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Thermal stability of concrete under accidental situation

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ABSTRACT : This paper presents an investigation of the behaviour of a high performance concrete at high temperature. Measurements of temperature distributions in the concrete specimens during heating showed high thermal gradients. About one third of 16x32 cm high performance concrete cylinders spalled explosively during heating at 1 °C/min. Calculations showed high thermal stresses and high water vapour pressure in the centre of the tested specimens, which can result in specimen spalling.

In order to increase concrete strength, to decrease concrete porosity and permeability, or to perform the durability, High Performance Concrete is used in many structures instead of Ordinary Concrete. In accidental situations, concrete structure can be exposed to high temperature, during fire or accidents like in nuclear reactors. The behaviour oh high performance concrete structure can then be different from that of ordinary concrete structure. For instance, experimental studies [1, 2, 3] showed that high performance concrete structure is more sensitive to spalling or explosion than ordinary concrete structure.

The aim of this study is to show the contributions made by different models to the problem of spalling of heated cylindrical specimens. The first part presents the tested concretes, and specifies their main characteristics, which are used in the second part for modelling purposes. The second part involves modelizations, to get close to the experimental temperature field, with models including the general laws of heat transfer in materials, to evaluate the thermal stresses in the specimens and to look at the variation of water vapour pressure within concrete.

I. EXPERIMENTAL CONTEXT

In practical terms, a comparison is established between the behaviour of a structure made with high performance concrete and that of an ordinary concrete containing the same aggregates. The both tested concretes have almost the same quantity of calcareous aggregates. They were formulated by the LCPC method [4]. The high performance concrete had a low cement content, with additions of silica fume and fillers to reduce the consequences of the exothermic hydration reaction. Water reducer and retarding admixture were also added to high performance concrete.

Table 1. Mix proportions for 1 m^3.

Constituents	Ordinary concrete (kg)	HP concrete (kg)
calcareous sand 0/5	772	782
fine gravel 5/12,5	316	318
gravel 12,5/25	784	815
calcareous fillers	0	57
silica fume	0	40,3
water	195	161
CPJ 55 PM cement	350	266
plasticizer	1,03 l	0
water reducer	0	9.08 l
retarding admixture	0	0,93
compressive strength (MPa)	38.1	61.1

The study is founded on a cylindrical concrete member. The diameter was 16 cm and the length was 32 cm. Thermocouples were inserted in fresh concrete (figure 1) in order to measure the temperatures within the specimen during heating up. The temperatures at the surface and at the interior points of the specimen were recorded, so as to determine the temperature field during heating.

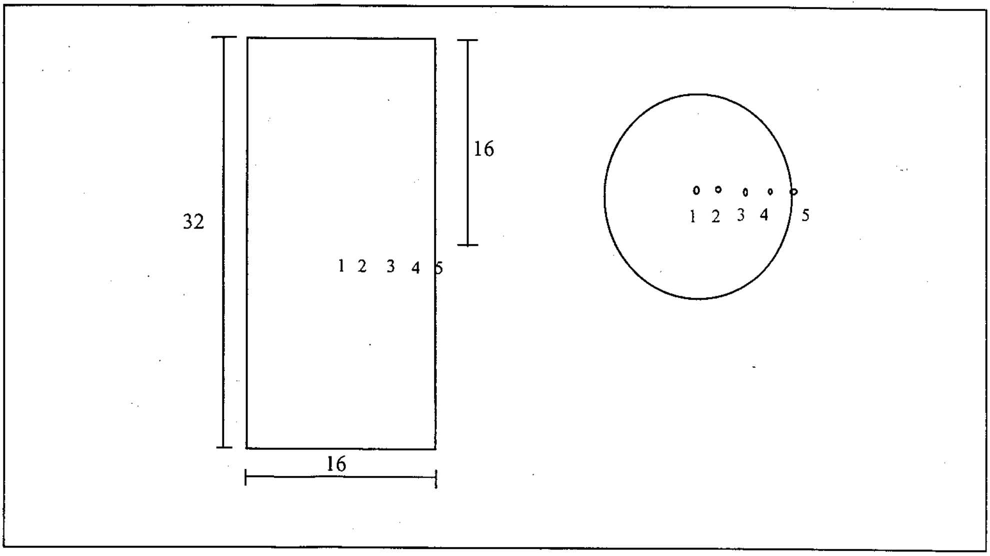

Figure 1. Thermocouples were inserted in fresh concrete

The tests were carried out at a heating rate of 1 °C/min, up to a maximum test temperature: 300 or 500 °C. The specimens were maintained at this temperature for 1 hour so that the temperature at the centre of the specimen could reach that of the surface temperature.

