

Ultra-high Durable Concrete: A Way towards Safe and Durable Structures

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Abstract

Durability of construction and building materials is a pivotal issue for any civil engineering project in the context of sustainable development. In this regard, developing any material with improved durability characteristics would be of great significance particularly for infrastructures encountered aggressive environments. Ultra-high performance concrete (UHPC) is one of this promising materials, as a high-tech self-compacting composite material, which shows advanced characteristics such as self-compactness, compressive strength higher than 150 MPa, and exceptional durability performances compared to other kinds of concrete. This material offers variety of sustainable applications. It enables designers to have slim sections with higher strength, ductility and durability for applications such as shell structures, interior and exterior architectural and structural elements in any shape and texture even in high-rise structures and aggressive environments. In this paper, the durability of a specific composition of UHPC was studied. The dense matrix of the designed UHPC exhibited ultra-high durability performance through long-term and intense carbonation and chloride-ion migration tests. As results demonstrated, even after 191 days, no carbonation depth was observed. No chloride depth was also detected after 14 days of being in the chloride solution with maximum voltage of 60 V.

Introduction

It was in 1995 that the first UHPC composition was introduced under the title of Reactive powder concrete (RPC) [1]. Afterwards, parallel investigations were carried out resulting in Ductal ® as one of the known commercially available types of UHPC [2]. The first application of this material was the 60-meter span Sherbrooke footbridge in Quebec, built in 1997 [3]. Some other applications of UHPC are provided in **Table 1**. Beside that, some of structural and architectural projects made of UHPC, particularly in aggressive environments, are shown in **Figure 1**.

Table 1: First applications of UHPC.

Project	year	Location	Reference
Sherbrooke Pedestrian Overpass, Quebec, Precast, post-tensioned space truss, 60 meter span	1997	Canada	[3]

World first industrial applications, Cattenom and Civaux power plants beams by BSI® and Ductal®	1998	France	[4]
world first UHPC road bridges on the Bourg-lès-Valence bypass in France's Drôme region	2001	France	[5]
Sunyudo (Peace) Footbridge on Han river in Seoul.	2002	South Korea	[6]
Tahara (Aichi) Footbridge	2004	Japan	[7]
Mars Hill Bridge, Wapello County, IA Three 1.1- m deep bulb-tee beams with 33.5 m Span	2006	United States	[8]
Highway 11 over CN Railway at Rainy Lake, Ontario, Joints between precast panels and shear connector panels	2006	Canada	[9]



a)



b)



c)



d)

Figure 1: a) Sherbrooke Pedestrian Overpass; b) Delicate veil façade made of Ductal®, Jean Bouin stadium in Paris [12]; c) Beams and girders at Cattenom electric power station, Lorraine, France [13]; d) Troughs for a wastewater treatment plant, Edmonton, Canada [14].

The main advantages of UHPC as a high-tech architectural and structural material include:

- Installation process of lightweight UHPC members, including handling and transportation, would be more convenient and safer.
- By elimination of a significant part of the reinforcement bars and stirrups, considerable human labors, supervision tasks and quality control activities could be decreased beside reduction of permanent load resulting in lighter structures [1].
- Improved tensile behavior compared to other types of concrete resulted from internal fibers [15]
- Due to its higher strength rather than normal concretes, UHPC could be recycled at the end of its life-cycle as high-quality aggregates for new generation of concretes resulting in lower extraction of natural resources beside enhanced durability, which all cause longer service life [16, 17].
- Extraordinary slim designs as the result of high strength and ductility [2].

Constituent Materials

Type I Portland cement (CEM I 42.5R according to EN 197-1 [18]) and silica fume (SF) from Elkem Microsilica® MS 940-U with an average particle size of 9.3µm and 0.15µm and fly ash (FA) provided from Pego thermal power plant, a Portuguese coal based one, were used in this research. A siliceous micro-sand, delivered from Rio Maior in Portugal, with a maximum size close to 1mm was also applied. Some physical properties and chemical analysis of the materials are reported in **Table 2**. A commercial superplasticizer (SP), MasterGlenium SKY 526®, with 30% of solid content was also used. The SP (**Table 3**) is a carboxylic ether polymer based as a brown liquid with properties according to the definitions and requirements of Standard EN 934-2, established for European concrete admixtures [19]. Micro steel fiber applied here has a length/diameter ratio of 65 with 2600MPa of tensile strength. More information regarding the constituent materials, their processing and percentages is beyond the aim of this paper, which is studying the durability of the material, and could be found in other publications by authors.

