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Moisture Migration and Thermo-mechanical behaviour of Concrete at High Temperature up to 310 °C

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Abstract

Ordinary concrete and high strength concrete have been used in situations in which they may be exposed to elevated temperatures. Concrete is also used in the construction of radiation shielding structures. Data on the concrete behaviour at high temperature is of concern in predicting the safety of buildings and constructions in response to certain accidents or particular service conditions. Prediction of mechanical behaviour, thermo-mechanical deformations and moisture migration in non-uniformly heated concrete is important for safe operation of concrete containment.

Experimental investigations were carried out on the behaviour of a concrete intended for nuclear applications. The tested concrete was subjected to heating – cooling cycles at 110 °C, 210 °C and 310 °C. Thermal, hygral and mechanical properties were analysed on 110x220 mm cylindrical specimens. This paper presents the results on :

- thermal gradient in the concrete specimens during the heating-cooling cycles,
- cement mortar dehydration, moisture migration and moisture escape from the concrete during the heating – cooling cycles,
- concrete deformation as result of the coupled heat and mass load,
- thermal stability of the tested concrete at high temperature,
- compressive strength, modulus of elasticity and splitting tensile strength of the tested concrete before and after the heating – cooling cycles.

This investigation develops some important data on the properties of concrete exposed to elevated temperatures up to 310 °C. Comparisons and interesting conclusions were drawn about the thermal stability at high temperature and the residual mechanical properties of the tested concrete.

Keywords : concrete, temperature, strength, modulus of elasticity, thermal conductivity, porosity, deformation.

Introduction

The global behaviour of a structure submitted to high temperatures is mainly related to thermo-mechanical effects (stress distribution, cracking). The local behaviour (spalling, surface micro-cracking, …) is rather linked to hydro-mechanical couplings. Water distribution and transport whether in a gaseous or liquid form plays therefore an important role in the local damage of concrete structures. For example, the level of saturation of concrete strongly modifies its permeability [1, 2] and consequently the pore pressure distribution. Drying generates humidity gradients which in turn induce strains, especially on the skin of concrete. During heating, the endothermal nature of vaporization creates locally high thermal gradients which can lead to tensile stresses exceeding the concrete strength [3]. The escape of water chemically bounded in the Calcium Silicate Hydrates (CSH) leads progressively to the failure of concrete for temperatures over 450°C. The type of aggregates influence strongly the behaviour of concrete submitted to high temperature. The aggregates thermal expansion is partly opposed to the drying of cement paste. This phenomenon makes it possible to think that limestone aggregates whose thermal coefficient of expansion is lower than that of siliceous aggregates is more favourable to the behaviour at high temperature of concrete. [4]. Recent studies showed a weak influence of the kinetics and durations of heat treatment on the residual properties of the concrete [1, 2, 5]. The present study investigated the effects of a short thermal load on concrete containing limestone aggregates for three temperature levels : 110°C , 210°C and 310°C. Several concrete properties were investigated : the evolution of the thermal gradients and strains in concrete during heating – cooling cycles, the evolution of the concrete residual properties after heat treatment.

Test Schedule

Materials

The concrete used is a standard concrete of 40 MPa of compressive strength containing limestone aggregates and CEM I PM ES CP2 cement. The concrete is indicated on table 1. The water/binder ratio is 0.43 and the aggregates/sand ratio is 1.1. This type of concrete is very workable (the slump test result was about 20 cm) and can be pumped easily. About thirty specimens were made including four specimens with type K thermocouples inserted in the centre and the surface of the specimen. Figure 1 indicates the positioning of a thermocouple to the centre of a specimen at the time of its manufacture. For the compression tests, the 110x220 mm cylindrical specimens were cut up.

FIGURE 1 : Installation of a thermocouple at the time of the specimen casting

TABLE 1 : Components quantities for 1 m^3 of concrete

	Val d'Azergues cement CEM I PM ES CP2 (France)	Sand 0/4 limestone Boulonnais (France)	Aggregate 5/12.5 limestone Boulonnais (France)	Water	Plasticizer Glénium 27 Marque
Mass (kg)	400	858	945	171	10

