

# Behaviour of high-performance concrete at high temperatures: some highlights

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## Abstract

High-performance concrete (HPC) is now used routinely in building and civil structures. The development of using HPC in structural applications and the growing need for justification of the fire resistance has led several laboratories to carry out research on properties at high temperature. This letter presents some main aspects related to physicochemical changes, thermal properties and mechanical properties for HPC at high temperature. It introduces a State of The Art prepared by the RILEM Technical Committee 227-HPB (Physical properties and behaviour of HPC at high temperature) and titled "Behaviour of HPC at high temperatures". This State of the Art will be published in the near future.

**Keywords:** High temperature; High performance concrete; Fire; Microstructure; Thermal properties

## 1 Introduction

At the end of the 1990s, the development of HPC and other new types of concrete (Self Compacting Concrete, Ultra High Fibre Reinforced Concrete ...) led researchers to carry out new research programs in order to determine the properties of these new concretes at high temperature. Of particular note are the works conducted and synthesised in the context of the European project HITECO [1] and the French National Project BHP 2000 [2, 3]. The use of this type of concrete (usually defined as having a compressive strength higher than 60 MPa) is often motivated by a high durability that gives to structures a longer life time compared to the use of ordinary concretes. The justification of the fire resistance of such structures requires extensive data, both experimental and numerical, relating to the behaviour of HPC at high temperature. Due to the fundamental differences from ordinary concretes (low water-to-cement ratio, W/C, superplasticiser, Silica fume, limestone filler...), HPCs can have a specific behaviour at high temperature, which is important to know for fire safety verification (or design) of structures. Physico-chemical reactions induced within the material by heating must then be clearly identified in order to know the concrete properties changes

with temperature. Among them, heat and mass transfer properties, as well as mechanical properties are essential to know. These properties are sometimes useful as input to simulation models, and may come in addition to codes like the Eurocode 2 for example. In addition, the analysis of properties changes with temperature allows better understanding of the behaviour of HPC under fire and allows anticipation of the behaviour of a structure.

In this context, the RILEM Technical Committee 227-HPB (Physical properties and behaviour of High-Performance Concrete at high temperature) has written a State of The Art untitled "Behaviour of High-Performance Concrete at high temperatures". The main objectives of this report are to collect, synthetize and analyse useful experimental data. It provides a vast and comprehensive review of existing knowledge about the behavior of concrete material under fire, with a special but not exclusive emphasis on HPC. This report will be published in the next months.

It is to be underlined the fact that a second complementary State of the Art was prepared by the same RILEM Technical Committee. It focuses on the modelling of the behaviour of concrete at high temperatures and will be published in 2018 too.

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In the same way, the phenomenon of spalling due to fire exposure, which is a particularly important issue for HPC, is being described in the RILEM Technical Committee SPF (Spalling of concrete due to Fire: testing and modelling).

These documents complement the previous synthesis on the behaviour of ordinary concrete at high temperatures. The articles written by the RILEM TC 200-HTC [4], Schneider [5] or the data collected by Bazant and Kaplan [6] can be cited.

The State of the Art report is arranged as follows. Section 2 collects and analyses the main physico-chemical reactions that take place into HPC when heated to high temperature (above 1000°C). Sections 3 and 4 are focused on the temperature dependency of heat and mass transfer properties of HPC. Section 5 is focused on the temperature dependency of mechanical properties.

In this letter we have chosen to present some main aspects related to the physicochemical changes, thermal properties and mechanical properties at high temperature.

## 2 Degradation reactions and microstructural transformations at high temperatures

When concrete made with plain Portland cement (OPC) or blended cements are subjected to heat, a number of chemical transformations and reactions of different kinds occur [7-9]. The main processes have been summarised in Table 1.

Apart from the crystal transformations occurring mainly in the aggregates, the processes comprise the so called degradation reactions of cement paste, these being reactions which bring about a progressive breakdown in the structure of the concrete. They occur more particularly in the hardened cement paste hydrated components, but also in the aggregates depending on the type of rock concerned [15], as described below.

