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The bleeding test: A simple method for obtaining the permeability and bulk modulus of fresh concrete

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ABSTRACT

This paper shows how the well-known bleeding test can be used as a simple and inexpensive method for measuring the permeability and the bulk modulus of fresh concrete, utilizing Darcy's law and a small-strain poromechanical approach. The permeability and the bulk modulus are two essential parameters for understanding the behavior of fresh concrete, in particular plastic settlement and plastic shrinkage cracking. The proposed methods are verified and validated by utilizing experimental data obtained from the literature.

1. Introduction

The intrinsic permeability [1] (also referred to as specific permeability [2]), κ [m^2], is a parameter of a porous medium describing transfer of fluids through its pore network [3–5]. It is an intrinsic property independent of pore fluid properties [3–5], while it depends on pore structure characteristics: total porosity, distribution of pore sizes, connectivity and tortuosity of pores, surface roughness of the flow paths [3]. After accounting for the properties of the pore fluid in addition to the intrinsic properties of the medium, the flow of a specific fluid through a particular porous medium can be characterized by means of the coefficient of permeability (also referred to as hydraulic conductivity), k [m/s] [3–6]:

$$k = \frac{\rho_f g}{\mu} \kappa \tag{1}$$

where ρ_f [kg/m^3] is the density of the pore fluid, g [m/s^2] is the gravity acceleration, μ [Pa·s] is the dynamic viscosity of the pore fluid. In this paper, *permeability* always refers to the coefficient of permeability expressed with Eq. (1), similarly as in [7,8]. Mobility coefficient (K [m^2/Pa·s]) and diffusivity coefficient (C [m^2/s]) are other parameters describing the ability of a fluid to move within porous media. The mobility coefficient K relates the pressure gradient to the fluid flux in Darcy's law and is analogous to the diffusivity coefficient in Fick's law [9]. It is expressed as:

$$K = \frac{\kappa}{\mu} \tag{2}$$

The diffusivity coefficient C, also referred to as Terzaghi's consolidation coefficient, is related to the mobility coefficient K by the following equation [6,10]:

$$C = \frac{K}{\lambda + n\beta} \tag{3}$$

where λ [1/Pa] and β [1/Pa] are the compressibility of the bulk and the pore fluid, respectively, and n [−] is the porosity. By assuming the pore fluid as incompressible [11] (i.e., assuming water as incompressible and considering negligible the effect of air content in the cementitious material [12]), Eq. (3) simplifies to:

$$C = \frac{K}{\lambda} = KB \tag{4}$$

where B [Pa] is the bulk modulus. The consolidation coefficient C derived from a soil mechanics approach does not consider the evolution of material properties in time due to chemical processes [13]. However, in the particular case of cementitious materials considered here, we will also account for the hydration process by considering the bulk modulus B as a function of time, see Section 2.2.

Knowledge of the elastic properties and of the bulk modulus in particular is essential for predicting the early-age shrinkage (e.g. [14,15]).

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The plastic settlement, or the consolidation of fresh concrete while still fully saturated, is directly proportional to its permeability and bulk modulus (see Eq. (4)). Also, as mentioned before, the permeability is an indicator of pore structure and pore fluid properties, which both affect the capillary pressure and the water transport in the unsaturated plastic shrinkage regime [16–18]. Additionally, in studies related to curing, permeability is a key factor which affects the curing water migration [19,20].

Besides determining the settlement and the horizontal shrinkage of fresh concrete, knowing the development of the bulk modulus is also essential to understand plastic shrinkage cracking, since crack propagation releases the stored elastic energy, which depends on the bulk modulus [21]. As permeability and bulk modulus are two key parameters for studying the early-age concrete properties, in particular in the fresh, plastic state, the present study is dedicated to quantify these parameters with a simple and robust approach.

Although numerous studies devoted to measuring and modeling the permeability after hardening of concrete have been published (e.g. [19, 22,23]), only a few are dedicated to the permeability at very early ages [7,8,24,25]. All of the developed methods for fresh cementitious materials are based on a soil-physics approach using Darcy's law. The pore pressure gradient either needs to be measured experimentally or it is obtained from available consolidation models. The latter is the most challenging issue for cementitious materials that, unlike soil, experience a rapid evolution of material properties due to cement hydration.

Picandet et al. [7] measured the permeability of cement pastes by a soil permeameter cell and a controlled oedometer with specimens of initial height 70 mm and 20 mm, respectively. Both methods work with a high constant water head. In the taller sample, Picandet et al. simulated the pressure gradient at each time instant by solving Terzaghi's consolidation equation for soil, neglecting hydration and the corresponding bulk modulus evolution. However, it will be shown later in this paper that the latter parameter has a significant impact on the pore pressure profile and its evolution in time cannot be neglected. Additionally, the small sample sizes used in [7] are not easily applicable for studying concrete with normal aggregate sizes.