Thermal loading and experimental device

The specimens were heated at a heating rate of 0.1°C per minute up to 110 °C, 210°C or 310°C. The temperature of the furnace was maintained at the target temperature during 30 minutes. Then the specimens were cooled gradually (at a cooling rate of about 1 °C per minute) at the ambient temperature. The furnace is ventilated and offers a useful volume of almost 1 m^3. The specimens were heated by batches of six. For each level of maximum temperature, one specimen is equipped with two gauges to measure vertical deformation and two gauges to measure horizontal deformation. A PID controller ensures the thermal regulation of the furnace. The data were recorded on a microcomputer via an automatic data acquisition apparatus. The specimens that were cured in watertight bags during 28 days were weighed before and after the heat treatment. For each batch, the weight of the specimen equipped with gauges and thermocouples were recorded during the heating – cooling cycle by means of an electronic balance connected to the microcomputer. The specimen equipped with gauges and thermocouples was put in a basket and hanged to a balance. The balance was outside the furnace. Figure 2 shows an equipped specimen in the basket. After the heating – cooling cycles, measurements of porosity (by means of mercury porosimetre) and thermal conductivity were carried out.

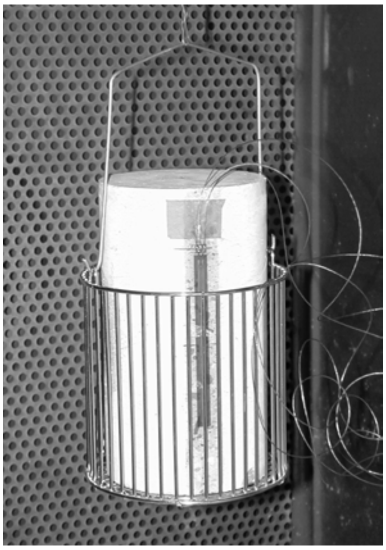

FIGURE 2 : Specimen equipped with gauges and thermocouples

Results and discussion

- Thermal gradient and mass loss

During the heating – cooling cycles, the temperature at the centre and at the surface of the cylindrical specimens were measured. The temperature difference between the surface and the centre of the specimens was calculated. The specimens mass losses were measured during the heating – cooling cycles. One noticed a similar evolution of the thermal gradient in the specimen and the derivative to the time of the specimen mass loss. This seems to confirm that thermal gradient is directly an effect of the mass transfer (liquid water, vapour). The vapour pressure is the thermodynamic force which induces water and vapour transfers in concrete therefore specimen mass loss. Figure 3 presents the evolution of temperature difference between the surface and the centre of the specimen and also the evolution of derivative to the time of the specimen mass loss.

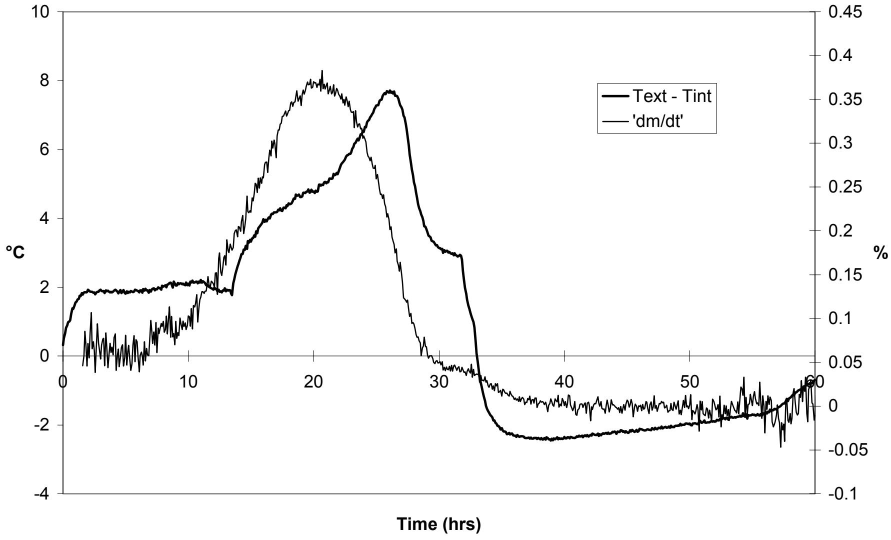

FIGURE 3 : Temperature difference between the centre and the surface of the concrete specimen and derivative to time of the mass loss expressed as a percentage in function of time for the test at 210°C.

For the test at 110°C, the temperature difference between the centre and the surface of the concrete specimen did not exceed 6°C during the heating and 3°C during the cooling. On the other hand, for the tests at 210°C and 310°C, one observes a sharp increase of temperature difference (then thermal gradient) between 100 and 174°C (more than 7°C), then a sharp decrease of this temperature difference. For the specimens heated up to 210°C and 310°C, the mass loss curves show an increase in the kinetics of dehydration until 140°C followed by a strong decrease until 190°C.