Figures 2 show the experimental temperature differences $\Delta\theta$ between the surface and internal points in the 16x32 cm specimen heated at 1 °C/min. The temperature measurements showed large differences between internal points (1, 2, 3, 4) and the surface of the specimen. The temperature difference between each of these points and the surface of the specimen increased, reached a maximum, then decreased. The maximum temperature difference is 143 °C for ordinary concrete instead of 132 °C for high performance concrete. Furthermore, the figures recorded for the ordinary concrete and the high performance concrete were almost similar.

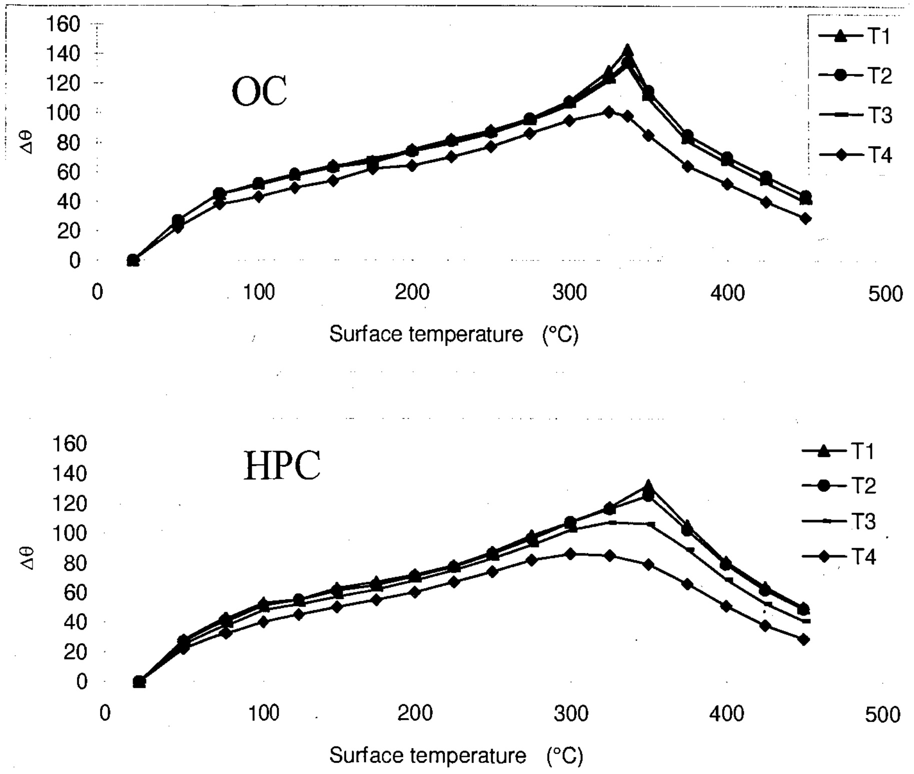

Figure 2. Temperature field in the central part of the specimen

The thermal gradient increased with the temperature rising. The maximum was achieved at 325 °C. The thermal gradient was very high near the heating surface (about 39 °C/cm of concrete). In the central part of the specimen, it was about 2 °C/cm of concrete.

Thermal stability

No spalling or explosion was observed when heating ordinary concrete specimens. About one third of 16x32 cm high performance concrete cylinders spalled explosively during heating at 1 °C/min. No spalling was observed when heating 11x22 cm cylinders. The specimens which did not spall present shrinkage cracks when the surface temperature exceeds 350 °C. All the spalling took place between 275 and 350 °C, in the rising phase of the temperature difference. The global thermal gradient was greater than 16.5 °C/cm while the maximum local thermal gradient was greater than 39 °C/cm of concrete. The structural effects are very clear in this phenomenon and that can be analysed by modelizations.

