Engineering Structures 59 (2014) 765–775

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Thermo-hydric analysis of concrete–rock bilayers under fire conditions

Anna Paula G. Ferreira [a], Michèle C.R. Farage [a,*], Flávio S. Barbosa [a], Albert Noumowé [b], Norbert Renault [b]

[a] Computational Modeling Graduation Program, Federal University of Juiz de Fora, Campus Universitário s/n, Martelos, 36036-330 Juiz de Fora, MG, Brazil
[b] University of Cergy-Pontoise, Laboratoire de Mécanique & Matériaux du Génie Civil, EA 4114, F-95000 Cergy-Pontoise, France

ARTICLE INFO

Article history:
Received 15 January 2013
Revised 20 September 2013
Accepted 29 November 2013
Available online 29 December 2013

Keywords:
High temperatures
Concrete
CAST3M

ABSTRACT

High temperatures due to fire are amongst the most critical situations to which concrete may be exposed. For safety purposes, it is important to understand and preview the consequences of fire on the structural integrity of concrete. Concerning high temperatures, the mechanical degradation suffered by a concrete structure is related both to energy and mass transport. Therefore, a realistic modeling of such a condition shall take into account not only a thermal analysis but also the complex physical–chemical reactions developed among the components of that heterogeneous material. This approach is adopted in the present study as an effort to better reproduce the consequences of fluid flow and chemical processes – cement hydration and dehydration – in the material.

Numerical simulations of the hygro-thermal behavior of concrete–rock bilayers subjected to fire conditions are performed through a transient and nonlinear model. The adopted model was evaluated by comparisons with data from an experimental program concerning thermal tests on a set of concrete–rock bilayer specimens, aiming to reproduce real world situations observed in some structures, such as tunnels.

1. Introduction

The use of concrete in civil structures that may be subjected to adverse conditions shall be based on studies about their behavior in such situations. Concerning fire exposure, there are several records of accidents involving concrete structures – such as tunnels – with catastrophic consequences, which justifies the experimental and numerical studies related to the subject [1,2], in order to minimize risks and ensure the safety of users. Cafaro and Bertola [3] and Vianello et al. [4] list a number of tunnel fires with casualties occurred in Europe during the last decades, for instance: Mont Blanc, France–Italy, in 1999 (39 casualties), Tauern, Austria, in 1999 (12 casualties) and Gothard, Switzerland, in 2001 (11 casualties).

High temperatures may lead the porous microstructure of concrete to deterioration and loss of efficiency of the whole structure [5]. Many phenomena and interactions are involved in the evolution of properties that occurs inside the heated concrete, which makes this type of problem highly non-linear [6]. Thus, to properly describe the behavior of concrete subjected to thermal loads, it is important to consider the coupled heat conduction, the fluid flow and the mechanical behavior. Cracking and spalling in heated concrete are important issues that depend both on hygro-thermal and thermo-mechanical factors [7–9].

Specifically in accidental fire exposures, the temperature increase is in general very fast, causing higher damage than the observed in structures designed to support long periods of high temperature exposure [10]. Concerning tunnels, it is also of interest to investigate the concrete–rock interface, in order to verify whether that region is even more susceptible to fire effects. To this end, the present work presents the results of a hygro-thermal model applied to a concrete–rock bilayer sample. Experimental results were employed for validation of the model, which was implemented in the CAST3M code, developed at the French Atomic Research Center (CEA, France) [11].

2. Concrete and rock under fire conditions

2.1. General aspects

This section provides an overall description of the effects of fire on the materials employed in this study: concrete and rock.

2.2. Concrete

When exposed to heating, concrete passes through different phases, as described by Dal Pont [12]:

* Corresponding author. Address: Departamento de Mecânica Aplicada e Computacional, Faculdade de Engenharia, Universidade Federal de Juiz de Fora, Campus Universitário s/n, Martelos, 36036-330 Juiz de Fora, MG, Brazil. Tel.: +55 32 2102 3470; fax: +55 32 2102 3401.

E-mail address: michele.farage@ufjf.edu.br (M.C.R. Farage).