The mass losses of all the specimens were relatively homogeneous (standard deviation lower than 0.35%). The mass loss recorded between 20 and 300 °C corresponds to the concrete dehydration. The free water in concrete was evacuated during the heating between 20°C and 110 °C. If one continued the heating until 210°C or 310 °C, a part of water in hydrated products like HCS escaped. It was noticed that the water loss for the specimens heated at 110°C was three times lower than that measured on the specimens heated at 210°C and 310°C. That confirms the small proportion of free water in this concrete compared to the hydrates water.

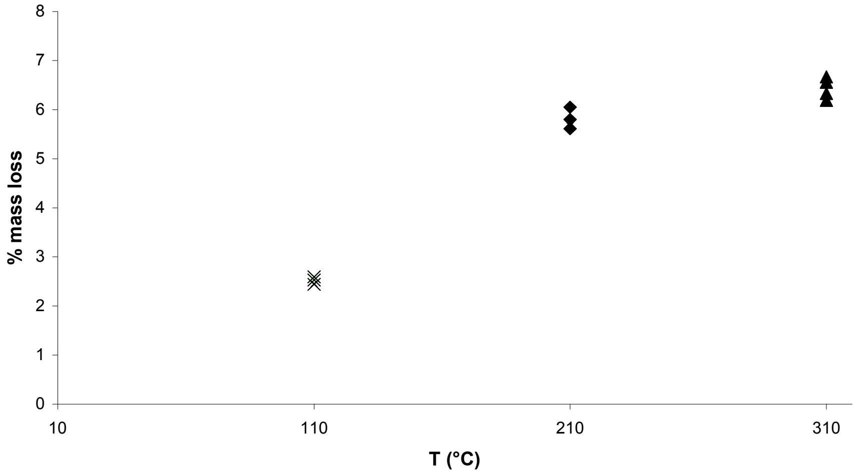

FIGURE 4 : Total mass loss expressed as a percentage of the initial specimen mass for the tests at 110°C, 210°C and 310°C.

- Deformations

The deformations were measured on the surface of the specimens during the heating – cooling cycles. For the test at 110°C, the measured total deformations are proportional to the temperature (figure 5). At about 110°C, disturbances appeared. They were probably due to a superposition of the water vaporization and other phenomena like cement paste shrinkage and aggregates expansion.

The temperature range from 100°C to 110 °C corresponds to the highest thermal gradients. The thermo-mechanical effects were very important and leaded to this behaviour. At the end of the test, positive residual deformations showed the shortening of the specimen which dried.

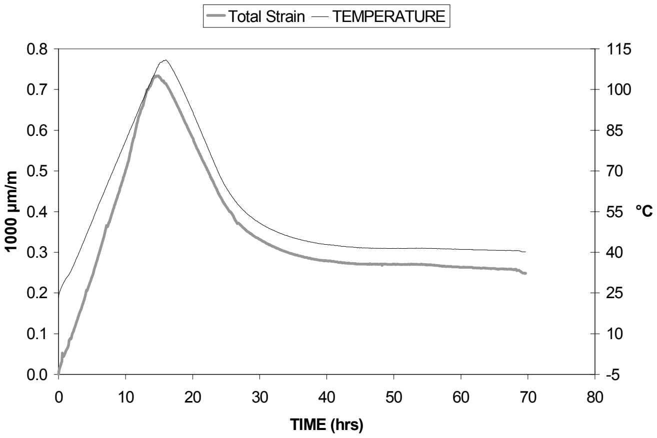

FIGURE 5 : Total orthoradial deformation and temperature at the surface of the concrete specimen during the test at 110°C

Figure 6 presents the evolution of deformation and temperature at the surface of the specimen during the heating - cooling cycle at 310°C. For the tests at 210°C and 310°C, the thermal gradients were more important and generated the appearance of high compressive stresses at the specimen surface during the heating. These stresses combined with degradations of the cement paste leaded to a damage of the concrete which resulted in abrupt variations of the deformation during the thermal loading

During the cooling, the thermal gradients were reversed. The centre of the specimen being hotter than the surface. There were compressive stresses at the centre of the specimen, the surface of the concrete being in tension. One observes on figure 6 that the slope of the curve of deformation in function of temperature (in function of time due to the linearity of the temperature and time) is higher between 140°C and 310 °C than that between 20°C and 140°C. This seems to be due to the beginning of dehydration of HCS which modifies the concrete microstructure.