II MODELIZATIONS

In order to achieve a better understanding of the phenomenon of instability of concrete at high temperature and a greater degree of predictability, it is necessary to acquire more knowledge about the influence of the constituents of concretes, and the thermo hydro mechanical mechanisms that provoke this kind of damage. Modelizations help to get data on thermal stresses and water vapour pressure in the concrete structure during heating. Using formula established by G.A. KHOURY [5] and G. TIMOSHENKO [6], analytical results were published in a previous paper [7]. In the present paper, numerical calculations are presented.

II.1 Numerical determination of the temperature field by finite element method

The temperature field in the structure is determined with the aid of a finite element code DELFINE (CASTEM) developed at the CEA (CEA is French Commissariat à l'Energie Atomique).

Materials data like thermal conductivity (λ), specific weight (ρ) and specific heat (c) are function of temperature. There is no internal heat source in the concrete. The boundary condition is of Dirichlet type. The surface temperature is a linear function of time. Calculations are conducted with the volumic heat presented on figure 3. There is a peak of water vaporisation between 100 and 150 °C. We had a second peak between 180 and 300 °C taking into account the hydrates decomposition.

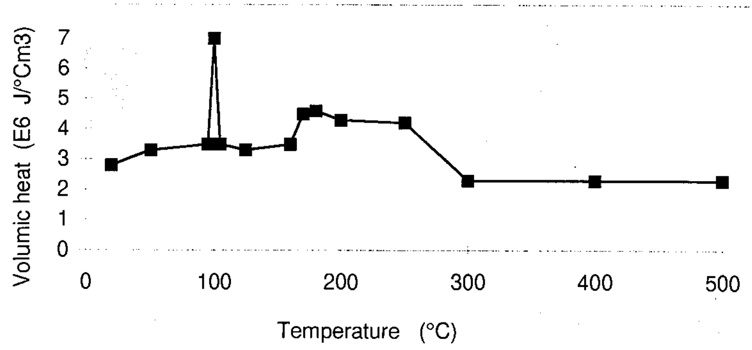

Figure 3. Volumic heat of concrete in function of temperature

The temperature rising at the surface of the specimen is linear. While the temperature rising in the centre of the specimen is not linear between 180 and 300 °C, due to the endothermic reaction of dehydration (figure 4) . The temperature difference between the centre and the surface of the specimen varied with the surface temperature. It showed a peak between 250 and 350 °C.

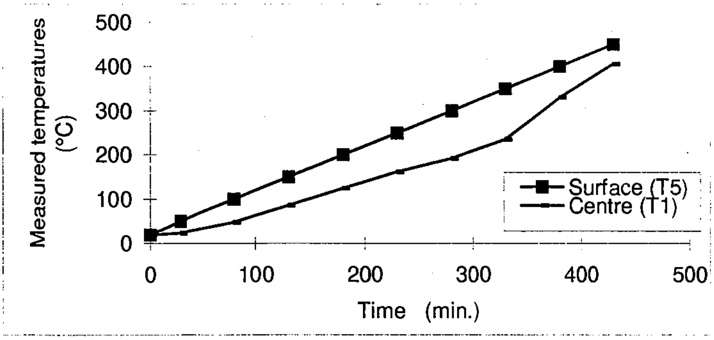

Figure 4. Experimental and calculated temperatures

II.2 Numerical calculations of elastic thermal stresses

A thermo mechanical analysis using finite element program made it possible to take into account the experimental temperature field while integrating in the model the modulus of elasticity and the thermal expansion in function of temperature. Modulus of elasticity and thermal expansion were determined experimentally. For high performance concrete at ambient temperature E= 34.6 GPA, α= 8.5x10^{-6}/°C. There is no mechanical loading on the concrete specimens during the heating-cooling cycles. Calculations were conducted with the temperature fields presented in the previous chapter.

These calculations showed a triaxial state of tensile stresses in the central part of the specimen, while towards the surface, compressive stresses appear in the axial and circumferancial directions, and also a very slight amount of radial stress. The maximum stress is that of axial stress at the centre of the specimen. Figure 5 shows the thermal stresses in the central part of the specimen. During heating, the central part of the specimen is in tension while the region near the surface is in compression. Maximum stresses occurred at about 350 °C.