- At temperatures from 100°C to 500°C the chemical reactions mainly take the form of dehydration of cement paste components (ettringite, CSH and portlandite) followed with water vapour expulsion [8-12]. The main component of cement paste, the CSH, progressively decomposes its structure within this range of temperatures by breaking the silicon chains length [8, 9]. The final stage of CSH dehydration is the formation of silicates with similar anhydrous cement structure type C2S [7, 8]. In situ analyses using Neutron Diffraction Spectroscopy (NDS) of crystalline phase changes occurring during progressive heating confirmed these transformations [13].
- At higher temperatures, up to 800°C, crystalline transformation of aggregates occurs, e.g.  $\alpha$  to  $\beta$  quartz transformation in siliceous aggregates. Decarbonation of carbonates plays a prominent part if the concrete contains limestone aggregates or filler such as in SCC [11, 14].
- Above 1200°C and up to 1300°C, some components of the concrete begin to melt. During melting some aggregates (e.g. igneous rocks such as basalt) show

degassing and expansion phenomena accompanied by release of gases trapped within the rock at the time of its formation [14, 15].

- Above 1300°C -1400°C concrete exists in the form of a melt, i.e. it has then turned into a liquid [14, 15].

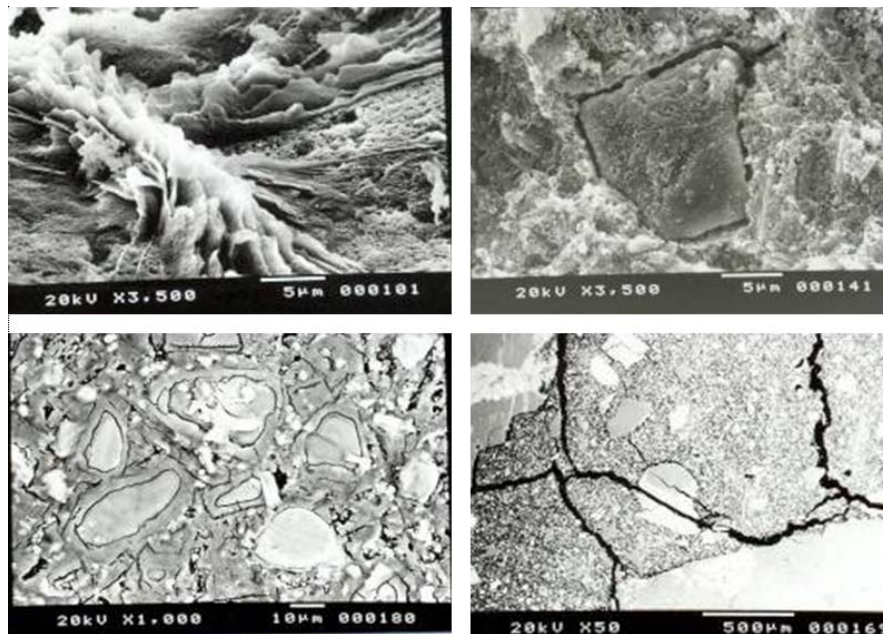
The microstructure of the concrete components altered due to the thermal processes [16-18] shows clear changes in microscopy observation. Cement paste and aggregate structure after heating to high temperature can be analysed using scanning electron microscopy (SEM) in fractured samples and using SEM-Back Scattering mode on polished samples, as shown in Figure 1.

- CSH has suffer a full dehydration at 400°C and the initial high density of cement paste and cohesive structure with anhydrous grains of cement is lost
- The ettringite and portlandite crystals are completely altered after dehydration
- Crack initiation and propagation in concrete can be followed with SEM at high temperature [16-18]. The temperature plays an important role in the microcracking of concrete. Cracking initiates at temperatures between 100 and 200°C and as the temperature increases, the density of microcracks increases [16, 17]. The microcrack initiation mechanism at high temperature in concrete is associated to differences in thermal expansion between cement paste and aggregates, or to differences in the local material properties and local temperature gradients. At temperatures above 300°C microcracks crossing the dehydrated CSH, through the interface with aggregates and anhydrous cement grains, become massive. The microcracks grow with the temperature increase, and become macrocracks above 500°C [16]. So that, the growth of microcracks to macrocracks is consequence of two processes dehydration reactions and thermal stresses. The evidence of the microcracking in the bulk dehydrated cement paste and interface with aggregates has been described above through the analysis of microscopy, although always after cooling [17]. The reason for the microcracking degradation process in concrete is not yet fully understood. Several investigations [6] pointed out that the deterioration of concrete is mainly caused by thermal incompatibilities of the aggregates and the cement paste matrix.
- At temperatures above 500°C aggregates as siliceous or calcareous are altered and cracks crossing the aggregates are developed. The bonding of cement paste and aggregate is also altered [16].

