Cement and Concrete Composites 84 (2017) 175–187

Contents lists available at ScienceDirect

Cement and Concrete Composites

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

Effect of chloride content on mechanical properties of ultra high performance concrete

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ARTICLE INFO

Article history:
Received 7 March 2017
Received in revised form
28 July 2017
Accepted 10 September 2017
Available online 14 September 2017

Keywords:
Chloride ions
Corrosion
Ultra high performance concrete
Steel fiber
Mechanical properties

ABSTRACT

Experimental results on the effects of chloride content of ultra high performance concrete (UHPC) are presented. The experimental variables are the amount of sodium chloride, ranging from zero to 3.0% per cement weight, and matrix strength, including normal mortar and high strength mortar. Sodium chloride is directly mixed with cement matrix in order to simulate harsh environments by promoting the corrosions of fibers and matrix. The effects of chloride content are evaluated in terms of visual observation, electrical resistivity change, compressive strength, bending strength, and dynamic Young's modulus. The experimental results show that UHPC has the superior capability to resist chloride ions due to its dense microstructures, which prevent the growth of rust crystals. Furthermore, the experimental findings suggest that the potentials for corrosion of steel fibers and for corrosion-induced matrix cracking are inconsequential in UHPC even if chloride ions penetrate into UHPC.

1. Introduction and motivation

Ultra high performance concrete (UHPC) is one of the most advanced cement based construction materials, having various engineering merits including compressive strength higher than 150 MPa [1], impact resistance [2] and high durability [3]. Based on the optimized particle packing design of the solid constituents, UHPC possesses a relatively small number of discontinuous pores and has a denser microstructure compared to those of conventional high performance concrete (HPC) or normal concrete, which results in high durability. The enhanced durability of UHPC allows innovative designs with longer service life and slender elements even under harsh environments. This concrete may incorporate steel fibers to overcome its brittleness, which may also be referred to as of 'ultra-high performance, fiber reinforced concrete (UHP-FRC or UHPFRC)' depending on the researchers to emphasize the incorporation of fibers [4].

Since its first structural application in the pedestrian bridge over the Magog River in Sherbrooke, Quebec, Canada in July 1997, and based on the aforementioned engineering advantages, UHPC has been used in diverse applications carried out world wide in the last two decades. Sritharan [5] asserted that UHPC's enhanced durability properties have stimulated broad applications in areas such as bridges, seismic columns and piles. For example, due to their high resistance against freeze-thaw cycles in an aggressive environment, in addition to their mechanical advantages, precast, prestressed UHPC beams and girders were used for a cooling tower at the Cattenom Nuclear Power Plant in France in 1999 [6]. Furthermore, structural connections using UHPC are the most popular applications in North America due to the high durability and bond strength of these materials, especially for the purpose of accelerated bridge construction [7].

In order to quantify UHPC's outstanding durability, various attempts have been carried out. For example, by investigating the change of relative dynamic modulus, Gao et al. [8] reported a 100% freeze-thaw resistance of UHPC even after 800 freeze-thaw cycles. Roux et al. [9] noted that the chloride diffusion coefficient of UHPC is 2.0×10^{-14} m^2/s, which is 30–600 times smaller than those of HPC and normal concrete. Schmidt and Fehling [10] reported that the total depths of penetration of chloride ions were 1 mm, 8 mm and 23 mm for UHPC, HPC and normal concrete, respectively, after a six hour quick-migration test with an applied voltage of 40 V. Ghafari et al. [11] presented that the cracking time in UHPC induced by accelerated corrosion was double compared with that of HPC. This outstanding durability of UHPC was originated from very-dense microstructures, which obtained by incorporation of low

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http://dx.doi.org/10.1016/j.cemconcomp.2017.09.006
0958-9465/

water-to-binder ratio, the use of nano-sized powders including silica fume and silica powder, and even some cases, heat curing [12,13]. The total volume of pores and their size distribution in the UHPC were much lower and smaller compared with conventional concrete [14]. Pyo and Kim [1] reported that total porosity of hardened UHPC ranges from 1 to 3 vol% under normal curing condition depending on various mix designs and steel fiber content; these values were about 5–10 times smaller than those of HPC and normal concrete.

Even though there have been various studies conducted to evaluate this material's outstanding durability characteristics, the effects of the corrosion of steel fiber on the mechanical properties of UHPC have seldom been investigated. An increase in chloride ion concentration in the cement matrix is one of the most detrimental durability factors because it accelerates initiation of corrosion in the metallic reinforcements [15]. The corrosion in the reinforcements causes spalling and cracking of the concrete, and this creates additional spaces for chloride to penetrate. It is generally acknowledged that blocking the paths of chloride penetration by densifying the microstructures of the concrete can be a fundamental solution to enhance the durability of concrete [16]. As mentioned above, it is well known that the diffusion speeds of chloride ions in UHPC, in terms of penetration depth, are significantly lower than those speeds in HPC and conventional concrete. However, the covering depth for steel fiber distributed randomly in the matrix was also thin, and thus fibers in the vicinity of the exposed surfaces can be corroded [17]. Similar to the corrosion of a steel reinforcement bar, the corrosion of steel fiber may accelerate the degradation of the durability of structures. Moreover, the rust of corroded steel fibers on concrete structures can lead to a negative impression from an aesthetic point of view.

