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Characteristics of concrete cracks and their influence on chloride penetration

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HIGHLIGHTS

- Complex geometrical parameters of concrete cracks were appropriately quantified.
- Chloride diffusion in concrete depends on the width, density and tortuosity of cracks.
- Effective crack width and density were proposed to describe the effect of cracks on chloride diffusivity.
- Critical crack width that influences the chloride diffusion in concrete has been clarified.
- Relationship between crack tortuosity and degree of crack orientation has been quantified.

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ABSTRACT

Concrete cracking usually is an unavoidable phenomenon in reinforced concrete (RC) structures and has a significant effect on chloride diffusion and thus the deterioration of the structures. However, actual concrete cracks have complicated characteristics, and the mechanisms in which they influence the chloride penetration have not yet been well clarified. This study presents a careful quantification of the geometrical parameters of actual concrete cracks, including density, orientation, tortuosity and width, and explores their correlation with the chloride diffusion properties of concrete. Uni-axial compression tests were conducted on concrete specimens to create various extents of cracking severity. Afterwards, a non-steady state migration method was employed to evaluate the diffusivity of sound and cracked concretes. The geometry parameters of concrete cracks were quantified by an image analysis technique after the migration tests. The test results suggest a linear relationship between the crack tortuosity and the degree of crack orientation. In addition, chloride diffusion into concrete depends greatly on the crack density and crack tortuosity in addition to the crack width. In particular, the crack tortuosity is a critical factor influencing chloride penetration when the crack width ranges from 150 to 370 μm. Considering the crack tortuosity and orientation, the effective crack width and effective crack density are proposed as correlated with the chloride diffusivity of cracked concrete.

1. Introduction

Chloride-induced steel corrosion is the main cause for the deterioration of reinforced concrete (RC) structures. Therefore, the chloride diffusivity of cover concrete is a crucial factor for the deterioration and the service life of RC structures, particularly in marine environments. For the past several decades, extensive investigations have been conducted to study chloride penetration in concrete; most studies focused on the chloride diffusion process in sound concrete [1–3]. However, due to the weakness of concrete as a quasi-brittle material, cracking is usually inevitable for RC structures when they are subjected to mechanical loading, weathering and other physical or chemical attacks. Moreover, cracks within a specific width range are often allowed in RC structures according to present codes of practice. Obviously, cracks in concrete may facilitate an easier access to aggressive ions and promote the deterioration of RC structures. Although the negative effect of cracks on the durability of RC structures has been well recognized, reliable approaches that quantify the information of cracks have not yet been established due to the complicated characteristics of actual cracks.

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Different methods have been employed to create cracks in concrete in laboratory studies. Overall, the cracks can be classified into two groups: artificial cracks (e.g., induced by a pre-set notch) and natural cracks (e.g., induced by pre-loading). The main advantage of using an artificial crack is that it can be easily fabricated and its parameters (e.g., crack width) are easy to define for developing analytical models [4–5]. However, the disadvantages are also obvious: artificial cracks have smooth surfaces and are not tortuous and rough as real cracks; the surface of the notch contains more cement than the surface of a real crack, and artificial cracks are relatively wider. The commonly used methods to produce natural cracks include the splitting method [6–8] and the mechanical expansion method [9], which can create tensile cracks in a concrete disk. Nevertheless, the natural cracks generated by these methods have a uniform width along the crack length and depth [6]. Another approach to produce natural tensile cracks is three- or four-bending concrete prisms [10–12]. Cracks induced by such a method are more realistic. However, how to characterize these actual cracks remains unclear and requires further study. In the past, crack width and depth were reported to significantly influence the permeability of concrete [6,13–18]. As a result, some researchers defined threshold crack widths beyond which the permeability of concrete will be significantly affected.

