Drying Process Simulation of Unsaturated Concrete Exposed to Air Condition

Van Quan Tran, Hoang Long Nguyen, Minh Viet Nguyen, Huu Nam Nguyen, Quang Hung Nguyen

Abstract**: *The paper focuses on establishanumerical model to simulate drying process of unsaturated concrete exposed to air condition. The model will be set up based on mechanisms of fluid flow. The first part of the paper will present the equations of fluid flow in unsaturated pore milieu and ion ingress into concrete. The numerical model will be performed by Comsol software. The numerical model will be compared with the experimental results from literature, the numerical model offluid flowis validated. The results show that the prediction of numerical model is relatively accurate in drying process of ordinary concrete but with high performance concrete, the accuracy of the model is not really high.***

Keywords**: *Unsaturated concrete, Drying process, numerical model, Fluid flow, Comsol***

I. INTRODUCTION

Concrete is the main material in construction works today. Therefore, the durability as well as the quality of concrete plays a very important role for the quality of the work, thereby reducing the cost of warranty repair. Quality and durability of concrete depend heavily on the main factors such as cement hydration, shrinkage of concrete, moisture transmission in concrete. The processes can be said to depend on the drying process of concrete when exposed to air. The prediction of the dry process of concrete helps to better understand the shrinkage time and thus predict the behavioral behavior of concrete during shrinkage. The paper focuses on building a simple numerical model to predict the normal process of concrete as well as high strength concrete. The first part of the paper introduces the basic theoretical equations of transmissions. Part two is to introduce model geometry, boundary conditions and initial conditions of simulation problem. After that, the model results will be compared with the experimental results from the literature to test the validate the numerical model. The conclusion of the article will be stated in the final section.

II. MODEL APPROACH

The mass transport in unsaturated concretes is characterized by a combined process of convection and advection. The advection phenomenon is generated by the velocity of the fluid resulting from the hydrodynamic process. The flow of water takes two forms: liquid and gas. The transport of moisture in the porous materials is subjected to different mechanisms simultaneously or not. Two types of models are commonly used: unsaturated flow theory (simple model) [1]and multiphase transfer models (reference model) [2]. In this part, we recall the model of water transfer resulting from the theory of unsaturated flows. The equations governing multiphase flows are described in Mainguy's thesis[3] for example. From the work of Celia et al [1], we present the simple model. In this model we assume that the gas pressure p_g is constant and uniform and is equal to the atmospheric pressure p_{atm}.

$$p_g = const = p_{atm} \tag{1}$$

Then we use the Richards equation which constitutes the general equation of the flows in unsaturated medium:

$$q = -K\big(\theta(h)\big)\nabla h \tag{2}$$

Where q is debit, K is hydraulic conductivity, θ is water content depending on the elevation of water h. The following continuity equation is then obtained taking into account the variation of the water content over time:

$$\frac{\partial\theta(h)}{\partial t} + div q = 0 \tag{3}$$

Richard's equation is presented in the form:

$$-\nabla\Big(K\big(\theta(h)\big)\nabla h\Big) + \frac{\partial\theta(h)}{\partial t} = 0 \tag{4}$$

With

$$K(h) = k_s k_r(h) \tag{5}$$

Richards equation assumes that: the effect of air on the movement of the liquid phase (air is present at atmospheric pressure), as well as the dynamic effects[5], [6]and hysteresis on the relations between hydraulic conductivity - matrix pressure and water content are neglected. Hydraulic conductivity K represents the ability of the porous medium to "drive" water. In saturated water, all the pores are filled with water and participate in the flow, the permeability is then maximum. Its value is called absolute permeability which is noted k_s [m²].