Table 2: Chemical and physical compositions of cement, SF and FA.

Components	CEM 42.5R	MS 940-U	FA
SiO ₂	19.79	> 90	48.02
Al ₂ O ₃	4.37	-	29.59
Fe ₂ O ₃	3.52	-	4.48
CaO	63.09	-	4.65
MgO	1.67	-	1.44
SO ₃	2.82	-	0.49
Cl ⁻	0.04	-	-
loss of ignition	3.01	< 3	3.0
Blaine surface area (cm ² /g)	4228	150000-300000	3848
Specific gravity (g/cm ³)	3.1	2.2-2.3	2.4

Table 3: Technical characteristics of Superplasticizer MasterGlenium SKY 526®.

Relative density (20°C)	1.07±0.02 g/cm ³
pH	6.0±1.0
Chloride ion content	≤ 0.1%
Solid content	30%

Mixing procedure and sample preparation

An effective low-energy mixing procedure was applied during this research including adding 70% of mixing water to the dry material and mixing for 3 minutes. It was followed by adding the optimum dosage of SP and mixing for at least 4 minutes, 6 minutes seems preferable based on visual assessment, and finally adding the remaining 30% of water and blending for an extra 6 minutes to reach a steady-state consistency. The fibers were added at the end of this stage with continuing the mixing for another one minute [20].

After mixing, the flowability of the fresh concrete evaluated by means of flow table for mortars according to EN 1015-3 [21] (See **Figure 2**). Once a steady state of flow was observed, after rising up the mini-slump cone, two perpendicular dimensions of expanded concrete were registered. Since self-compactness of UHPC is a prerequisite, the average of these measurements, without dropping the table, was registered as criteria for flowability. Based on this method, the material exhibited 19 cm of flow diameter in average.



Figure 2: Flow table test apparatus (a) and flow diameter after test (b).

The casting of all specimens was performed on a vibration table. They were allowed to remain on vibration table for 20 seconds. Afterwards, their surfaces were smoothed with a trowel and were covered with a thin plastic sheet to prevent any water loss from the exposed surface. After 24 hours the specimens were demolded and were placed in $20\pm 2^\circ\text{C}$ water bath until the day of tests. This curing method was named as normal curing method (NC). 28-day compressive strength of three cubes with dimensions of $50\times 50\times 50\text{ mm}^3$ were 152 MPa in average with standard deviation of 4.2.

Chloride ion migration

The first test performed in this research to evaluate the durability of the UHPC is accelerated non-steady-state chloride migration test to find out its diffusion coefficient based on a Portuguese specification [22]. For this aim, three cylindrical specimens with diameter and thickness of 10cm and 5cm respectively were cut from 28-days-NC cylinders having 20cm height and 10cm diameter. Then the surface-dried samples were placed in a vacuum chamber with a pressure of 1-5 kPa for 3 hours. In the following step, the chamber was filled with a solution of $\text{Ca}(\text{OH})_2$ while the vacuum pump was working. All parts of the samples should be immersed completely in the solution. Afterwards, the air valve was opened to let the air enter into the chamber. The specimens were remained in this situation for more 18 ± 2 hours. The next step was to prepare cathodic solution with a ratio of 100g NaCl in 900g of water and anode solution with a ratio of approximately 12g NaOH in 1 liter of water. The cathode reservoir was filled with NaCl solution. The specimens then were fixed tightly with two stainless steel clamps in silicon tubes in order to prevent any leakage of NaOH or NaCl to the opposite side. The test setup is shown in **Figure 3**.



Figure 3: Chloride-ion- migration test setup.