The above transformations, either due to dehydration processes in cement paste or differences in thermal expansion of concrete components occurring due to heating result also in evolution of porosity, the extent of which depends on the initial pore size distribution and on the type of concrete [9, 16, 17, 19, 20-24].

**Table 1.** Transformation and decomposition reactions at high temperature in the main components of concrete [4-8].

Temp. (°C)	OPC cement paste	OPC+BFS cement paste	HP cement paste	SC cement paste	Aggregate
20-80	slow capillary water loss & water expansion	slow capillary water loss & water expansion	hydration cement grains	slow capillary water loss & water expansion	
80-90	ettringite decomposition		ettringite decomposition	ettringite decomposition	
80-100	capillary water loss	capillary water loss		capillary water loss	
100-200	physically bound CSH water loss CSH decomp. formation of $\alpha$ C <sub>2</sub> SH	physically bound CSH water loss CSH decomp. formation of $\alpha$ C <sub>2</sub> SH	physically bound CSH water loss CSH decomp. formation of $\alpha$ C <sub>2</sub> SH	physically bound CSH water loss CSH decomp. formation of $\alpha$ C <sub>2</sub> SH	
200-350	katoite & $\alpha$ C <sub>2</sub> SH decomposition formation of Mayemite formation of jaffeite & $\alpha$ C <sub>2</sub> S	katoite & $\alpha$ C <sub>2</sub> SH decomposition formation of Mayemite formation of jaffeite & $\alpha$ C <sub>2</sub> S	katoite & $\alpha$ C <sub>2</sub> SH decomposition formation of Mayemite formation of jaffeite & $\alpha$ C <sub>2</sub> S	katoite & $\alpha$ C <sub>2</sub> SH decomposition formation of Mayemite formation of jaffeite & $\alpha$ C <sub>2</sub> S	
400-450	$\text{Ca(OH)}_2 \rightarrow \text{CaO} + \text{H}_2\text{O}$	$\text{Ca(OH)}_2 \rightarrow \text{CaO} + \text{H}_2\text{O}$ Less quantity		$\text{Ca(OH)}_2 \rightarrow \text{CaO} + \text{H}_2\text{O}$	
570					quartz transformation $\alpha\text{SiO}_2 \rightarrow \beta\text{SiO}_2$
650-800				filler decomposition $\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$	lime decomposition $\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$
800-1200	melting dehydrated phases		melting dehydrated phases	melting dehydrated phases	
>1200					melting aggregates



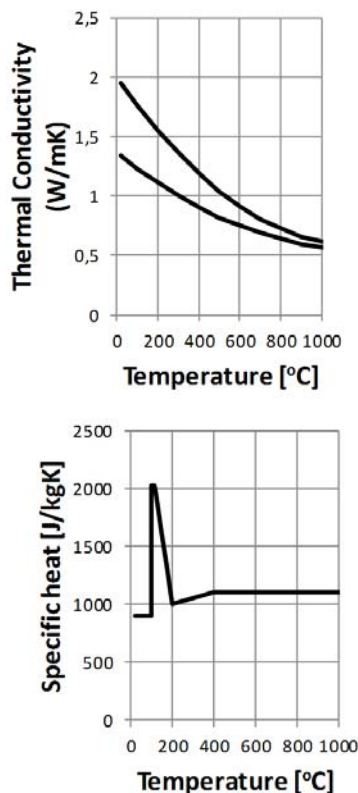
**Figure 1.** Microstructural changes in HPC after high temperature exposure. a) Dehydrated portlandite 500°C in C60 OPC concrete. b) Alteration of a gabbro aggregate and cement paste in a C70 concrete after 600°C. c) Dehydration of cement paste and anhydrous grains C60 after 500°C and d) Microcracking in dehydrated cement paste and aggregates in C90 (9%SF) concrete after 500°C. Reproduced with authorization from [16].

### 3 Thermal properties

Thermal properties have a fundamental influence on the behaviour of building materials during fire exposure as heat penetration governs the degradation of the mechanical properties and in a larger perspective the performance of the whole member or structure. The most cited set of effective thermal properties for concrete is found in the Eurocode EN 1992-1-2 (2004) [25]. However, these are effective thermal properties, meaning that they are not fundamental properties as they implicitly include effects of moisture transport and are fitted to give the best possible match between experimental data and calculations. This chapter gives a more detailed discussion on the influences on thermal properties from different factors.

