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Hygro-thermo-mechanical analysis of spalling in concrete walls at high temperatures as a moving boundary problem

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ABSTRACT

A mathematical model allowing coupled hygro-thermo-mechanical analysis of spalling in concrete walls at high temperatures by means of the moving boundary problem is presented. A simplified mechanical approach to account for effects of thermal stresses and pore pressure build-up on spalling is incorporated into the model. The numerical algorithm based on finite element discretization in space and the semi-implicit method for discretization in time is presented. The validity of the developed model is carefully examined by a comparison between the experimentally determined data stated in literature and the results obtained from the numerical simulation.

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1. Introduction

Mathematical modelling seems to be an effective and powerful tool to simulate the heated concrete behaviour (see e.g. [22]). Several models based on more or less general physical background have been developed to simulate transport processes in heated concrete (see [27] and references therein). All developed models build on a system of conservation of mass and energy, but differ in the complexity of phase description of state of pore water as well as chemical reactions and different physical mechanisms of coupled transport processes in a pore system. A descriptive phenomenological approach was used to explore hygro-thermal processes in concrete exposed to temperatures exceeding 100 °C starting with the Bažant & Thonguthai model [5]. Here, the liquid water and water vapour are treated as a single phase, moisture, and the evaporable water is assumed to be formed by the capillary water only. The main advantages for usage of this approach is relative simplicity and small number of parameters that can be obtained from experiments. However, in such a way it is impossible to consider the effects of phase changes of water and the applicability of the single-fluid-phase models for temperatures above the critical point of water is disputed. These deficiencies led to the development of more detailed multi-phase description, see e.g. the works of [21,13] for specific examples. Coupled multi-phase models reflect the multi-phase structure of concrete, interactions between phases, phase changes of fluids and solids and non-linear couplings between thermal, hygral and mechanical processes. However, such increase in complexity comes at the expense of a large number of model parameters, which determination can be hardly obtained directly from experiments. Moreover, multi-phase models are computationally expansive. Despite rapid progress in computer technologies, complex models still exceed capabilities of recently developed numerical algorithms and computational hardware. Therefore, in this paper we will adopt a pragmatic concept and consider the simplified model obtained directly from the complex multi-phase description. Relative importance of thermodynamic fluxes will be quantitatively evaluated at the level of material point and these results will allow us to neglect less important transport phenomena without lost of capability to realistically predict behaviour of concrete at extremely high temperatures.

High-temperature exposure of concrete can lead to the risk of concrete spalling and, consequently, to the damage of the entire structure (see e.g. [25] and references therein, for the examples see [34,53,54]). It is generally accepted that the spalling process in rapidly heated concrete is caused by two main processes – increase

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Nomenclature

Symbol	Description
α_c	convective heat transfer coefficient [W m^{-2} K^{-1}]
β_c	convective mass transfer coefficient [m s^{-1}]
ϵ_{tot}	total strain [–]
ϵ_θ	free thermal strain [–]
ϵ_σ	instantaneous stress-related strain [–]
ϵ_{cr}	creep strain [–]
ϵ_{tr}	transient strain [–]
η_s	volume fraction of the solid microstructure [–]
η_w	volume fraction of liquid phase [–]
η_g	volume fraction of gas phase [–]
ϕ	porosity [–]
ρ_s	density of the solid microstructure [kg m^{-3}]
ρ_g	gas phase density [kg m^{-3}]
ρ_a	dry air phase density [kg m^{-3}]
ρ_v	vapour phase density [kg m^{-3}]
$\rho_{v\infty}$	ambient vapour phase density [kg m^{-3}]
ρ_w	liquid phase density [kg m^{-3}]
μ_w	liquid water dynamic viscosity [Pa s]
μ_g	gas dynamic viscosity [Pa s]
σ	stress [Pa]
σ_{ht}	stress caused by hygro-thermal processes [Pa]
σ_{tm}	stress caused by thermo-mechanical processes [Pa]
σ_{SB}	Stefan–Boltzmann constant [W m^{-2} K^{-1}]
θ	absolute temperature [K]
θ_∞	ambient absolute temperature [K]
λ_c	effective thermal conductivity of moist concrete [W m^{-1} K^{-1}]
τ	characteristic time of mass loss governing the asymptotic evolution of the dehydration process [s]
c	mass of cement per m^3 of concrete [kg m^{-3}]
c_p^w	specific heat at constant pressure of liquid water [J kg^{-1} K^{-1}]
c_p^v	specific heat at constant pressure of water vapour [J kg^{-1} K^{-1}]
c_p^a	specific heat at constant pressure of dry air [J kg^{-1} K^{-1}]
c_p^s	specific heat at constant pressure of solid phase [J kg^{-1} K^{-1}]
c_p^g	specific heat at constant pressure of gas mixture [J kg^{-1} K^{-1}]