After the specimens were placed in the cathodic reservoir, the anode solution was poured on the top of silicon tubes and the power supply was connected with a primary voltage of 30V. The initial current flow was $264\mu\text{A}$ in average which is lower than 5mA indicating high resistivity of the material to current flow. According to the Portuguese norm [22] the final voltage as well as test duration were

adjusted to 60 V and 96 hours respectively due to second average initial current flow of 661 μA which was still lower than 10 mA. After the adjustments, the cathodic container was covered with a plastic sheet in order to prevent fast water lose due to evaporation. After 96 hours one of the samples was washed, dried and splitted into two pieces. The final step was to spray AgNO_3 solution to the broken surface of specimen to evaluate the chloride ion penetration depth. According to **Figure 4** it was observed that however the steel fibers within UHPC seems to have negative impacts through providing paths to complete an electric circuit, this did not happen and no penetration depth after 96 hours was observed as a result of dens matrix in UHPC. With respect to this result, it was decided to continue the test for more 10 days. After totally 14 days, the two other specimens were divided into two sections and the solution of AgNO_3 was sprayed on their surfaces. The results were the same as the previous sample. Not only no penetration depth was observed but also the corrosion of steel fibers in the surface was not a matter of concern and seemed in very surface of the specimens (See **Figure 4**). In addition, the color of cathodic solution in the reservoir had not been changed too much as the result of steel fiber corrosion as shown in **Figure 5**.



Figure 4: Corrosion of specimens' surface.



Figure 5: The cathodic solution at the beginning (a) and after 14 days in 60 V (b).

The diffusion coefficient based on this test method is determined using the following equation:

$$D = \frac{0.0239(273 + T) \times L}{(U - 2) \times t} \left[x_d - 0.0238 \sqrt{\frac{(273 + T) \times L \times x_d}{U - 2}} \right] \quad \text{Eq.1}$$

where D is the diffusion coefficient in $10^{-12} \text{ m}^2/\text{s}$, T is the average value of initial and final temperature in anolyte in $^{\circ}\text{C}$, U is the absolute value of the applied voltage in V, L is the thickness of the specimen in mm, x_d is the average of penetration depth in mm and t is the duration of the test in hours. Since just the exterior face of the samples are contaminated with chloride solution without any penetration

depth, the thickness of the surface was measured using ImageJ software [23] and considered as penetration depth. Even with this consideration, the average of penetration depth in eight measured points are 0.096 mm, which correspond to a very small negative diffusion coefficient value extremely close to zero (**Figure 6**).

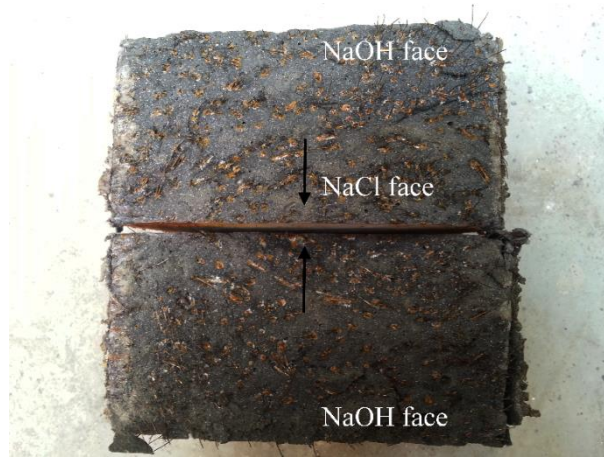


Figure 6: A broken and AgNO₃-sprayed specimen after 14 days of chloride migration test in 60V.

Carbonation

The carbonation test described here is in accordance with European technical specification for accelerated carbonation test [24]. The prismatic specimens with dimensions of 4cm x 4cm x 16 cm of 28 days NC were used for this test. After curing period, the samples were conditioned in laboratory (20±2°C and 55±5 % RH) for 14 days. Then, all faces of the prism except two faces were sealed using melted paraffin and were placed in carbonation chamber with (4±0.5)% CO₂ concentration and temperature of (20±2)°C and (55±5)% RH for at least 70 days. A phenolphthalein solution was used as the indicator and was sprayed on the crashed surface of the specimens. The un-carbonated parts of concrete remain in purple color as a measure to determine the depth of carbonation. Since, no carbonation depth was observed as shown in **Figure 7**, the test was continued until 77, 103, 144 and 191 days from starting date of placing the specimens in the carbonation chamber. In each test age, a 5 cm-section of the prim was broken and the end surface of the remained prism was sealed again and was returned to the carbonation chamber.