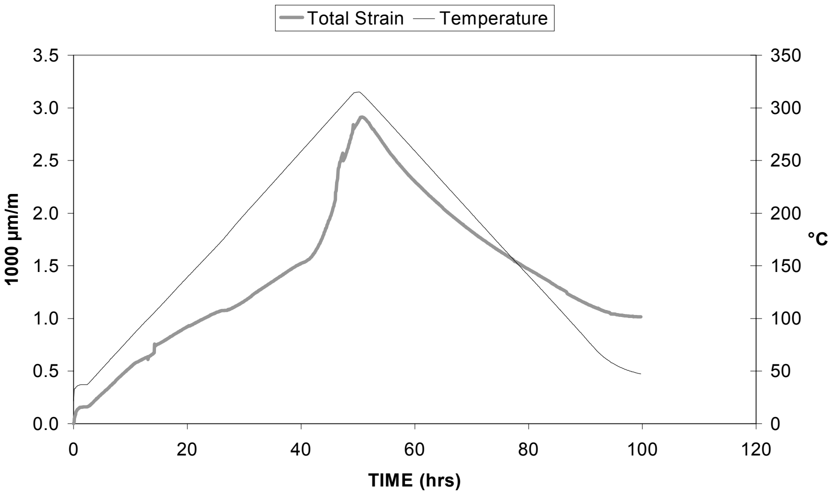

FIGURE 6 : Total orthoradial deformation and temperature at the surface of the specimen during the test at 310°C.

- Residual Mechanical Properties

Measurements of compression strength, splitting tensile strength and modulus of elasticity were carried out on the specimens before and after heat treatment. The tendency which one can draw from these various measurements is that the degradation of the mechanical properties of this concrete between 20 and 110°C was very limited. From 210 °C, one noticed a significant evolution of the modulus of elasticity (-35%) presented on figure 7 and of splitting tensile strength (-13%) presented on figure 8. The compressive strength decrease was 7 % for the test at 210°C and 35 % for the test at 310°C (see figure 9).

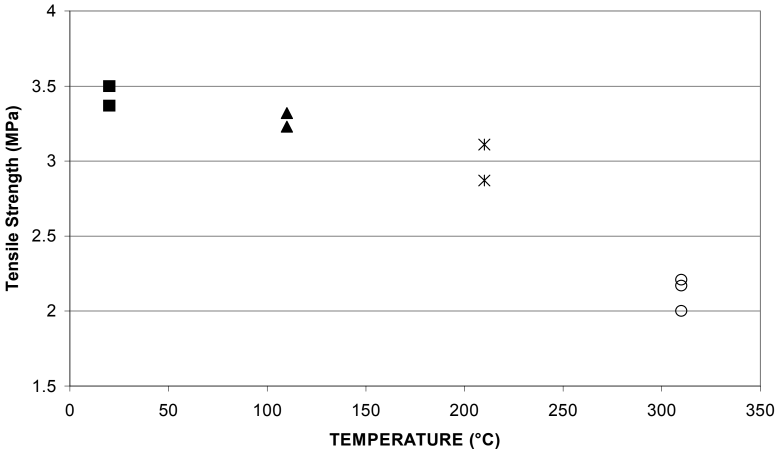

FIGURE 7 : Splitting tensile strength for the 4 batches of specimens.

