Petra Rozehnalová; Anna Kučerová; Petr Štěpánek

Processes in concrete during fire

In: Jan Chleboun and Petr Přikryl and Karel Segeth and Jakub Šístek and Tomáš Vejchodský (eds.): Programs and Algorithms of Numerical Mathematics, Proceedings of Seminar. Dolní Maxov, June 8-13, 2014. Institute of Mathematics AS CR, Prague, 2015. pp. 181–187.

Persistent URL: `http://dml.cz/dmlcz/702682`

Programs and Algorithms of Numerical Matematics 17
J. Chleboun, P. Přikryl, K. Segeth, J. Šístek, T. Vejchodský (Eds.)
Institute of Mathematics AS CR, Prague 2015

PROCESSES IN CONCRETE DURING FIRE

Petra Rozehnalová, Anna Kučerová, Petr Štěpánek

Brno University of Technology, Faculty of Civil Engineering
Veveří 331/95, 602 00 Brno, Czech Republic
rozehnalova.p@fce.vutbr.cz, kucerova.a@fce.vutbr.cz, stepanek.p@fce.vutbr.cz

Abstract

Paper deals with hydro-thermal performance of concrete exposed to a fire. It is introduced mathematical model, numerical approach and some results provided by the model.

1. Introduction

Behavior of concrete exposed to the high temperature plays crucial role in the assessment of the reliability of concrete structure. There exist several mathematical models that aim to predict and simulate such a behavior. One of the first models was developed by Bažant and Thonguthai. Its improved version is described in [3] or in [4]. Another model was formulated by Gawin et al. [6] or by Dwaikat and Kodur in [5]. These models differ in its complexity, dimension, number of variables and equations. Their common characteristic is that models contain nonlinear differential equations and lot of empirical data.

In the paper we introduced mathematical model which is slightly revised and modified approach of [4]. The model belongs to the simpler ones because the only one phase (free water) is assumed. Surprisingly some phenomena observed in experiments can by explained by the analysis of the model.

2. Physical phenomena

Let us describe physical processes, which occur in concrete during fire. Concrete is non-combustible material with low thermal conductivity. Although concrete does not contribute to fire load of the structures significant changes occur in its structure during a fire exposure. Besides reduction of mechanical, deformation and material properties also chemical composition of concrete is varied during heating [3].

Concrete, as a porous material, contains a large amount of pores, which can be filled fully (saturated concrete) or just partially with water. The water occurred in the pores is evaporable water and starts to evaporate at early beginning of the fire. The first changes of concrete structure arise at 105 °C as stated in [8], when chemically bounded water is released from cement gel to the pores. Some small micro-cracks start to appear as the capillary porosity arises. The peak of the dehydration process is reached around 270 °C. The color of concrete is changed and a slight decrease of strength, modulus of elasticity and changes in material properties like thermal conductivity can be noted. Temperature of 300 °C is the extreme temperature beside which the concrete structure is irreversibly damaged [7]. In range of 400–600 °C calcium hydroxide decomposes into calcium oxide plus water (rise of amount of free water) and transition of α and β quartz, accompanied by increase in its volume, induces another creation of severe cracks in concrete.

Simultaneously with a change of temperature can be investigated also the change of mass of free water (mostly vapor) and distributions of pore pressure. The pore pressure is one of the main reasons of concrete spalling, which happened at the beginning of heating (10–30 minutes) and is accidental. Small or grater areas of concrete cover can be broken and cross section of member is reduced then. Furthermore in most cases the reinforcement is exposed directly to the fire and the member is heated faster, which can lead to loss of loadbearing capacity.

3. Mathematical model

The aim is to model behavior described above. We consider two-dimensional model. Let Ω be a domain representing a concrete skeleton with the points $\mathbf{x}=(x_1, x_2)$. Let us denote by Γ the boundary of domain Ω. The boundary consists of two parts: Γ_R, which represents part exposed to the fire and Γ_N, which is exposed to the atmosphere. It is supposed that Γ_R and Γ_N are non-intersecting sets and $\Gamma_R \cup \Gamma_N = \Gamma$. By $\mathbf{n} = (n_1, n_2)$ is denoted outer unite normal of Ω.

In the model, there are three unknowns: $w(\mathbf{x}, t)$ denotes amount of free water, $P(\mathbf{x}, t)$ is pore pressure and $T(\mathbf{x}, t)$ is temperature in the point $\mathbf{x}$ and time t.

