# NUMERICAL MODEL FOR CONCRETE EXPOSED TO HIGH TEMPERATURE

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## Abstract

*Fire in concrete structures causes serious damage in the form of deterioration of strength properties and may lead to failure of the structures. Estimating the extent of damage is very important for repair or retrofitting of the concrete structures. In the present study a Hygro-thermo-mechanical model is developed to estimate the pore pressure, temperature and displacements. These parameters are treated as state variables which intern vary with the extent of the dehydration process when concrete is exposed to high temperature. Concrete is treated as a deformable, multiphase porous material. The model is developed based on the poromechanics concepts. Phase changes and chemical reactions (dehydration) are taken into account in the model development. The model is a coupled chemo-hygro-thermo-mechanical process (accounting for the extent of dehydration). The model accounts for the characteristic of various phases of concrete such as moisture, energy and transport phenomena. Evolution of material properties (porosity, permeability, strength properties) with the extent of temperature of concrete is considered in the model.*

***Keywords:*** *Concrete, High Temperature, Pore Pressure, Hygro Thermo Mechanical Model, Damage*

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## 1. INTRODUCTION

The properties of concrete such as elastic modulus, compressive strength, porosity etc. rapidly change when exposed to high temperature. It is very important to know the residual properties ofconcrete after fire for repair and rehabilitation of the structure. Estimating development of pore pressure is also very important for weakly permeable materials such as concrete when exposed to high temperature. If the pore pressure increases beyond the tensile strength of concrete then it causes serious explosive spalling. The subject of this paper is development of thermo hygro mechanical modelling of concrete when exposed to high temperature. The mathematical model is based on the concepts of poromechanics developed by Oliver Coussy (2004). The particular focus of the present work is on the computation of temperature and pore pressure distributions and damage of concrete when exposed to high temperature.The model developed in the present study accounts dehydration phenomena, hygro and heat transport, as well as damage behavior of concrete. The dehydration of concrete is modelled using Bazant (2000) approach. The dehydrated water is also considered in the balance equation which intern contributes to the pore pressure development.Expressions for the thermal damage is similar to those given in Gawin et. al. (2006). Compressive strength, tensile strength and modulus of elasticity are considered as function of temperature specified in the Eurocode.

## 2. MATHEMATICAL MODEL

### 2.1. Basic Equations

The basic equations of the model with the following assumptions were developed.

### 2.1.1 General Assumptions

- Concrete treated as multiphase porous medium consists of solid phase, water and water vapor.
- Concrete is partially saturated.
- Dry air effect in variation of pressure is neglected. According to Dwaikat (2009) the density of water and water vapor is much higher than the mass of dry air, hence majorly vapor pressure contributes in spalling phenomena of concrete.

### 2.1.2 Balance Equations

The mass balance equation for water and water vapor can be written as

$$\frac{\partial \eta_w \rho_w}{\partial t} + \nabla.(\eta_w \rho_w v_w) = \frac{\partial w_e}{\partial t} - M^{vap} \qquad (1)$$

$$\frac{\partial \eta_v \rho_v}{\partial t} + \nabla.(\eta_v \rho_v v_v) = M^{vap} \qquad (2)$$

Where $M^{vap}$ is the rate of mass transfer during vaporization of liquid water, $w_e$is mass of dehydrated water due to dehydration. $\eta_w\rho_w$ and $\eta_v\ \rho_v$ is the mass fractions of liquid water and water vapor respectively. Further $\eta w\rho_w = \varphi S_w\ \rho_w$

and $\eta_v \rho_v = \varphi (1-S_w) \rho_w$, where $\varphi$ is porosity, $S_w$ is the saturation, $\rho_w$ is the density of water and $\rho_v$ is density of water vapor. $v_w$ and $v_v$ are velocity of water and water phase, which is represented as Darcy's law.

Darcy's law of water and water vapor represented as follows

$$\eta_w \rho_w v_w = -\rho_w \frac{Kk_{rw}}{\mu_w} \nabla p_w \tag{3}$$

$$\eta_v \rho_v v_v = -\rho_v \frac{Kk_{rg}}{\mu_g} \nabla p_v \tag{4}$$

And,

$$p_w = p_v - p_c \tag{5}$$

Where K is the permeability, $k_{rw}$ and $k_{rg}$ are relative permeability of water and gas respectively. $P_v$ is the pressure of water vapor, $p_c$ is the capillary pressure, $\mu_w$ and $\mu_g$ represents the dynamic viscosities of water and gas.

