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A geometrical model for void saturation in air-entrained concrete under continuous water exposure

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HIGHLIGHTS

- The presence of over-pressure in concrete pores/voids account for the moisture transport characteristics.
- A geometrical model for gradual saturation of air void proposed, based on which service life is predicted.
- Air void characteristics are simulated using an S-shaped curve and the effect is investigated by the geometrical model.

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ABSTRACT

Moisture transport properties in concrete have been shown to have great implications on the freeze-thaw (F-T) durability. In this paper, the slow process of gradual air void filling in air-entrained concrete under continuous wet exposure is further explored based on Fagerlund's work. The concomitant effect on the air-void properties is quantified by a geometrical model, where the change in specific surface and void spacing is computed due to gradual void saturation of different size classes based on the linear traverse method. This information, when combined with the measured secondary rate of water absorption, is able to predict the time to reach a critical saturation level gauged by the threshold void spacing, as exemplified by an air-entrained 0.45 water-cement (w/c) ratio concrete mix. Air void characteristics (air content and the size distribution), the important factors in controlling internal frost durability, are simulated using an S-shaped curve and their effect on the critical time is investigated by this geometrical model.

1. Introduction

Concrete is a versatile construction material with its applications extending from bridge piers embedded deep into the ground to offshore platforms [1]. As a result, concrete is exposed to a variety of mechanical loads (compression, flexural, torsion and dynamic, etc.) and environmental loads (fire hazard, penetration of deleterious species, etc.). The transport of liquid into concrete is the culprit of many durability-related issues [2]: water saturation of concrete leading to frost damage; migration of chloride ions causing the corrosion of reinforcements; ingress of sulfate inducing detrimental expansion, let along the alkali-aggregate reaction (AAR), carbonation, etc. Furthermore, the porous skeleton of concrete and the presence of cracks substantially expedite the transport process. Nowadays, there is an increasing interest in the investigation of concrete transport properties as the performance-based criteria that facilitate rapid evaluation and innovative design in concrete durability at the material level [2–4]. Thus, a better comprehension on the mechanisms governing liquid transport into concrete forms an essential component in the construction of performance-based methodology for concrete durability [2].

Liquid transport in concrete is primarily a mixed mode of capillary suction and diffusion [5,6], both of which are unsaturated flow. Moisture ingress by capillary suction is a rapid process in capillary and gel pores by capillary forces [7]. Concrete sorptivity is an indicator of capillary suction rate and is uniquely related to capillary porosity and pore structure of the porous hydration products within the Portland cement paste. Thus, this property has been proposed as a predictor for quality control [8] and service life design [9] of concrete structures. Several attempts have also been made to correlate it with salt frost scaling [10–12].

In concrete with artificially entrained air voids, there is a gradual and slow diffusion of water into the originally air-filled voids. This process, accelerated by a pumping effect when concrete is under freezing-thawing (F-T) exposure [13], undermines the frost

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durability of concrete. Fagerlund laid the theoretical foundation for the water absorption in the air voids at ambient temperature [6,14]. However, application of his model for service life prediction requires the knowledge of some physical parameters (such as the diffusivity of air in water), the diffusion paths between a web of air voids and the size distribution of air void system, all of which were difficult to determine and thus assumptions were made. In this paper, an effort is made to propose a geometrical model based on the linear traverse method for calculating the change in the air void properties (specific surface and void spacing) associated with gradual void saturation. Ultimately prediction of the time to reach a critical saturation point can be realized by the introduction of the measured moisture uptake characteristics under a controlled moisture condition. This work will hopefully pave the way towards service life design of concrete structures for internal frost durability when the actual moisture-time history is known.

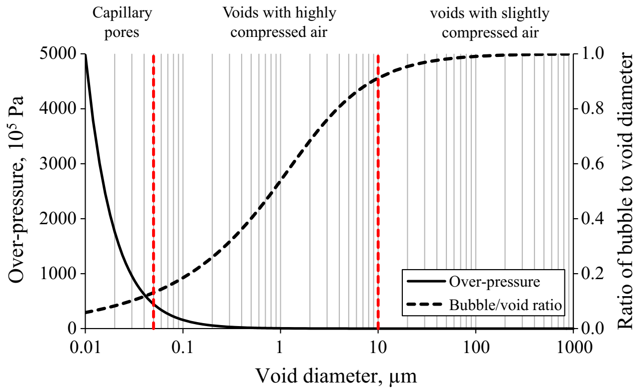


Fig. 2. Over-pressure and bubble-void diameter ratio as a function of void diameter (Calculation equations are listed in the Appendix).