Mass balance equation of free water takes into account diffusive flow (L 1.2) and variation (L 1.1) of free water. Source of the free water is water dehydrated from the skeleton (R 1.1). The equation is:

$$\underbrace{\frac{\partial w}{\partial t}}_{L\,1.1} + \underbrace{\nabla \cdot \mathbf{J}}_{L\,2.1} = \underbrace{\frac{\partial w_{\mathrm{deh}}}{\partial t}}_{R\,1.1} \quad \text{in } \Omega \times (0, \infty) \ , \tag{1}$$

where $\mathbf{J}$ is flow of free water. Function $w_{\mathrm{deh}} = w_{\mathrm{deh}}(T)$ gives mass of dehydrated water. It is empirical function, we adopted the one specified in [5].

Enthalpy balance equation considers conductive (L 2.2) and convective (L 2.3) heat flows. Source terms in the equation describes effects caused by dehydration of skeleton (R 2.1) and evaporation of free water (R 2.2). Then, the equation is:

$$\underbrace{\rho_s C_s \frac{\partial T}{\partial t}}_{L\,2.1} + \underbrace{\nabla \cdot \mathbf{q}}_{L\,2.2} - \underbrace{C_w \nabla T \cdot \mathbf{J}}_{L\,2.3} = -\underbrace{\Delta H_{\mathrm{deh}} \frac{\partial w_{\mathrm{deh}}}{\partial t}}_{R\,2.1} + \underbrace{\Delta H_{\mathrm{evap}} \frac{\partial w}{\partial t}}_{R\,2.2} \quad \text{in } \Omega \times (0, \infty) \ , \tag{2}$$

where $\mathbf{q}$ means heat flux, $\rho_s = \rho_s(T)$ density of concrete , $C_s = C_s(T)$ specific heat of concrete, C_w specific heat of water, ΔH_{deh} enthalpy of dehydration, $\Delta H_{\mathrm{evap}} = \Delta H_{\mathrm{evap}}(T)$ enthalpy of evaporation.

State equation Now, we have three unknowns and only two equations, (1) and (2). For that reason we add state equation

$$w = \Phi(P, T), \tag{3}$$

where Φ is empirical function described in [10], p. 530.

Constitutive relationship: According to [3], the heat and moisture flux can be considered in the form of Fourier's respectively Darcy's law, i. e.:

$$\mathbf{J} = -\frac{K}{g}\,\nabla P \quad \text{and} \quad \mathbf{q} = -\lambda\,\nabla T,$$

where $K = K(T, P)$ denotes permeability of concrete and $\lambda = \lambda(T)$ thermal conductivity and g gravitational acceleration (included for the reasons of dimensionality).

Boundary conditions: The model is completed with boundary conditions. They are of the Robin type:

$$-\mathbf{J}\cdot\mathbf{n} = \beta_N(P - P_\infty) \qquad \text{on } \Gamma_N \times (0,\infty), \tag{4}$$
$$-\mathbf{J}\cdot\mathbf{n} = \beta_R(P - P_\infty) \qquad \text{on } \Gamma_R \times (0,\infty), \tag{5}$$
$$-\mathbf{q}\cdot\mathbf{n} = \alpha_N(T - T_\infty) \qquad \text{on } \Gamma_N \times (0,\infty), \tag{6}$$
$$-\mathbf{q}\cdot\mathbf{n} = \alpha_R(T - T_{\mathrm{en}}) + e\sigma(T^4 - T_{\mathrm{en}}^4) \qquad \text{on } \Gamma_R \times (0,\infty), \tag{7}$$

where $\alpha_R,\ \alpha_N$ are heat transfer coefficients for boundary exposed to the high temperature and to the atmosphere , $\beta_R,\ \beta_N$ denote coefficients of moisture transfer through the boundary Γ_R resp. Γ_N, e emissivity of concrete and σ Stefan- Boltzmann constant. P_∞ resp. T_∞ denotes outer pressure resp. temperature and finally $T_{\mathrm{en}} = T_{\mathrm{en}}(t)$ gives temperature caused by fire.

Initial conditions: To describe environment for $t = 0$, we prescribe initial conditions

$$P(\mathbf{x}, 0) = P_0 \qquad \text{for } \mathbf{x} \in \Omega, \tag{8}$$
$$T(\mathbf{x}, 0) = T_0 \qquad \text{for } \mathbf{x} \in \Omega, \tag{9}$$

where P_0 and T_0 are pressure and temperature in $t = 0$.

