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Influence of the thermomechanical loading on the behavior of high performance concrete and ordinary concrete

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Abstract. The present article aims to present an experimental study to investigate the behavior of high performance concrete and ordinary concrete that were subjected to thermomechanical loading. The mechanical properties of both types of concrete, which underwent heat treatment, were studied at room temperature. In addition, the compressive strength was tested and calculated at different ages, namely 7, 14, 28 and 60 days. For each test, the samples were heated at a rate of 5 °C/min, until the following temperatures were reached, i.e. 250 °C, 350 °C, 450 °C, 600 °C and 900 °C. The target temperature was kept constant for one hour in order to ensure that it was uniform throughout the sample, before cooling. Moreover, the sample weight was measured before and after heating in order to determine the weight loss of the samples tested. The findings allowed concluding that the mechanical characteristics of concrete were enhanced after exposure to temperatures within the range from 250 °C to 450 °C.

Key words: High Performance Concrete; Ordinary Concrete, Thermomechanical Loading; Constraint/Deformation; Elastic modulus; Ultrasound.

1. Introduction

It is worth indicating that a quite large number of studies on high performance concrete subjected to thermomechanical loadings are currently available in the literature. For example, that has previously been carried out by Bouabdallah (2006, 2008), Horszczaruk et al. (2015), Torelli et al. (2020), Noumowé (1995), Drzymała et al. (2017), and Tsimbrovska (1998). In particular, Simonin (2000) investigated the effect of thermomechanical loading on the behavior of refractory concretes.

On the other hand, several research works were performed in order to examine the influence of temperature on recycled concrete aggregates (Liu et al., 2018). Similarly, a number of researchers in the field attempted to investigate the behavior of prestressed concrete subjected to high temperature gradients (Dubois et al., 1967). Furthermore, Nguyen et al. (2019) performed a study on the thermomechanical behavior of reinforced concrete samples at high temperatures. Moreover, Alarcon-Ruiz (2003) analyzed the effect of temperature on concrete microstructures. With regard to the recycling of building materials, it is worth mentioning the work of Prajapati et al. (2021) and Liu et al. (2018) who sought to examine the effect of temperature on recycled concrete aggregates. Further, several numerical simulations were performed on various types of concrete. In this context, Courivaud et al. (1997) carried out a study on cellular concrete that was subjected to a vapor pressure gradient at high temperatures. In the same context, Douk et al. (2021) carried out a numerical investigation of the thermomechanical behaviour of concrete beams with and without textile-reinforced concrete (TRC) strengthening. On the other hand, another research was carried out by Yermak (2015) on the behavior of concrete incorporating fibers and exposed to high temperatures. In the same context, Nastica (2019) investigated the shrinkage and creep strains of concrete subjected to low relative humidity and high temperature environments. Further, other similar studies were also carried out in the same field.

The present work aims primarily to conduct an experimental study on the behavior of ordinary concrete (OC) and high performance concrete (HPC) that were subjected to thermomechanical loadings. In order to carry out this study, it was decided to prepare a series of test specimens from ordinary concrete and high performance concrete. These test pieces were then exposed to different temperatures, i.e. 20, 250, 350, 450, 600, and 900 °C. This experimental study was carried out at different ages, i.e. 7 days, 14 days, 28 days and 60 days. It should be noted that the thermomechanical loading tests were carried out after cooling the specimens to reach ambient temperature. The results obtained concern the evolution of the compressive stress of ordinary concrete and high performance concrete as a function of temperature at different ages, the evolution of mass loss of ordinary concrete and high performance concrete as a function of temperature and age. Afterwards, these results were compared with those obtained at room temperature (20 °C).

2. Experimental study

2.1. Materials used

Portland cement type II CEM II A 42.5 was used, with limestone gravel 3/8 and 8/15, Crushed sand 0/5 and siliceous sea sand 0/1.

Table 1. Characteristic of the cement used

Identification	Cement class	Type of addition in cement	Clinker %	Density
CP	CPJ 42,5	Pozzolanic (6 - 20 %)	80 - 94 %	3,1

Table 2. Characteristic of the materials used

Test		Gravel 8/15 mm	Gravel 3/8 mm	Crushed sand	Sea sand
Densities		2,735	2,727	2,714	2,642
Absorption Coefficients		1,52	1,75	2,65	2,11
Los Angeles		23,56		-	-
Sand Equivalent Test	ESV	-	-	76,86	72
	ESP	-	-	70,53	67,69

