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A poromechanics model for plastic shrinkage of fresh cementitious materials

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ABSTRACT

When fresh cementitious materials are exposed to evaporation, drying of the pore fluid leads to capillary pressure development and plastic shrinkage. Plastic shrinkage occurring after the solid percolation threshold plays an important role in the initiation and propagation of plastic shrinkage cracks, which may compromise the durability and decrease the service life of concrete structures.

In this study, a poromechanics approach to plastic shrinkage is developed. Novel experimental methods are utilized to quantify the material properties used as model input. An independent set of measurements is further used to validate the developed model. It is shown that the bulk modulus evolution plays a prominent role in controlling the plastic shrinkage of cementitious materials.

1. Introduction

In fresh concrete, similarly as in soils, the pore pressure changes due to the effects of gravity and evaporation [1], see also [2] for the case of concrete. The pore pressure evolution is accompanied by an increase of effective stress [1,3]. The resulting volumetric contraction, when occurring in concrete after placement and before final set, is referred to as *plastic shrinkage* [4]. When plastic shrinkage is restrained (for example, by the subgrade, by the reinforcement or by self-restraint in a concrete slab, or by the presence of the stress risers in the ASTM standard [5]), deviatoric stresses due to restrained deformations arise. Eventually, the fresh concrete cracks when the stress surpasses the failure limit. Plastic shrinkage cracks are preferred pathways for the penetration of harmful ions, liquids and gases into concrete structures and they may jeopardize their durability and ultimately reduce their service life [6,7]. In order to mitigate plastic shrinkage cracking, a thorough understanding of the mechanisms of plastic shrinkage is needed.

Plastic shrinkage is generally considered to occur in two regimes or states: bleeding state (also referred to as saturated state, where it is also called *plastic settlement* [2,8]) and drying state (where saturation degree can drop below 1 due to external drying).

1.1. Bleeding state

The process of water flowing from the bulk of fresh concrete towards its surface, due to the effect of gravity is referred to as *bleeding* and the water (or, more precisely, pore fluid) accumulated on the top surfaces is called *bleed water* [2,9,10]. As long as the bleed water is present, the pores remain saturated. Initially after placement, before the percolation of solid particles, the weight of the solid particles is sustained by the pore fluid, generating hydrostatic pore pressure. At a certain time instant, the solid particles percolate and can therefore transfer the stress due to their weight through the freshly formed solid network. As a consequence, the minimum absolute value of pore pressure is reached due to self-weight of the pore fluid itself, Eq. (1). At this point, the gradient of total pore fluid potential [2] (the pressure potential plus the gravitational potential) becomes zero and, according to Darcy's law, the upward water flow stops and bleeding ceases. Therefore, Eq. (1) can be referred to as the suspension threshold or the solid percolation threshold [11], when bleeding ceases:

$$\psi_p \textit{ at suspension threshold} = \rho_f g (h - z) \tag{1}$$

In Eq. (1), ψ_p [Pa] is the pore fluid's pressure potential, ρ_f [kg/m^3] is the density of the pore fluid, assumed equal to the density of water, $g = 9.81$ [m/s^2] is the gravity acceleration, h [m] is the height of the concrete layer (sample) and z [m] is the elevation from the bottom of the sample. The pore fluid pressure potential takes positive values for fluid under compression and negative for fluid under tension (capillary pressure). In fresh cementitious materials, the solid percolation is caused in the bleeding state primarily by cement hydration [11]. In other words, cement hydration forms a solid network and arrests the bleeding process [2,9]. The process of bleeding was discussed in a recent paper [2], in which relationships for the permeability and bulk modulus evolution for saturated fresh concrete were derived. Also, a simple method for reducing the risk of plastic shrinkage cracking has