4. Numerical methods

Equations (1)–(3) together with boundary conditions (4)–(7) and with initial conditions (8), (9) form mathematical model. This model is implemented in Matlab, where we use following approach.

For time discretization we use Rothe method. It leads to a system of nonlinear partial differential equations. To solve this we used finite element method in each time step. Basis and test functions are bilinear polynomials as we choose, for spatial discretization, square conforming uniform mesh. Integrals appearing in finite element method are computed by Gaussian quadrature. Finite element method provides system of nonlinear equations, which is solved by Newton's method. Stopping criteria is residual tolerance set to the value 10^{-8}.

5. Example

Let us present results of our model problem. The set Ω is a rectangle 50 mm × 100 mm. Γ_R is left and upper side of the Ω and so Γ_R is right and lower side.

The data of the model were set as follows: $C_w = 4180$ J kg^{-1} °C^{-1}, $\Delta H_{\text{deh}} = 2.44 \cdot 10^{-6}$ J kg^{-1}, $g = 9.81$ m s$^{-}2$, $\alpha_R = 25$ W m^{-2} °C^{-1}, $\alpha_N = 4$ W m^{-2} °C^{-1}, $\beta_R = 20 \cdot 10^{-9}$ s m^{-1}, $\beta_N = 10 \cdot 10^{-9}$ s m^{-1}, $e = 0.7$, $P_\infty = P_0 = 1330$ Pa, $T_\infty = T_0 = 25\,$°C.

For thermal conductivity of concrete λ holds, see [2], $\lambda_{\text{low}} \leq \lambda \leq \lambda_{\text{up}}$, where

$$\lambda_{\text{low}}(T) = 2 - 0.2451\,\frac{T}{100} + 0.0107\left(\frac{T}{100}\right)^2, \quad \lambda_{\text{up}}(T) = 1.36 - 0.136\,\frac{T}{100} + 0.0057\left(\frac{T}{100}\right)^2.$$

In the model was set $\lambda = \frac{\lambda_{\text{low}}+\lambda_{\text{up}}}{2}$.

Following [2], density of concrete ρ_s and specific heat of concrete $C_s(T)$ is:

$$\rho_s(T) = \begin{cases} 2500 & \text{for} \quad 20\,°\text{C} \leq T \leq 115\,°\text{C}, \\ 2500\left(1 - 0.02\,\frac{T-115}{85}\right) & \text{for} \quad 115\,°\text{C} \leq T \leq 200\,°\text{C}, \\ 2500\left(0.98 - 0.03\,\frac{T-200}{200}\right) & \text{for} \quad 200\,°\text{C} \leq T \leq 400\,°\text{C}, \\ 2500\left(0.95 - 0.07\,\frac{T-400}{800}\right) & \text{for} \quad 400\,°\text{C} \leq T \leq 1200\,°\text{C}, \end{cases}$$

and

$$C_s(T) = \begin{cases} 900 & \text{for} \quad 20\,°\text{C} \leq T \leq 100\,°\text{C}, \\ 800 + T & \text{for} \quad 100\,°\text{C} \leq T \leq 200\,°\text{C}, \\ 900 + \frac{T}{2} & \text{for} \quad 200\,°\text{C} \leq T \leq 400\,°\text{C}, \\ 1100 & \text{for} \quad 400\,°\text{C} \leq T \leq 1200\,°\text{C}. \end{cases}$$

Enthalpy of evaporation is given in [9],

$$\Delta H_{\text{evap}}(T) = 2.672 \cdot 10^5\ (374.15 - T)^{0.38} \qquad \text{for } T \leq 400\,°\text{C}.$$

