

## LONG TERM CARBONATION OF UHPC

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### Abstract

The durability of a concrete structure is based on its capability to resist physical and chemical conditions to which it is exposed. Carbonation is one of the two processes aiming into reinforcement corrosion. The ease to carbonate depends on the accessible porosity and of the binding capacity of the cement phases towards the carbon dioxide gas. The use of a high performance concrete contributes to the two properties due to its reduced porosity and higher cement content proportion. This work presents medium term (16 years) performance of the UHPC called CRC “composite reinforced concrete” made originally by Aarlborg Portland with high content in cement, silica fume and low water/cement ratio. The behavior shows that the carbonation has been less than 1mm equally than the concrete was in a younger state. That is, the CRC seems almost immune to the advance of carbonation which supposes the maintenance of the passivity of the reinforcements and of the added metallic fibers.

### Résumé

La durabilité d'une structure en béton repose sur son aptitude à résister aux sollicitations physiques et chimiques auxquelles il est exposé. La carbonatation est un des deux principaux mécanismes qui entraîne la corrosion des armatures. La progression de la carbonatation dépend de la porosité accessible et de la capacité des hydrates à fixer le dioxyde de carbone. L'utilisation d'un béton à hautes performances permet de renforcer ces deux propriétés en raison d'une plus faible porosité et d'un dosage en ciment plus élevé. Cet article présente le comportement à une échéance de 16 ans d'un BFUP, de type CRC « Composite Reinforced concrete », développé à l'origine par Aarlborg Portland et contenant des dosages élevés en ciment et fumée de silice, ainsi qu'un faible rapport Eau/Ciment. Les résultats montrent que la profondeur de carbonatation est inférieure à 1 mm et identique à celle du béton au plus jeune âge. Le CRC apparaît comme presque immunisé contre l'avancement de la carbonatation.

## 1. INTRODUCTION

The term High Resistance Concrete, HRC has been generally applied to concretes with mechanical strengths higher than 50 MPa. These high resistances can be achieved by means of reducing the w/c below 0.4 (by making use of superplasticizers) and adding a pozzolanic material (mainly silica fume), having the rest of the mix proportions to be adjusted

accordingly. With the addition of fine silica fume or other fine blending materials, the strength increases due the filling effect of the powder in addition to its pozzolanic activity. For being above 100 MPa of strength [1] besides the mineral addition, the cement content has to be increased which enables to reduce even more the w/c ratio. The size of the aggregates has to be decreased in accordance to the maximum compacity.

The superior strength and lower porosity enabled to evolve from the concept of High Resistance Concrete to that of High Performance Concrete, HPC and to that of Ultra-HPC that was applied for the concretes with strength values above 120-150 MPa [2]. These concretes, in which the addition of fibers was necessary to compensate the microcracking originated from the self-dessication produced due to the low w/c ratio, encountered a wider concept including much better durability [3].

The longer durability was thought to be based in the lower porosity which was assumed to make almost immune the concretes to external attack. However, it was verified soon that the durability is a too wide concept which cannot be generalized and that cannot be ascribed indiscriminately to be similar for all HPC's [4-5]. Each type of concrete should be tested for the resistance to each type of attack and a ranking of life expectancy of these concretes should be established in the different environments.

### **1.1 Composition of CRC**

Compact reinforced Concrete, CRC is a very particular type of fiber reinforced concrete which was developed in 1986 by Aarlborg Portland in Denmark [3, 6-11] that provides high compressive strengths of 150 to 400 N/mm<sup>2</sup> with remarkable ductility and which resists the penetration of any liquid or aggressive gas.

CRC is typically used in combination with steel fibers and conventional rebars which is based in a mix proportioning that is different of the standard concretes. Thus, CRC is based in: a) high volume of cement, sometimes with limited maximum grain size of 10 µm, b) large amounts (until about 30 %) of ultra-fine particles, typically in the range of 50 Å- 0.5 µm and sometimes fly-ash with maximum size of 10 µm, c) very low w/c ratios (usually below 0.2), d) large amounts of superplasticizers (about 1-2 % by weight of cement), e) from low size aggregates to ultrafine quartz particles and f) different proportions (which may reach 6% in volume) of small fibers. In spite of the low w/c ratios and the presence of fibers, CRC exhibit high slump values. The matrix is fluid and cohesive and responds well to the compaction. Other UHPC have been developed in the last decade [2, 12].

