Cement and Concrete Research 42 (2012) 1261–1272

Contents lists available at SciVerse ScienceDirect

Cement and Concrete Research

journal homepage: http://ees.elsevier.com/CEMCON/default.asp

Geometry of crack network and its impact on transport properties of concrete

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ARTICLE INFO

Article history:
Received 2 July 2011
Accepted 29 May 2012

Keywords:
Concrete (E)
Crack density (B)
Crack length (B)
Connectivity (B)
Transport properties (C)

ABSTRACT

This paper investigates the crack network geometry in concretes subjected to cyclic axial loading. A total of 24 cylinder specimens of two concretes (OPC and HVFC) were cast and eight levels of cracking extents were created for each concrete. Disks were extracted from the cylinders and the crack geometry was evaluated for sections both perpendicular and parallel to loading. The crack geometry is quantified by crack density, length, orientation and connectivity. The crack length is found to obey log-normal distribution, and the crack orientation and connectivity are correlated strongly with crack density. The volumetric density is identified as a consistent parameter to describe the impact of crack network on altered transport properties. The effective porosity, capillary sorptivity, gas permeability and electrical conductivity all have strong dependence on crack density. In particular, the gas permeability is proved to be sensitive to both small range and large range of crack density.

1. Introduction

Structural concrete is a typical quasi-brittle material and liable to cracking under internal shrinkages or external loadings [1,2]. For concrete structures during the service life, the degradation of mechanical and durability properties is related intimately to the initiation and propagation of cracks. Cracks turn concrete materials from continuous media to discrete ones, significantly changing the mass transport processes [3,4]. Thus, quantitative investigation on the crack geometry and its impact on transport properties can provide insight into the durability performance of structural concretes in service conditions. So far, numerous studies have been carried out on the influence of mechanical loading damage on concrete transport properties [5–10]. However, from these investigations, the impact of cracking damage on transport properties has not been clearly demonstrated due to the different loading schemes and different damage characterizations. To obtain a clear relationship between the cracking and its impact, one has to cope with the detailed crack geometry, besides the global quantification of cracking extent [11].

The cracks in concrete materials form a multi-scale and complex network [12]. The available observations have confirmed the statistical even chaotic nature of crack networks under mechanical loadings [13–15], creep [16], shrinkage [7,17] and sulfate attack [18]. Mathematical morphology [19] and stereology methods [20] have been employed to characterize the crack network [21–23]. Under isotropy hypothesis of crack distribution and given statistic laws for crack length, the stereology parameters can be extracted from 2D images and used to generate the 3D crack pattern [20]. These stereological parameters have been applied to describe the crack networks in concrete [21,23]. In experimental aspects, several techniques have been employed to observe crack patterns and treat the multi-scale characteristics of cracks [12]. For 2D observation, the available techniques include optical microscopy, fluorescent microscopy and scanning electronic microscopy and confocal laser microscopy [24]. For 3D observation, the neutron radiography [5] and computerized microtomography [25,15] have been used. To help the image processing, dye impregnation [11,26,27], fluorescent epoxy or resin [23,28,29] and Wood's metal intrusion method [30,29] have been developed to prepare samples for observation. In fact, the local precision and the global representation of cracks can rarely be both available at one observation level [12,26]. Compromise should be made between the two aspects, in particular, as the altered material properties are in question.

This paper focuses on the mechanical cracks in concrete and the impact of the geometry of crack network on the material transport properties. To this aim, concrete specimens were firstly subjected to axial and cyclic loadings to generate different cracking extents and the geometry of formed crack networks is quantified for crack density, length distribution, orientation and connectivity. Then the transport properties of specimens were measured for effective porosity, capillary sorptivity, gas permeability and electrical conductivity. The impact of crack network on these properties is investigated through the crack geometry parameters. In the following, the experimental procedures are introduced in Section 2 and the crack geometry

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doi:10.1016/j.cemconres.2012.05.017

quantification is given in Section 3. The geometry analysis of crack networks is discussed in Section 4 and the correlation between the geometry parameters and the transport properties is investigated in Section 5. The concluding remarks are provided in Section 6.

2. Experimental procedures

The whole experimental procedure includes three phases: (1) Phase I is the loading phase in which different cracking extents were generated through cyclic axial loading, (2) Phase II is dedicated to the transport properties of cracked specimens, (3) the crack pattern and geometry are observed in Phase III. The procedure is illustrated in Fig. 1 and the experimental details are given in the following.

2.1. Materials and specimens

Two concretes of medium strength class for structural use were prepared: an ordinary Portland cement concrete (OPC) with water–cement ratio of 0.55 and a high volume fly-ash concrete (HVFC) with binder containing 30% fly ash and water–binder ratio of 0.50. The mix proportioning and strength are given in Table 1. The PI cement used in this study corresponds to CEM-I cement according to European standard [31].