2. Experimental

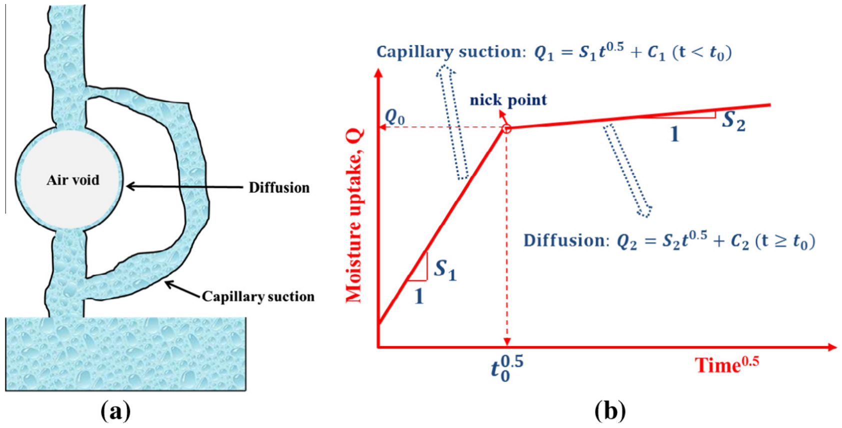
Moisture uptake in air-entrained concrete is tested on thin disk specimens of 12 mm thick by regularly measuring the weight gain of the specimens with the bottom surface in contact with water. The concrete mix had a 0.45 w/c ratio and was prepared using Type I Portland cement, silica sand as fine aggregate with a 2.43 fineness modulus and lime stone as coarse aggregate with a 25 mm nominal maximum size. Mix design was 290 kg/m^3 cement, 775 kg/m^3 silica sand and 1115 kg/m^3 gravel. The dosage of air entrainer was 1.2 ml/kg cement to achieve an air content of 5.1%. 150 mm by 300 mm cylinders were cast and demoulded after one day. Then, they were moist cured for 27 days at 20 °C, followed by air curing (~40%RH) at 20 °C for around 1 year.

12 mm thick specimens of an approximately 100 mm by 100 mm cross section were cut from the cylinders by a concrete saw. The specimens were dried in the oven at 50 °C until near constant weight was achieved. Lateral surfaces of the specimens were then sealed by the aluminum foil with butyl rubber. This was followed by the presaturation process with the test surface immersed in demineralized water by 5 mm. The weight gain was regularly recorded and the moisture uptake curve was constructed. Two specimens were tested for this measurement.

3. Mechanism of moisture transport in concrete

Moisture migration process in concrete is of great relevance to its frost durability, and the governing mechanisms is the diffusion and capillary suction [5], since field concrete is rarely under a pressure gradient. Liquid transport in air-entrained concrete can be visualized as a continuous paste matrix with dispersed air voids enclosed by a spectrum of capillary pores of different sizes and degrees of connectivity. This process is clearly illustrated by Fagerlund [6] with a sketch re-constructed as shown in Fig. 1(a). When concrete comes into contact with water, capillary suction is activated to pump water up in those well-connected pores immediately. Water keeps flowing upward and then bifurcates upon encountering the air voids which have a much greater diameter and thus reduced suction. After all the connected capillary pores are filled, the main mechanism switches to the slow dissolution-diffusion of air into the voids or poorly connected capillary pores (Fig. 1(a)).

As a result, the liquid uptake in air-entrained concrete can be characterized by a bi-linear pattern as presented in Fig. 1(b), featuring an initially rapid capillary suction process followed by a slow diffusion-controlled transport into air voids or poorly connected pores [15]. Rate of transport can be described by the slope, the first segment being sorptivity [7] or the initial rate of absorption [16] S_1 (mm/h$^{0.5}$) and the second one being the secondary rate of absorption S_2 (mm/h$^{0.5}$). The inflection point indicates the arrival of capillary saturation in connected pores. Both the capillary suction and diffusion processes are square-root time dependent, thus moisture uptake in concrete can be described as Eqs. (1) and (2) [17]. In the case of a high w/c ratio concrete with good pore connectivity, the second stage can be a rough indication of air void filling, which has been supported by a higher absorption rate with a higher air content [6,14,17,18].



(a) (b)

Fig. 1. Illustration of moisture uptake process in air-entrained concrete (the left sketch is out of scale for the sake of better visualization, since the nominal diameter of an air void is several orders of magnitude larger than the capillary pores).