Models based on a physical representation of the structure of the poral network make it

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Van Quan Tran, University of Transport Technology, Hanoi, Vietnam.
Hoang Long Nguyen, University of Transport Technology, Hanoi, Vietnam.
Minh Viet Nguyen, Institute for Hydropower and Renewable Energy, Hanoi, Vietnam.
Huu Nam Nguyen, Institute for Hydropower and Renewable Energy, Hanoi, Vietnam.
Quang Hung Nguyen, Thuyloi University, Hanoi, Vietnam
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possible to describe the curve of evolution of the permeability as a function of the water content. They are based on an integration of the capillarity models and are valid at the macroscopic scale, since the porous medium can be considered as homogeneous. The most commonly used models are the relations of Van Genuchten[4]and Brooks and Corey [7] making it possible to describe well the curve K(θ) [8]. They use the parameters obtained by the water retention curve h(θ), generally easier to obtain experimentally, as well as the value of ks, to predict the evolution of the permeability as a function of the water content. Brooks and Corey's relationship is based on the equation:

$$K(h) = k_s S_e^{\frac{2}{\lambda}+l+2}(h) \tag{6}$$

where l is the tortuosity factor which can be equal to 0.5 [9] in most cases and λ = m×n; $S_e$effective saturation. If one chooses the van Genuchten model to describe the water retention curve.

We use van Genuchten's relationship here:

$$K(h) = k_s S_e^l \left[1 - \left(1 - S_e^{\frac{1}{m}}\right)^m\right]^2 \tag{7}$$

This relation is obtained by combining the expression of the capillary pressure -saturation relationship with the expression of the hydraulic conductivity of the material based on the porous distribution of Mualem [18], the expression of the capillary pressure resulting from the expression following:

$$p_l - p_g = p_c \tag{8}$$

The value of the parameter l = 0.5, in Van Genuchten's relationship, was originally used for soils. Savage at Janssen has shown that it can also be applied to cementitious materials [10]. According to Van Genuchten, the relations between S_e; θ; h are expressed as:

$$\theta = \theta_r + S_e(\theta_s - \theta_r) \tag{9}$$

$$S_e = \frac{1}{(1 + |\alpha h|^n)^m} \tag{10}$$

$$m = 1 - \frac{1}{n} \tag{11}$$

The Van Genuchten model is the most widely used in the literature to describe the water retention curve and applies to cementitious material. The Brooks and Corey model is validated over a limited range of capillary pressure (for p ≥ p_i) and is well adapted to the data obtained for coarse, reworked soils with a narrow pore size distribution, it does not allow a good representation of the retention near saturation conditions.

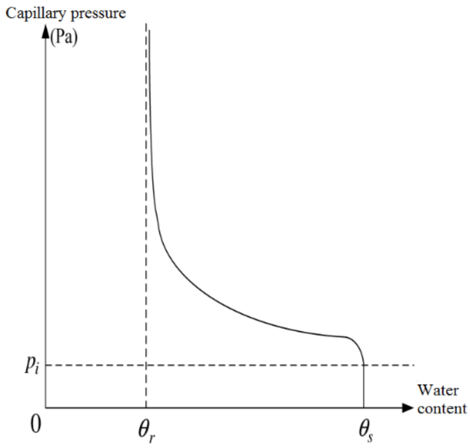

Fig.1: Representation of a water retention curve

III. Comparisons of Reference Model and Simple Model for the Drying of Cementitious Materials

A. Materials

They are fully described in the work of V.Baroghel-Bouny[11]. In this article, 3 materials are used: CO (ordinary cement), BO (ordinary concrete) and BH (high performance concrete). We simply give in the table the water /cement ratio W/C of these materials (see Table 1).

Table 1:W/C ratio of material used

Material	BO	BH	CO
W/C	0.487	0.267	0.348
Accessible porosity	0.122	0.082	0.303

The geometric characteristics of the materials are as follows: cylindrical specimens 16 cm in diameter and 10 cm in height. We assume an isotropic behavior of the material in all the planes perpendicular to the axis of the cylinder. It is also assumed that initially the distribution of the different phases is homogeneous. Finally, the contours of the specimens were protected from water transfer by aluminum foil. It can then be assumed that the transfer phenomena take place only in the direction of the axis of the specimen. The problem thus relates to a unidirectional flow (seeFig. 2)