### **1.2 Properties of CRC**

The first main characteristic is the high mechanical strengths in compression in the range of 150-800 MPa. The incorporation of small size fibers improves also very much the ductility of the material with flexural strengths ranging from tenths of 120 MPa to tenths of 400 MPa. This extreme ductility is achieved by using, in addition to the fibers, very strong aggregates, much higher amounts of reinforcement or a steel type of much better quality than the conventional one.

Apart from the enhancement of the mechanical properties of UHPC the properties dealing with the durability are also very important. Thus, the resistance to chemical attack, to frost and to the penetration of aggressive substances until the reinforcement, is very much improved. In a study involving one of present authors made around 20 years ago [4, 6, 13] when the material was still in its development phase, this better behavior was found to be

based in: a) a dramatic reduction of porosity which is composed only of microcapillar or gel pores, b) a reduction or complete consumption of portlandite and c) a large amount of unhydrated particles.

The almost complete lack of capillary pores together with the better packing of particles and the large quantities of unhydrated cement, appeared to make unfeasible the presence of evaporable or free water, and in consequence makes the material almost immune to any type of aggression needing water for its progression. The very low porosity reduced also very significantly the gas permeability. Regarding the protection of the reinforcements, in spite of the pozzolanic combination of the portlandite, the rebars exhibited a perfect passive behavior. This passivity has been only disrupted when the chlorides were forced to penetrate until them by means of applying an external electrical current [2, 6]. When depassivated, the steel rods corrode at the same corrosion rates than in conventional concretes. Regarding carbonation resistance, the results at that preliminary stage showed the almost impenetrability of the carbon dioxide gas because any sign of neutralization could be found in spite of placing the specimens in atmospheres with 100 % CO<sub>2</sub> concentration during 3 months.

In present paper are presented results of the carbonation resistance of CRC after being exposed during around 16 years at the atmosphere indoors and outdoors, in the garden of the Institute exposed to rain or any climatic event. The results show that the CRC has been carbonated only in the external surface but the phenolphthalein exhibits the red color just when scratching the material less than one mm from the surface.

## 2. EXPERIMENTAL

As it was mentioned, CRC is obtained by mixing about 900 kg of cement and 20-25 % microsilica with w/c ratios down to 0.15 using appropriate superplasticizers. Steel fibres in a length of 12 mm and of 0.4 mm in diameter are also incorporated about 6 % in volume in order to provide ductility in the structural behavior. The main reinforcements are of high strength steel as compressive strength between 150-400 MPa is typically reached.

For the sake of present long term study, beams under permanent load were prepared by Aarlborg for the European Project MINISTRUCT [7] to obtain flexural cracks of 40 cm in length, 5 cm in height and 10 cm in width were used for these tests (figures 1 and 2). The main reinforcement had 1 cm of cover. The load deformation is introduced with a frame by submitting the beams to a constant load of 4-point bending, as shown in figure 1 and 2.

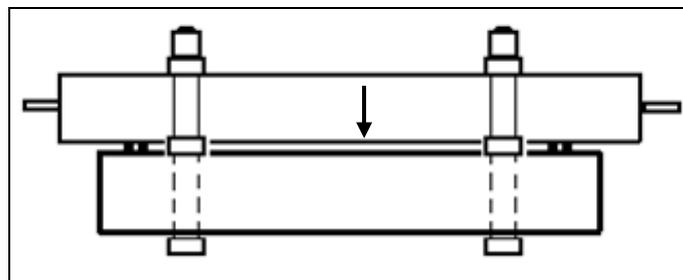


Figure 1: Mounting rig, where the specimens are loaded to a constant center deflection before being exposed outdoors to carbonation.

Deflections of 0.2, 1 and 2 mm. corresponding to bending stresses of 10, 30 and 55 MPa were induced, in order to produce microcraks that at the maximum deflection induced visible

cracks of 0.05 and 0.1 mm. The specimens studied (figure 2) are 16 years old and have been held indoors and at the open air exposed to the classical climatic events.