Combine equations 1 and 2 to eliminate the vaporization term. Considering Darcy's law, the final form of mass balance equation can be written as

$$\frac{\partial m}{\partial t} - \frac{\partial w_e}{\partial t} = \nabla\left[\left(\rho_w \frac{Kk_{rw}}{\mu_w} + \rho_v \frac{Kk_{rg}}{\mu_g}\right)\nabla p - \rho_w \frac{Kk_{rw}}{\mu_w}\nabla p_c\right] = 0 \tag{6}$$

Where, $m = \eta_w \rho_w + \eta_w \rho_w = m_w + m_v$ (6.1)

The capillary pressure $p_c$ is expressed in the form of kelvin equation

$$p_c = -\rho_w \frac{TR}{Mw} \ln\left(\frac{p_v}{p_{sat}}\right) \tag{7}$$

Where $p_{sat}$ is the saturated vapor pressure, which can be represented as a function of temperature by the following formula

$$p_{sat} = \exp\left(23.5771 - \frac{4042.9}{T - 37.58}\right) \tag{8}$$

Where T is a temperature in Kelvins.

Enthalpy balance equation for multiphase system

$$\rho C_p \frac{\partial T}{\partial t} - \nabla.\lambda_{eff} \nabla T = \dot{w}_e H_e$$

Where $\rho C_p$ is the heat capacity of the multiphase system which can be defined as follows

$$\rho C_p = \rho_w C_p^w \eta_w + \rho_v C_p^v \eta_v + \rho_s C_p^s \eta_s \tag{9}$$

Where $C_p^w$, $C_p^v$ and $C_p^s$ are heat capacities of water, water vapor and solid phase of the system, $\rho_s$ is the density of solid matrix and $\eta_s$ is the volume fraction of the solid phase.

$\lambda_{eff}$ is the thermal conductivity of the concretegiven by Gawin et.al.

$$\lambda_{eff} = \lambda_e \left(1 + \frac{4\phi \rho_w S_w}{(1-\phi)\rho_s}\right) \tag{10}$$

and

$$\lambda_e = \lambda_e^{ref} \left(1 + A_T (T - T_{ref})\right) \tag{11}$$

$\lambda_e^{ref}$ is the thermal conductivity of dry concrete, $A_T$ is the experimental coefficient and $T_{ref}$ is the reference temperature.

The sorption isotherm for the free water present is proposed by Bazant et.al. (1981)

$$\rho_c \left(\frac{m_0 p_v}{\rho_c p_{sat}}\right)^{1/m(T)} \quad \text{For } \frac{p_v}{p_{sat}} \le 0.96$$

$$m_w = m_{0.96} + \left(\frac{p_v}{p_{sat}} - 0.96\right)\frac{m_{1.04} - m_{0.96}}{0.08} \quad \text{for}$$

$$0.96 < \frac{p_v}{p_{sat}} < 1.04 \tag{12}$$

$$m_{w0}\left[1 + 0.12\left(\frac{p_v}{p_{sat}} - 0.96\right)\right] \quad \text{For } \frac{p_v}{p_{sat}} \le 1.04$$

Where $\rho_c$ is the mass of cement per unit volume of concrete, $m_{w0}$ is the mass of water for saturation at any temperature per unit volume of concrete, $m_0$ is the mass of water for saturation per unit volume of concrete at room temperature. For dehydrated water, a simplified formula given by Bazant and Kepaln is employed in the calculations

$$0 \quad \text{for } T \le 100^o C$$

$$w_e = \quad 0.04\rho_c \frac{T-100}{100} \quad \text{for}$$

$$100^o C < T \le 700^o C \tag{13}$$

$$0.24\rho_c \quad \text{for } T > 700^o C$$

The tensile strength of the concrete is considered as a function of temperature specified in the Eurocode 2 (2004).

Momentum balance equation

$$div\,\boldsymbol{\sigma} + \rho\,\mathbf{g} = 0 \tag{14}$$

Where $\boldsymbol{\sigma}$ is the stress tensor, $\rho$ is the density and $\mathbf{g}$ is the acceleration due to gravity.

