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Analysis of stress-induced cracks in concrete and mortar under cyclic uniaxial compression

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HIGHLIGHTS

- The internal circular crack appears first in cylinder specimens under compression.
- A unified expression is proposed to evaluate the volume strain of cylinder specimens.
- AE hit-rate can reflect the mechanical behavior of concrete in real time.

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ABSTRACT

A series tests on concrete and mortar cylinders under cyclic uniaxial loading were carried in this study to investigate the effect of internal stress-induced cracks on their mechanical properties. It was found that the radial strain cannot be changed continuously because the internal circular cracks appear firstly inside the specimens. Moreover, a unified approach for calculating the apparent volumetric strain of the cylindrical specimens at both elastic and inelastic stages was proposed. Additionally, the Acoustic emission (AE) experimental result shows that the AE hits rate can well reflect the crack formation and propagations of the concrete specimen under the cyclic axial compression.

1. Introduction

Concrete is one of the most frequently-used building materials which can date back to at least 6500 BCE. On a macroscopic scale, it is a composite material composed of fine and coarse aggregates bonded together with cement paste that hardens over time. Accordingly, concrete is a heterogeneous, multicomponent and multiphase brittle material. However, the most principal disadvantage of the concrete is its poor tensile strength which leads to the propagation of cracks at relatively low loads [1–3]. There are many complicated reasons causing different types of cracks in concrete, from which the stress-induced crack is one of these types which has been under consideration in many investigations [4–7].

Using scanning electron microscopy, Nemati [8–10] investigated the morphology and distribution of the stress-induced microcracks in concrete specimens with different strength grades under uniaxial and confined loadings. These studies found that the density and branching of the microcracks decrease with the increase of the confining stress. Loo [11–12] noted through experiments that the microcracks are normally produced at a stress-to-strength ratio ranging between 0.15 and 0.44, and these microcracks do not propagate unless the stress-to-strength ratio exceeds 0.5. According to the measured circumferential and axial strains, Lim [13] put forward a non-destructive method to evaluate the microcracks in concrete cylinders under uniaxial compression. Narayanan [14] investigated the load-induced damage in the concrete from distributed microcracks to localized cracking using bonded lead zirconate titanate patches. A series of experiments was, as well, conducted by Akçaoğlu [15] to study the influence of aggregate size and shape on concrete microcracking under different compressive stress levels. A numerical simulation program, named Concrete Fracture Process Analysis, was developed by Teng [16] to simulate the initiation, propagation and coalescence of cracks. Additionally,

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Ma [17] implement a mesoscopic finite element simulation to investigate the flexural failure process of fully-graded concrete using random aggregate models. A robust coupling model of the discrete element method and the finite element method is proposed by Xu [18] to estimate the moduli of particle-reinforced composites. Deformation analysis of shear band in granular materials are conducted by Lei [19] via many robust plane shear tests and numerical simulations. Xu [20] proposed an n-phase micromechanical framework to predict the effective thermal conductivity and elastic modulus of multicomponent particulate composites. Moreover, some studies [21,22] have focus on the basic mechanical properties of particle reinforced composites on mesoscopic scale.

On the other hand, the acoustic emission (AE) testing is widely used in the research of concrete materials as a dynamic nondestructive technology to detect the internal cracks [23–30]. Many researchers carried out relevant research works using this technology. With regard to material testing, Wu [31], Mihashi [32] and Chen [33] found that the aggregate size has a great influence on the mechanical properties of the concrete as well as on the propagation of cracks by using the AE testing. Additionally, Elaqra [34] and Landis [35] explored the mechanical response and microcracks growth during the compressive loading of concrete specimens through AE testing. Ranjith [36] focused on the effect of different displacement rates and moisture contents on the mechanical properties of concrete cylindrical specimens. Carpinteri [37–39] studied the stress-induced cracks and the failure mechanism of concrete and rocks specimens by AE and electromagnetic emission technologies. On the other hand, on the structural level, Watanabe [40] and Sagar [41] investigated the extent of the compressive failure zone by using the AE method in three-point loaded beams. Lei [42] presented a novel approach to realize micro-damage alarming and identification of concrete combined with wavelet packet analysis. Sutter [43] investigated the mechanical performance of lightweight composite-concrete beams by AE analysis and Digital Image Correlation.