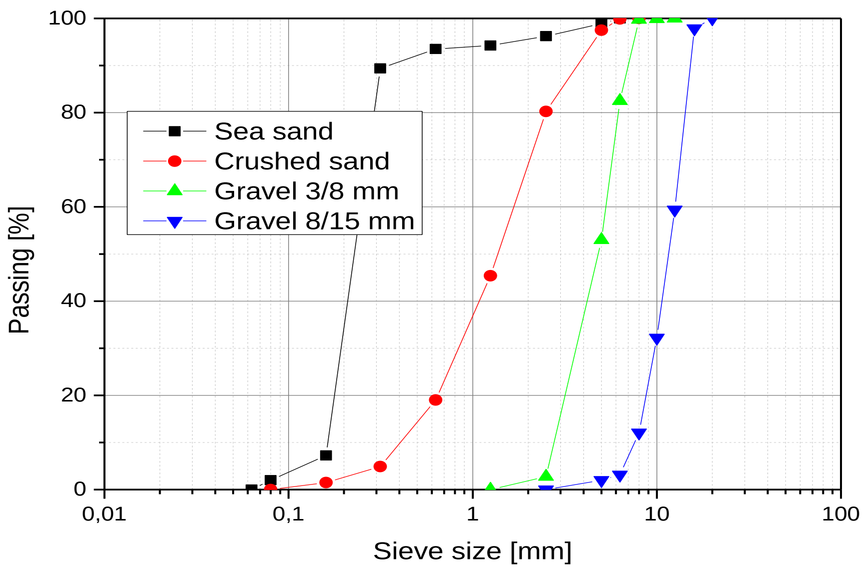

Fig 1. Particle size curve.

2.2. Formulation of concretes

Table 3 illustrates the composition of the different types of concrete.

Table 3. Composition of concretes under study

Constituents (Kg/m^3)	Ordinary Concrete "OC"	HPC
Gravel 8/15 mm	777	
Gravel 3/8 mm	415	1011
Crushed sand	372	-
Sea sand	372	722
CPJ Cement	353	400
Pozzolana	-	40
Plasticizer, [2,5 % by weight of cement]	-	10
fine limestone	-	72.2
Total amount of water	172	140
Water/cement ratio	0.49	0.29
Slump test [cm]	8	15

2.3. Equipment

It is worth noting that the thermal loading of both types of concrete specimens, of dimensions (7x7x7) cm^3, was carried out using an electric furnace SCM 011, of internal dimensions (130x120x270) mm^3, and whose temperature can reach a maximum value of 1200 °C, as shown in Figure 2.

Fig 2. Furnace 1200°C (SCM 011).

2.4. Thermal loading

We have taken into account the damage caused by the thermal gradients that developed between the core and the surface of the specimen during the different heating phases, with a rate of 5°C/min and a plateau of 1h 30min, in order to get as close as possible to the situation of real fires. During the cooling phase, the cooling rates should be sufficiently slow, similar to cooling in the open air.

The bearing temperatures were 250°C, 350°C, 450°C, 600°C and 900°C. The choice of temperatures was made according to the following description. The temperature range from 250 °C to 350 °C corresponds to small endothermic peaks, indicating the effects of decomposition and oxidation of metallic elements (ferric). At the temperature 400°C, there is portlandite decomposes and gives free lime. At 600°C, the C-S-H phases decompose and cause the formation of β-C2S. In the second step, there is dehydration of the hydrated calcium silicates and therefore engender a new form of calcium silicates. Finally, at 900°C, there is decomposition of calcium carbonate. Limestone decomposes at around 800 °C. A strongly endothermic reaction takes place and releases carbon dioxide (Noumowé, 1995).

For each material, a test was carried out on unheated specimens in order to have a reference value (20°C ± 2).

The heating-cooling cycles therefore have the following form:

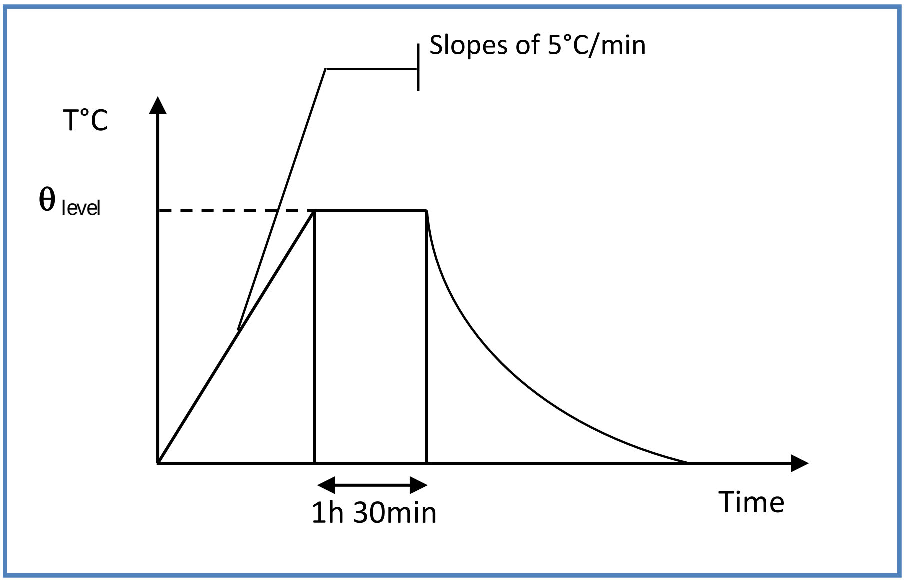

Fig 3. Pattern of heating-cooling cycles.

