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A new method to simulate permeability degradation of stressed concrete

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HIGHLIGHTS

- A methodology to determine the permeability degradation of stressed concrete.
- Easy to determine permeability with different mechanical properties and geometries.
- Permeability starts to degrade when stress reaches a certain threshold value.
- Aggregate fraction is the most influential factor for permeability degradation.
- Aggregates with sharper edges tend to result higher permeability values for concrete.

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ABSTRACT

Concrete permeability is usually determined by testing unstressed, non-damaged specimens in laboratories as a constant. In reality, however, concrete is subjected to various operational loads in the time span of its service life. Therefore, the permeability of stressed concrete can be time-variant and completely different from that of unstressed conditions. This paper intends to develop a new methodology to determine the permeability of stressed concrete over time, based on the damage mechanics of concrete meso-structure in conjunction with Monte Carlo simulation and finite element analysis. It is found in this study that the permeability of concrete starts to increase when the applied stress in concrete reaches a certain threshold value for the given aggregate fraction. It is also found that the aggregate fraction is the most influential factor for permeability degradation of concrete. The significance of the developed methodology is that it can determine the permeability degradation of concrete with different mechanical properties and geometries of constituent materials under various applied loads over time, which would be otherwise impractical experimentally.

1. Introduction

Permeability of concrete is considered as the most influential property which controls its strength, serviceability and durability [1,2]. It also governs the ingress of aggressive agents with water, oxygen or chlorides that can cause infiltration, corrosion of reinforcing steel and degradation of concrete strength [1]. As the strength of concrete decreases with the increase of its permeability, an increase in permeability can be considered as a degradation in its durability assessment.

The concrete permeability is usually determined by testing well-cured, unstressed, non-damaged specimens in laboratories as a constant. However, in the time span of its service life, concrete structures are subjected to stresses in various forms such as mechanical, thermal, chemical, environmental or a combination of these [3]. Therefore, the permeability of stressed concrete due to various operational loads can be time-variant and completely different from that of unstressed laboratory conditions. Hence, the applicability of the permeability data produced on undamaged concrete in laboratories has limitations in real life scenarios of concrete in service.

Some researchers [1,2,4,5] have attempted to investigate the time variant permeability, referred to as permeability degradation in this study, of stressed concrete experimentally. There are however some practical difficulties. One such difficulty is to conduct the permeability tests under an increasing applied load as setting up a test for increasing load is quite challenging. To overcome this difficulty, some researchers stressed the specimens first and carried out the permeability tests afterwards [1,4,6]. Very few researchers have succeeded in carrying out the tests while the load is being applied simultaneously [7]. Another difficulty is the extremely excessive time in conducting permeability tests. To overcome this, the water (or gas) has been pressurised to obtain a quick

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steady state flow and to have a sufficient outflow for volume measurements [1]. Based on published research, it can be observed that the water/gas permeability of concrete is related to the applied stress (e.g., compression, tension, flexure), rate and amount of loading (as a percentage of ultimate) in its direct resemblance to crack initiation and propagation in concrete [3]. Furthermore, it may not be practical to test the permeability of concrete with a number of different material constituents and property combinations, because of the excessive time required for achieving a steady state flow for each test.

With these difficulties in testing concrete for its permeability, an increasing interest has been developed among researchers to determine the permeability of stressed concrete numerically with computer simulations. The significance of determining permeability through computer simulations can be twofold. One is that numerical methods can determine the permeability of concretes with different combinations of material properties and geometries at will which would otherwise be impractical not just due to excessive testing time. More importantly, the numerical method can determine the permeability of concretes under various applied loads over time, which can be replicated as practically as possible to the operational loads.

The permeability of intact concrete is influenced by two primary factors [2]. One is the porosity and the interconnectivity of pores in cement matrix. The other factor is the pre-existing micro-cracks in concrete, mainly in the cement-aggregate interface, which is also termed as Interfacial Transition Zone (ITZ). The permeability of the same concrete under loading also depends heavily on the presence of stress induced cracks. Loading affects the crack formation and propagation by interconnecting the cracks and voids, which changes the transport properties of concrete and the durability of concrete structures [8]. For normal concrete, its permeability decreases with the application of load up to a certain threshold value of load level and then it increases rapidly afterwards. According to Hoseini, Bindiganavile and Banthia [3], the initial reduction of permeability is due to the contraction of voids upon the application of load. The slight increase afterwards is caused by the micro-cracks development within ITZs. Subsequently, with further increase in load, the micro-cracks initiated at ITZs become localized through the cement mortar and result in a rapid increase in permeability.