A total of 12 cylinder specimens of $\phi150\times400$ mm and 9 cubic specimens of 100 mm were prepared for each mix. After demoulding at age of 1 day, the cylinder specimens were cured under condition of 20° with 95% relative humidity to age of 28 days (OPC) and 96 days (HVFC) respectively. Then the specimens, OPC and HVFC, were stored in another room maintained at 20°, 65% relative humidity for 30 days before mechanical loading. The cubic specimens were cured to 28 days, 56 days and 96 days (HVFC) to obtain the compressive strength.

2.2. Mechanical loading

Compressive loading was applied axially on the $\phi150\times400$ mm cylinder using Toni Expert machine under displacement control, the longitudinal strain rate controlled to 2000 με/min. To ensure the assumed crack pattern (parallel to axial loading), two measures were taken during the loading process: (1) the top and bottom surfaces of cylinder specimens were polished to assure a good contact with loading plates; (2) two semi-rigid steel belts were installed near the top and bottom zones of specimens to avoid the local crushing in these zones.

For each specimen, 3 cycles with a maximum load of 240 kN (about $f_c/3$) were first performed to eliminate the possible creep strain. Then, the specimen was subject to a cyclic loading–unloading scheme: the first cycle was conducted with the maximum load controlled to 550 kN (about $0.75f_c$); then the next cycle was conducted with the maximum load increased by 50 kN (about $0.07f_c$); a total of 5 cycles were conducted at each load level; at the end of each loading phase the compression plates were held for 30 s to allow fracture stabilization. The above scheme was repeated until an expected axial residual strain was reached. The ultrasonic velocities were measured perpendicular to axial direction before and after damage, v_0 and v_d, and a damage factor D is defined as,

$$D = 1 - v_d^2/v_0^2. \tag{1}$$

For details on ultrasonic measurement one can refer to [32]. Finally, including the intact states eight levels of axial residual strain were obtained, ranging from 0 to 700 με for OPC specimens and from 0 to 500 με for HVFC specimens. Fig. 2 provides the cyclic loading and stress–strain curves for Specimen OPC7 with the largest residual axial strain 702 με.

Table 1
Mix proportioning and strength of OPC and HVFC.

Proportioning/strength	OPC	HVFC
Crushed coarse aggregate, 5–20 mm (kg/m^3)	1038	1074
River sand, 0–5 mm (kg/m^3)	692	703
Cement PI 52.5 (kg/m^3)	400	280
Fly ash (kg/m^3)	–	120
Water (kg/m^3)	220	200
Water to cement/binder ratio (−)	0.55	0.50
Cubic strength at 28 days (MPa)	50.0	44.4
Cubic strength at 56 days (MPa)	54.5	51.9
Cubic strength at 96 days (MPa)	–	56.6

2.3. Transport properties

From a concrete cylinder, two disk specimens of 50 mm thickness were sawed out and oven-dried at a temperature of 60° to constant weight. Then these disks were tested for air permeability by Cembureau method [33] and capillary sorptivity by surface suction method [34]. Afterwards, these disks were vacuum-saturated with water, and the effective porosity for each disk was evaluated by gravimetry method between its dried and saturated states. Then the electrical conductivity was measured by alternative current method on the vacuum-saturated disks [35]. The experimental details can be referred to [32].

It is to note that the transport properties correspond to the damage extents created under the loading schemes described in Section 2.2. Compared to the normal structural concretes in use, the adopted damage extents/stress levels are too large/high to be representative. However, the damage extents are chosen as such to facilitate the correlation study between the crack geometry and altered transport properties. Certainly the damage-property results obtained in this study should be used with a notion of realistic damage extent of materials.

2.4. Crack geometry observation

This study used the dye impregnation to treat the concrete crack surface and the crack geometry was observed by digital optical

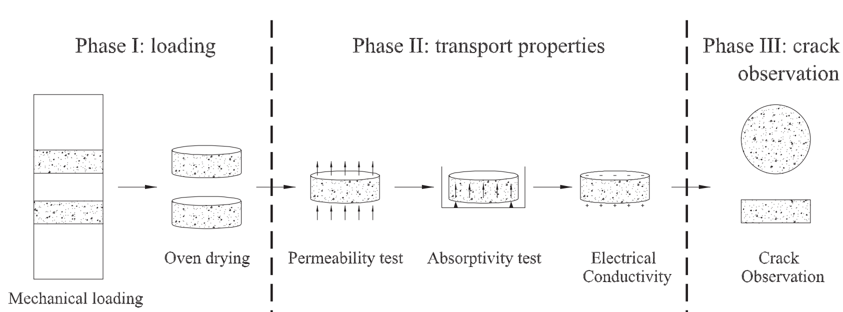

Fig. 1. Experimental procedure: loading (Phase I), transport properties test (Phase II) and crack geometry observation (Phase III).