The field variables chosen for the present model is vapor pressure $p_v$, Temperature T and displacement vector **u.**

### 2.2.1 Initial and Boundary Conditions

Initial Conditions at time t=0 for whole domain and boundary,

$p_v = p_{v0}$, $T=T_0$, $u=u_0$ (15)

Boundary conditions can be Dirichlet's type

$$p_v = p_v^b \text{ on } \Gamma_v$$

$$T = T^b \text{ on } \Gamma_T \quad (16)$$

$$u = u^b \text{ on } \Gamma_u$$

Neumann Type boundary conditions

$$(\eta_w \rho_w v_w + \eta v \rho_v v_v) n = \beta_c (\rho_v - \rho_{v\infty}) \quad \text{on} \quad \Gamma_v^q$$

$$(\lambda_{eff} \nabla T) n = -h_T (T - T_\infty) - e\sigma_0 (T^4 - T_\infty^4) \text{ on } \Gamma_T^q \quad (17)$$

$$\boldsymbol{\sigma}.\boldsymbol{n} = \boldsymbol{t} \text{ on } \Gamma_u^q$$

Where n is the unit normal vector, $\Gamma$ is the boundary, $\beta_c$ and $h_T$ are convective mass and heat exchange coefficients, e is the emissivity, $\sigma_0$ is the Stefan Boltzmann constant and $\boldsymbol{t}$ is the traction vector.

Thermal damage is given by Gawin et. al.

$$D_T(T) = 1 - \frac{1}{3}\left( \frac{E_c(T)}{E_{c,ref}} + \frac{f_c(T)}{f_{c,ref}} + \frac{f_t(T)}{f_{t,ref}} \right) \quad (18)$$

Where D is Damage, $E_c$ is the elastic modulus of concrete, $f_c$ is the compressive strength of concrete and $f_t$ is the tensile strength of concrete.

The weak form of the above equations obtained by means of Gelarkin method. Then COMSOL and MATLAB is used to obtain solution of the equations.

## 3. VALIDATION

The above described model is validated by comparing the model predicted temperature and pore pressure with the experimental values given in the study byKalifa et. al.(1999).In the above study (Kalifa et. al.(1999)) experiments are conducted on 120mm thick concrete wall by rapid heating at one side and other side of the wall by exposing to environmental conditions. The heating rate was 5°C/sec up to 2 min then they kept constant temperature of 600°C throughout the test period. The temperature was measured at 2mm, 10mm, 20mm, 30mm, 40mm, 50mm and 120mm from the heating side. Pore pressure was measured at the locations 20mm 30mm and 40mm from heating side. Material properties, initial and boundary conditions specified in the test were used to carry out the analysis. The boundary and initial conditions, wall geometry and FEM mesh are shown in the Table 1, figure 1 and figure 2 respectively.

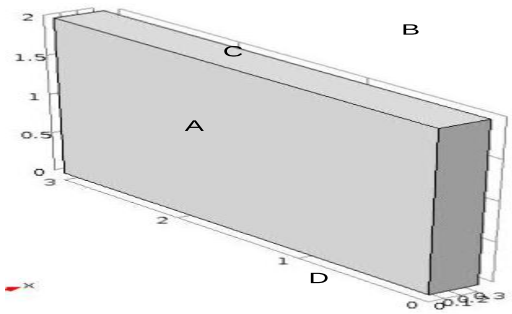


**Fig1:** Wall Geometry

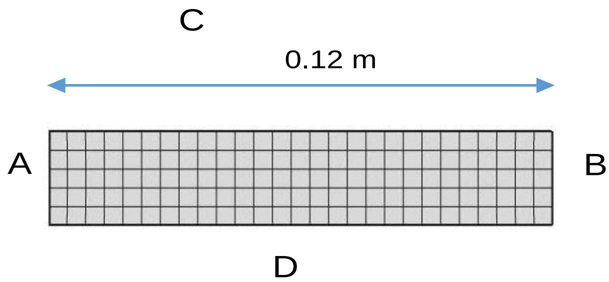


**Fig 2:** 2D FEM Mesh

Figure 3 shows the comparison of simulated temperature results with present study and experimental temperature data of various locations. The model results is close agreement with the experimental results for all the measured locations. Figure 4 shows the pore pressure comparison of simulated results with experimental data measured at the location of 30 mm from the heating side. Its seen that the simulation results closely agrees with experimental data.