0141-0296/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.engstruct.2013.11.033

1. As soon as the heating starts, temperature rises on the heated surface. The moisture inside the concrete, composed of liquid water and water vapor, moves toward the cold area of the concrete specimen by diffusion.
2. When temperature reaches 100 °C, water begins to boil. The water vapor moves toward the cold zones and condenses. The latent heat required for the boiling of water slows the increase of temperature until the complete boiling of water in that portion of concrete.
3. At the same time, the vapor that condenses in the cold zone may bind to the non-hydrated cement and a new hydration takes place. At this phase, the formation of new calcium silicate hydrate (CSH) provides an improvement of mechanical properties of concrete.
4. The increase of temperature also causes dehydration. Around 105 °C, the chemical bonds that form the CSH begin to be destroyed, transforming the hydrated products in anhydrous products and water. The water that is released into the concrete vaporizes, absorbing heat. The dehydration reaction progressively reaches several hydrated products that are part of the concrete: as soon as temperature rises, more free water is generated and more water vaporizes. The vaporization is an endothermic reaction and influences the heating of concrete, slowing down the heat propagation.
5. Free water tends to move toward cold zones of concrete. Since concrete and, in particular, the high performance concrete (HPC) has a low permeability [13], liquid water and water vapor do not penetrate so quickly in cold area. In addition, the formation of water after dehydration is faster than the release of water and vapor. The result of the combination of this two effects is that the pore pressure increases and may reach values of the order of several atmospheres. It is also observed that the peak pressure moves toward the cold regions of the concrete progressively increasing its value. As indicated in a number of experimental studies [14–16], the increase in gas pressure in the pores is also the basis of the phenomenon of spalling.

The spalling is the detachment of fragments of the concrete surface exposed to the heating and may seriously damage the integrity of the entire structure by direct exposure of structural steel to fire, increasing the risk of buckling under compression, the loss of the isolation property and other consequences. This phenomenon is usually explained by two mechanisms [15,17]:

Thermo-mechanical process: Characterized by high temperature gradients, especially in the first centimeters of the exposed surfaces. Those gradients are, in general, due to rapid heating (as accidental fires, for instance) and induce high compressive stresses near the exposed surface – which may locally exceed the concrete compressive strength and cause the ejection of pieces.

Hygro-thermal process: The movement of fluids is due to pressure and molar concentration gradients (Darcy's Law and Fick's Law). The fluids tend to move to the inner and colder areas of concrete. Thus, water vapor begins to condense and an obstruction of humidity ("moisture clog") is gradually created near the exposed surface. This obstruction is considered as a region of concrete with high content of water, acting as a barrier to the fluid flow, which increases pore pressure. These pressures may locally exceed the concretes tensile strength and result in the occurrence of spalling.

It is well known that high performance concretes are more susceptible to explosive spalling due to its lower permeability and porosity. Those characteristics lead to the development of higher pressures inside the pores since the fluid flow is difficult.

2.3. Rock

As observed in the concrete, high temperatures modify the microstructure of rock. This material also presents differential expansion, since it is composed of minerals with different properties which may also present anisotropy of thermal expansion [18,19]. This phenomenon causes a stress concentration in the contact of the grains, resulting in cracking. There are models developed to predict the thermo-mechanical behavior of rocks – some of them may be found in the works of Hettema [20] Fredrich and Wong [21] apud Lion [19,22] and Nguyen et al. [22]. Studies cited by Yavuz et al. [23] identified the following microstructural processes in a limestone due to temperature: (a) Exposure to 100 °C causes dilatation of calcite and compaction of grains. However, the compaction effect does not block the migration of water in the pores due to clay content; (b) Up to 200 °C the shrinkage of clay against dilatation of calcite is observed. Pores generate space for the expansion of components and thus no effective porosity increase is measured; (c) At 300 °C, the expansion of calcite is most remarkable and effective than the shrinkage of the clays, but no crack is observed in the grains; (d) Cracking within the grains starts at 400 °C and separation along the contact surfaces of the grains is observed. Thus, with the microcracking, effective porosity approaches the total porosity by connection of closed pores. (e) Cracking within grains and separation along the grain boundaries continues up to 500 °C, and the effective porosity is slightly larger than the initial porosity.

3. Experimental program

The experimental data employed herein were obtained at the *Laboratoire de Mécanique et Matériaux du Génie Civil (L2MGC)* of the University of Cergy-Pontoise, France [24,25]. Tested specimens consisted of concrete–rock bilayers made of conventional concrete and high performance concrete and limestone (Fig. 1), aiming to reproduce a typical sample of a tunnel structure. The goal was to submit the double layered blocks to temperatures up to 600 °C and 750 °C, measuring the temperature evolution at specific points along the height and observing the different effects of temperature on the two types of concrete, rock and interface region.

3.1. Concretes formulations

Two different types of concrete were employed in the study: conventional concrete (CC) and high performance concrete (HPC). Each type of concrete was used in the fabrication of two bilayer samples, as shown in Fig. 2. The compositions of the tested

Fig. 1. Bilayer samples made of concrete and rock.