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A numerical model for simulating liquid flow in and around discrete concrete cracks (ACME 2016)

***Chuansan Ma[1], Tony Jefferson[1], Diane Gardner[1], Robert Lark[1]**

[1]School of Engineering, Cardiff University, Queens Buildings, Cardiff, CF24 3AA

*mac1@cardiff.ac.uk

ABSTRACT

A vascular self-healing system, which facilitates the storage, delivery, release, dissipation and curing of liquid self-healing agents, has been proved in the laboratory to be able to improve the durability of cementitious materials. To better understand the healing mechanisms associated with the system, and to optimise its design, a numerical model of the vascular system is proposed. In this study, the dissipation of the healing agent in and around discrete cracks after being released from the delivering flow network is simulated. This flow process comprises the flow of the liquid in the macro-crack space and the flow into the surrounding porous concrete matrix. The flow in the discrete crack is modelled by a modified Lucas-Washburn (L-W) equation, where an additional flow term Q has been introduced to take account of the mass being absorbed by the surrounding matrix. This flow term is determined by a 2D finite element continuum model of the surrounding matrix and is based on isothermal unsaturated flow theories. A mass balance equation is added to account for the interflow between the macro-crack and the matrix. This is achieved by treating the crack as an internal boundary within the matrix and computing the flow across this boundary. The simulation results suggest that imbibition has a significant influence on the flow in the macro-cracks and the degree of influence is related to the permeability as well as to the degree of saturation of the adjacent fracture process zone.

Keywords: *concrete, finite element model, moisture transportation, capillary movement, self-healing*

1. Introduction

Concrete structures are prone to cracking, and these cracks can lead to durability problems and increased maintenance costs. As a result, self-healing concrete has attracted much attention in recent years and has shown great potential to resolve some of these durability issues. Among the various existing self-healing techniques, the biomimetic vascular self-healing system is seen to be one of the most promising and versatile systems [1], and it has been applied to real structures at engineering scale [2]. It could also be easily combined with other self-healing techniques to form an integrated self-healing system [3]. Despite the huge efforts and vast advances in the development of vascular self-healing systems, there has been a lack of understanding, analysis, and simulation of the healing mechanisms and processes. This is, however, crucial to the further development of such systems. This study is to look at the crack filling process of the liquid self-healing agent after being released from the flow network in to the crack planes using a coupled numerical model.

Past experiments and previous literature have suggested that the movement of liquid in concrete cracks is primarily driven by capillary pressure [4,5]. This capillary flow in the crack comprises two distinct flow processes, i.e. the capillary flow in the macro-crack; and imbibition into the surrounding matrix. The flow in the macro-crack has been historically simulated by the modified Lucas Washburn (L-W) equation, which accounts for various factors such as dynamic contact angle and stick slip etc. [4]. However, the influence of the fluid absorbed (or expelled) from the adjacent porous matrix has not previously been included in the equation. For a typical self-healing flow problem, the influence of the matrix flow on the 'discrete' fluid flow in the macro-crack could be particularly important because the matrix around the macro-scale cracks has much higher permeability and porosity due to the developed fracture process zone.

In this study, the combined effect of these two flow processes is modelled by coupling the modified L-W equation with a finite element isothermal flow model of the surrounding matrix. The coupling is realised by adding a mass balance equation for the interflow between the discrete crack and the matrix through the crack faces. This is achieved by treating the crack as an internal boundary within the matrix and computing the flow across this boundary. The individual models for the crack and matrix flow, as well as the coupled flow model, were firstly calibrated and then validated using a range of experimental data. This paper describes a new way of coupling the 2D FE unsaturated flow model with the LW capillary flow equation, so that a better understanding of the movement of liquid healing agents in cementitious cracks can be achieved. The modelling scheme of a specific boundary condition is presented here, i.e. the liquid is freely available at the crack mouth and is not constrained by the delivery system.

2. The coupled model

The capillary flow in the discrete crack is described by a modified Lucas-Washburn Equation as shown in equation (1):

$$p_{c0}(z)(1-\beta_s) - \frac{2\beta_m \dot{z}}{b(z)} + \rho g z \sin(\phi) - \int_0^z \frac{\bar{v}(x)}{\frac{k(x)}{\mu} + \frac{\beta_w b(x)}{2}} dx = 0 \tag{1}$$

where p_{c0} is the surface tension at the meniscus; b(x) is the crack width for a planar water channel; z is the present rise height of the meniscus and $\dot{z}$ is the velocity of the meniscus; μ is the viscosity of the flow agent and k(x) is the effective permeability term that accounts for the shape of the flow cross-section and may vary along the profile of the flow channel. A model that includes factors to account for stick-slip (β_s), friction dissipation at meniscus (β_m), and wall slip (β_w) has been proved to achieve better agreement with experiment results [4] than a model based on the standard L-W equation. Assuming a general expression for imbibition (flow) $q(x')$ along the crack faces. Based on the mass conservation law, the relationship between the moving velocity of the meniscus and the velocity at any point within the flow section is expressed in equation (2).