**Table 1:** Boundary and initial conditions

| | | |
|---|---|---|
| **Boundary Conditions** | | |
| **Diritchlet Type** | | |
| Side | State variable | Boundary condition |
| **D** | $u_y$ | 0 |
| **Cauchy's Type** | | |
| **Side** | State variable | Boundary condition |
| **A** | $P_v$<br>$T$ | $p_\infty$= 1903.9 Pa, βc = 0.019 m/s<br>293.15+ t*4.833 for t< 120 s<br>$T_\infty$ (t)= 703.15+(t-120)*0.0016 for t> 120 s<br>$\alpha_c$ = 18 W/m$^2$ K<br>eσ0= 0.5*5.1*10^-8 W/m$^2$/K |
| **B** | $p_v$<br>$T$ | $p_\infty$= 1903.9 Pa, βc = 0.009 m/s<br>293.15 K, $\alpha_c$ = 4 W/m$^2$ K<br>eσ0= 0.5*5.1*10^-8 W/m$^2$/K |
| **C&D** | $p_v$<br>$T$ | $q_{gw}$=$q_w$=0<br>$q_T$=0 |
| **Initial Conditions** | | |
| $p_{v0}$ = 2013.3 Pa<br>$T_0$ = 293.15 K<br>u=0 | | |

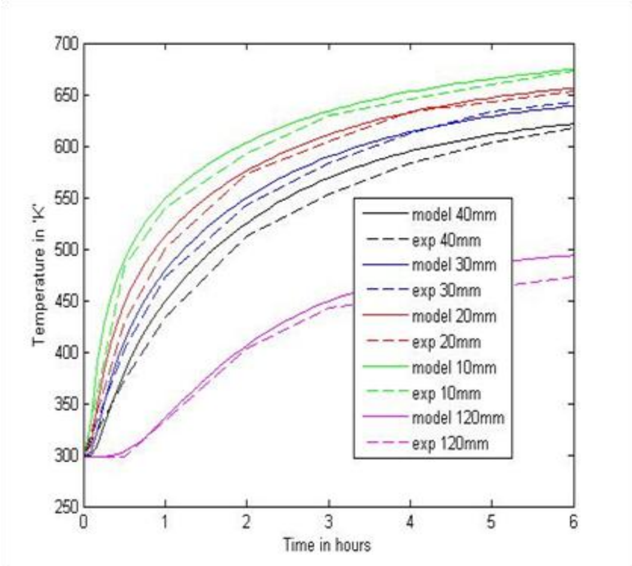


**Figure 3:** Comparison of experimental and model results for temperature distribution of wall at various locations with time.

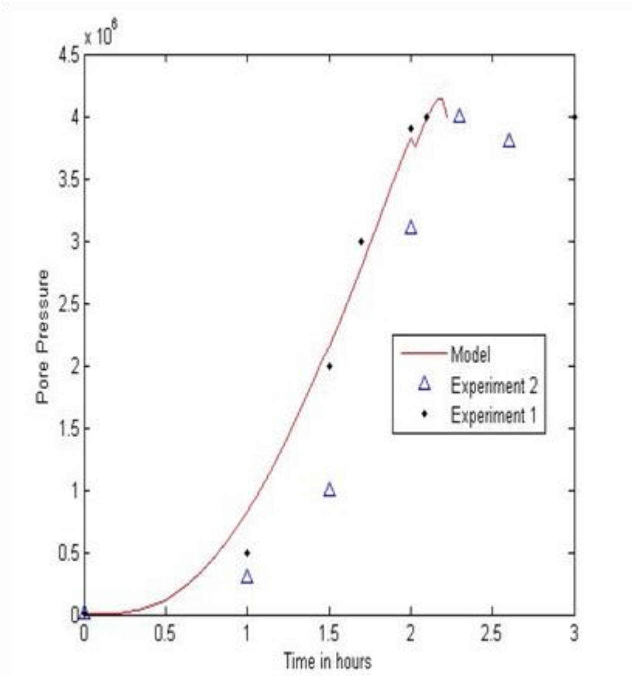


**Figure 3:** Comparison of experimental and model results for temperature distribution of wall at various locations with time

## 4. CONCLUSIONS

[1]. A simplified hygro thermo mechanical model based on poromechanics developed to estimate the temperature, pore pressure in heated concrete.

[2]. The predicted results closely matching with the experimental results.

[3]. The work is under progress for estimating damage, which will be presented at the time of presentation

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