Recently, with the advances in computational techniques, researchers have been trying to use meso-scale computer simulations in determining the permeability of concrete [9,10]. At meso-scale concrete is considered as a 3-phase heterogeneous material consisting of cement mortar, aggregate and ITZ. It is acknowledged that the research on meso/micro structural simulation of concrete as a multi-phase material has been undertaken but the knowledge on the change of concrete permeability at meso-structural level and under various loads is very scarce and there is no numerical method to determine the time variant permeability of concrete, i.e., permeability degradation, caused by stress induced micro-cracks. Moreover, there are some limitations on capturing the initiation, propagation and interconnecting of stress-induced cracks using existing models of meso/micro structural simulation, resulting in unreliable permeability predictions. Up to-date, especially for meso-scale concrete, the best approach to address these issues is to replace the fracture mechanics with the damage mechanics as suggested by many researchers [8,10,11]. This will be explored in the current study.

The intention of this paper is to develop a new methodology to determine the permeability of stressed concrete over time, based on damage mechanics of meso-structure of concrete. Firstly, a representative meso-structure of concrete as a 3-phase material is simulated using Monte Carlo techniques. Secondly, based on the simulated meso-structure of concrete, finite element models are developed for the stress analysis, in which a user subroutine is created for the identification of individual damage to each element of the mesh and for the determination of load-induced overall damage. The permeability of concrete corresponding to the overall damage of bulk concrete is determined as the final step. A worked example is presented as verification and also demonstration of the application of the developed methodology. Further, a parametric study on the effects of concrete constituent factors, including aggregate fraction, particle size distribution of aggregates and the distribution of aggregates on the permeability degradation of concrete is undertaken to identify the most influential factors. The merit of the developed methodology is that it can determine the permeability degradation of concrete with different mechanical properties and geometries of constituent materials under various applied loads over time, which would be otherwise impractical experimentally.

2. Simulation of meso-structure of concrete

In order to represent concrete as realistically as possible, it has to be modelled as a heterogeneous material consisting of all 3-phases of cement mortar, aggregate and ITZ. The meso-structure of concrete depends greatly on the aggregate fraction, aggregate particle size distribution and aggregate distribution [12]. Fine aggregates are usually considered within the cement mortar phase. For computational modelling of concrete at this level, aggregate particles are usually assumed as spheres for 3-D problems and circles for 2-D problems [13]. Aggregates in real concrete are neither circular nor spherical in shape. Though different shapes can be accommodated in computer simulations, this is more of an assumption for the convenience of aggregate distribution/generation and also for reducing the computational effect without compromising the technical development. However, the current study accommodates two other aggregate shapes in the simulations to see the effect of the aggregate shape on the permeability of concrete. The concept of these simulations is the same as circular shape. It is also assumed that the particle size and the distribution of aggregates are random.

The size distribution of aggregate particles in a given concrete mix can be obtained experimentally by conducting a sieve analysis. However, based on the theory of stereology, particle size distribution of aggregates in concrete can be considered following Fuller mix [12]. For a Fuller mix, the cumulative distribution function (CDF) for the aggregates in concrete of a two-dimensional problem can be expressed as follows.

$$P_{2d}(d) = \frac{d^{1.5}f(\alpha_0, \beta_0) - d_0^{1.5}f(\alpha, \beta)}{d^{1.5}f(\alpha_0, \beta_0)} \tag{1}$$

where, d = diameter of aggregate ($d_0 \le d \le d_m$), d_0 is the smallest aggregate diameter and d_m is the largest aggregate diameter in the concrete mix. Coefficients α, α_0, β, β_0 and $f(\alpha, \beta)$, all related to d, d_0 and d_m, are expressed as follows [13,14].

$$f(\alpha, \beta) = \frac{2}{5}cos^{1.5}\alpha sin\alpha + \frac{2\sqrt{2}}{5}\left[2E\left(\beta, \frac{1}{\sqrt{2}}\right) - F\left(\beta, \frac{1}{\sqrt{2}}\right)\right] \tag{2}$$

$$\alpha = arccos\left(\frac{d}{d_m}\right), \quad \alpha_0 = arccos\left(\frac{d_0}{d_m}\right) \tag{3}$$

$$\beta = arcsin\left(\sqrt{2}sin\frac{\alpha}{2}\right), \quad \beta_0 = arcsin\left(\sqrt{2}sin\frac{\alpha_0}{2}\right) \tag{4}$$

E() and F() in Eq. (2) are the Legendre's standard elliptical integrals [12]. The Eq. (1) for 2-D problems is developed based on the size distribution of intersecting circles of a randomly located π-plane. The conversion of aggregate volume fraction (AVF) to