THERMO-HYDRO-CHEMICAL-MECHANICAL ANALYSIS OF CONCRETE AT HIGH TEMPERATURES

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Summary This paper presents an experimental and numerical analysis of a hollow cylinder submitted to high temperatures. The evaluation of heat and mass transfers, evolution of the phases constituting the porous medium, mechanical performances of concrete are taken into account in a full three phases coupled analysis. A hollow cylinder has been heated up to 523.15K (250$^\circ C$) at a $5K/h$ velocity on the internal side and submitted to gas pressure/temperature measurements. A numerical simulation of the cylinder has been performed, showing a good correlation with the experimental observations.

INTRODUCTION

The problem of a porous medium (i.e.concrete) subjected to high temperatures is of great interest in civil engineering. The porous structure of concrete is subjected to strong alterations when exposed to high temperatures i.e. a fully coupled model is necessary. Chemical decomposition of the cement paste (i.e. dehydration) introduces in concrete pores free liquid water and modifies microstructure geometry and transport properties. During the dehydration process, considerable amounts of heat are consumed. The sorption isotherms of concrete are strongly temperature dependent, influencing the hygro-thermal behaviour of concrete. Permeability has a sharp increase above 378.15K i.e. when dehydration is considered to begin. Moreover physical properties of fluids (i.e. liquid water and air) change with temperature. Concrete is an hygroscopic material with a considerable portion of the pores belonging to the lower range of meso pores, meaning that during air/vapour diffusion, Knudsen effects must be considered. Physical properties of fluids (liquid water and moist air) saturating the medium are also strongly temperature dependent. For what the solid phase is concerned, isotropic damage effects, together with thermo-chemical damage, are taken into account. The present model, deriving from the coupled formulation presented in [1],[2],[3], [4] takes into account all the mentioned phenomena.

THE MATHEMATICAL MODEL

Concrete is a porous multiphase material where the voids are filled with liquid and gas. The liquid phase consists of bound water (or adsorbed water) which is present in the whole range of the medium, and capillary water. The gas phase is a mixture of dry air and water vapour (condensable) and is assumed to behave like an ideal gas. The mathematical model consists of a series of balance equations: mass of solid skeleton, mass of dry air, mass of the water species (in liquid and in gaseous state, taking into consideration phase changes i.e. evaporation-condensation, adsorption-desorption, hydration-dehydration process), enthalpy of the whole medium (latent heat of phase changes, heat effects of hydration-dehydration) and linear momentum. These balance equations are completed by an appropriate set of constitutive and state equations and some thermodynamic relationship. The governing equations of the model are given in terms of the chosen state variables. This choice is of particular importance: from a practical point of view, the chosen quantities should be easy to measure during experiments. From a theoretical point of view they must describe in a unique way the medium thermodynamic condition. State variables have been determined in the number of five: gas pressure p_g, capillary pressure p_c, temperature T and displacement vector of the solid matrix $\mathbf{u}(u_x, u_y)$.

Conservation equations are obtained by means of the hybrid mixture theory in the formulation proposed by Lewis and Schrefler [1]. The full development of the model equations starting from the local microscopic balance equations with successive volume averaging is presented in [1], [3]. In the pores, water is usually present as a condensed liquid which, thanks to the surface tension, is separated from its vapour by a concave meniscus (capillary water). The equilibrium equation between liquid water and gas is given by means of the well-known Laplace equation. Due to the curvature, the equilibrium vapour water pressure differs from the liquid water pressure and the relationship can be obtained by means of the Kelvin equation. The law describing moisture transport is Darcy's law in association with Fick's law. Darcy law is applied as constitutive equation. $\mathbf{K}$ is the intrinsic permeability, K_{rw} and K_{rg} are relative permeabilities of the liquid and the gaseous phase. Intrinsic permeability is a material characteristic depending only on concrete microstructure. During heating of concrete at high temperature complex physical and chemical processes take place, leading to inner structure changes and intrinsic permeability augmentation. Permeability is strongly dependent on damage. For the bound water flow a generalized Fick's law is applied (see [3] for further details details). For the description of the diffusion of the binary gas species mixture (dry air and vapour) Fick's law is applied.

