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THE COUPLED EFFECT OF TEMPERATURE AND MOISTURE ON FRESHLY CASTED CONCRETE (FCC), IN HOT WEATHER, PART I

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ABSTRACT

Concreting in hot weather requires an understanding the effects of environmental factors, high air temperature, wind velocity and low relative humidity, any combination of these factors affects property and quality of fresh or hardened concrete. The present study devoted to propose a theoretical model describing the heat transfer and mass transport occurring in convective conditions in a hot weather. We are interested in the effect of temperature and moisture on the progress and distribution of evaporation which affects the concrete, many physical effects must be considered: fluid flow, heat transfer and transport of participating fluids and gases. The validation of the model will represented in the next paper in the part II of modeling of the effect of temperature and moisture on freshly casted concrete (FCC),In hot weather.

Keywords: Weather, Environment, moisture, Theoretical model, Fcc.

1. INTRODUCTION

Under high evaporation rates, mainly caused by wind, low relative air humidity and high temperature, concrete may crack even before the material has reached a significant strength [1]and [2]. A general trend was observed in that as the wind speed increases, the shrinkage also increases [3]. High ambient temperature applied on the concrete increases the temperature of the fresh concrete and cause the high-water demand. This results in an increased rate or evaporation and in more rapid hydration, that lead to accelerated setting and lower long-term strength of concrete [4-8]. Furthermore, the material characteristics of concrete are temperature dependent. Thus, any increase in temperature induces a significant change in thermal properties such as heat capacity, heat of vaporization, conductivity, and in mass transport properties such as diffusivity, dynamic viscosity. Which in turn affect the overall mechanical (strength, stiffness, fracture energy, etc.) and durability properties of hardened concrete materials [9]. A numerical simulation model is presented to predict the drying of concrete. Coupled equations of heat and moisture transport in porous materials, including the hydration phenomenon, are incorporated into the model. In freshly casted concrete(FCC), moisture movements are typically characterized by high rates of diffusion followed by gradually lower and lower rates 10 to 12 hours after placement [10,11]. This drying characteristic is inherently related to a material property referred to as the moisture diffusivity (D) which has been generally accepted to be dependent upon the pore water content within the cement paste. It has been observed that moisture diffusivity may change significantly with variations in the moisture content or the relative humidity of the concrete [12,13].

2. MATHEMATICAL MODEL

There are many models in the literature describing moisture transport under a temperature gradient in porous materials as hygrothermal models [12, 13]. Mostly based on fluid mechanics using the laws of mass (Fick and Darcy) transport and heat (Fourier) diffusion [10]. The concept of maturity is introduced to describe the level of development of hydration process of freshly concrete [14]. For solving simultaneously, the coupled and nonlinear partial differential equations (PDEs), COMSOL Multiphysics [15] is chosen to conduct the numerical modelling and simulation. COMSOL is a finite element analysis software and can provide the CAD tools for geometry modelling and boundary defining, as well as various predefined physics interfaces that can be coupled together to solve partial differential equations (PDEs), and finally present the results graphically [16].

2.1 Governing equations

Here, we presume that the main mechanisms governing the transfer of heat are the thermal conduction and convection due to air movement and latent heat. The liberated heat of cement concrete during hydration which considered as an exothermic reaction up to 500J per gram pf cement [6,8]. This heat source must be incorporated in any early age of heat transfer.

It should be noted that the use of the concept of maturity, is to define the dependent time of the temperature in hydration process, which lead to introduce the equivalent age concept [14].

Different kinds of transport equations and boundary conditions are required in order to simulate the heat and moisture transfer in concrete. These equations are outlined below in accordance with the considered medium. The equations require dedicated boundary conditions in order to close the problem and solve the coupled equations [17,18].