$$\bar{v}(z)A(z) = \bar{v}(x)A(x) - \int_x^z q(x')dx' \tag{2}$$

Substituting equation (2) into equation (1) and rearranging leads to the modified governing equation of the crack flow, which is as follows:

$$p_{c0}(z)(1-\beta_s) - \frac{2\beta_m \dot{z}}{b(z)} - \rho g z \sin(\phi) - \int_0^z \frac{\bar{v}(x)}{\frac{k(x)}{\mu} + \frac{\beta_w b(x)}{2}} dx - Q = 0 \tag{3}$$

where:

$$Q = \int_0^z \frac{\left(\int_x^z q(x')\,dx'\right)}{A(x)\left(\frac{k(x)}{\mu} + \frac{\beta_w b(x)}{2}\right)} dx \tag{4}$$

The resulted additional double integration term Q accounts for the influence of the total imbibition. It may be seen that this height reduction term is an integral function of the flow field at the crack faces, which is then solved using an isothermal-hygral finite element model of the imbibition in the porous matrix continuum.

The governing equation for this microscopic flow is based on the mass balance equation of the water content in the domain [6, 7], as shown in equation 1.

$$\dot{\overline{\rho_v}} + \dot{\overline{\rho_l}} + \nabla \boldsymbol{q_v} + \nabla \boldsymbol{q_l} + \dot{\overline{\rho_{vl}}} + \dot{\overline{\rho_{lv}}} = 0 \tag{5}$$

where $\dot{\overline{\rho_v}}$ and $\dot{\overline{\rho_l}}$ are the time differentiation of vapour mass and water mass in the domain; $\nabla \mathbf{q_v}$ and $\nabla \mathbf{q_l}$ are the mass flux of vapour and water out of the domain; because the mass balance equation of water content includes both liquid and vapour water, the phase change between the liquid water and water vapour $\overline{\dot{\rho_{vl}}}$ and $\overline{\dot{\rho_{lv}}}$ may be cancelled. The movement of the water content is driven separately by the capillary pressure gradient and vapour concentration gradient. Darcy's law and Fick's law are used to determine the flow term due to capillary pressure and vapour diffusion respectively. Different flow properties have been applied to elements at different locations to account for the larger permeability in micro-cracked zones and surface zones. Capillary pressure p_c is the primary variable for the model and the van Genuchten equation is used to establish the relationship between saturation degree and capillary pressure. The relative permeability and vapour diffusion coefficient are functions of the water content; therefore the problem is nonlinear. Newton-Raphson iteration is adopted for solving the resulting nonlinear equations and the element averaged capillary pressure and the flow properties are updated within each iteration for a new cycle of calculation until the p_c converges for this time step.

A Dirichlet type of boundary condition is applied in the problem, prescribing a constant capillary pressure value which is equivalent to a constant saturated surface in contact of water. The oscillation of results near the sharp front has been eliminated by using mass lumped scheme for the formulation of mass matrix. The flux though the saturated nodes could then be calculated by substituting the known capillary pressure field into the left hand side of the finite element formulation. These resulting flux values are the equivalent nodal flux per unit width in $\mathrm{gs^{-1}m^{-1}}$, which are then transformed into the equivalent distributed flux over the wetted surface in $\mathrm{gs^{-1}m^{-2}}$ through the following operation:

$$\mathbf{f} = \mathbf{F} \cdot \mathrm{N}^{-1} \tag{6}$$

The flow rate profile over the saturated boundary is then obtained by susing equation (7):

$$\mathrm{q(x)} = \begin{cases} \mathrm{f_j} + (\mathrm{x} - \mathrm{h_j})\frac{\mathrm{f_{j+1}} - \mathrm{f_j}}{\mathrm{he}}; & \mathrm{x} \in (\mathrm{h_j}, \mathrm{h_{j+1}}) \\ \mathrm{f_n} + (\mathrm{x} - \mathrm{h_j})\frac{\mathrm{f_{z_{i-1}}} - \mathrm{f_n}}{\mathrm{he}}; & \mathrm{x} \in (\mathrm{h_n}, \mathrm{z_{i-1}}) \end{cases} \quad \text{j=1,2,…,n-1} \tag{7}$$

where n is the total number of saturated nodes on one side the crack profile, $\mathrm{f_j}$ is the flux value at the $\mathrm{j^{th}}$ saturated node, and $\mathrm{h_j}$ is the elevation of the $\mathrm{j^{th}}$ saturated node. Equation (7) enables the construction of a continuous function for the flow rate profile over the wetted surface under the meniscus. This function is then used directly for the calculation of Q in equation (4) for the current time step.

3. Results and experimental validation

The finite element model for the imbibition in porous concrete matrix is validated by a series of experiments where both the mass of water being absorbed by the concrete as well the internal relative humidity level are monitored. The validated parameters are then used in the coupled flow model.

