MICRO STRUCTURAL ORIGIN OF THE APPARENT THERMAL TRANSIENT CREEP OF CONCRETE AT HIGH TEMPERATURE

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ABSTRACT

This research has been conducted within the framework of the study of concrete behaviour at high temperature. The aim of this study is to model the thermal damage mechanisms of concrete and to investigate the behaviour of concrete specimens when they are simultaneously subjected to a constant compressive load and to high temperature. A new approach, the multiphase Digital Concrete Model and the damage model MODEV, both implemented on finite-element software SYMPHONIE, has been used to model the thermal damage of concrete. In this approach, 2 main categories of concrete thermal damage mechanisms are considered:

- Mechanical thermal damage as a result of restrained thermal strain on a macroscopic and mesoscopic scale: This damage can be due, on one hand, to the temperature gradient or the boundary conditions, or even the geometric shape on a macroscopic scale. It can be due, on other hand, to the differential expansion between the cement paste and the aggregates on a mesoscopic scale.
- Purely thermal damage as a result of the different chemical transformations, which occur mainly in cement paste: dehydration, important mass loss beyond 120°C, and other chemical transformations.

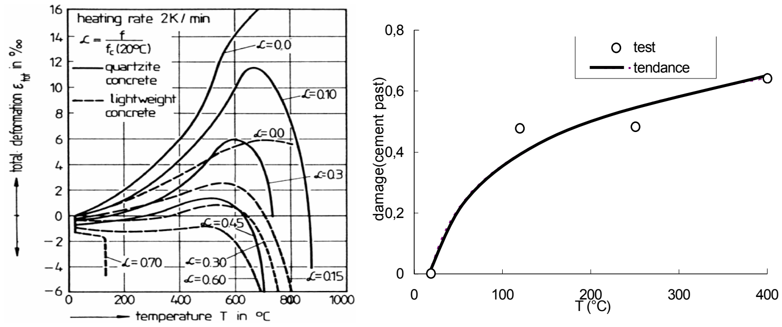
In order to study the behaviour of concrete specimens when they are subjected such loading, numerical simulations of the experimental tests carried out by Holst [4] have been performed. The “Digital Concrete” model is used to scrutinise the structural mesoscopic effects and to quantify the damage induced. Material and thermal characteristics are randomly distributed accordingly to the material mixture: granulates, sand and cement paste. Theses simulations show that the « transient thermal strain», noticed during experimental tests [5]), is a structural effect and is due to heterogeneous nature of concrete at mesoscopic scale.

Keywords: transient thermal creep, thermal damage, multi-scale model, high temperature, micro macro.

1. INTRODUCTION

This research has been conducted within the framework of the study of concrete behaviour at high temperature. The experimental studies show an important influence of the temperature on concrete behaviour. The objective is to understand and to simulate the strain mechanisms at high temperature. It particularly focuses on the evolution of the thermal strain of concrete specimens when they are simultaneously subjected to a constant compressive load and to high temperature. In fact, experimental tests show that the thermal strain is strongly influenced by the compressive load. Figure 1a shows the total strain of concrete samples heated under a constant compressive load given by Schneider [12], several levels of compressive load were tested, from 0% up to 60% of the compressive strength of concrete. Several authors explain these observations by an additional strain, called transient thermomechanical interaction strain or transient creep strain [3], [5], [11], [13]. This additional strain is considered as a function of both the temperature and the stress. Literature review is available in Khoury & al. [5].

In our opinion, these tests results do not reflect an intrinsic material behaviour, but should be considered as a structural behaviour of concrete due to the microscopic thermal damage. To show the structural effect of such loading, numerical simulations of the experimental tests carried out by Holst et al [5] have been achieved. The microscopic multi-phase Digital-Concrete F.E. model (DC) (Mounajed [7]), as well as the macroscopic deviatoric damage model MODEV (Mounajed & al. [8], Ung [14]) have been used to evaluate thermal damage at macroscopic and microscopic level. These two models are implemented in the general F.E. code SYMPHONIE.