2.2 Conservation equation:

Based on the principle of the conservation of energy including the heat generation Q [9,17], the thermal process of transfer is governed by the Fourier's law as follows: [12,13,19,20,]

$$\rho c_p \dot{T} = \nabla.(k\nabla T) + Q \quad (1)$$

K: thermal conductivity of concrete (W/m.K)
ρ: density of concrete (kg/m^3)
T: temperature (K)
C_P: heat capacity of concrete (J/(kg.K))
Q: heat generation rate (W/m^3)

2.3 Degree of hydration and equivalent age

The equation 2 describes the changes of temperature during hydration. For every change in temperature, we have a new equivalent age (time) [21, 22, 23].

$$\dot{t}_e = \frac{dt_e}{d\tau} = exp\left[\frac{E}{R}\left(\frac{1}{T_r} - \frac{1}{T(t)}\right)\right] \quad (2)$$

Where:

t_e : is equivalent age at the reference curing temperature;
dτ : time interval or the hydration time parameter (h);

E : activation energy (J/mol);
R : universal gas constant (8.314 J/mol□K) ;
T_r: reference temperature (K); T: Concrete temperature (K).
The maturity equation shows a coupling between the equivalent time and the degree of hydration which is intended to constitute a measure of how far the reactions between cement and water have developed [16,21 24,25].

$$\dot{\alpha} = \frac{d\alpha}{dt} = exp\left[\frac{E}{R}\left(\frac{1}{T_r} - \frac{1}{T}\right)\right]\frac{\alpha_u \beta}{t_e}\left(\frac{\tau}{t_e}\right)^{\beta}.exp\left[-\left(\frac{\tau}{t_e}\right)^{\beta}\right] \quad (3)$$

With:
T_r: is the reference temperature;
β : is the hydration shape parameter;
α_u : is the ultimate degree of hydration, which can be presented as follows [26]:

$$\alpha_u = \frac{1.031.w/c}{0.194+w/c} \quad \textbf{(4)}$$

Where: w/c the water–cement ratio,
Since the degree of hydration is defined as the ratio between the quantity of hydrated and the original quantity of binder [15, 21].It worth to note that the degree of hydration can reach 1 if the hydration has been achieved .However it may be 0, if the reaction is not start.

$$Q = H_u.C.\dot{\alpha} \quad \textbf{(5)}$$

Where
H_u: ultimate heat of hydration (J/kg)
C: total amount of cement (kg/m^3)

3. MOISTURE TRANSFERT

The mobility of water along adsorbed water layers is rather limited (especially for hindered adsorbed water) and the transport mechanism is completely different compared to the transport of capillary water and water vapor. In addition, all moisture transport mechanisms are influenced by concrete microstructure (in particular the microstructure of calcium silicates hydrates), which, in turn, depends on the extent of the chemical reactions that characterize concrete at early ages. Moreover, these chemical reactions often involve water, which may be subtracted from the system (e.g. during cement hydration) or released into the system, [38].
The different water transport mechanisms should be modeled independently through the formulation of separate diffusion equations since each single mechanism has its own driving force (capillary pressure, vapor pressure for the water vapor, etc.). However, the complexity of the phenomena hampers this kind of approach and calls for a simplified approximated analysis. First of all, it is possible to simplify the problem by postulating the existence of local thermodynamic equilibrium [27,28,29,30]. The general equation for moisture transfer through a porous media under isothermal conditions is described through the second Fick’s law [20] Equation (6). This governing equation is based on the conservation of mass, and expresses the flux of water mass per unit time q reads: In this study, as widely accepted in the literature,

$$q = -D_h.\nabla h \quad (6)$$

Where:
q : is moisture flux, [kg / (m^2. s)]

D_h : Coefficient of moisture diffusivity; [m^2. s^{-1}]
∇h : is a gradient of relative humidity.
The moisture mass balance requires that the variation in time of the water mass per unit volume of concrete (water content w) be equal to the divergence of the moisture flux **q** [31, 28].It should be noted that in this model there is on different between water and vapor water in term of mass.