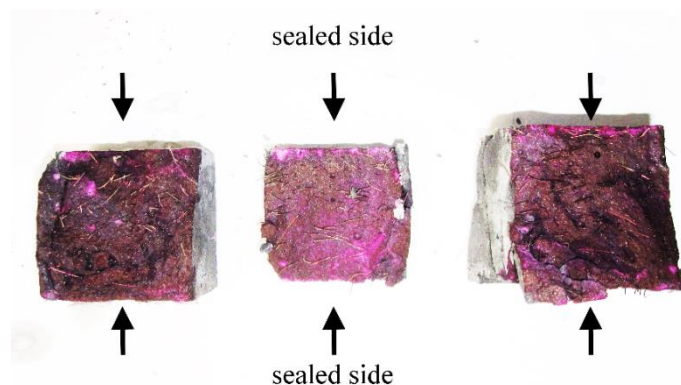


Figure 7: Carbonated specimens after 70 days.

As can be seen from **Figure 7**, a very thin layer on the right and left surface of the samples is carbonated. The other samples with higher exposure time in carbonation chamber also did not demonstrate more carbonation depth as depicted in **Figure 8** due to dense matrix of UHPC indicating amazing durability of the developed material.

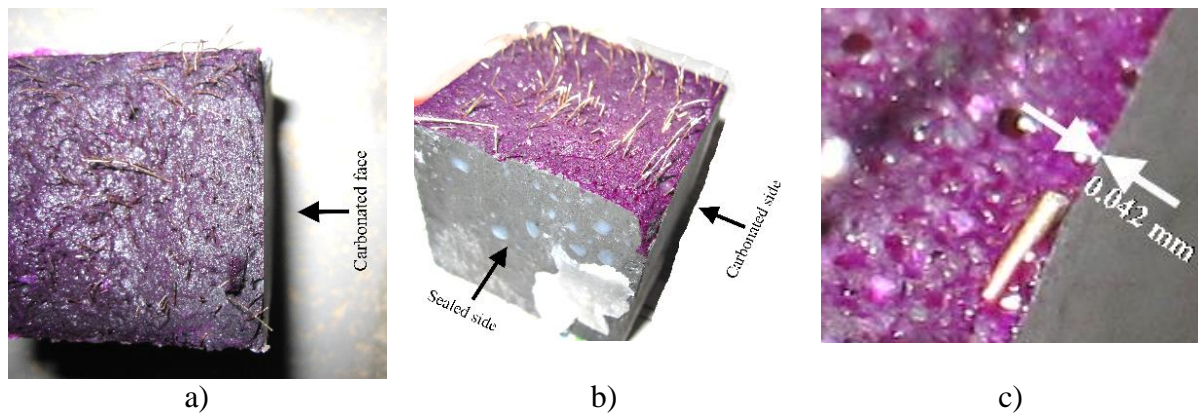


Figure 8: Carbonated specimens after 103 days (a) and 144 day (b) and the carbonated surface thickness after 191 days (c).

By measuring the thickness of the carbonated surface by using ImageJ software, it is $42\mu\text{m}$ after 191 days of carbonation as shown in **Figure 8 C**.

Conclusion

Durability of one type of UHPC was evaluated in this paper through chloride ion migration and carbonation tests. After 14 days of chloride test in its maximum applied voltage and 191 days of conditioning in carbonation chamber, no penetration depth was detected in both tests. This phenomenon is a result of very dense matrix of the UHPC which itself resulted from very fine used particles as well as very low water/binder ratio (less than $0.2 w_t$). Furthermore, it was found that steel fibers, due to their short and discontinues length, do not affect the material's resistance to chloride attack through providing paths to complete an electric circuit. In addition, they were just rusted very slightly at the surface of the samples and not in depth. These all, would be of great significance regarding serviceability, safety and durability of structures particularly in aggressive environments such as coastal projects.

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