Using the feedback-controlled splitting test method, Aldea et al. [16] and Wang et al. [6] reported that a crack opening displacement smaller than 50 μm under loading rarely affects the water permeability of concrete; however, for a crack opening larger than 50 μm but less than 200 μm, the water permeability of concrete increases by an order of magnitude compared to that of uncracked concrete; and for a cracking opening larger than 200 μm, the water permeability of concrete increases rapidly. Jang et al. [19] and Djerbi et al. [20] introduced cracks into concrete using a splitting test and concluded that when the crack width exceeds approximately 55–80 μm, the diffusion coefficient of concrete starts to increase with crack width. Park et al. [21] reported that a more rapid increase in the diffusion coefficient of concrete occurs when the crack width is larger than 200 μm. Similarly, Ismail et al. [9] adopted a mechanical expansive core to test the chloride diffusion in the cracked mortar and reported that the chloride diffusion along the crack path is not impeded when the crack opening in the mortar is greater than 200 μm, whereas in the cases of fine cracks (<60 μm), the self-healing of mortar may impede chloride diffusion. However, with the deployment of a notched artificial crack, Marsavina et al. [4] concluded that the influence of crack width on chloride penetration is less pronounced, even if notch widths are 0.2 mm. Marsavina et al.'s research indicated the chloride penetration depth increases with the crack (i.e., notch) depth.

Recently, very few studies have indicated that besides the crack width and depth, other crack parameters such as crack density, cracking orientation, and crack tortuosity may have crucial effects on chloride diffusion in concrete [6,22–24]. However, the issue of how to model these effects and quantitatively correlate them with chloride penetration in concrete remains unsolved. This paper aims to provide a further understanding of the influences of various crack parameters (i.e., crack density, crack orientation, crack tortuosity and width) on chloride diffusion in concrete. To generate various extents of severity of cracking, different levels of uni-axial compressive loads were applied to the concrete prisms. After loading, the crack geometry parameters in the planes perpendicular and parallel to the loading direction were quantified using an image analysis technique. To exclude the self-healing effect of concrete cracks, a non-steady state migration method was employed to rapidly evaluate the diffusivity of sound and cracked concretes and the impact of all the crack geometry parameters. Based on analyses on the test results, effective crack density and effective crack width were defined to correlate well with the chloride diffusion in concrete.

2. Experimental program

2.1. Materials

The Portland cement used in the mix was 42.5 ordinary type produced in Hangzhou, and complied with the Standards [25–27]. The fine aggregate used was a local river sand with a fineness modulus of 2.40, and the coarse aggregate was a locally available crushed gravel with a maximum size of 20 mm. The concrete was mixed using tape water, and the mix proportions are listed in Table 1. The cubic compressive strengths of concretes were tested after 28 and 56 days of curing, and the average measured values were 25.3 and 28.1 MPa, respectively.

2.2. Preparation of cracked specimens

Cubic specimens with the dimensions 200 mm × 200 mm × 200 mm were cast in the wood moulds and compacted with a mechanical vibrator. Twenty-four hours after the casting, all of the specimens were de-moulded and then cured in a room at a temperature of 20 °C and with 95% relative humidity for 56 days. In total, 30 cubic specimens were prepared, in which 12 specimens were used to test the mechanical properties on the 28th and 56th days, and the other 18 concrete specimens were prepared for the chloride penetration test. To investigate the effects of various crack parameters such as crack width, crack density, crack tortuosity, crack length, and cracking orientation, nine different levels of uniaxial compressive loads (0%, 30%, 40%, 50%, 60%, 70%, 75%, 80% and 85% of the compressive strength of the concrete) were applied to the 18 cubic specimens to generate multiple cracks in the concrete (Table 2). To minimize the boundary effect and avoid local crushing, the top and bottom surfaces of the cubic specimens were smoothly polished and levelled with some refined sands before loading. After unloading, a concrete cylinder with a diameter of 100 mm and a height of 200 mm were drilled from each cubic specimen with different damage levels (Fig. 1a). Then, two concrete discs, 50 mm in thickness, were cut off from the central part of the cylinders using a diamond blade saw (Fig. 1b). To identify the effect of the cracking pattern or the cracking orientation on chloride transport, the concrete cylinders were taken along the *x* and *y* directions (as shown in Fig. 1), respectively. To maintain the integrity of the test specimens, the lateral curve surface of the discs was ere wrapped with plastic film firstly, and then coated with epoxy resin. Table 2 summarizes the information of all the test specimens.

2.3. Chloride penetration tests

The non-steady state migration method developed by Tang [28] was adopted to evaluate the chloride penetration in concrete disks, following NT BUILD 492 [29]. This test method can be finished within a few hours so that the self-healing and other time-

Table 1
Mix proportions of the concrete.

Quantity (kg/m^3)				Water/ cement ratio	Cubic compressive strength (MPa)	
Cement	Sand	Coarse aggregate	Water		28 days	56 days
430	559	1118	185	0.43	25.3	28.1