e	emissivity of the interface [–]
f_c	uniaxial compressive strength of concrete [Pa]
f_t	uniaxial tensile strength of concrete [Pa]
F	failure function [–]
h_e	enthalpy of evaporation per unit mass [J kg^{-1}]
h_d	enthalpy of dehydration per unit mass [J kg^{-1}]
H^w	specific enthalpy of liquid water [J kg^{-1}]
H^v	specific enthalpy of water vapour [J kg^{-1}]
H^s	specific enthalpy of chemically bound water [J kg^{-1}]
$\boldsymbol{J}_w$	liquid water mass flux [J kg^{-1}]
$\boldsymbol{J}_v$	water vapour mass flux [kg m^{-2} s^{-1}]
$\boldsymbol{J}_M$	moisture flux [kg m^{-2} s^{-1}]
K	intrinsic permeability [m^2]
K_{rw}	relative permeability of liquid water [–]
K_{rg}	relative permeability of gas [–]
ℓ	thickness of a concrete wall [m]
m_d	mass source term related to the dehydration process [kg m^{-3}]
$m_{d,eq}$	mass of water released at the equilibrium [kg m^{-3}]
m_e	vapour mass source caused by the liquid water evaporation [kg m^{-3}]
M_w	molar mass of liquid water [kg kmol^{-1}]
M_a	molar mass of dry air [kg kmol^{-1}]
P	pore pressure due to water vapour ($P = P_v$) [Pa]
P_c	capillary pressure [Pa]
P_v	water vapour pressure [Pa]
P_a	dry air pressure [Pa]
P_g	gas pressure [Pa]
P_w	pressure of liquid water [Pa]
P_s	water vapour saturation pressure [Pa]
q_c	heat flux vector [W m^{-2}]
R	gas constant [J kmol^{-1} K^{-1}]
RH	relative humidity ($RH = P_v/P_s$) [–]
S_w	degree of saturation with liquid water [–]
S_B	degree of saturation with adsorbed water [–]
S_{ssp}	solid saturation point [–]
v_g	velocity of gaseous phase [m s^{-1}]
v_w	velocity of liquid phase [m s^{-1}]
v_a	velocity of dry air [m s^{-1}]
v_v	velocity of vapour [m s^{-1}]

of pore pressure end development of thermal stresses – that may act separately or, which is more likely, in a combined way (see e.g. [38, Section 4]).

In literature, we can find many criteria to asses the risk and, in some cases, also the amount of concrete spalling (for a brief summary of some of these criteria, see e.g. [25,38]). In our previous work [7], we have employed a heuristic engineering approach, originally proposed by Dwaikat and Kodur [15, Section 3.3], in which the spalling is supposed to occur if the effective pore pressure exceeds the temperature dependent tensile strength of concrete. In the present paper, we extend this criterion in order to take into account not only the pore pressure (which seems to be not the dominant mechanism of spalling, as observed by recent experimental investigations [31,46] and numerical simulations [48]) but also the thermal stress as a driving force of spalling.

The paper is organised as follows. In Section 2, we specify general thermodynamical and mechanical assumptions on concrete as a porous multi-phase medium to obtain a reasonably simple but still realistic model to predict hygro-thermal behaviour of concrete at very high temperatures. This Section is concluded by presentation of conservation of mass and thermal energy, carefully derived in Appendix A by quantitative parameter analysis. In Sections 3 and 4, constitutive relationships are discussed in details and suitable boundary conditions for description of transport processes through the surfaces of the concrete wall are presented, respectively. Section 5 deals with the problem of moving boundary for spalling simulation. Our approach is based on the combined effect of pore pressure and thermal stresses in concrete under high temperature exposure. In Section 6, the complex problem is formulated as a fully coupled system of highly nonlinear partial differential equations (PDE's) supplemented with appropriate boundary and initial conditions. Based on the full FEM (in space) and semi-implicit (in time) discretization of the mentioned system of PDE's, an in-house research MATLAB code has been developed for the solution of the system of nonlinear algebraic equations. The numerical algorithm is presented in Section 7. Section 8 brings the complete list of material properties of moist concrete at high temperatures used in the numerical model. Section 9 is the key part of the paper. Here we present validation of the model by comparison of the numerical results with experiments reported

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