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Nomenclature

b [m/s]	bleeding rate
B_0 [Pa]	initial bulk modulus
B_b [Pa]	bulk modulus in bleeding state
B_e [Pa]	bulk modulus in drying state
B_s [Pa]	bulk modulus of solid grains
E [Pa]	elastic modulus
E_a [kJ/mol]	the apparent activation energy of concrete
G [Pa]	shear modulus
$\vec{g}$ [m/s^2]	gravity acceleration vector
h [m]	height of sample
k_{eff} [m/s]	effective coefficient of permeability
k_r [−]	relative permeability
m [−]	pore size distribution index
$\dot{m}_{hydr}$ [kg/m^3·s]	rate of water consumption during cement hydration
M_{cem} [kg/m^3]	the initial mass of cement in the mixture
$\vec{n}$ [m]	vector normal to the surface
n_{cap} [m^3/m^3]	capillary porosity
n_{tot} [m^3/m^3]	initial volumetric water content (mixing water)
p_a [Pa]	atmospheric pressure
p_{ae} [Pa]	air entry pressure
$p_{ae\text{-}t0}$ [Pa]	initial air entry pressure
p_c [Pa]	capillary pressure
p_{over} [Pa]	applied air overpressure
p_{pel} [Pa]	pseudo-elastic limit
q [m/s]	pore fluid flux
$\dot{Q}$ [J/(s·g)]	isothermal heat flux
r [m]	equivalent pore radius (according to Young-Laplace equation)
R [J/mol K]	universal gas constant
S_w [−]	saturation degree
t [min]	time from mixing start
t_{FSB} [h]	time of final set (Vicat) in the bleeding state
t_{FSD} [h]	time of final set (Vicat) in the drying state
t_{ISD} [h]	time of initial set (Vicat) in the drying state
t_* [min]	hydration characteristic time
T_c [K]	actual concrete temperature
T_{iso} [K]	reference isothermal temperature
W_v [m^3/m^3]	volumetric water content
z [m]	elevation from bottom of sample
α [−]	hydration degree
γ [Pa·m]	surface tension of pore fluid
$\varepsilon_{xx} = \varepsilon_{yy}$ [−]	horizontal strains
ε_{zz}[−]	vertical strain
ε_{vol} [−]	volumetric strain
θ [rad]	contact angle
ν [−]	Poisson's ratio
ξ [−]	parameter defining the maximum effect of capillary pressure on fresh concrete stiffness
ξ_V [−]	parameter defining the maximum effect of capillary pressure on fresh concrete stiffness calibrated by the Vicat test
ρ_C [kg/m^3]	concrete density
ρ_{cem} [kg/m^3]	cement density
ρ_f [kg/m^3]	density of the pore fluid
ρ_s [kg/m^3]	solid density
σ_{sw} [Pa]	self-weight stress
σ_{ex} [Pa]	external load (stress)
σ_{eff} [Pa]	effective stress
ψ_p [Pa]	pore fluid's pressure potential
ψ_m [Pa]	matric potential
ω [1/Pa]	parameter controlling the rate of increase of fresh concrete stiffness with capillary pressure
ω_V [1/h]	parameter controlling the rate of increase of fresh concrete stiffness with capillary pressure, calibrated by the Vicat test

been recently proposed. This method is based on ensuring that the total amount of the accumulated bleed water is larger than of evaporated water at any time until the time of set (opposite to the common controlling of only the bleeding vs. evaporation *rates*) [10]. The literature about bleeding of fresh concrete (e.g., [8,12–14]) has been discussed in depth in [2,10].

1.2. Drying state

In the drying state (i.e. soon after the rate of evaporation of free water from the concrete surface becomes higher than the rate of bleeding and all accumulated bleed water is eventually removed by evaporation [10]), the water flow is governed by the external environmental drying (evaporation flux). In these conditions, the water flow will continue after the limitation stated in Eq. (1) due to the gradient of negative pore pressure (capillary pressure, p_c [Pa]).

Furthermore, after the solid percolation threshold, (i.e. the transition between suspension of solid particles in pore fluid and solid body), chemical shrinkage also contributes to the pore pressure evolution in the process of self-desiccation [15], acting as a sink term for the reduction of the degree of saturation [16] (see Eqs. (13) and (16)).

In the drying state, since the evaporative flux is higher than the bleeding flux, the rate of water expulsion from the pores is higher and therefore the solids percolate faster than in the case of pure self-weight consolidation. Also as explained in this paper, according to the consolidation equation, the direct contribution of the capillary pressure (i.e. isotropic stress) on the distances between the solid particles (and therefore on the stiffness) accelerates this process.

Although several experimental investigations have been dedicated to plastic shrinkage in the drying state (e.g., [4,17–24]), only few authors developed analytical and numerical models of plastic shrinkage.

1.3. Previous approaches to modelling plastic shrinkage

The primary studies related to the mechanism of the plastic shrinkage in the drying state [9,25,26], proposed an estimation of the maximum capillary pressure exerted on the solid particles. It was a function of the surface tension of the pore fluid, surface area of particles and porosity. Later, Radocea [27,28], see also [29], modeled the plastic shrinkage of cement-based materials by relating the total volumetric deformation to the evaporated water and to the water transferred to the surface, with the latter as a function of the bulk stiffness. A relationship was derived for the evolution of the capillary pressure by defining two isotropic material property parameters, called *plastic shrinkage modulus* and *pore structure function*. No distinct functions were derived for vertical and horizontal shrinkage. Radocea [27,28] concluded that the stiffening of the cement paste brought about both by consolidation and cement hydration contributes to increase the rate of capillary pressure development. A drawback of this method is that the gradient of pressure over the thickness of the sample is neglected. On the contrary, the present study shows that both the coefficient of permeability and the gradient of pore pressure (which are coupled) govern the water flux. Moreover, Radocea included into the plastic shrinkage modulus the effect of both parameters, permeability and stiffness, while they need to be utilized separately in order to obtain the evolution of pore pressure more accurately (as discussed both in [2] and in this study).

In other studies, prediction methods of plastic shrinkage cracking were generally developed without explicitly modelling the plastic