#### 3.1 Thermal conductivity

Thermal conductivity is the rate of heat flow through a body of unit thickness and unit area with a unit temperature difference between the two surfaces. Regarding thermal conductivity of concrete the curves presented in the Eurocode EN 1992-1-2 (2004) [25] are an often cited resource. The curve for conductivity, shown in Figure 2a, represents an upper and a lower limit of conductivity.



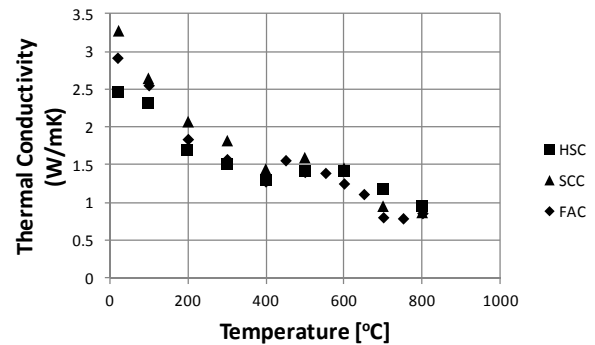
**Figure 2.** Thermal data from the Eurocode 1992-1-2 (2004) [25]. a) Temperature dependent thermal conductivity, lower and upper curve. b) Temperature dependent specific heat for concrete with 3% moisture.

The conductivity to use for normal strength and for high strength concrete is then defined inside this span in the

National annex for each European country. Important to remember when using the conductivity from the Eurocode is that it is adjusted based on results from fire testing, i.e. if using the conductivity from the Eurocode the specific heat defined in the Eurocode, shown in Figure 2b, must also be used as they were both included in this process.

There is no standardised test method for determination of high temperature thermal conductivity of concrete. Great care must be taken when using thermal data from different sources. Below 150°C the moisture content influences the thermal conductivity to a great extent. Neville [26] points out that measurements with steady state methods under moist conditions give an underestimation of the thermal conductivity due to moisture migration and he recommends the use of transient methods such as the hot wire in these cases.

In Figure 3 an example of temperature dependent thermal conductivity for three different types of HPC measured with the transient plane source method can be seen.



**Figure 3.** Temperature dependent thermal conductivity for high strength concrete (HSC), self compacting concrete (SCC) and fly ash concrete (FAC) with w/c ratios of 0.25-0.28 [27].

There is a variety of parameters that influence the thermal conductivity of HPC. Influencing parameters on the thermal conductivity of concrete are:

- Type of aggregate
- Aggregate volume
- W/C of cement paste
- Moisture content

In the cooling phase the thermal conductivity can be assumed to remain constant at the same value as at the highest temperature reached [28, 29].

#### 3.2 Heat capacity

The heat capacity or specific heat is the amount of energy per unit mass required to change the temperature by one degree. If the thermal effect of phase transitions and chemical reactions are included in the specific heat, the measured quantity is usually referred to as an apparent specific heat [6].

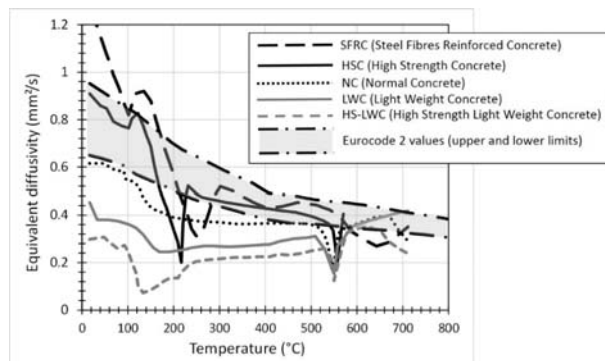
When summarising the influencing parameters Schneider & Horvath [30] found no clear effect of the type of aggregate under 800°C but at higher temperatures the apparent specific heat of calcitic aggregates rises rapidly due to

decarbonation. Rich mixes seem to give a higher apparent specific heat caused by the latent heat during dehydration and, as indicated by the specific heat curve in the Eurocode 1992-1-2 [25] shown in Figure 2b, at temperatures under 200°C the moisture content is important.

### 3.3 Thermal diffusivity

The thermal diffusivity is the rate at which temperature changes can take place i.e. this value describes how quickly a material reacts to a change in temperature.

