Construction and Building Materials 170 (2018) 520–526

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

A predictive model of the effective tensile and compressive strengths of concrete considering porosity and pore size

Dongqi Li [a], Zongli Li [a,*], Congcong Lv [b], Guohui Zhang [c], Yueming Yin [a]

[a] College of Water Resources and Architectural Engineering, Northwest A&F University, Yangling 712100, PR China
[b] College of Hydraulic & Environmental Engineering, China Three Gorges University, Yichang 443002, PR China
[c] Faculty of Electric Power Engineering, Kunming University of Science and Technology, Kunming 650051, PR China

HIGHLIGHTS

- A predictive model of the effective tensile and compressive strengths is established.
- The distribution and influence of pore size are considered in the strength model.
- Rationality and accuracy of the proposed expressions are assessed.
- Porosity higher influences compressive strength than tensile strength.
- Tensile and compressive strengths decrease with increases in porosity and pore size.

ARTICLE INFO

Article history:
Received 8 August 2017
Received in revised form 28 February 2018
Accepted 2 March 2018

Keywords:
Concrete
Tensile strength
Compressive strength
Porosity
Pore size
Predictive model

ABSTRACT

Pores, voids correspond to inevitable products in the formation of concrete and significantly affect its macroscopic effective strength. A lot of researches show that both porosity and pore structure have significant influence on the concrete strength and differences exist with respect to those influences on the tensile and compressive strengths. In this paper, first, the relationships between the effective tensile and compressive strengths of concrete and porosity are expressed respectively from the proposed simplified center pore model. Second, in order to further consider the influence of the pore structure, the pore size is chosen as the representative index of pore structure and an influence function related to the pore size is proposed based on the correlation analysis. The total influence coefficient of pore size is obtained by combining the pore size distribution function and influence function. Taking the total influence coefficient into account in the relation between the effective strength and porosity, explicit formulae of porous concrete effective tensile and compressive strengths are finally deduced. Through comparing the present approach with a few classical analytical solutions and experimental observations, the results indicate the reliability and accuracy of the proposed approach and the derived equations are simple and convenient to use. Analysis and discussion suggest that the effect of porosity on the compressive strength of concrete exceeds that of the tensile strength and that the effective concrete strength with the same porosity can be improved by decreasing the pore size.

1. Introduction

As widely-known, pores, voids and other defects govern the most important mechanical properties of cement-based materials and especially in terms of strength and permeability [1–3]. The strength of cement-based materials depends on the formation of cementitious material. However, the defects are considered as factors that reduce the effective cementitious area and further weaken the cement-based materials strength. In order to understand this influence, several related theories were proposed to predict the effective strength.

Initially, many researchers select the porosity as the only factor to establish strength models of cement-based materials. Powers proposed a gel space ratio theory to examine the compressive strength of Portland cement [4]. Hansen [5] assumed that defects were focused into a spherical void and that strength was proportional to the gel area on the maximum cross section of the void. Furthermore, many typical semi-empirical equations were also proposed to reflect the relationship between strength and porosity

* Corresponding author.
E-mail address: bene@nwsuaf.edu.cn (Z. Li).

https://doi.org/10.1016/j.conbuildmat.2018.03.028
0950-0618/

such as power, index, linear, and logarithmic equations [6–9]. The equations are widely used to predict the strength of porous materials [10,11]. However, the experimental results show that these strength models are not accurate enough for strength prediction, because not only the porosity but also the pore structure, such as pore size and pore-connectivity, has vital influence on the strength.

Therefore, various researchers investigated the effect of pores structure on the strength. Based on the Hanshin model, Huang et al. [12] introduced the concept of relative specific surface area of the pores structure into the strength equation and proposed an expression of compressive strength. Deo and Neithalath [13] explored the relationship between pore structure and concrete compressive strength by examining the response of pervious concrete. Gao et al. [14] studied the relationship between pore structure and concrete strength by examining samples involving the defects which are obtained the addition of air entraining agents. Jin et al [15] expressed the relation between strength and pore structure of hardened mortar by introducing the ratio parameter of fractal dimension to capillary pore volume. Although the fractal theory characterized the pore size distribution accurately, the influence of pore structure on the effective strength was not further explained. Griffith theory was adopted to evaluate the strength of porous materials and the influence of pore size was also considered [16–18]. However, many researchers suggested that differences exist with respect to the impacts of pore structure on the tensile and compressive strengths [2,19,20] and the model based on Griffith theory is unable to explain this phenomenon. The relationships between the tensile and compressive strengths and pore structure are required to be established separately.

Recently, various scholars attempted to use meso-mechanics theory of composite materials to examine elastic parameters of porous materials, such as the self-consistent method, Mori-Tanaka method, and three-phase sphere model [21]. However, the effective strength of porous materials was not obtained by meso-mechanics theory.

Given the fore-mentioned reasons, the objective of this paper is to establish a mathematical model of concrete effective strength which not only considers the influence of pore structure on the strength but also expresses the different relationships between the tensile and compressive strengths and pore structure. The rationality and accuracy of the developed model are verified by comparison with three classical analytical solutions and experimental observations. Finally, the influences of porosity and pore structure on the tensile and compressive strengths are analyzed and discussed.