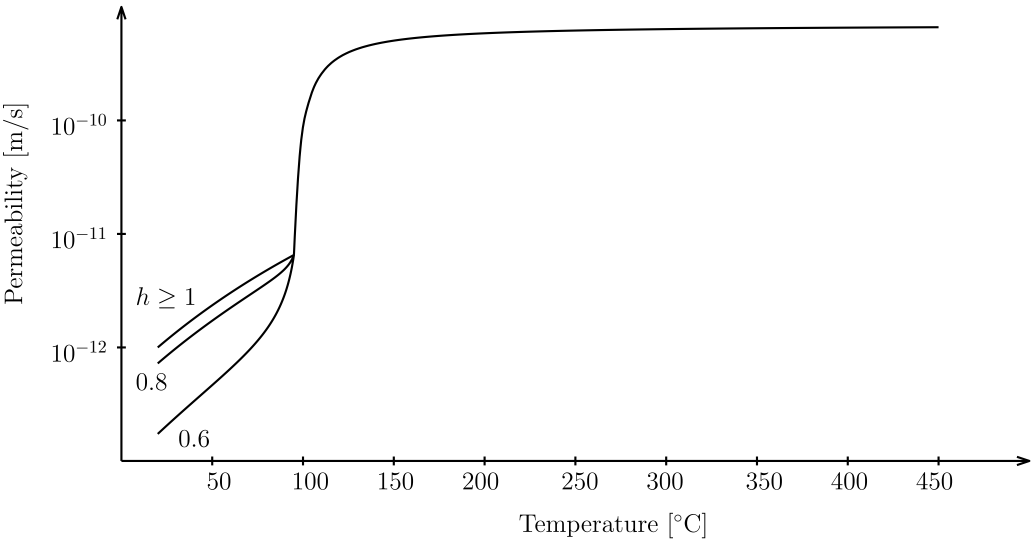

Figure 1: Logarithmic plot of permeability $K\left(T, h(T,P)\right)$ of concrete

As T_{en}, we used ISO curve given by [1], $T_{\text{en}}(t) = T_0 + 345\,\log(480\,t + 1)$.
Permeability $K(T,P)$ can be found in [3] and is given by relationship:

$$K(T,h) = \begin{cases} 10^{-12}\left(\alpha + \frac{1-\alpha}{1+\left(\frac{1-h}{0.25}\right)^4}\right) e^{2\,700\left((T_0+273.15)^{-1}-(T+273.15)^{-1}\right)} & \text{for} \quad T \leq 95\,°\text{C}, \\ & \qquad\quad h \leq 1, \\ 10^{-12}\, e^{2\,700\left((T_0+273.15)^{-1}-(T+273.15)^{-1}\right)} & \text{for} \quad T \leq 95\,°\text{C}, \\ & \qquad\quad h > 1, \\ 10^{-12}\, e^{2\,700\left((T_0+273.15)^{-1}-(368.15)^{-1}\right)}\, e^{\frac{T-95}{0.881+0.214(T-95)}} & \text{for} \quad T > 95\,°\text{C}, \end{cases}$$

where several auxiliary functions are used. We define $\alpha(T)$ and $h(T,P)$ as

$$\alpha(T) = \left(1 + \frac{19\,(95-T)}{70}\right)^{-1}, \quad h(T,P) = \frac{P}{P_s} = \frac{P}{e^{23.5771 - \frac{4\,042.9}{(T+273.15)-37.58}}},$$

where P_s is a saturated vapour pressure. Plot of the permeability is on the Figure 1.
Results of the model are on the Fig. 2. Time step is set to 5 sec., number of mesh elements is 20×40.

6. Conclusion

Development of reasonable models for the prediction of behavior of concrete structures is strongly required by the applied research in civil engineering. Practical validation of the models suffers from the lack of data from experiments. Sufficiently general formulation of the problem should be a motivation for further research.