It has to be pointed out that in practice most of the thermal analyses aimed at determining the temperature distribution inside a concrete member exposed to fire are based on the simple assumption of a heat transient governed just by conduction (Fourier's equation), with no influence of transport phenomena nor internal heat sources or sinks. Nonetheless, the effect of heat sinks due to the endothermic chemo-physical transformations (vaporisation of water; dehydration of CSH,  $\alpha$  to  $\beta$  quartz transformation; dissociation of calcium hydroxide, etc.) may be implicitly lumped into a higher equivalent value of the specific heat. Also the mass transfer due to moisture and gas migration in the porous network may contribute to an effective value of the thermal conductivity. The combination of these parameters leads to the equivalent value of the thermal diffusivity, which may be characterised as a whole via the inverse analysis of a thermal transient occurring in a simple concrete cylinder. In Figure 4 an example of the true thermal diffusivity deduced from temperature measurements performed during heating of cylinders is shown [31].



**Figure 4.** The thermal diffusivity for different concretes recalculated from experiments on cylinders [31]. The Eurocode curve in the figure is omitting the influence of water.

## 4 Mechanical properties

When it comes to justify the fire resistance of a concrete structure by calculation, by using either an engineering model (Eurocode 2 for example) or an advanced model, the temperature-dependency of the mechanical properties must be known. For an elastic calculation, assessing the modulus of elasticity is mandatory, as well as its change with temperature, which is often representative of the thermal degradation of the material. In the context of advanced calculation models, e.g. taking into account the plasticity of the material, knowledge of compressive strength, tensile

strength and degradation of the bond with the reinforcement is also necessary.

When doing an advanced calculation, the thermo-mechanical behaviour of the material under fire is simulated. Knowledge of thermal properties is therefore necessary in order to correctly simulate the heat diffusion in the material under the effect of a fire. Then, the coupling with the mechanical behaviour is usually done through the thermal expansion coefficient, obtained as the derivative of the free thermal expansion curve of the material (free means without mechanical loading). Moreover, the behaviour of a concrete element initially mechanically loaded, and simultaneously subjected to a gradual rise in temperature (as in the case of columns) strongly depends on the so-called "transient thermal strain" (TTS). This phenomenon is specific to concrete and constitutes an independent component of the total deformation under fire of a loaded structure element. It is both observed on ordinary concrete and on HPC. TTS depends on several parameters as the mechanical load level, the type of aggregates, the polypropylene fibres content or the heating scenario. The influence of these parameters is further analysed in the State of the Art. In this letter, the main aspects of TTS are first presented, then a comparison between OC and HPC is analysed.

### 4.1 Transient thermal strain of concrete

Whatever the type of concrete (OC or HPC), the mechanical strains under non-stationary heating combines thermal strain ( $\epsilon_{th}$ ) and the transient thermal strain ( $\epsilon_{tr}$ ).

It is generally agreed that the total strain of heated concrete subjected to mechanical load ( $\epsilon$ ) is equal to:

$$\epsilon = \epsilon_{\sigma} + \epsilon_{th} + \epsilon_{creep} + \epsilon_{tr} \quad (1)$$

where:

$\epsilon_{\sigma}$  is the instantaneous stress-dependent strain,

$\epsilon_{th}$  is the thermal strain,

$\epsilon_{creep}$  is the creep strain,

$\epsilon_{tr}$  is the transient thermal strain, which is the topic of this paragraph.

This assumption is in agreement with (EN 1992-1-2 Eurocode 2) standard recommendations. Assuming that classical material creep  $\epsilon_{creep}$  is negligible due to the relatively short duration of the experiment (around 10 hours), the previous equation can be written as below:

$$\epsilon_{tr} = \epsilon - \epsilon_{th} - \epsilon_{\sigma} \quad (2)$$

This expression allows the  $\epsilon_{tr}$  component to be simply assessed by measuring:

- the thermal strain ( $\epsilon_{th}$ ) of the sample,
- the thermal strain under load ( $\epsilon$ ) of the sample

Transient thermal strain strongly influences the global structural behaviour under fire, especially for structural elements in compression (columns and walls) [32]. It appears during the non-stationary heating of concrete under sustained mechanical load [5, 33-37]. It was shown that the presence of this phenomenon could relax the compressive

stresses in a column subjected to temperature [39, 40] and that this strain component can reach a high magnitude. Extensive studies of this phenomenon have been conducted for ordinary concretes by [35-38]. More recent studies have been carried out, principally for HPC, in order to assess and understand contributing mechanisms of transient thermal strain activation. Particularly, the experimental parametrical studies of transient thermal strain on HPC [2, 39, 41-43, 45-48] examined the influences of several parameters: load level, original compressive strength of concrete, the nature of aggregate, fibres, the heating scenario and the initial moisture content. As the results indicate, water in cement paste plays a substantial role in the development of transient thermal strains. In the following, TTS is compared between an ordinary concrete and a HPC.