Assad et al. [8] opted for the falling pressure head method, which allowed faster stabilization of the flux within 4 to 10 min, depending on the mortar composition. Also in this study, the effect of bulk modulus evolution on the gradient of pore pressure was not accounted for in the analysis. Furthermore, in both previously-mentioned methods, the high pressure heads applied to the specimens may lead to changes in material properties, e.g. due to washing out of finest particles, the so-called leaching effect [7,8], or due to unusually high compaction of the material.

Methods for measuring the evolution of elastic properties at very early age are based on elastic wave propagation [26,27]: e.g. Ultrasound Pulse Velocity (UPV) and Ultrasound Wave Reflection (UWR). Such methods do not allow a direct measurement of the bulk modulus, rather of the two elastic moduli (Young's and shear). Since before solid percolation time, shear waves cannot properly propagate, the shear modulus cannot be measured, thus also excluding indirect monitoring of the bulk modulus evolution.

In this paper, we propose to use the bleeding test [25] as a simple and easily accessible test for studying the properties of concrete in its fresh state, though of course limited to mixtures that experience bleeding. Bleeding is a consequence of self-weight consolidation [12,28–30]; in some references, it was also referred to as an effect of a sedimentation process [25]. The bleeding rate in the constant rate period is an intrinsic property of cementitious materials [25] and can be used as a key value for obtaining the permeability. An approach to calculate the permeability of fresh concrete using the bleeding rate was previously proposed by Powers [25]. However, opposite to the present model, which assumes the existence of small strains, the latter was a large-strain model based on the sedimentation approach in which the hydraulic gradient was expressed in terms of the unbuoyed weight of the solids.

Since the buildup of the bulk modulus in fresh cementitious materials arrests bleeding, modeling deformations of the fresh concrete and comparing them to the results of bleeding tests allows also to determine the evolution of the bulk modulus of concrete in the fresh state.

The model was validated with experimental data on bleeding of concrete with samples of different height obtained from [12]. The permeability model was then used to calculate the permeability of concretes tested in [31], having different w/c and paste contents, to verify the robustness of the proposed model.

2. Poromechanical model

2.1. Analytical model for obtaining the permeability

Bleeding is a phenomenon taking place due to self-weight consolidation that manifests in water accumulating at the top surface of freshly-placed concrete. It takes place in the initial few hours after concrete mixing in the so-called dormant period of cement hydration. In the case the concrete layer is sufficiently deep, bleeding can also extend to the beginning of the acceleration period [25]. A schematic illustration of a bleeding test is shown in Fig. 1.

The total surface displacement of fresh concrete is the sum of vertical deformations due to chemical shrinkage, thermal expansion and self-weight consolidation/bleeding [18,32]. As discussed in [11], water flow and bleeding are caused by dissipation of excess pore water pressure as it is transferred from the fluid to the solid skeleton. Water flow in a porous medium can be described by Darcy's law. According to Darcy's law, the water flux q [m/s] is the consequence of the gradient of total pore fluid potential (Ψ_T [Pa]) in a porous material (concrete):

$$\vec{q} = -\frac{\kappa}{\mu}\nabla\psi_T \tag{5}$$

Its component in the vertical direction for one-dimensional consolidation is:

$$q = -\frac{\kappa}{\mu}\frac{\partial\psi_T}{\partial z} \tag{6}$$

Using a soil physics approach [3], one can define Ψ_T as:

$$\psi_T = \psi_z + \psi_p \tag{7}$$

where Ψ_z is the gravitational potential [Pa], being the gravity-induced energy stored in the unit volume of pore fluid at certain height from a reference level, and Ψ_p [Pa] is the pressure potential (hydrostatic

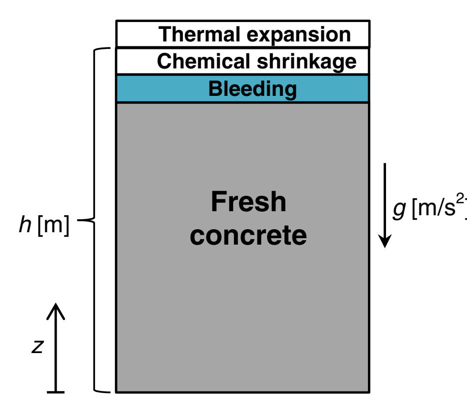

Fig. 1. Schematic illustration of self-weight consolidation/bleeding. h [m] is the initial sample height.