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Effect of crack density and connectivity on the permeability of microcracked solids

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ABSTRACT

In composite theory microcracks in solid are usually treated as degenerated inclusions separately embedded in matrix. For heterogeneous engineering composites like concrete and rock, the real cracking patterns are more complicate and quite different from this assumption due to the natural clustering and inter-connection of microcracks. This paper investigates the permeability of solids containing a crack network with finite connectivity following both theoretical and numerical approaches. Firstly, no connectivity is assumed for cracks and the interaction direct derivative (IDD) method is employed to obtain the crack-altered permeability of solids. Then the amplification of permeability by crack connectivity is quantified for parallel crack cases and for general crack patterns. This amplification effect is modeled by a crack length augmentation factor. In this way the IDD method is extended to evaluate the permeability of cracked solids for a finite crack connectivity before total percolation of cracks. Afterwards, by a carefully designed Monte-Carlo algorithm, the representative volume element (RVE) is built numerically for cracked solids with cracks having random spatial locations and random lengths. The permeability of 2D cracked solids is solved by finite element method (FEM). Through this numerical tool, the effect of both crack density and connectivity on the permeability is solved, and especially the relation between crack connectivity and the geometrical coefficient of crack clustering is put into evidence. From this study it is showed that the extended IDD method can be adapted to a microcracked solid with finite connectivity and can provide good estimates for the permeability.

1. Introduction

Evaluating the effective properties, physical or mechanical, of composite materials has applications in various areas of materials science and engineering. Generally, the effective properties depend not only on the properties of each phase but also on the specific microstructure of material, including phase volume fractions, spatial distribution and geometry of phase domains as well as possible clustering and connectivity of the phases (Torquato, 1991). The classical composite theory treats the phase topology as matrix-inclusion or polycrystalline packing structure (Nemat-Nasser and Hori, 1993). For the matrix-inclusion structure, only the matrix phase is continuous and inclusions are separately embedded in matrix without overlapping. In this image, cracks in solid are regarded as special inclusions, degenerated from flat circular or elliptics dispersed in matrix (Hoenig, 1983; Kachanov, 1992).

Heterogeneous composites like concrete and rock have a typical matrix-inclusion structure with aggregates or mineral grains as inclusions dispersed randomly in a porous matrix (Mehta and Monteiro, 2006). Under mechanical loads or environmental actions, the damage process of this matrix-inclusion structure includes the nucleation of new

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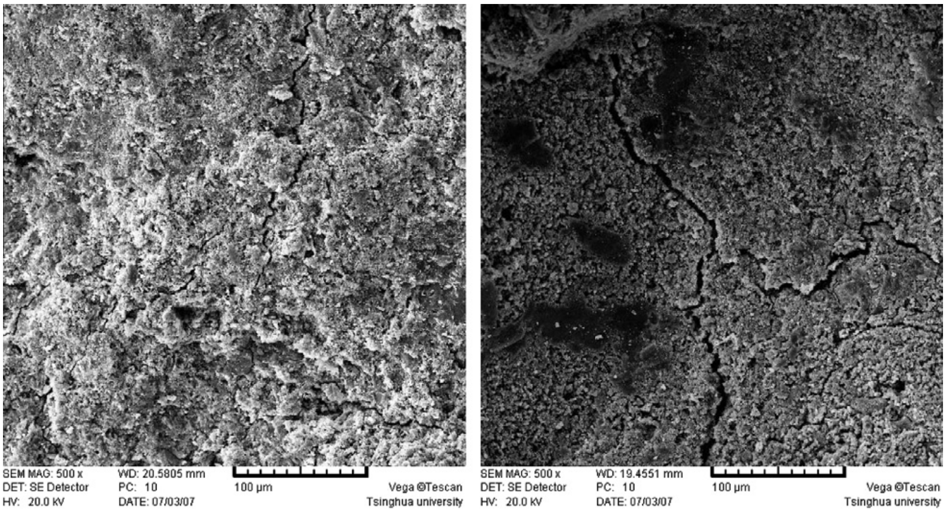

Fig. 1. Microcracks in concrete samples subjected to drying (left) and compressive loads (right).

microcracks as well as the propagation, clustering and connecting of existing ones (Krajcinovic, 2000). The clustering and inter-connection make the microcracking pattern obviously different from the assumption of isolated crack inclusions in matrix-inclusion structure (Ringot and Bascoul, 2001), see Fig. 1. Properties study on cracked concretes showed an important influence of crack orientation and connecting degree on the material permeability (Jensen and Chatterji, 1996), and the connectivity of cracks should be considered as an intrinsic parameter for damage process (Krajcinovic, 1997).

Thus, how to identify the connectivity of cracks and take it into account in the effective properties analysis deserves more attention. The most commonly used micromechanic models for properties evaluation of solids containing crack-like inclusions are based on effective medium theory (EMT) (Hashin, 1968). These models include the dilute solution (Kachanov, 1992), the self-consistent scheme (SCS) (Budiansky and O'Connell, 1976), Mori–Tanaka method (MT) (Benveniste, 1987), the differential scheme (DS) (Norris, 1985) and the generalized self-consistent scheme (GSCS) (Huang et al., 1994), all using the concept of the Eshelby tensor. The EMT models reduce the properties analysis to one isolated inclusion placed into an "effective matrix" or undergoing an "effective field". However, direct application of this notion to connected cracks, especially for mechanical stability analysis, seems problematic since the inter-connections of cracks determines the mechanical behavior and the overall effect of connected cracks cannot easily be represented by an equivalent crack (Kachanov, 1992; Guéguen et al., 1997). The continuum percolation theory provide an alternative way to consider the connectivity of crack network and its impact on the material permeability (Efros and Kisin, 1986). In percolation theory the permeability of matrix is neglected completely, the analysis is focused on the formation process of percolation (critical) path and the permeability estimate is only valid at or above the percolation threshold (Xia and Thorpe, 1988; Hunt, 2001). However, its validity for crack connectivity far below the percolation threshold is still to be explored (Berkowitz and Balberg, 1993). The EMT and percolation theory are incompatible as they are founded on mutually exclusive basic assumptions (Guéguen et al., 1997). For engineered materials like concrete the analysis of physical properties as permeability is of interest in its service state, for durability considerations, with a finite connecting degree for cracks and rather below percolation state. Apparently, neither aforementioned approach can be used directly. The numerical simulation provides the last alternative for permeability analysis. The mechanical properties of cracked solids with crack clustering has been investigated numerically, through either representative volume element (RVE) or repeating unit cell (RUC) (Drago and Pindera, 2007), to study the effect of crack orientation (Kushch et al., 2009) and clustering (Kushch et al., 2009) on the stiffness and stress intensity factor.

This paper attempts to investigate the impact of crack connectivity on the solid permeability following both micromechanic and numerical approaches. The solid is considered to have a 2D homogeneous matrix and dispersed rectilinear cracks. For case of cracks without contact, the authors derive the explicit estimate of crack-altered permeability following the interaction direct derivative (IDD) method of the effective medium theory, and this solution is extended to cracks with finite connectivity. At the same time, the RVE is constructed numerically containing randomly oriented cracks. Through the numerical tool, the IDD estimate for isolated cracks is validated and the geometrical coefficient of crack clustering in the extended IDD model is studied in terms of crack connectivity and density in details. Finally the description of crack connectivity and its impact on solid permeability is discussed in depth.

2. IDD estimate for permeability

For the inclusion-matrix structure of composites, a micromechanic scheme named the effective self-consistent