Impact of flexural loading induced cracks on chloride penetration of UHPC

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Abstract

Ultra-high performance concrete (UHPC) has been implemented in bridge construction for anti-corrosion purposes in costal and marine environment and regions utilizing de-icing salts in North America and Canada. However, the durability of cracked UHPC has not been systematically studied. In particular, the influence of cracks and crack patterns on the chloride penetration resistance of UHPC is not well understood. This paper reviewed the existing literature regarding the chloride penetration of uncracked and cracked UHPC. It shows that the chloride penetration through uncracked UHPC is one to two orders of magnitude lower than that of uncracked normal strength concrete. Limited studies reported that cracks significantly increase chloride penetration in UHPC. However, due to lack of quantitative studies, the influence of crack width, geometry, and patterns have not been fully understood, neither has an acceptable crack width been established for UHPC to ensure long-term durability for design and maintenance. Based on the current knowledge gaps, a comprehensive study is carried out to examine the influence of crack width on the chloride penetration through UHPC by a modified non-steady chloride migration test. This research is expected to establish the correlation between crack characteristics to the chloride penetration resistance of UHPC, and ultimately to corrosion resistance of UHPC structures, which will provide a guide to the design and maintenance of UHPC structures under coastal and marine environments.

Keywords: UHPC, chloride penetration, cracks, corrosion resistance

1. Introduction

Ultra-high performance concrete (UHPC) is composed of an optimized gradation of granular constituents, a low water-to-cementitious materials ratio (w/cm), and a high percentage of discontinuous internal fiber reinforcement. Compared to conventional concrete, UHPC has high compressive strength, tensile strength, post-cracking ductility, tight crack width, and excellent durability. In particular, UHPC has extremely low porosity and a disconnected pore system, leading to low transport properties and chloride penetration. As a result, UHPC shows very high corrosion resistance compared to conventional concrete, and provides excellent protection for embedded steel reinforcement against corrosion. Currently, UHPC has been extensively researched and implemented in bridges and other structures, especially in marine and coastal environments and regions where de-icing salts are commonly used, for its anti-corrosion performance.

Despite excellent resistance to chloride penetration, after cracks are generated on the surface of UHPC, the chloride penetration could substantially increase as cracks serve as additional channels for chloride penetration. Extensive studies show that crack width, depth, and density all affect the chloride penetration in normal concrete. Crack width has a significant influence on the chloride penetration; wider cracks lead to higher chloride penetration. The same trend is expected for UHPC, which has also been reported by a few studies in literature. However, due to lack of quantitative studies, the influence of crack width, geometry, and patterns has not been fully understood, neither has an acceptable crack width been established for UHPC to ensure long-term durability for design and maintenance.

This paper presents a brief review of the chloride penetration through cracked UHPC and identified the related knowledge gaps. In addition, a brief description of an ongoing research effort is presented, which comprehensively investigates the influence of cracks on chloride penetration of UHPC.

2. Influence of cracks on chloride penetration in UHPC-State of Knowledge

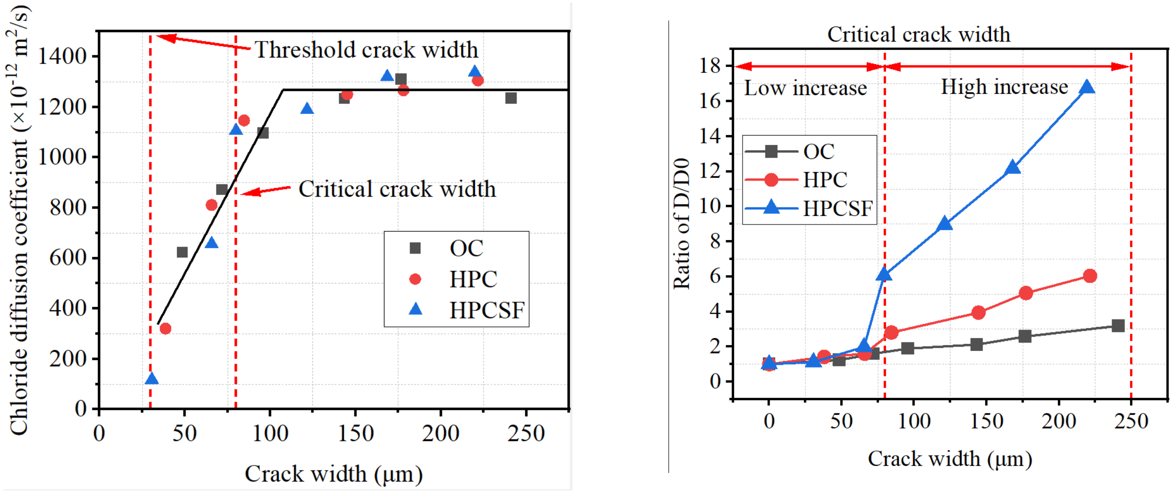
UHPC has been widely studied for its resistance to chloride penetration. Chloride ions could penetrate UHPC via several distinct mechanisms including permeation, migration, diffusion, and absorption. In literature, migration and diffusion behavior of chloride ions are often characterized to evaluate the chloride penetration through concrete materials, as recommended in several standard testing methods. In particular, the rapid chloride migration test (RCMT) (NT BUILD 492) and bulk diffusion test (ASTM C1556; NT Build 443) are commonly used methods in literature for both conventional concrete and UHPC. RCMT measures the migration coefficient of chloride ions through concrete materials under an external electric field, and the bulk diffusion test measures the diffusion coefficient of chloride ions through concrete materials. A summary of the measured chloride migration or diffusion coefficient of uncracked UHPC is provided in Table 1 as compared to the typical values of those of conventional concrete. It can be seen that the chloride penetration resistance of UHPC when uncracked is one to two orders of magnitude lower than that of normal strength concrete.

