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Fracture mechanics of air-entrained concrete subjected to compression

Zhijun Zhang, Farhad Ansari *

Department of Civil and Materials Engineering, University of Illinois at Chicago, 842 West Taylor Street, Chicago, IL 60607-7023, USA

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Abstract

Air voids are entrained in concrete for protection of constructed elements, especially highway pavements, against freeze–thaw damage. Entrained air void systems inadvertently reduce the compressive strength of the concrete. The present study describes development of an analytical model for evaluation of the effects of entrained air void system on the compressive strength of concrete. The model developed here will assist in predicting the compressive strength of concrete for specified mix designs. The constitutive relationships for air-entrained concrete were established by considering a micro cracked porous material with randomly distributed circular air voids and uniformly oriented cracks from the air voids. Linear elastic fracture mechanics was employed to explain the evolution of damage due to the individual voids and cracks that emanate from such voids. The damage model considers the interactions among the voids and cracks during various stages of loading. The analytical results from this study were evaluated through an experimental program for comparison of the computed and measured compressive strengths. A wide range of samples were examined that included concretes with air contents ranging from 2% to 13% air by volume of concrete. The experiments involved microscopic determination of air content and spacing factors as well as compressive strength tests for all the concrete samples.

Keywords: Concrete; Compressive strength; Fracture mechanics; Entrained air voids; Cracks; Constitutive relationship

1. Introduction

Concrete contains numerous inclusions, flaws, cavities, and other inhomogeneities. It fails under compression by a process of progressive micro fracturing with extreme complexity, which involves slow crack growth and local materials damage prior to global failure. Compressive failure of concrete involves strain localization and simultaneous progression of cracks from a multitude of defects. Experimental observations including examination of concrete samples by scanning electron microscopes (SEM) have shown that in uniaxial compression, microcracks propagate in the direction of the applied compressive stress, and eventually link to form

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* Corresponding author. Tel.: +1 312 996 2437; fax: +1 312 996 2426.
E-mail address: fansari@uic.edu (F. Ansari).

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Nomenclature

a	radius of air void
C^0_{ijkl}	compliance tensor
E_0	Young's modulus of material in the absence of void
E_e	effective elastic modulus
f'_c	compressive strength
k	parameter of array of air voids (see Fig. 6)
K_I	stress intensity factor
K^1_I	stress intensity factor at single crack tip
K^2_I	stress intensity factor due to crack–crack interaction
K_{IC}	fracture toughness
l	half length of void-emanating crack
L	normalized crack length (l/a)
N_0	number of air void in unit area
P	air void content in volume percentage
S	spacing factor
t_0	parameter of array of air voids (see Fig. 6)
V_0	Poisson ratio of void-free concrete
f, f_0	elastic potential energy with and without cavities
Δf	elastic potential energy due to the introduction of cavities
$\Delta f^{(i)}_n$	Δf due to the ith cavity
$\Delta f^{(k)}_v$	Δf due to the kth void
$\Delta f^{(l)}_c$	Δf due to the lth crack
ρ	crack density parameter
ε_{ij}	strain tensor
σ_{ij}	stress tensor
$\Delta\varepsilon_{ij}$	strain tensor due to the cavity

larger cracks leading to failure [1]. Materials global failure could only be properly addressed by considering the interaction of local defects. In the more broad sense of brittle or quasi-brittle materials, this problem has been extensively dealt within the past [2–12]. Some of these models, although based on linear elasticity, can predict the nonlinearity due to the mechanism of interaction and coalescence of the voids and cracks. In the context of fracture mechanics, the effect due to defects–defects interaction on the stress intensity is largely dependent on the size and geometry of the array of such defects.

A number of studies report on three-dimensional analysis of cracks formed in brittle materials [13–17]. Dyskin et al.'s [14] experiments with PMMA materials indicate formation of wing shaped crack surfaces within the volume of the material. The three-dimensional models developed for PMMA and rock type materials could explain the mechanism of growth for the wing shaped cracks [15]. However, such models are unrealistic for applications in materials such as concrete with pre-existing voids and fissures. Progression of damage in concrete under compression is complicated because of localized inhomogeneities not only due to aggregates and cement-aggregate interface but also from voids and microcracks. Voids play a crucial role in determining the compressive strength of concrete, particularly if the concrete is air-entrained. Air entrained concretes are widely used in construction of structures in northern climates, especially in highway pavements, for protection against damage by freeze–thaw action. Introduction of air voids weakens the solid and reduces the compressive strength of concrete. The reduction in compressive strength due to the introduction of the entrained air bubble system is independent of parallel contributions from other parameters that commonly influence the strength. Typically, a strength loss of 15 to 20% can be anticipated for most air-entrained concretes. In principle, void volume will have a considerable effect on the elastic modulus and the local, as well as the global,