3. Results and discussion

3.1. Density of concrete

Figures 4 (a), (b), (c), and (d) were utilized to make a direct comparison between the weight changes of both types of concrete. These weight variations were measured on the prepared specimens, at different ages, during the same heating cycle, with the heating rate of 5 °C/min. These changes were recorded for different temperatures. It is important to mention that the ambient temperature was taken as the reference temperature (temperature before placing the sample inside the oven) in order to accurately assess the reduction in weight after heating.

Furthermore, it is worth noting that the weight of each concrete specimen went through three distinct phases that are described below:

- In the first phase, for temperatures between 20 °C and 250 °C, a rapid decrease in the test piece weight was observed as the temperature went up.
- In the second phase, corresponding to temperatures between 250 °C and 600 °C, a slight decrease in the weight of the test piece was noted.
- In the third phase, between 600 °C and 900 °C, a weight change, similar to that observed in the first phase but more important, was noticed. The weight loss results mainly from the evaporation of the water existing inside the concrete through cracks caused by the expansion of concrete.

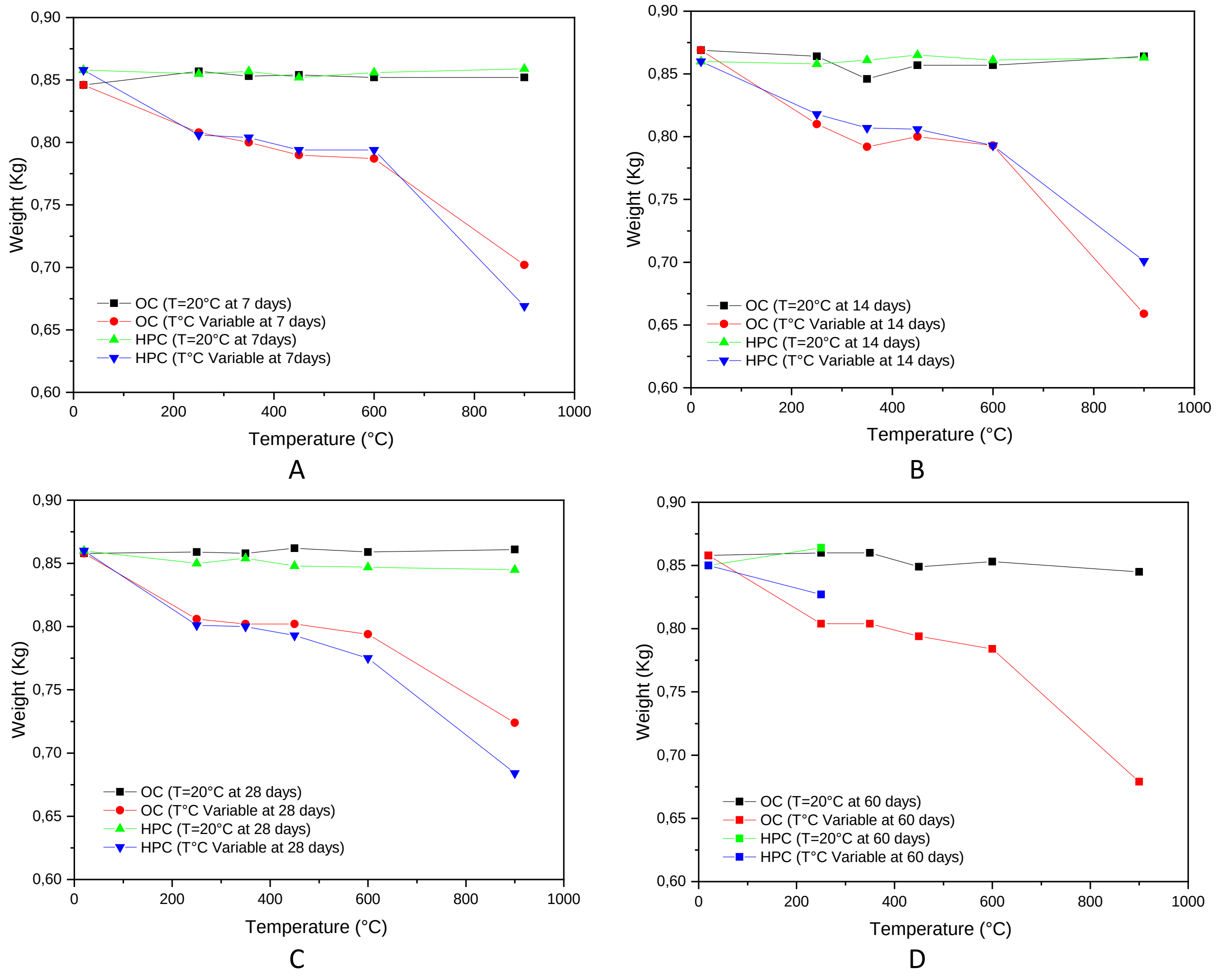

Fig 4. Evolution of weight of ordinary concrete and high performance concrete as a function of temperature.

3.2. Mass loss of concrete

Likewise, Figures 5 (a), (b), (c) and (d) present a direct comparison of the evolution of mass loss values for both types of concrete (OC and HPC), at different ages (7 days, 14 days, 28 days and 60 days), during the same heating cycle. The heating rate was equal to 5 ° C/min. The mass loss rates were recorded as a function of temperature. It was observed that the loss of mass of each concrete specimen went through three distinct phases:

- In the first phase, the mass loss of the test piece increased rapidly as the temperature went up to reach 250 °C.
- In the second phase, which corresponds to temperatures between 250 °C to 600 °C, the mass loss of the test piece continued to increase slowly.
- The third phase corresponds to temperatures above 600 °C; here the mass loss increased significantly again, in a similar manner as in the first phase.