(a)

(b)

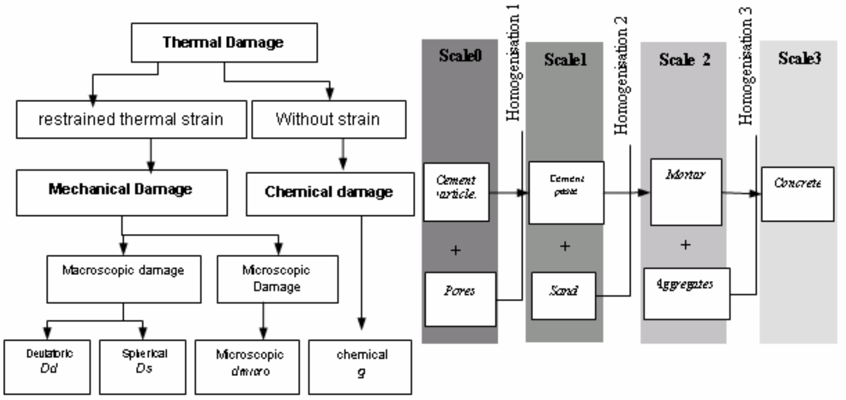
Figure 1: (a) total strain vs temperature [12], (b): Physical and chemical thermal damage origin

2. MULTI-SCALE APPROACH

1.1 *Principle of the multi-scale identification of thermal damage*

The thermal damage of concrete presents a specific mechanism directly associated to the nature of this heterogeneous material. The analysis of the different standard macroscopic models shows the insufficiency of this approach regarding the representation of the complex mechanisms involving the thermal damage. All concrete macroscopic models assume the homogeneity of this material, thus a free displacement specimen, subjected to uniform thermal loading, expands without stresses and so without damage. However, experiments conducted in laboratories show that the process of thermal damage of concrete begins early, even at relatively moderate and homogeneous temperatures.

Here, we propose a new approach to study thermal damage of concrete. This approach is based on the multi scale Homogenization of concrete using the Digital Concrete model. Several scales of modelling are taken into account, ranging from the cement paste to the concrete material [9]. Thus, the concrete is considered as a combination of three materials: cement, mortar, and concrete. Each material is considered on its specific scale, and homogenisation is needed on each scale to go to the following upper one. Figure 2b shows the basis of this approach. The mechanical and thermal characteristics of cement paste and sand aggregates are conjointly introduced into the Digital Concrete DC model in order to homogenize the mortar behaviour. This process is repeated for concrete homogenization by introducing in the DC model, the characteristics of the homogenized mortar, obtained in the previous step, and the characteristics of aggregates. This step enables to obtain the thermo-mechanical behaviour of concrete. The local DC model considers a random approach to generate the internal structure of a heterogeneous material as concrete, mortar or cement paste on a smaller scale. The proposed approach considers a multi-phase material with successions of *n* phases spatially distributed in a random manner. In the present simulations, to represent concrete, the following phases are taken into account: 1st phase: Solid skeleton of the matrix cement P_1; 2nd phase: A random distribution of aggregates with the possibility of analyzing this phase in n sub-phases to represent different sizes and natures of aggregates P_{21}, P_{22}... P_{2n}.



(a) (b)

Figure 2: (a): thermal damage approach (b): Multi scale homogenization

1.2 *Thermal damage model*

In the proposed approach, we have decomposed into two main categories the basic mechanisms leading to the thermal damage of concrete [6] [9].