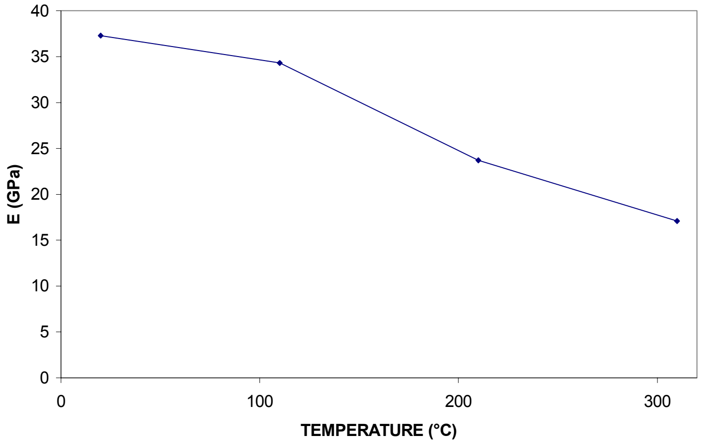

FIGURE 8 : Residual modulus of elasticity in function of temperature

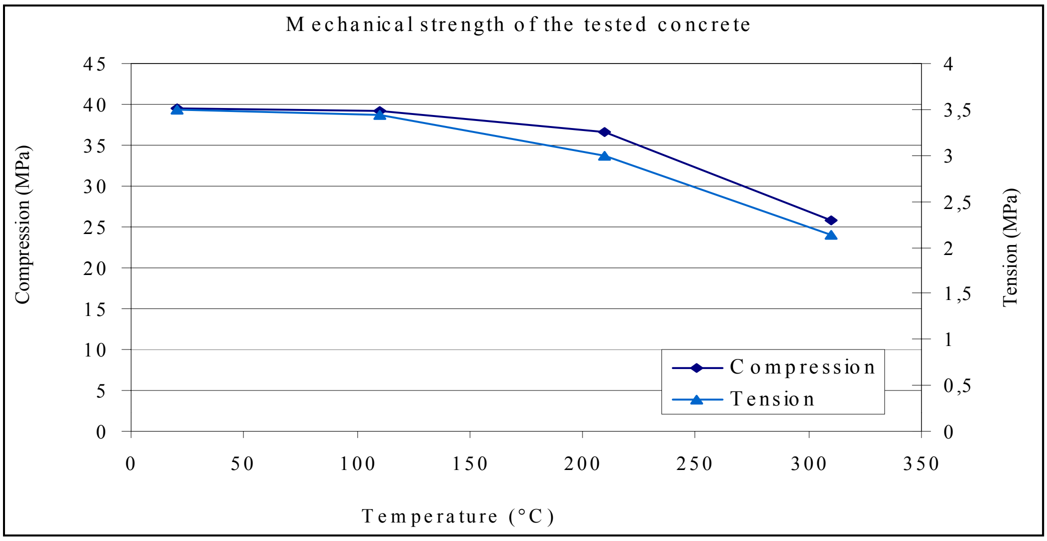

FIGURE 9 : Residual compressive strength in function of temperature

- Thermal conductivity

The thermal conductivity of the studied concrete was measured before and after the heating – cooling cycles. The results showed that the evolution of the residual thermal conductivity of concrete is relatively limited until 110°C. Beyond this temperature, the cement paste dehydration and probably its damage generate a significant decrease of concrete thermal conductivity. It appears that the modelling of thermal transfers in the concrete at high temperature has to take into account the decrease of thermal conductivity when this material is exposed to a high temperature. These experimental results will permit to improve the modelization carried out previously [7].

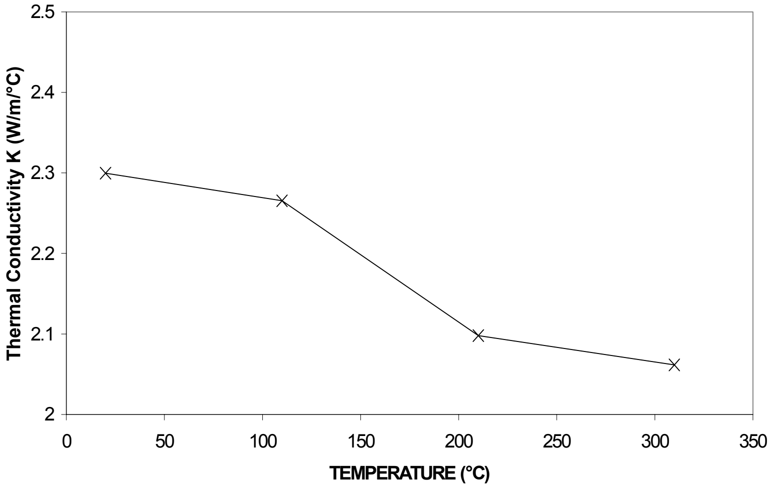

FIGURE 10 : Thermal conductivity of the concrete in function of temperature

- Porosity

Measurements of porosity by using a high pressure porosimetre (up to 418 MPa) were carried out on concrete samples (a few grams). The samples were taken on a non-heated specimen and on specimens heated at 110 °C, 210 °C and 310 °C and cooled. For each batch, four samples were tested. The non-heated samples were dehydrated by using liquid nitrogen freeze-drying. The whole measurements was treated in an identical way in order to carry out relevant comparisons. The evolution of total porosity is presented in table 2. The pore sizes distribution is presented in figure 11.