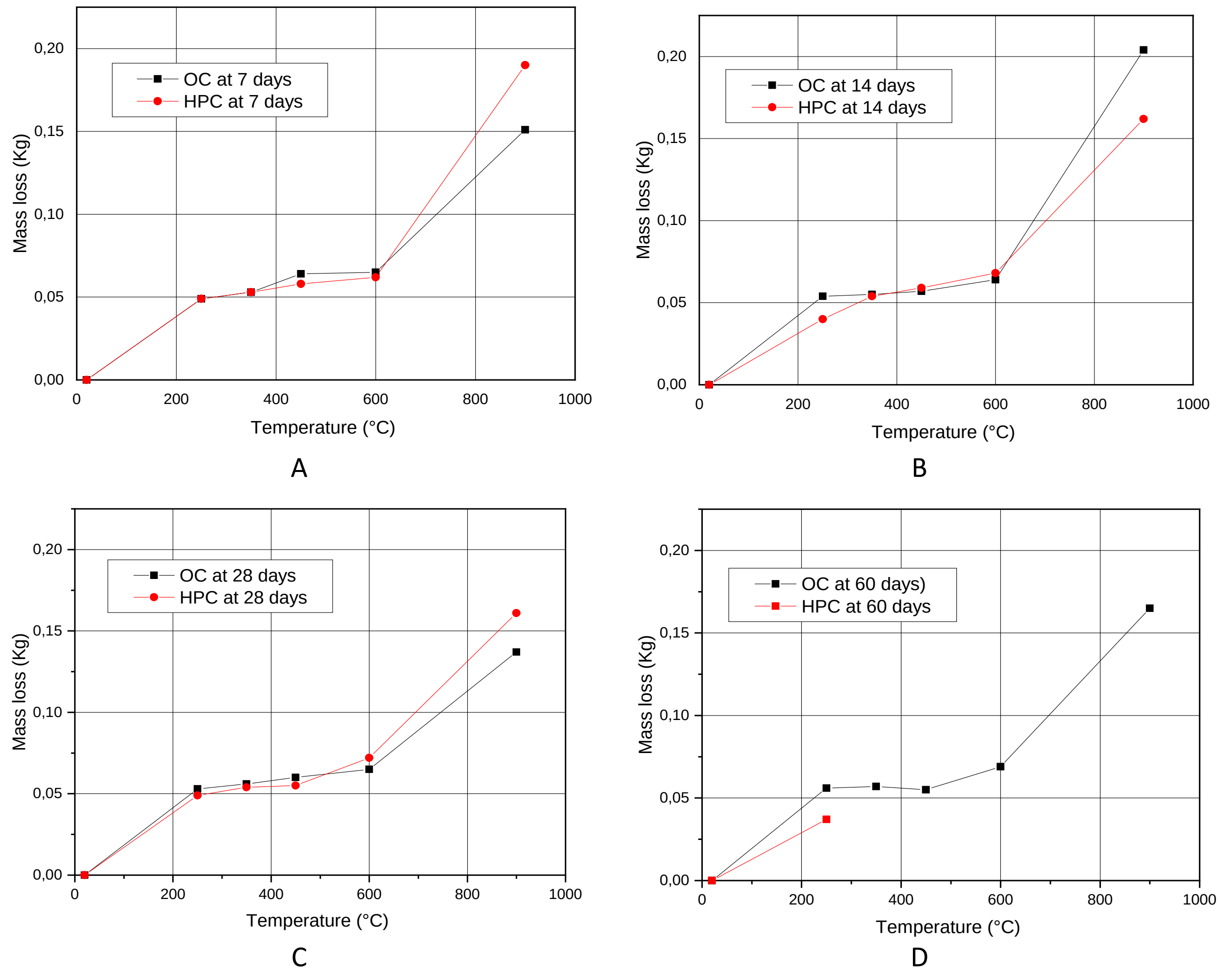

Figure 5. Variation of mass loss as a function of temperature.

3.3. Compressive strength as a function of temperature and age

Figures 6 (a), (b), (c) and (d) display the evolution of compressive stress as a function of temperature, for different ages (7, 14, 28, and 60 days). Simple comparison of the results obtained indicates that the compressive strength of high performance concrete is significantly higher than that of ordinary concrete. It was also observed that for the two types of concrete under study, as the temperature increased, the compressive strength went up until reaching the maximum threshold value. Beyond this maximum value, the compressive strength started to decrease, though the temperature was still increasing.

Figure 6 (a) clearly shows an increase in compressive strength for the temperature range between 20 °C and 250 °C for ordinary concrete, and between 20 °C and 350 °C for high performance concrete. Figure 6 (b) indicates that the compressive strength went up while the temperature dropped between 20 °C and 450 °C for ordinary concrete, and between 20 °C and 350 °C for high performance concrete. With regard to Figure 6 (c), it shows that the compressive strength was rising proportionally with temperature between 20 °C and 250 °C for ordinary concrete, and between 20 °C and 350 °C for concrete high performance. Finally, in Figure 6 (d), one may easily see compressive strength increase for temperatures between 20 °C and 250 °C for ordinary concrete, and between 20 °C and 250 °C for high performance concrete. Beyond these temperatures, the compressive strength started to drop though the temperature was still increasing.

