Kodur et al. (2020) [37] show that the UHPC had a conductivity 55% higher than those obtained in this research. After 300°C, the values between both researches tend to converge. In relation to the NSC proposed by the EN 1992-1.2, the UHPC tested by Kodur et al. (2020) were 133.8% higher. The notable variability in these results is understandable, and can be attributed to varying moisture content, cement type, aggregate, test conditions and measurements techniques used in each research, as explain by Kodur et al. (2020) [37], Kodur et al. (2019) [52], Bazant and Kaplan (1996) [54].

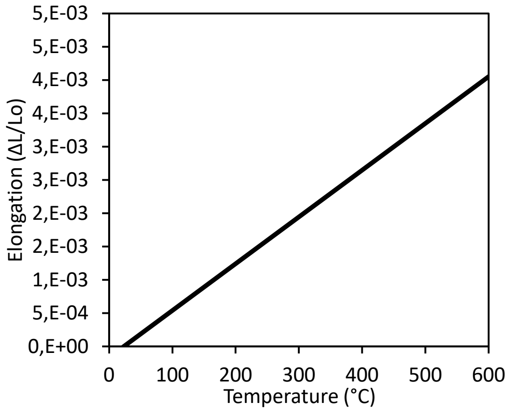
PROPOSAL OF PROCEDURES FOR STRUCTURAL FIRE DESIGN

In this section, due to the absence of the NBR 15200 standard, parametric data are proposed to support the fire-design of UHPC structures in case of fire.

ELONGATION

Figure 4 and Equation 3 show the proposed thermal elongation values for UHPC at different temperature ranges.

Figure 4 – Proposal of thermal elongation values for UHPC

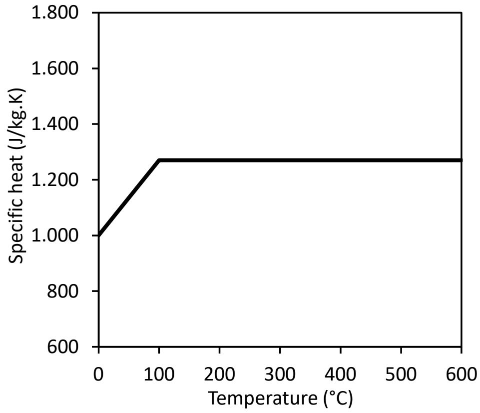


$$\frac{\Delta L}{L_o} = 7x10^{-6}xT - 2x10^{-4} \ (R^2=0.96) \qquad (3)$$

SPECIFIC HEAT

Figure 5 and Equation 4 show the proposed specific heat values for UHPC at different temperature ranges.

Figure 5 – Proposal of specific heat values for UHPC



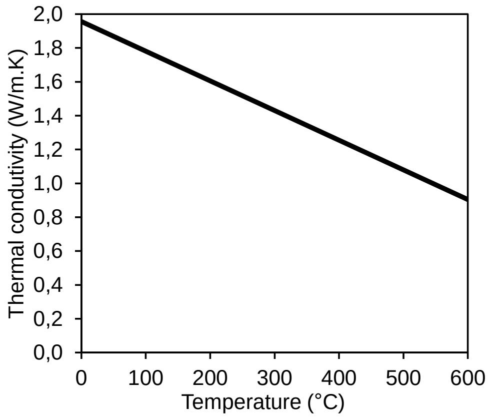
$C_p = 2.7\ x\ T + 1000$ [J/kg.K] (R^2=0.99) 25≤T<100°C (4)

$C_p = 1270$ [J/kg.K] (R^2=0.95) 100≤T≤600°C

CONDUCTIVITY

Figure 6 and Equation 5 show the proposed specific heat values for UHPC at different temperature ranges.

Figure 6 – Proposal of thermal conductivity values for UHPC



$k_\theta = -1.8x10^{-3}xT + 1.95$ [W/m.k] (R^2=0.95) (5)

CONCLUSIONS

The general conclusions of this paper are:

- This research demonstrated that UHPC specimens tested before 700 days are susceptible to concrete spalling;
- When compared to NSC (according to EN 1992-1.2 parameters), UHPC showed higher thermal diffusivity;

- In this sense, in relation to NSC, UHPC will have a higher average temperature;
- When compared to NSC and HSC, UHPC has the lowest thermal elongation;
- UHPC has a specific heat higher in relation to the others concretes (NSC, HSC). It can be attributed to the lower permeability and dense microstructure of UHPC that requires more heat for evaporation of water;
- Thermal conductivity of UHPC is also higher than NSC. Steel fibers can justify these results;
- New equations were proposed to define the thermal, physical and mechanical parameters of UHPC at high temperatures. These equations are essential for researchers who intend to carry out numerical research with the UHPC;
- As future research, it is recommended to compare the fire performance of UHPC with NSC. In the view of the authors, this comparison should be holistic and from a structural perspective. The combination of mechanical and thermal results are the motivation: in relation to NSC, UHPC has a larger thermal field but is less mechanically affected by temperatures;

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