$$\frac{dw_l}{dt} + \frac{dw_n}{dt} = -\nabla q \tag{7}$$

$$\frac{dw_l}{dh}\frac{dh}{dt} + \frac{dw_n}{dt} = c_h\dot{h} + \frac{dw_n}{dt} = \nabla(D_h \nabla h) \tag{8}$$

The Eq(8) it can be written as follow:

$$c_h\dot{h} = \nabla(D_h \nabla h) - \frac{dw_n}{dt} \tag{9}$$

Where
w_l: is moisture content at current time *t*, [kg/m^3],
w_n: *stands* for the amounts of moisture consumed by hydration, [kg/m^3],
q: is moisture flux, [kg / (m^2s)].
c_h: moisture capacity; kg.m^{-3}
h: is relative humidity. %

According to (Bažant and Najjar 1972) Moisture capacity in this study is almost the case for mature concrete and relative humidifies above 0.15. It is worth mentioning here in this study that the moisture capacity is deemed constant. Furthermore, the function *D(h)* is assumed as homogenous. For old enough normal concrete the second term in Eq (9) is neglected, but for the early age normal concrete it must be taken in consideration. Furthermore, never has negligible values, unless hydration has ceased [32, 33]. Experiments carry out by Mills and Hedenblad [26,34] show that per each gram of hydrated Portland cement: approximately 0.253 g of water is chemically bound.

$$w_n = 0.253 c\alpha_u \tag{10}$$

Where
w_n : chemically bound water;
α_u : degree of hydration;
c : cement content.
The concrete is in the fresh state and consider that the water / cement ratio is high, about 0.5, therefore self-drying can be considered to have negligible effect on the HR development of the concrete. In this study, as typically done in literature [33,35], while the homogenous moisture diffusion coefficient *D(h, T)* is expressed as follows:

$$D(h,t) = D_1\left[m + \frac{1-m}{1+[(1-h)/(1-h_c)^n]}\right] exp\left[\frac{E_A}{R_u}\left(\frac{1}{T} - \frac{E}{293}\right)\right] \tag{11}$$

Where
D_1 :is the diffusivity value at (h=1) [kg.m^{-3}]
m = 0.05, n = 15;
h_c : 0.80;

$\frac{E_A}{R_u}$: is the activation temperature (K);
T is the temperature (K);
T_0 =293K is chosen as the reference temperature.
The maximum of moisture diffusion coefficient can be estimated as follows [35]:

$$D_1 = \frac{D_{1,0}}{(f_{cm}-8)/10} \tag{12}$$

Where
$D_1 = 1x10^{-9}\ m/s^2$;
f_{cm} : is the mean compressive strength (MPa);
However, the activation temperature has a temperature dependency of the activation energy as follows [36]

$$\frac{E_A}{R_u} = \theta_0 \left(\frac{3}{T+10}\right)^k \tag{13}$$

Where
θ_0= 4,600 K
k = 0.39 for ordinary Portland cement

4. THERMAL CONDUCTIVITY AND HEAT CAPACITY OF FRESH CONCRETE

Thermal and physical properties such as mass density, heat capacity, moisture capacity and thermal conductivity are depending by hydration and moisture, as denoted in the literature [6-8] the corresponding equations given by:

$$w = w_l + w_s \tag{13}$$

Where
w_l: water amount; w_s :concrete Skelton amount include all components
Using the volume fraction the Eq.(13) written as

$$\rho_{eq} = \rho_l\, \theta_l + \rho_s \theta_s \quad such\ as\ \ \theta_l + \theta_s = 1 \tag{14}$$

According to Lamond and Pielert [7] the heat capacity is defined as

$$C_p = \sum_{i=1}^{n} m_i\, C_{p_i} \tag{15}$$

Where
m_i : amount of i component of the concrete (kg);
C_{p_i}: amount of I component of heat capacity (J/kg.K);
However, the equivalent volumetric of heat capacity in this case is done, by COMSOL Multiphysics [15]

$$\left(C_p \rho\right)_{eq} = C_{p_l} \rho_l\, \theta_l + C_{p_s} \rho_s \theta_s \tag{16}$$