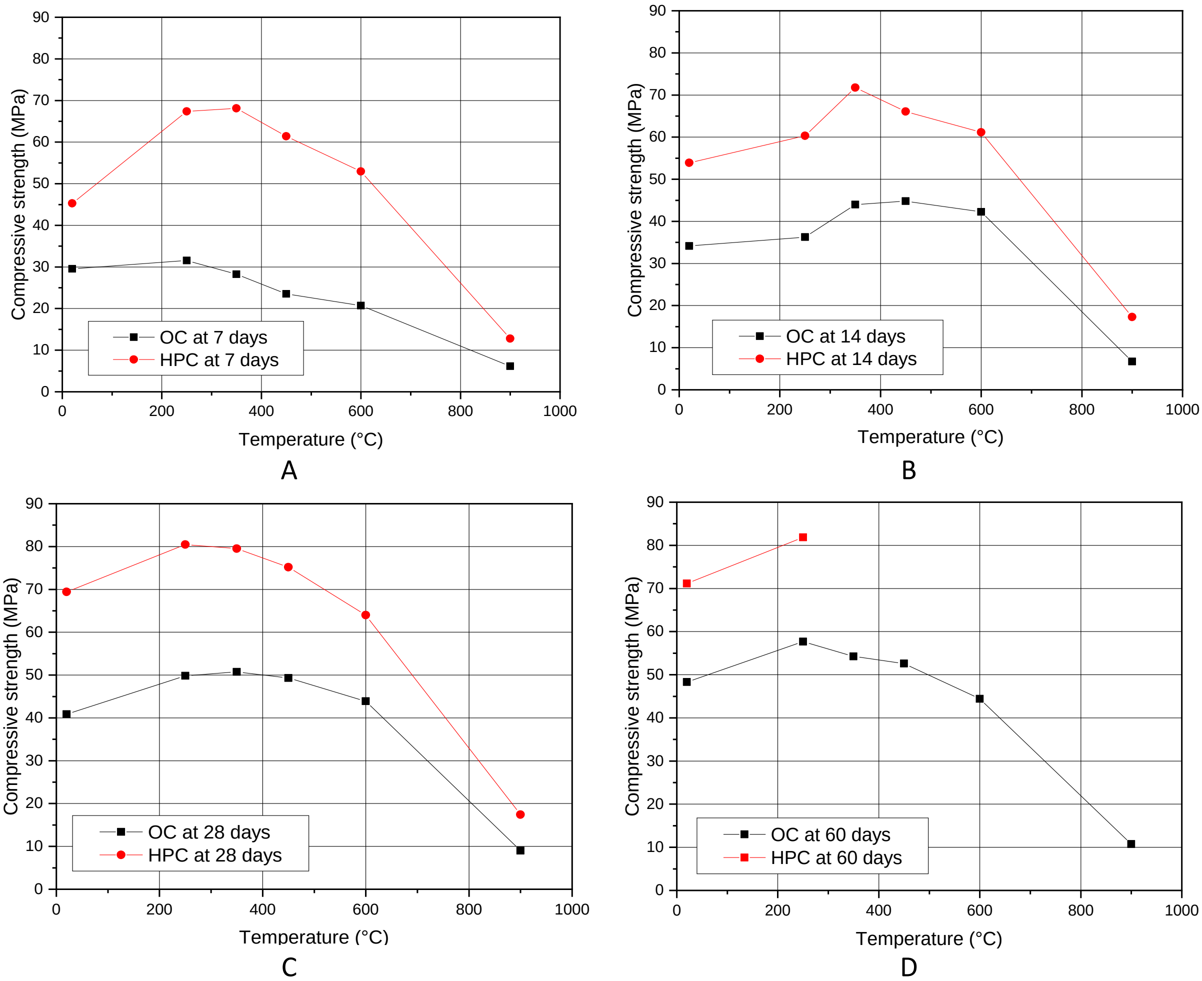

Fig 6. Evolution of the compressive strength as a function of temperature.

3.4. Variation of deformation as a function of applied stress

The deformations of the specimen were measured as a function of the uniaxial compression. Two 1/100 comparators were placed on the press plate to measure the uniaxial displacement, as is clearly shown in Figure 7.

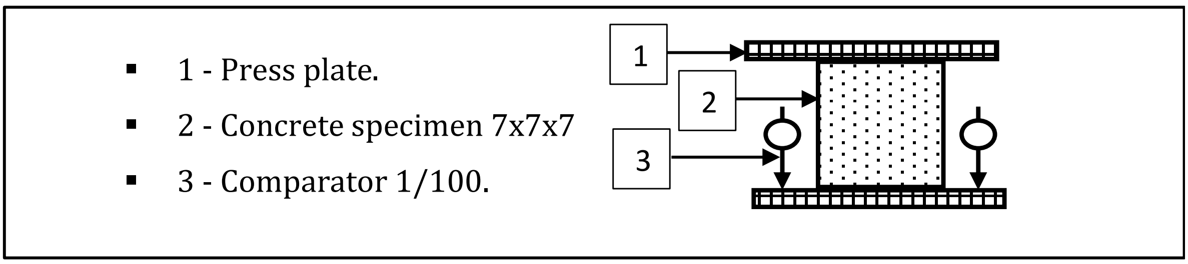

Fig 7. Apparatus used to measure the longitudinal deformations of the specimens subjected to uniaxial compression.

The displacements were observed on each comparator. The average of the values given by the two comparators represents the uniaxial displacement of the specimen. The deformations of specimens 7x7x7 cm were calculated using the following expression:

$$\varepsilon = \frac{\Delta l}{L} \qquad \text{Eq 01.}$$

- ε: relative compressive deformation.

- Δl: displacement.
- L: length of the test piece 7 cm.

Furthermore, Figures 8 (a), (b), (c) and (d) show the evolution of deformations of ordinary concrete as a function of stress, for different temperatures. It was observed that the concrete deformations observed at 7 days were greater than those recorded at 14, 28 and 60 days. In addition, it was noticed that at 7 days, the compressive strength was very low compared to those obtained at 14, 28 and 60 days. This can be explained by the fact that the compressive strength increased and the deformation decreased with age, which allows saying that age has a positive effect on the evolution of the compressive strength.

On the other hand, it was noted that beyond 14 days, the compressive strength of the test pieces, subjected to temperatures 250 °C, 350 °C and 450 °C, increased while deformations decreased in comparison with those observed at the reference temperature (room temperature 20 °C). It should be mentioned that at the temperature of 600 °C, concrete became very deformable, although the compressive strength was increasing. Beyond this temperature, i.e. at 900 °C, the compressive strength began decreasing and the deformations increased considerably.