TABLE 2 : Concrete porosity in function of the test temperature

	20 °C	110°C	210°C	310°C
Total mercury porosity (%)	11.9	11.2	14.6	15.1

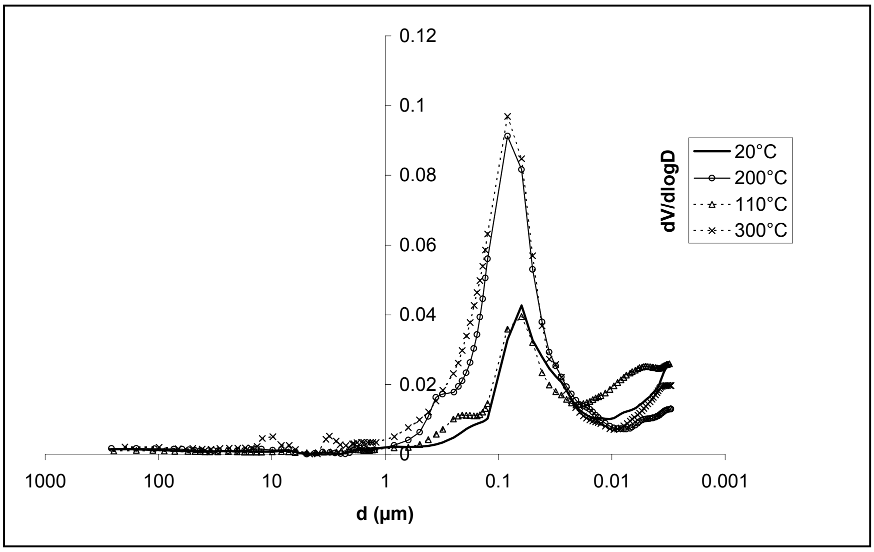

FIGURE 11 : Pore sizes distribution of the tested concrete in function of the test temperature

It was observed that the concrete porosity varied very little when the temperature does not exceed 110°C. The concrete specimens heated up to 210°C and 310°C presented a porosity higher than that at the ambient temperature. The pore sizes distribution of the specimens heated at 210°C was very close to that of the specimens heated at 310°C. This seems to indicate that the porous structure of the concrete does not vary between 210°C and 310°C. This is in accordance with the observation that the mass loss varied little between 210°C and 310°C.

On figure 11 one observes a peak of porosity around the diameter of pore 0.2 µm. One notices a widening of the curves and an increase of the peak height in function of the test temperature. The increase of the peak corresponds to a high increase of pore diameters close to 0.2 µm. According to Mehta P.K. [8], this pore sizes range corresponds to the capillary vacuums in the concrete.

Conclusions

The study presented in this article is of concern the characterization of concrete exposed to high temperature. The chosen test temperatures were 110°C, 210°C and 310°C. The high temperature behaviour was compared to that at ambient temperature (the reference temperature). The study included thermal and mechanical properties of concrete at high temperature : to determine thermal gradients in concrete during heating – cooling cycles, to quantify the water escaped from the concrete during the heating, to determine the concrete residual mechanical properties (compressive strength, splitting tensile strength, modulus of elasticity), to determine thermal conductivity and porosity of the concrete in function of the heating – cooling cycle temperature. All of these data will be used for modelling of the behaviour of concrete structure at high temperature.

The tests made it possible to check the good behaviour of a concrete containing limestone aggregates undergoing a short excursion in temperature. The tests results showed a very weak deterioration of the mechanical properties of the concrete between 20 and 110°C. The decrease of compressive strength, splitting tensile strength and modulus of elasticity remains lower than 35 % of the initial value even after a heating at 310 °C.

The results on mechanical properties are consolidated by that on mass loss and porosity. When the temperature reaches raised values, between 210 °C and 310 °C for example, the water loss is very significant. The modification of the hydrates generates a degradation of the concrete microstructure. These tests clearly highlighted the correlation between the kinetics of dehydration and the evolution of thermal gradients within the specimens.

For modelling purposes, it is important to use right data on the hygro-thermo-mechanical properties of the concrete to predict its behaviour at high temperature. In order to complete this study, it is planned to look further into the knowledge of this concrete by determining the sorption/desorption isotherms and by measuring the specific heat.

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