In this model the thermal irradiation and solar radiation are neglected, and Thermal convection is expressed by Newton’s Law of cooling as

$$q_c = h_c(T_s - T_a) \tag{17}$$

Where
q_c: thermal convection;
h_c: is the heat convection coefficient (W/m^2 K);
T_s : is surface temperature (K);
T_a : is air temperature (K).
It should be not that the heat convection coefficient h_c in Eq. 17 is a function of many variables such as wind speed, surface roughness, and geometric configuration of exposed structure. The following relationship between heat convection coefficient and wind velocity can be used [35]

$$h_c = 7.6\, v^{0.78} \tag{18}$$

where *v* is the wind speed (m/s)

5. BOUNDARY CONDITIONS

Eq.(1) expresses the balance of thermal energy within the body; the last term in this equation represents the heat sources or heat sinks due to liquid-to-vapor phase change and to the adsorption or desorption process. Whereas, Eq.(9)expresses the balance of moisture within the medium; the last term in this equation represents the amounts of moisture bounded by hydration. The boundary flux defined on convective form for surfaces in contact with ambient air[37].

$$-q.n = \beta_h.(h - h_a) \tag{19}$$
$$0 = \nabla.(k\nabla T) + Q \tag{20}$$

β_h :is the moisture surface factor
h_a: is the humidity of the ambient air.
p_w: the water pressure can be converted to a corresponding relative humidity, as shown in Eq. (21) , based on calculations of Bazant and Najjar 1972 [33] . This relative humidity can then be directly prescribed on the surface.

$$h = 1 + p_w/(p_{\text{ref}}.\left(\frac{T}{T_{\text{ref}}}\right))\quad p_w > 0 \tag{21}$$

According to Bazant [33] $p_{\text{ref}} = 1360\text{atm}$ and $T_{\text{ref}} = 298K$

6. COUPLING EQUATIONS

$$\rho c_p\dot{T} - \nabla.(k\nabla T) = H_u.C.exp\left[\frac{E}{R}\left(\frac{1}{T_r} - \frac{1}{T}\right)\right]\frac{\alpha_u\beta}{t_e}\left(\frac{\tau}{t_e}\right)^{\beta}.exp\left[-\left(\frac{\tau}{t_e}\right)^{\beta}\right] \tag{22}$$

$$\acute{c}_p\dot{T} = \nabla(D_h\nabla h) - \frac{dw_n}{dt} \tag{23}$$

Such as $\acute{c}_p = c_h c_p$
$\acute{c}_p$:is a function of temperature and humidity in concrete

6.1 Three processes had been interacted

In hot weather, a significant amount of heat is generated by the chemical processes (e.g. binder hydration), which in turn influences the thermal processes (e.g. temperature increments and changes of the equivalent thermal conductivity). The current model does not consider the radiation on the surfaces. However, the quantity bounded by hydration is taken in account, which is worth thing mentioned herein [38].

The binder hydration process in the fresh costed concrete is in turn controlled by its water content, which can be explained by the relationship between the residual water content and binder hydration degree obtained.

7. CONCLUSION

This coupled model presented it (maybe) suitable for modelling the behaviour of very young concrete structures. This model is considered as the thermal, chemical and hydraulically model (TCH) where all the processes are interacting. The governing PDEs (partial differential equations) of the three transport phenomena are coupled and solved simultaneously for potentials driving herein adopted. Binder hydration not only produces substantial amounts of heat that contribute to the temperature rise, but also the porosity of FCC reduced by generates hydration products, and consequently the hydraulic permeability decreases. Decreasing the permeability of the FCC helps to achieve good durability and environmental performances during drying processes.

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