## 4.2 HPC versus OC

Thermal strain, thermal strains under load and transient thermal strains for a HPC ( $f_c = 120.7$  MPa, calcareous aggregates) and for an OC ( $f_c = 39.3$  MPa, calcareous aggregates) are presented and compared in Figure 5 (results from [45] described in detail in [41, 43]). In the lower graphs, transient thermal strain curves are presented as a result of subtraction of thermal strain values from the thermal strains under load. First, it can be observed that thermal strains of those two concretes are quite close, due to the same type of aggregates used for both concretes. From 20°C to about 400°C, the thermal strain curves are almost linear. Above 400°C the strains increase more rapidly due to crack development in both concretes.

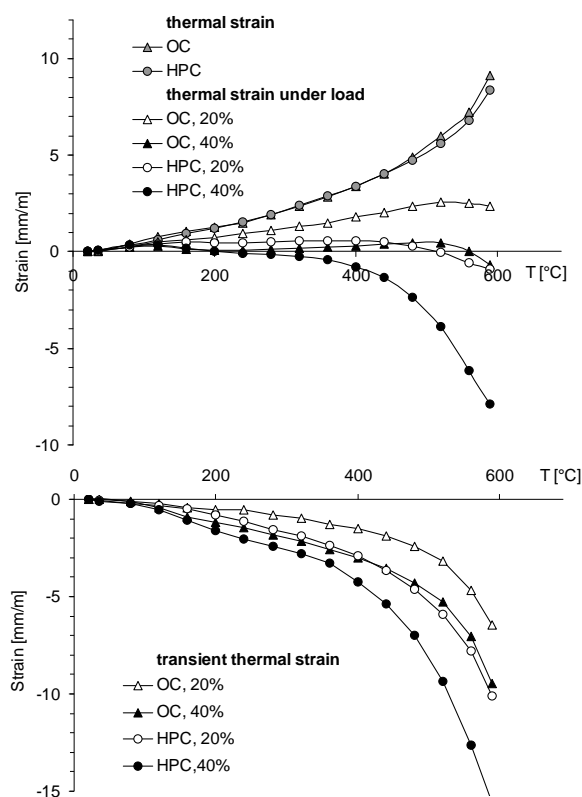
Although the thermal strain of both concretes are quite similar, significant differences are observed for TTS. Indeed it can be observed that transient thermal strains is significantly more important in HPC concrete. More results are needed in order to explain the concrete-type dependency of TTS. It may be explained by transfer properties (since TTS relies on water movement into the porous media). At all events, these results clearly show that the structural response of a concrete structure when exposed to fire can strongly differ depending on the type of concrete. In the case of HPC, the TTS component is non negligible and has to be taken into account when doing a calculation.

## 5 Conclusions

This letter anticipates some highlights on the behaviour of HPC at high temperature which will be presented in a much more detailed way in a State of the Art to be published in the next months.

Qualitatively, the behavior of HPC does not differ much from that of ordinary concrete, except for the spalling phenomenon which will be addressed in a future letter. Nevertheless, owing to its denser microstructure, its lower free water content and its higher volume of unhydrated cement particles, the kinetics and extent of the various microstructural and chemical changes of HPC display some particularities. Furthermore, these mixes often contain specific constituents for example silica fume – a key

component to reach compressive cylinder strength above 70/80 MPa – or polypropylene fibers, the most common solution to prevent or limit spalling.



**Figure 5.** Thermal strains, thermal strains under load and transient thermal strains for HPC and OC (results from [41, 42], reproduced with authorization from [42]).

The State of the Art will especially target a group of users composed by Universities and testing laboratories, building material companies and industries, material scientists and experts, building and infrastructure authorities, designers and civil engineers and standardisation bodies.

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The State of the Art is dedicated to the memory of Prof. Ulrich Schneider. Prof. Schneider was the first chairman of the RILEM HPB Technical Committee.

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