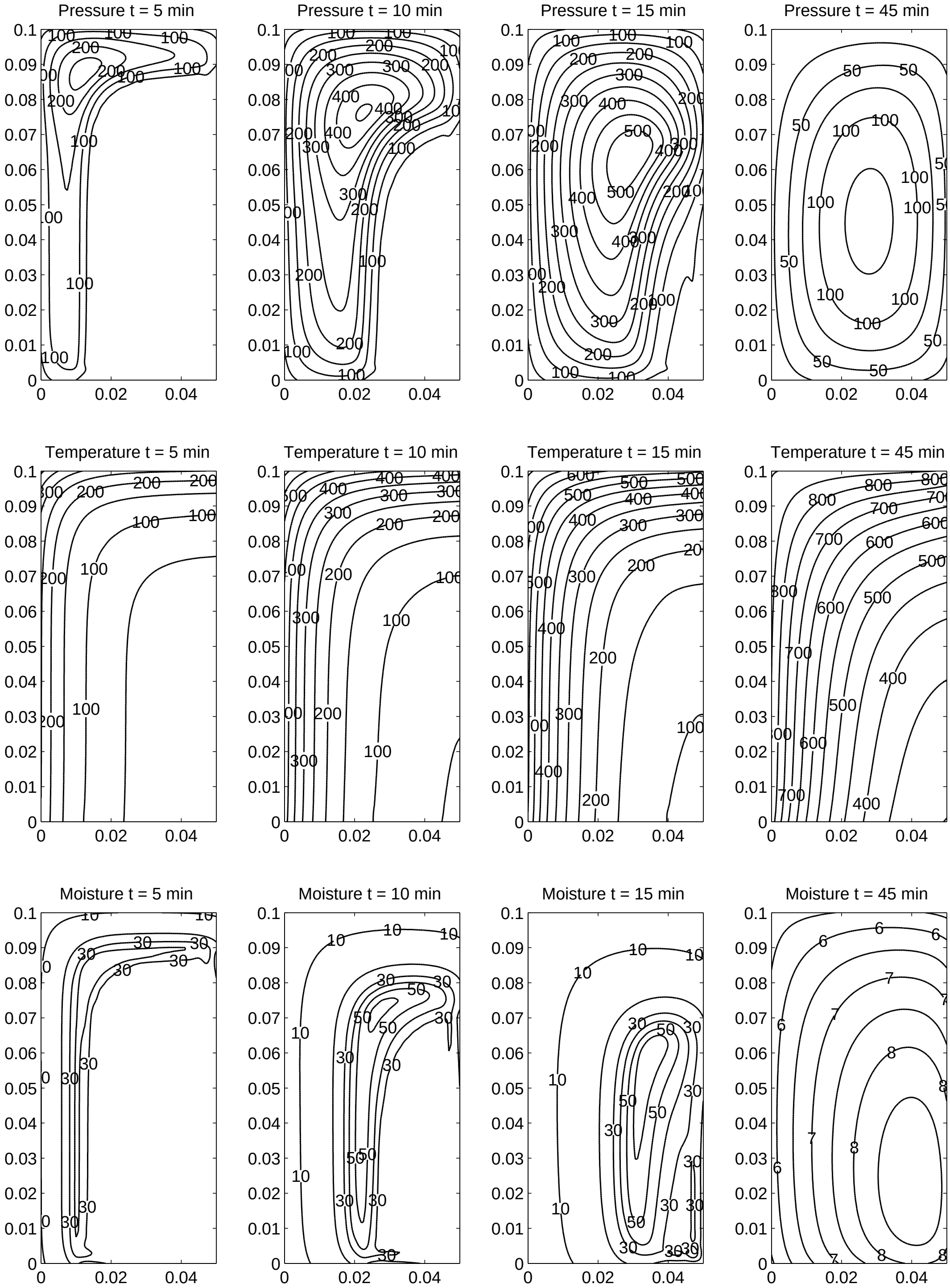

Figure 2: Time development of pressure P [kPa], temperature T [°C] and moisture [kg m^{-3}]. Time step: 5 sek, number of spatial elements: 20×40.

Acknowledgments

This work was supported by Brno University of Technology, grant No. FAST-J-14-2362.

References

[1] ČSN EN 1991-1-2 (730035) eurokód 1: Zatížení konstrukcí - Část 1-2: Obecná zatížení - zatížení konstrukcí vystavených účinkům požáru, 2004.

[2] ČSN EN 1992-1-2 (730035) eurokód 2: Navrhování betonových konstrukcí - Část 1-2: Obecná pravidla - navrhování konstrukcí na účinky požáru, 2006.

[3] Bažant, Z. and Kaplan, M.: *Concrete at high temperatures: material properties and mathematical models*. Longman Group Limited, 1996.

[4] Beneš, M., Štefan, R., and Zeman, J.: Analysis of coupled transport phenomena in concrete at elevated temperatures. Appl. Math. Comput. **219** (2013), 7262–7274.

[5] Dwaikat, M. and Kodur, V.: Hydrothermal model for predicting fire-induced spalling in concrete structural systems. Fire Safety Journal **44** (2009), 425–434.

[6] Gawin, D. and Pesavento, F.: An overview of modeling cement based materials at elevated temperatures with mechanics of multi-phase porous media. Fire Technology **48** (2012), 753–793.

[7] Hertz, K.: *Analyses of concrete structures exposed to fire: U-050*. Department of Buildings and Energy, Technical University of Denmark, 1999.

[8] Ingham, J. P.: Application of petrographic examination techniques to the assessment of fire-damaged concrete and masonry structures. Materials Characterization **60** (2009), 700 – 709. 11th Euroseminar on Microscopy Applied to Building Materials (EMABM).

[9] Moran, M., Shapiro, H., Boettner, D., and Bailey, M.: *Fundamentals of engineering thermodynamics*. John Wiley & Sons, 2010.

[10] Černý, R. and Rovnaníková, P.: *Transport processes in concrete*. Taylor & Francis, 2002.