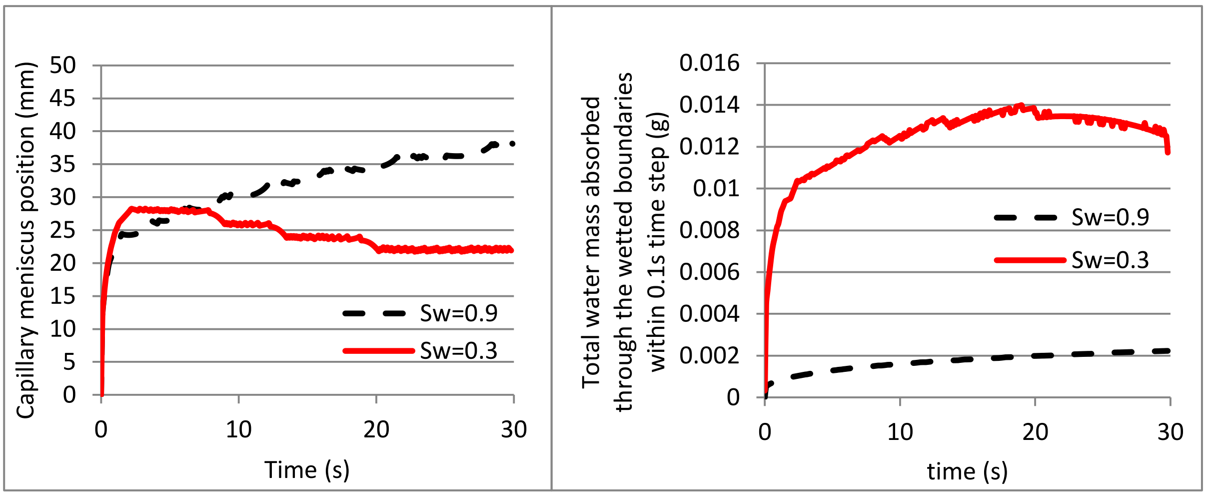

Figure 1: Comparison of the capillary flow in a 0.05mm crack with different moisture condition in surrounding concrete matrix, with (a) Capillary rise height and (b) Total mass of water absorbed through crack faces.

no dramatic difference, the drier concrete with Sw=0.3 absorbs much more water and reduces the development of the capillary rise. The case with Sw=0.9 absorbs much less water and therefore has less influence on the capillary rise. It is also observed that the magnitude of the influence of the imbibition is also related to the crack width. The flow in wider cracks is less affected by the imbibition flow compared with narrower cracks.

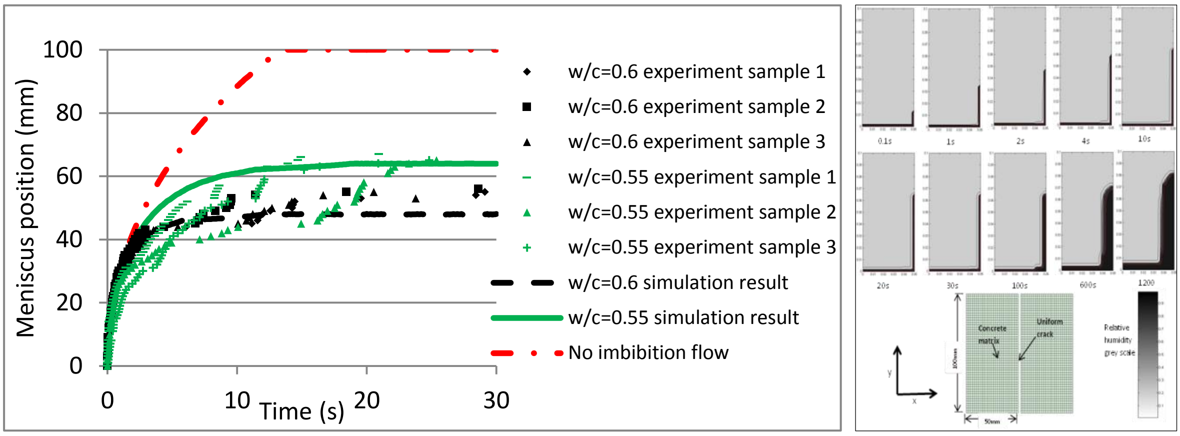

Figure 2: (a) Comparison between experiments and simulation for different concrete mix with 0.05mm crack width. (b) Contour plot of the moisture condition in one side of the concrete matrix during the capillary rise process

Experiments were carried out where the capillary rise in a discrete crack was recorded by a high speed camera. Figure 2 (a) shows that the coupled model is able to capture the capillary rise difference caused by the different permeabilities of different concrete mixes. Compared with the traditional L-W equation where no imbibition is considered, the couple model has shown more accurate simulation of the flow in the macro-crack. Figure 2(b) illustrates the development of the moisture conditions in the surrounding matrix, which has great implications on the design of vascular system to facilitate different self-healing techniques.

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