Tensile stresses as well as pore fluid pressure are assumed as positive. The effective stress is given in the usual manner as a function of the total stress tensor, pressure and the Biot's coefficient.The constitutive relationship for the solid skeleton is classically obtained by means of the tangent matrix $\mathbf{K}_T$ as a function of strain. Mechanical damage effect is taken into consideration following the Mazars scalar isotropic model. During heating concrete is subjected to many changes in its inner structure with strong alterations of material properties. This degradation is not only due to mechanical damage, but must lead also to thermally induced material deterioration. This kind of damage has been called thermo-chemical damage V. Full details of thermo-chemical damage in association with classical mechanical damage are given in [3] (see fig.1).

RESULTS AND DISCUSSION

The experiment has been performed on a hollow cylinder heated from the internal side, equipped with temperature and pressure sensors for the monitoring of the behaviour of concrete. The cylinder is 1.5m in height with an internal radius of 0.25m and an external of 0.55m. Microcracks (due to heating) on the external face had to be limited for avoiding moisture escape. For this reason the cylinder has been encircled by a steel layer. The concrete used in the analysis is an ultra high strength concrete of M100 type whose general characteristics at reference state are presented in [4]. Concerning temperature measurements a standard thermocouple of type K has been used. For what concerns the monitoring of gas pressures, a cylindrical sensor type of 3cm in height and 1.5 cm in diameter has been adopted. Only three pressure sensors have been used.The hollow cylinder has been discretized using the finite element method by means of 150 eight-node serendipity elements (501 nodes).Initial, boundary conditions and concrete characteristics are fully presented in [4]. Computations for the first 60 hours of the experimental analysis, using time steps of 4s. Temperature and gas pressure profiles show a good correlation with experimental results (fig.2 and 3).

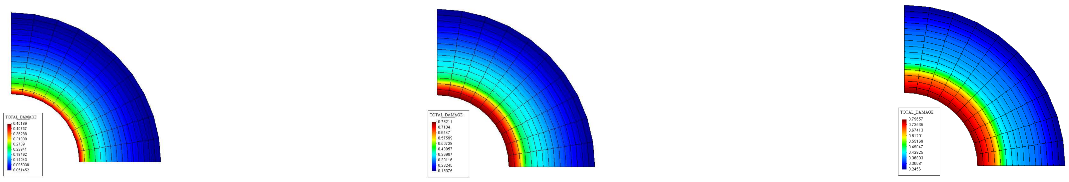

Figure 1. Total damage at t=20h, 40h, 60h

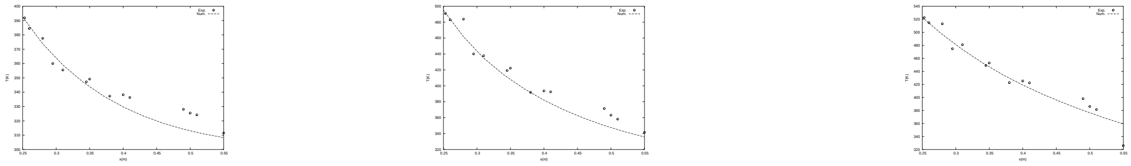

Figure 2. Numerical and experimental temperature vs radius at t=20h, 40h, 60h

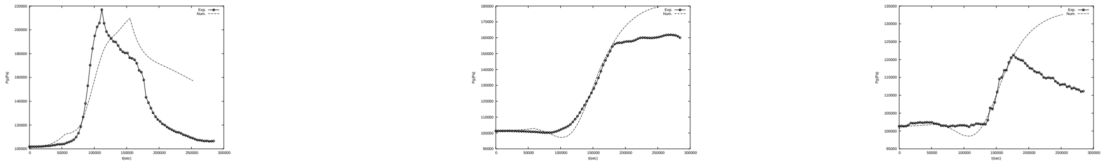

Figure 3. Numerical and experimental gas pressure vs time on sensor 1 (3cm), 3 (16cm) and 4 (25cm)

CONCLUSION

High temperatures effects have been considered through temperature/pressure dependance of many parameters by means of phenomenological expressions widely validated. An experimental set-up has been presented together with the related temperature and pore pressure measurements. The subsequent numerical analysis has shown qualitatively acceptable results, comparable to the observed data, allowing a deeper understanding of concrete at high temperatures.

References

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