Scheydt and Muller [14] mentioned that, although the UHPC has very-dense microstructures, strong deformation induced by autogenous shrinkage led microcrack where might be a pathway for chloride ion. From this reason, for the UHPC exposed to NaCl solution for 16 months, the chloride ion concentration on the surface area, i.e., 1–2 mm depth, was higher than 2% per binder weight, which is a critical threshold for conventional concrete. Hashimoto et al. [18] studied the effect of chloride penetration on initially-cracked UHPC and found that the corrosion of steel fiber had degraded in tensile softening behavior while bonding stress was not reduced. In the author's previous study [19], it was reported that steel fiber in fiber-reinforced high performance concrete (90 MPa at 28 days of curing) was corroded by repetitive chloride attack and that the mechanical properties, including the post cracking strength, strain capacity, and peak toughness, were degraded by this corrosion. Note that the strain capacity meant the strain value at the maximum strength of the materials. However, studies in the literature on critical chloride content for UHPC on corrosion of steel fiber, considering mechanical properties and durability, can hardly be found. Based on extensive research on the effects of chloride ions on concrete durability, range from 0.3 to 2.0% of chloride per binder weight is known to be a critical value causing initiation of corrosion of reinforcement in conventional concrete structures [20,21]. The range for UHPC may be different from this range.

The objective of this research is to evaluate the effects of chloride concentration in three different strength levels of the matrix, namely, UHPC, high strength mortar (HSM), and normal mortar (NM). It should be noted that, to evaluate the critical chloride content in concrete, various test methods have been applied in extensive research studies; these methods include low diffusion by immersing the specimens in chloride solution, accelerated migration using electrical charges, and simple mixing of the chloride sources in fresh mixtures [22]. Among these, direct mixing was adopted in the present study. Three different sodium chloride levels of zero, 1.5% and 3.0% per cement weight were directly mixed with cement matrix. Various experiments were carried out for the characterization, including a compressive strength test, a third-point bending test, and evaluation of dynamic Young's modulus and electrical resistivity change. To the best of the authors' knowledge, there is a lack of published results regarding the effects of chloride content on the mechanical properties of UHPC; this was the primary motivation for the work described in this paper.

Table 1
Mix design of mortars and UHPC (proportion by weight).

Series	Cement	Silica Fume	Silica Powder	Water	NaCl (%)	Cl^- Content		Superpla-sticizer†	Steel fiber (Vf)§	Sand I*	Sand II**
						(% cw)[a]	(% bw)[b]				
NM-0	1	–	–	0.5	0	0	0	–	2	–	2.41
NMnf-0	1	–	–	0.5	0	0	0	–	–	–	2.5
NM-1.5	1	–	–	0.5	1.5	0.91	0.91	–	2	–	2.41
NMnf-1.5	1	–	–	0.5	1.5	0.91	0.91	–	–	–	2.5
NM-3	1	–	–	0.5	3	1.81	1.81	–	2	–	2.41
NMnf-3	1	–	–	0.5	3	1.81	1.81	–	–	–	2.5
HSM-0	1	–	–	0.3	0	0	0	0.0025	2	–	1.45
HSMnf-0	1	–	–	0.3	0	0	0	0.0025	–	–	1.5
HSM-1.5	1	–	–	0.3	1.5	0.91	0.91	0.0025	2	–	1.45
HSMnf-1.5	1	–	–	0.3	1.5	0.91	0.91	0.0025	–	–	1.5
HSM-3	1	–	–	0.3	3	1.81	1.81	0.0025	2	–	1.45
HSMnf-3	1	–	–	0.3	3	1.81	1.81	0.0025	–	–	1.5
UHPC-0	1	0.25	0.25	0.22	0	0	0	0.009	2	0.3	0.7
UHPCnf-0	1	0.25	0.25	0.22	0	0	0	0.009	–	0.32	0.74
UHPC-1.5	1	0.25	0.25	0.22	1.5	0.91	0.72	0.009	2	0.3	0.7
UHPCnf-1.5	1	0.25	0.25	0.22	1.5	0.91	0.72	0.009	–	0.32	0.74
UHPC-3	1	0.25	0.25	0.22	3	1.81	1.45	0.009	2	0.3	0.7
UHPCnf-3	1	0.25	0.25	0.22	3	1.81	1.45	0.009	–	0.32	0.74

†Solid content.
§volume fraction.
*Silica sand (median grain size = 0.15 mm).
**Silica sand (median grain size = 0.53 mm).
[a,b] percentages of chloride ion by weight of cement and binder.