Table 1 Chloride penetration for uncracked UHPC

Test method	Chloride migration/diffusion coefficient of UHPC m^2/s ($ft.^2/s$)	Reference	Chloride migration/diffusion coefficient of normal concrete m^2/s ($ft.^2/s$)m^2/s ($ft.^2/s$)	Reference
Rapid chloride	$3E^{-14}$ - $6.63E^{-12}$ ($3.2E^{-13}$ - $7.14E^{-11}$)	Peng et al.; Chen et al.; Karim et al.; Song et al.;	$1.67E^{-12}$ - $1.91E^{-13}$ ($1.80E^{-11}$ - $2.05E^{-10}$)	Liu et al.; Shafikhani

migration test		Pourjahanshahi and Madani; Riding et al.		and Chidiac; Oh and Jang
Bulk diffusion test	$6E^{-15}$ - $5.9E^{-13}$ ($6.46E^{-14}$- $6.35E^{-12}$)	El-Dieb; Tanaka et al.; Piérard et al.; Sohail et al.; Riding et al.	$2E^{-13}$ - $7.97E^{-12}$ (2.15 E^{-12} -$8.58E^{-11}$)	Shafikhani and Chidiac

After cracks are formed on the surface of concrete materials, they could behave as flow channels for harmful substances to pass through, thereby cracked concrete and UHPC materials are expected to have lower resistance to chloride penetration than uncracked materials. Extensive studies have shown that chloride penetration increases rapidly as the crack width increases in normal strength concrete. There also exist two threshold values for crack widths (i.e. threshold crack width and critical crack width) regarding chloride penetration in normal strength concrete (Djerbi et al.), as shown in Figure 1 (a). For crack width below the threshold crack width, cracks could be fully sealed such that the crack does not have an observed effect on the chloride penetration; for crack widths above the threshold crack width but below the critical crack width, chloride penetration through cracks increases almost linearly with increasing crack width; and for crack widths larger than the critical crack width, chloride diffusion through cracks is no longer influenced by crack width since the walls of cracks behave similarly to an external surface directly exposed to the chloride environment. The chloride penetration for the whole specimen increases rapidly with crack widths larger than critical crack width, as shown in Figure 1 (b). After the crack width exceeds the critical value, the chloride diffusion coefficient of the whole specimen increases more rapidly, which could be explained by larger exposure area provided by the crack walls for lateral chloride penetration. For normal strength concrete, the threshold crack width was reported to be 30-100 µm (0.0012 to 0.0039 in.) (Ismail et al.; Şahmaran and Yaman; Djerbi et al.; Jang et al.; Yoon and Schlangen; Wang et al.), and the critical crack width was reported to be in the range of 80-400 µm (0.0031 in. to 0.016 in.) (Aldea et al.; Ismail et al.; Şahmaran and Yaman; Audenaert et al.; Jang et al.; Wang et al.; AL-Ameeri et al.). In addition, increasing crack depth (Marsavina et al.) and crack density (Wang et al.) were also reported to increase the chloride penetration for normal strength concrete. A similar behavior could be expected for cracked UHPC. The threshold and critical crack widths for UHPC could be different from those of normal strength concrete because they are highly related to self-healing behavior and crack patterns.



(a) Effect of crack width on chloride diffusion coefficient through the crack

(b) Effect of crack width on ratio of chloride diffusion coefficient for whole specimens of cracked specimens to that of uncracked specimens

Figure 1 Crack width against chloride diffusion coefficient for concrete (Djerbi et al.)