Based on the above-mentioned research, the geometrical modality and characteristics of the stress-induced cracks inside concrete and mortar specimens under cyclic uniaxial compression are investigated by X-ray microtomography in this study. Currently, it has been observed that radial strain cannot be changed continuously, thus the differential of dispersed functions associated with radius does not exist when the internal circular cracks appears internally. Hence, the classical formula for calculating the volumetric strain would no longer be applicable after concrete cracking. Accordingly, a unified expression with a clear physical meaning for calculating the volume strain of concrete cylinder is put forward, called herein as the apparent volumetric strain, which is valid in both elastic and cracking stages. At last, through theoretical analysis and laboratory experimentation, it has been found that there is a very close relationship between the proposed apparent volumetric strain, the AE signals and the mechanical behavior of concrete.

2. Experiment procedures and theoretical analyses

2.1. Mix proportions of concrete and mortar

Two types of specimens with different proportions of the composite cementitious materials (concrete and mortar) were studied. In Table 1, the chemical composition of the cement is summarized. Both concrete and mortar were prepared with a water-to-cement weight ratio of 0.6. Standard sand and fine gravel with a maximum grain size of 2 mm and 20 mm, respectively, were used. Mixture proportion of concrete and mortar are listed in Table 2, while the dimensions and loading methods of these specimens are presented in Table 3. It is worth pointing out that concrete-I and mortar-I are used as control specimens under monotonic loading to investigate the distribution and characteristics of the inside stress-induced cracks.

Table 1
Chemical analysis of the Portland cement.

Constituent	Percentage (%)
Silicon dioxide (SiO_2)	22.3%
Aluminum oxide (Al_2O_3)	5.5%
Ferric oxide (Fe_2O_3)	2.1%
Calcium oxide (CaO)	63.8%
Magnesium oxide (MgO)	1.7%
Sodium oxide (Na_2O)	0.3%
Titanium oxide (TiO_2)	0.1%
Potassium oxide (K_2O)	1.1%
Phosphorous oxide (P_2O_5)	0.2%
Manganese oxide (MnO)	0.1%
Sulphur trioxide (SO_3)	2.7%

2.2. Distribution and evaluation of microcracks in concrete and mortar

Two groups of preliminary experiments (cylindrical specimens with radius of 50 mm and height of 100 mm) under monotonic load were carried out to characterize the compressive stress-induced cracks in the concrete and mortar, as shown in Fig. 1. The reason for choosing such small specimens as preliminary experiments is that the stress-induced cracks in concrete (or mortar) can sufficiently be developed inside the specimens. Horizontal and vertical strain gauges (with 60 mm long) were attached to the external surface of each specimen to measure the volumetric strain. The specimens were slowly loaded in compression, while the load and strain were collected by data logger TDS-530. The test was stopped when the vertical cracks appear on the surface of the specimens. At the end of the loading process, the internal cracks of the specimens were displayed using X-ray computerized tomography technique, as shown in Figs. 2 and 3.

From X-ray tomography images shown in Figs. 2a and 3a, it is obvious that internal circular cracks first develop inside the concrete and mortar specimens. The cross-section is macroscopically divided into two parts by these internal circular cracks; the core and outer crack zone as can be seen in Figs. 2b and 3b. The experimental results showed that the cracks are mainly generated outside the internal circular crack, which is termed as the outer crack zone, while the core area is slightly cracked. Surface vertical cracks were observed during the test. These vertical cracks extend outwards from the internal ring cracks and their number was found to increase proportionally with the load increase.

Based on these characteristics, it is obvious that the radial strain cannot change continuously after the internal circular crack appears. Therefore, the classical volumetric strain formula by Timoshenko [44] becomes no longer applicable for evaluating the change in the volume of cracked specimens. The expression of the unit volume change is shown in Eq. (1), in which strains ε_x, ε_y and ε_z can be measured by the strain gauges, while part of them cannot be measured when the horizontal internal circular crack appears under axial load. Therefore, this equation becomes only valid in the elastic stage. In cylindrical specimens, the volumetric strain can be written as given by Eqs. (2) and (3) based on the fact that the principal strains ε_x, ε_y and ε_z, are equal to ε_r (the radial strain), with $\varepsilon_r = \varepsilon_c$; ε_c is the average circumferential strain and ε_h represents the axial strain [45]. It is worth noting, on the basis of Eq. (2), that there is a linear relationship between the radial strain and the circumferential strain. However, there exists discontinuous