1. **Mechanical damage** of thermal origin accompanied with strains and due to the restrained thermal strains on a macroscopic and microscopic scale: The original mechanical damage can be the temperature gradient or the boundary conditions, or even the geometric shape on a macroscopic scale, and the differential expansion between the cement paste and the aggregates on a microscopic scale. This damage is decomposed into mechanical macroscopic damage D_{macro} and mechanical microscopic damage $D_{micro.}$

The mechanical thermal damage of concrete is modelled with the deviatoric damage model MODEV which is based on the damage mechanics approach and on the thermodynamics. This model uses a non-symmetrical criterion in strain. MODEV introduces 2 scalar equivalent strains representing respectively local sliding and crack opening. They are calculated respectively from deviatoric and spherical parts of the strain tensor. MODEV model considers also 2 scalar damage variables, corresponding respectively to sliding and crack opening degradation mechanisms. Each damage variable has its own evolution law [14]. The damage variables are independent from the temperature and can be obtained directly from the mechanical behaviour law.

2- **Purely thermal damage** without strains due to the different chemical transformations, which occurs mainly in cement paste: dehydration, important mass loss beyond 120°C, and other chemical transformations. This damage has been identified from experimental tests performed on cement samples [6] [10]. Figure 1b shows this damage function, obtained by fitting experimental results [6] and introduced into the DC model.

3. SIMULATION OF CONCRETE SPECIMENS SUBJECTED TO COMPRESSIVE LOAD AT HIGH TEMPERATURE

To study the thermal damage of concrete specimens when they are heated under compressive load, the experimental tests carried out by Holst [4] have been simulated. Cylindrical specimens (68 x132mm^2), have been subjected to several constant compressive loads and heated up to 800°C with a heating rate of 4,98 °C/min.

The tests are modelled in 2D, with an axisymetrical model. A constant compressive load is applied at the top of the specimen at the beginning of the heating stage and is maintained constant during the test. The load represents 0%, 20%, 40% or 60% of the compressive strength of the HSC (108 MPa). Figure 4 (a) shows the geometry, the mesh and the boundary conditions adopted for the computations. The thermo mechanical characteristics of the HSC are given by Holst [4]. To perform the computations with the Digital Concrete model, it is also necessary to know the properties of cement paste and aggregates separately (tensile and compressive strengths, thermal expansion coefficient, fracture energy, Young modulus...) most of theses information, not available in [4], are chosen from literature [1], [6]. Materials parameters used in the simulation are presented in table 1, where E is the Young modulus, f_t the tensile strength, G_f the fracture energy and ν the Poisson's ratio. Bc and α, are two parameters of the damage model MODEV. The aggregate size distribution of the concrete is described in figure 3.

	E (Mpa)	ν	f_t (Mpa)	G (Mpa)	G_f (N/mm)	α	B_c
Cement Paste	20000	0.2	4	15	0.1	0.3	80
Aggregates	80000	0.28	10	20	0.15	0.3	70

Table 1. Materials parameters defined for the cement paste and for concrete aggregates.

The evolution of the thermal expansion coefficients (α_{th}) of concrete components (cement paste and aggregates) with temperature is given in table 2, and table 3.

T (°C)	α_{th} ($°C^{-1}$)
20	10 e-6
120	15 e-6
400	-5 e-6
1200	-25 e-6

Table 2. Thermal expansion coefficient of cement paste.

T (°C)	α_{th} ($°C^{-1}$)
20	3 e-6
200	9 e-6
500	21 e-6
800	57 e-6

Table 3. Thermal expansion coef. of aggregates.

The thermal damage in the specimen, obtained after one hour of heating, is presented in Figure 4 (b). The damage computed, using a macroscopic model for such test, is often very small compared to the damage obtained at the constituent's scale, using the DC micromechanical approach. This damage is mainly due to the strong difference between the coefficients of thermal expansion of cement paste and aggregates; a uniform temperature variation generates strain gradients in the material which is now analysed as a structure. These strain gradients are responsible of the induced damage zones at the mesoscopic level. Simulations and experimental results are in good agreement. Figure 4 presents for simulations and experiments, the evolution of the total strain versus the temperature for the 4 loading levels (0, 20, 40 and 60%). These results confirm that, the evolution of the total strain is mainly due to the thermal degradation of concrete stiffness at high temperature. No additional strain component such transient or creep strain [3], [5], [11], [13] is needed to explain the evolution of the total strain versus temperature.