Fig.2: Model geometry

B. Boundary and initial condition

After their manufacture, the specimens were protected from exchanges with the outside for 2 years. At the end of this period, the hydration reaction is complete and the material has reached a water balance. The relative humidity within the material is then uniform. The values of the initial relative humidity of each of the tested materials are summarized in Table 2

Table 2: Initial state of each material at the beginning the experiment

Material	BO	BH	CO
Internal relative humidity $(h_{r_i}^{i})$	0.9	0.65	0.85
Ambient relative humidity (h_r^e)	0.5	0.5	0.5
Temperature controlled (°C)	20	20	20

In order to make the connection between capillary pressure and relative humidity, we use, from equation 8, the following Kelvin-Laplace relation:

$$p_c = \rho_l \frac{RT}{M_\upsilon} \ln h_r \qquad (12)$$

As part of equation 12, the parameters given in Table 3 and van Genuchten model parameters in the work V. Baroghel-Bouny [4], we find the following boundaryand initial condition (see Table 5):

Table 3: Physical parameter of drying model

Masse of water volume ρ	Perfect gas constant R	Molar mass of water M_υ	Temperature
1000 kg/m^3	8.3147 $J.K^{-1}.mol^{-1}$	0.018 $Kg.mol^{-1}$	293 K

Table 4: Simplified fluid flow model parameters

Material	BO	BH	CO
Permeability $k_s(m^2)$	3.10^{-21}	5.10^{-21}	1.10^{-21}
n	1.78	1.94	1.86
m	0.440	0.485	0.461
l	0.5	0.5	0.5
α	0.0537	0.0213	0.0266
θ_s	0.122	0.082	0.303

Table 5: Boundary and initial condition

Material	BO	BH	CO
Initial condition $h_i(m)$	1426	7024	2650
Boundary condition $h_e(m)$	11302	11302	11302
Initial effective saturation	0.81	0.57	0.82

IV. VALIDATION OF SIMPLE MODEL

We model the specimen with different drying times: 7 days, 62 days, 127 days and 359 days. Simulations are performed by COMSOL software. Numerical results of simple model are compared with experimental data and numerical results of reference model which are extracted from Mainguy's thesis. Fig. 3, 4 and 5showeffective saturation in 7, 62, 127 and 359 days of 3 types of samples: (a) ordinary concrete, (b) high performance concrete and (c) cement mortar, respectively. The comparison shows a similarity of two models: simple model and reference model to predict effective saturation of cementitious material.

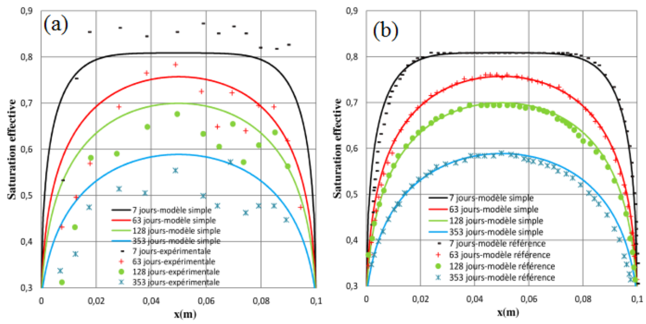

Fig. 3: Effective saturation comparison between simple model and a) experimental data; b) reference model of ordinary concrete[3]

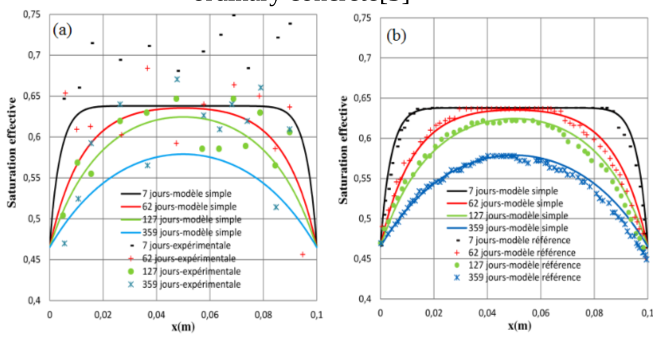

Fig. 4: Effective saturation comparison between simple model and a) experimental data; b) reference model of high-performance concrete[3]