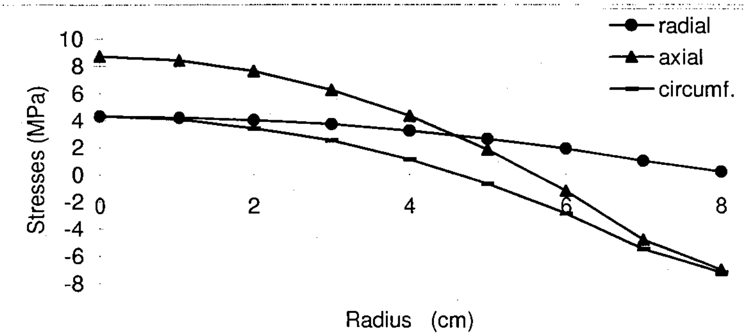

Figure 5. Radial, axial and circumferencial thermal stresses at 300 °C for HP concrete.

II.3 Water vapour pressure

Water vapour pressure being an object of suspicion in the analysis of instability of concrete at high temperatures, it was necessary to study the changes that take place in this parameter during heating. This was done by using the TEMPOR2 program [9] that include a coupled heat and moisture transfer model. The methodology is based on two equations (balance of heat and conservation of mass), the thermodynamic properties of water, the desorption isotherms (water in function of temperature and pressure).

Data : Concrete age (30 d), Relative Humidity (95 %), Thermal conductivity (1.6 J/ms°C), Geometry (16x32 cm cylinders), Heating rate (1 °C/min), Initial temperature (25 °C).

Figure 6 presents the water vapour pressure in the high performance concrete specimen. The pressure increased with the temperature. In the whole cross-section of the specimen, it was observed that during heating, the pressure peak moved towards the centre of the specimen. The closer it came to the centre, the higher was the pressure peak.

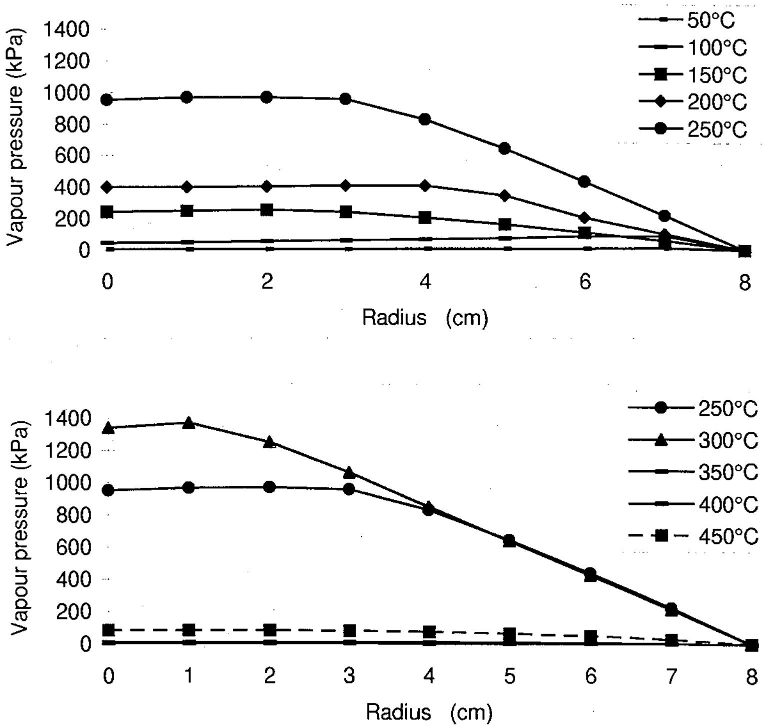

Figure 6. Pressure = f(T) shows a peak about 300 °C for HP concrete.

The maximum pressure appeared in the centre of the specimen. The peak is located at a surface temperature between 250 and 300 °C.

CONCLUSION

The experimental and numerical studies show that:

- The both tested concretes have similar thermal fields.

- High performance concrete element can present severe thermal instability during heating. The rupture is an explosive spalling in the centre of the cylindrical specimen. It involves tensile strength instead of compressive strength. There is a scale effect in this phenomenon. The study pointed out the specimen dimensions. The influence of the thermal characteristics c (specific heat) is underlined.

- Coupled thermal stresses fields and water vapour pressure result in instabilities in the concrete element. There is a critical temperature range (250-350°C) where the effects of thermal and hygral transient phenomena are maximum: the rate of water vaporisation in the concrete is elevated and the thermal gradient are very high. Thermal stresses and water vapour pressure are higher in high performance concrete specimen.

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