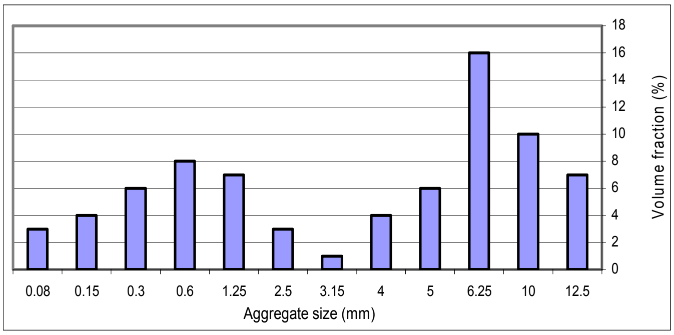


Figure 3. Aggregate size distribution adopted for the simulations.

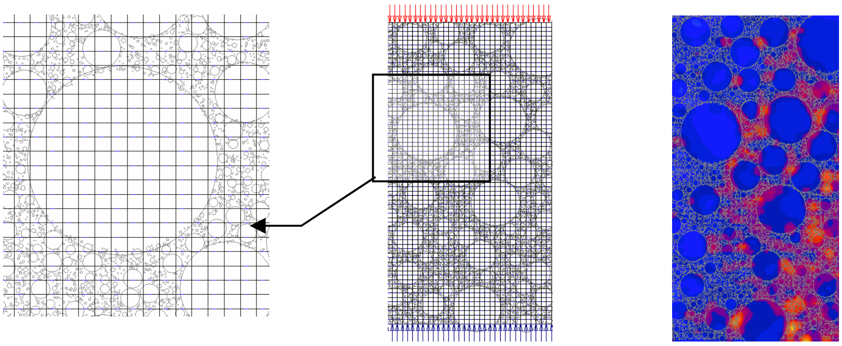


Figure 4: Mesh and boundaries conditions; Thermal damage after one hour

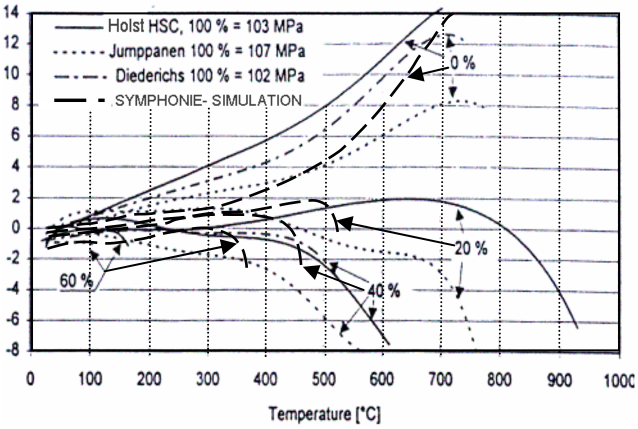


Figure 5: Model response for coupled thermal and mechanical loads compared to tests results (up to 500°C)

4. CONCLUSION

In order to understand the mechanisms leading to the deterioration of concrete under the effect of combined compressive and thermal loading, and to show the structural effect of such loading, numerical micromechanical simulations of the experimental tests carried out by Holst [4] have been achieved at mesoscopic scale. These Simulations, show that the experimental “transient strain of concrete” do not reflect an intrinsic material behaviour, but should be considered as structural behaviour due to both restrained boundary conditions and microscopic thermal damage. These simulation results confirm that, the evolution of the total strain of concrete specimens when subjected to such loading is mainly due the thermo mechanical degradation of concrete properties at high temperature. So, no additional strain component such transient or creep strain is needed to obtain the evolution of the total strain versus temperature.

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