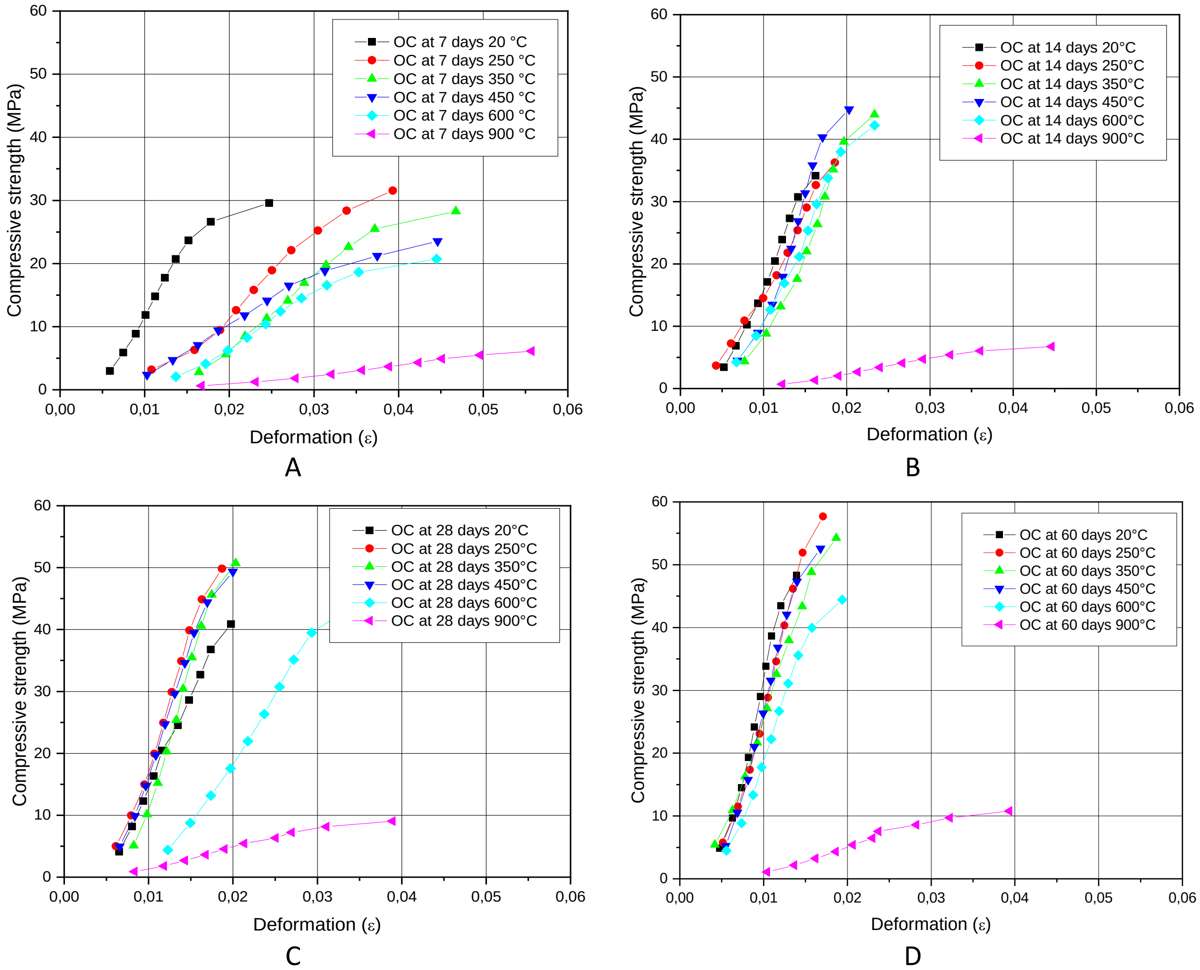

Fig 8. Evolution contrainte/déformation du béton ordinaire, at 7, 14, 28 and 60 days.

Figures 9 (a), (b), (c) and (d) present the evolution of deformations of high performance concrete as a function of stress, at different temperatures. It was observed that the compressive strength values of high performance concrete increased remarkably at temperatures 250 °C, 350 °C and 450 °C, for all ages, in comparison with those obtained at room temperature (20 ± 2) °C. Note also that at the temperature of 600 °C, the compressive strength increased and caused much larger deformations than those observed at ambient temperature. Above this temperature, i.e. 900 °C, a very large deformation, and a very low compressive strength, were recorded.

The curves of Figure 10, obtained at 7, 14 and 28 days, at the temperature of 250 °C, allow concluding that the heat treatment of high performance concrete (HPC) increased the compressive strength but decreased deformations.

The same phenomenon, i.e. high compressive strength and low deformation, occurred at a temperature of 350 °C, at 7 and 14 days.

Furthermore, the stress/strain curves indicate that at 7 days the elastic phase of high performance concrete and ordinary concrete ends at 80% of the breaking load. Then, after, the material enters the plastic phase. For the other ages, namely at 14, 28, and 60 days, the elastic phase ends at 90% of the breaking load. The plastic phase begins immediately after. Phenomenon of bursting at 60 days for HPC; The bursting and explosive behavior of high performance concrete was observed at 60 days for HPC (figure 9 (d)). This behavior may be attributed to temperatures within the range between 250 °C and 450 °C.