2. Effective strength of porous concrete

2.1. A simplified central pore model

Various researchers concentrated on the pore in the center of the model to investigate deformation characteristics and the strength of porous material. Hill [22] and Christensen and Lo [23] investigated elastic parameters of composite material based on a three phase sphere model. Du et al. [24] developed a hollow sphere model to study the effective strength of porous concrete. In view of these findings, this paper assumes that the concrete with defects is composed of a central round pore inclusion embedded in non-porous concrete matrix. The equivalent process of the porous concrete is illustrated in Fig. 1. First, with respect to the meso-scale, concrete is considered as a four-phase composite material composed of aggregates, cement paste, an interface transition region (ITZ), and initial defects as shown in Fig. 1(a). Second, aggregates, cement paste, and ITZ are considered as the matrix, and the defects in the cement paste and ITZ are concentrated in the center of the matrix as the inclusion phase to establish the central pore model as shown in Fig. 1(b). The central pore model is subject to an externally applied uniaxial tensile load, and the locations are defined as M, N, O, and P respectively when variable ρ corresponds to the inside radius a and the variable φ corresponds to $0, \frac{\pi}{2}, \pi$ and $\frac{3\pi}{2}$.

The defects including cracks and voids expand, propagate and collapse under external load, which is the main factor leading to the nonlinear elastic behavior of concrete. Thus the concrete matrix without defects can be assumed as isotropic, homogeneous, and elastic, which is consistent with the assumption in literature [24]. According to Wong and Chau research [25] and Chen et al. research [26], the defects are randomly distributed in the concrete, and the cross section porosity in the concrete volume fluctuates within a small range and is considered to be equal. Besides, the cross section porosity is generally adopted to represent the concrete porosity in the research of concrete mechanical properties [14,25–27]. Therefore, in this paper the representative cross section with average porosity is selected to research the relation between the concrete strength and porosity. To aid in the convenience of calculation, the model presented in Fig. 1(b) is changed into a polar coordinate system model as shown in Fig. 1(c), and the corresponding original stress boundary is transformed based on the elastic theory [28] as follows:

$$(\sigma_\rho)_{\rho=b} = \frac{q}{2} + \frac{q}{2}\cos 2\varphi,\ (\sigma_\rho)_{\rho=a} = 0,\ (\tau_{\rho\varphi})_{\rho=b} = -\frac{q}{2}\sin 2\varphi,\ (\tau_{\rho\varphi})_{\rho=a} = 0 \quad (1)$$

where q denotes externally applied uniaxial tensile load (MPa), φ denotes the angle (°) shown in Fig. 1(b) and (c), and subscripts ρ and φ denote radial direction and circumferential direction, respectively.

Based on the superposition principle of elastic mechanics, the boundary conditions are divided into two parts. The first and second parts of the stress boundary condition are as follows:

$$\left(\sigma^{\mathrm{I}}_\rho\right)_{\rho=b} = \frac{q}{2},\ \left(\tau^{\mathrm{I}}_{\rho\varphi}\right)_{\rho=b} = 0,\ \left(\sigma^{\mathrm{I}}_\rho\right)_{\rho=a} = 0,\ \left(\tau^{\mathrm{I}}_{\rho\varphi}\right)_{\rho=a} = 0 \quad (2)$$

$$\left(\sigma^{\mathrm{II}}_\rho\right)_{\rho=b} = \frac{q}{2}\cos 2\varphi,\ \left(\tau^{\mathrm{II}}_{\rho\varphi}\right)_{\rho=b} = -\frac{q}{2}\sin 2\varphi,\ \left(\sigma^{\mathrm{II}}_\rho\right)_{\rho=a} = 0,\ \left(\tau^{\mathrm{II}}_{\rho\varphi}\right)_{\rho=a} = 0 \quad (3)$$

Based on the lame solution of elastic mechanics [28], the radial, circumferential, and tangential stresses of the equivalent ring applied to the first part of the stress boundary condition are obtained. With respect to the second part of the stress boundary condition, the stress components are obtained by a semi-inverse method of elastic mechanics [29]. Subsequently, the matrix stresses that satisfy the two-part boundary conditions are superimposed, and the total radial, circumferential, and tangential stresses are obtained as follows:

$$\sigma_\rho = \frac{q}{2}\frac{\rho^2 - cb^2}{\rho^2(1-c)} - \frac{q}{(c-1)^3}\left[\frac{4c^2+c+1}{2} - 2(c^3+c^2+c)\frac{b^2}{\rho^2} + \frac{3(c^3+c^2)b^4}{2\rho^4}\right]\cos 2\varphi \quad (4)$$

$$\sigma_\varphi = \frac{q}{2}\frac{\rho^2 + cb^2}{\rho^2(1-c)} + \frac{q}{(c-1)^3}\left[-6c\frac{\rho^2}{b^2} + \frac{4c^2+c+1}{2} + \frac{3(c^3+c^2)b^4}{2\rho^4}\right]\cos 2\varphi \quad (5)$$

$$\tau_{\rho\varphi} = \frac{q}{(c-1)^3}\left[-3c\frac{\rho^2}{b^2} + \frac{4c^2+c+1}{2} + (c^3+c^2+c)\frac{b^2}{\rho^2} - \frac{3(c^3+c^2)b^4}{2\rho^4}\right]\sin 2\varphi \quad (6)$$