Currently, only very limited studies focused on the influence of cracks on chloride penetration in UHPC. Although many of the tests did not directly measure the chloride diffusion or migration coefficient, they observed that wider and deeper regions can be penetrated by chloride ions in UHPC with larger crack widths, and higher chloride content was also found in UHPC with larger crack width. Hashimoto et al. showed that after the crack width exceeds 500 µm (0.020 in.), chlorides can penetrate more regions horizontally and vertically in UHPC based on visual observation because self-healing behavior cannot fully fill the cracks to mitigate the effect of cracks on chloride transport properties. Lv et al. measured the chloride content within cracked UHPC dog-bone specimens with maximum crack width in the range of 20 to 30 µm (0.00079 to 0.0012 in.) after exposure to bulk diffusion test for one year and observed that the chloride content was up to three times higher for samples with maximum crack width of 30 µm (0.0012 in.) than that of samples with maximum crack width of 20 µm (0.00079 in.). Ma et al. measured the chloride diffusion coefficient of UHPC samples cracked under different levels of tensile and compressive stresses. They observed that with increasing tensile stress levels from 0 to 50% of the ultimate tensile strength, the chloride diffusion coefficient gradually increased from 1.2 x 10^{-12} to 3.3 x 10^{-12} m^2/s (1.29 x10^{-11} to 3.55 x10^{-11} $ft.^2/s$). As the tensile stress level increased further to 80%, the chloride diffusion coefficient increased rapidly to 14.4 x 10^{-12} m^2/s (1.55 x 10^{-10} $ft.^2/s$). Similarly, as the compressive stress level increased from 0 to 50% of the compressive strength, the chloride diffusion coefficient gradually increased from 1.2 x 10^{-12} to 2.4 x 10^{-12} m^2/s (1.29 to 2.58 x 10^{-11} $ft.^2/s$), while as the compressive stress level further increased to 80%, the chloride diffusion coefficient increased to 3.8 x 10^{-12} m^2/s (4.09 x 10^{-11} $ft.^2/s$).

Although literature suggests that the cracks may influence the chloride penetration resistance of UHPC, the influence of crack width is not quantitatively nor comprehensively studied. The threshold and critical values of crack width regarding chloride penetration are not well-established. To ensure adequate durability of UHPC structures under chloride environments, such as coastal and marine environments, such knowledge is necessary to facilitate establishment of an acceptable crack width limit for design and maintenance practices. This represents a major knowledge gap. In addition, the influence of crack depth and density on the chloride penetration is also not well-understood.

3. Research plan

To fill the knowledge gaps found in literature, a comprehensive study was planned to measure the influence of crack width on the chloride penetration of UHPC and establish an acceptable crack width limit to ensure the durability of UHPC, which is currently being carried out. A total of 189 beam specimens in size of 6 in. × 6 in. × 21 in. will be prepared using three different mix designs of UHPC (including two commercial mixtures and one non-proprietary mixture) and cured for 28 days in a standard moist room at 23 ± 2 °C (73.4 ± 3.6 °F) with relative humidity ≥ 95%. These specimens will be subsequently loaded under flexure according to ASTM C1609-19 with central point bending test to generate single cracks of different targeted crack widths from 0-1000μm (0 to 0.04 in.). Then, cylindrical cores will be extracted from both cracked regions and uncracked regions (for reference) for subsequent RCMT, following a method modified from NT Build 492, as shown in Figure 1. During the RCMT, an external potential of 30 V will be applied on the UHPC specimens for 10 days. After the test, the maximum chloride penetration depth of the cracked UHPC specimens will be quantitively measured by a colorimetric method, and the non-steady chloride migration coefficient of cracked UHPC will be analyzed for each cracked specimens to determine the influence of cracks on the chloride penetration.

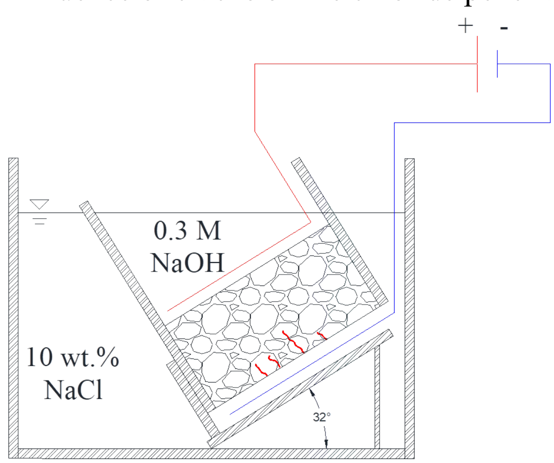


Figure 2 Modified rapid non-steady chloride migration test

4. Conclusion

Due to refined pore structures, UHPC has extremely high resistance to chloride penetration. Under uncracked conditions, chloride penetration within UHPC is one to two orders of magnitude lower compared to normal strength concrete. When cracks forms, they could serve as additional flow channels for chloride penetration, and literature suggests that chloride penetration within UHPC notably increases as crack width increases. However, due to lack of comprehensive and quantitative data, the influence of crack width on the chloride penetration resistance of UHPC is still not well-understood, and acceptable crack width limit of UHPC for design and maintenance practices has not been established. To fill this knowledge gap, a comprehensive study to measure the influence of crack width on the chloride penetration of UHPC and establish an acceptable crack width limit to ensure the durability of UHPC is currently being carried out.

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