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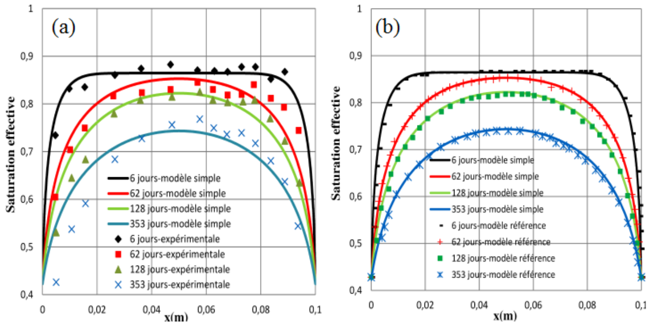

Fig. 5: Effective saturation comparison between simple model and a) experimental data; b) reference model of cement mortar [3]

V. CONCLUSION

For years, the multi-phasic model has been considered as the reference model (Mainguy Model) which is used for water transfer in unsaturated concrete. The comparisons above show that the results of the simple model are extremely close to the results of the multi-phasic model presented in Mainguy's thesis. The results of the simple model are, moreover, very satisfactory compared to the experimental data. The advantage of the simple model is the smallest number of unknowns and therefore a reduced calculation time. The simple model will help us find the convection speed of the solution. Therefore, we will use this model to model the transport of ions in concrete in the tidal cycle.

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AUTHORS PROFILE

Van Quan Tran is a researcher of durability of geomaterials and construction building materials at University of transport technology, Hanoi, Vietnam. Dr. Tranholds a Ph.Ddegreefrom Ecole Centrale de Nantes-France in 2016. During Apr. 2016 due to Mar. 2017, heis the postdoctoral on Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement (Cerema), France. His researches focused on Durability of geomaterials clay, treated soil, concrete, Modelling of hydro-thermo-chemo-mechanical, Hydration mechanisms of cementitious materials, Thermodynamic modeling, Geochemical model of concrete.

Hoang Long Nguyenwas born in 1976, Hung Yen, Vietnam. He received the Engineering’s degree and M.S. degrees in Civil Engineering and Motoway-Airport Road from the University of Transport and Communications and Military Technical Institute of Vietnam in 1999 and 2005, respectively. In 2011, he hold a PhD degree from the Military Technical Institute of Vietnam. Since 1999, he is a lecture and researcher at University of Transport Technology, Hanoi, Vietnam. He is also Vice Rector of University of Transport Technology since 2013. He is an Associate Professor since 2018. He is also principal investigator and member of many science projects of Vietnam Ministry of Transport. His research focus on bituminous materials in Construction.

Minh Viet Nguyen is a researcher of hydraulic construction at Institute for Hydropower and Renewable Energy. He holds a PhD degreein 2017 on His research focus on hydraulic power and renewable energy. Now, he is director of Institute for Hydropower and Renewable Energy.

Huu Nam Nguyen is a researcher of hydraulic construction at Institute for Hydropower and Renewable Energy. Now, he is a PhD student. His research focus on hydraulic power and renewable energy.

Quang Hung Nguyenwas born in 1975 in Hanoi, Viet Nam. He received the Engineering’s degree and M.S. degrees in hydraulic construction from the Thuyloi University of Vietnam, in 1997 and 2000 and the PhD. degree in hydraulic structure from Wuhan University, China. Since 1998, he is a lecture in Faculty of Civil Engineering, Thuyloi University and becomes Associate Professor since 2009. From 2007 to 2013, he was Deputy Director of the Institute of Civil Engineering, designed and built many key projects of Vietnam. He is also principal investigator and member of many national science projects as well as Vietnam Ministry of Agriculture and Rural Development. Since 2013, he has been a senior expert in hydraulic construction of Vietnam Ministry of Construction. He is the Advisor of more than 200 bachelors, 40 masters, 2 PhD specialized in hydraulic construction.