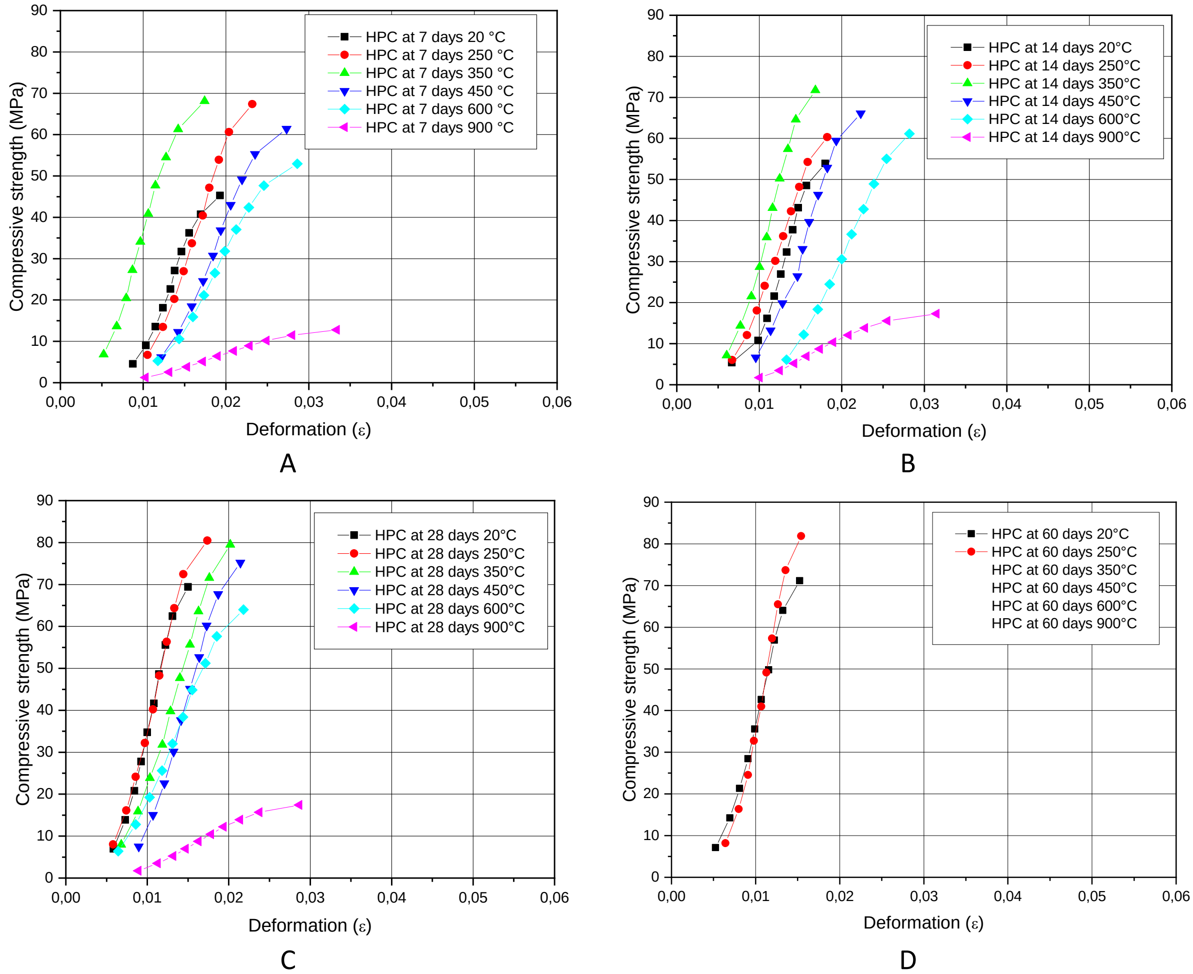

Fig 9. Evolution of the compressive strength as a function of deformation, at 7, 14, 28 and 60 days.

4. Conclusion

This experimental study made it possible to highlight the influence of thermomechanical loading on the behavior of ordinary concrete and high performance concrete. In addition, the thermal loading was carried out at different temperatures (250, 350, 450, 600 and 900 °C). This thermal loading was done at the rate of 5 °C/min, while keeping the temperature constant for a period of

1h30min. The findings of the present study allowed drawing the following fundamental conclusions:

- The mass loss of high performance concrete at the temperature of 600 °C was significantly greater than the initial quantity of water. This suggests that in addition to water, there were other constituents that escaped from concrete.
- The two temperatures 250 °C and 350 °C had a positive effect on high performance concrete. Indeed, a compressive strength increase was observed in the samples that underwent heat treatment.
- The bursting and explosive behavior of high performance concrete was observed at 60 days. This behavior may be attributed to temperatures within the range between 250 °C and 450 °C. The bursting of concrete can be manifested by the detachment of pieces of concrete, one after the other, or by explosive spalling of a structural element.

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