Figure 2: 16-year-long exposure to environment

### 2.1 Tests performed

On these specimens the tests that have been performed are:

- Corrosion rate measurements (corrosion potential, concrete resistivity and polarization resistance method) by means of the portable corrosion rate meter GECOR 08 [14] whose probe has a guard ring and uses the “modulated confinement of the current” for the determination of the corrosion rate, corrosion potential and resistivity of the concrete.
- Carbonation depth through the use of phenolphthalein indicator.
- XRD in the powder scratched from the surface

### 3. RESULTS

The corrosion measurements made give the representative results shown in Table 1 for specimens held indoors and outdoors. They indicate that the bars continue in a passive state because the  $I_{\text{corr}}$  values are  $< 0.1 \mu\text{A}/\text{cm}^2$  [15] just in the lower limit of measurement of the corrosion rate meter and the values of  $E_{\text{corr}}$  are in a range of low risk [16]. The resistivity is higher in the specimen maintained indoors.

Table 1: Results of Corrosion measurements

	CRC 1 (outdoors)	CRC 5 (indoors)
$E_{\text{corr}}$ (mV)	-66	-39
$I_{\text{corr}}$ ( $\mu\text{A}/\text{cm}^2$ )	0.001	0.001
Resistivity ( $\text{k}\Omega\text{cm}$ )	1880	3600



Figure 3: Aspect of one specimen after 16 years exposed outdoors. Right: a detail with the protruding surface fibers which are slight corroded

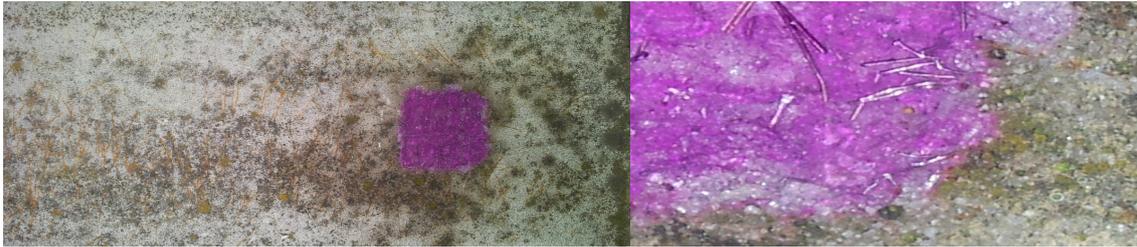


Figure 4: Phenolphthalein test which shows that below less than 1 mm from the external surface the concrete remains alkaline and the fibers exhibit (right part) free of any rust.

The aspect of one of the specimens held outdoors during 16 years is depicted by figure 3. Aspect of the fibres that protrude at the concrete surface are presented in the right part of the figure. The fibres are slightly corroded although any sign of surface spalling or surface disruption could be noticed.

Regarding the carbonation tests by using phenolphthalein, Phn., indicator, they show that the surface was carbonated as it resulted colorless when applying the Phn., however when scratching just less than 1 mm of the surface layer the color is red as shown in figure 4 and the fibers were completely clean without signs of corrosion (right part of figure 4).

The aspect of the beams held indoors is shown in figure 5. The corrosion of the superficial fibers is less pronounced. Regarding the carbonation the result obtained is the same: the surface is carbonated but as soon as the surface is scratched, the material shows to remain alkaline and the fibers are clean of rust (figure 6).

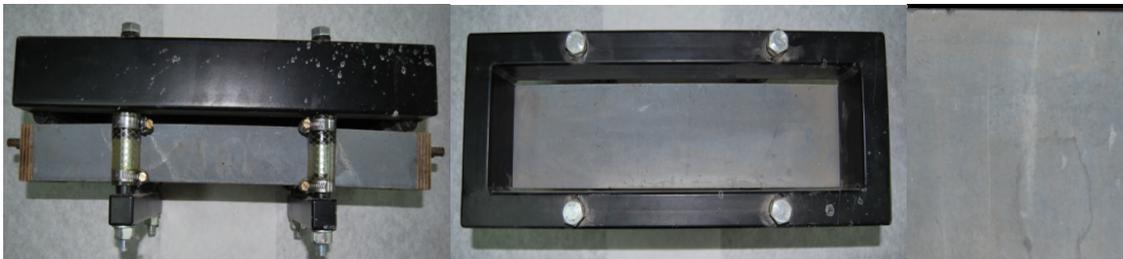


Figure 5: Aspect of the beams held in indoors conditions during 16 years. In the right part is shown the microcraks induced in the top part of the beam due to the bending.

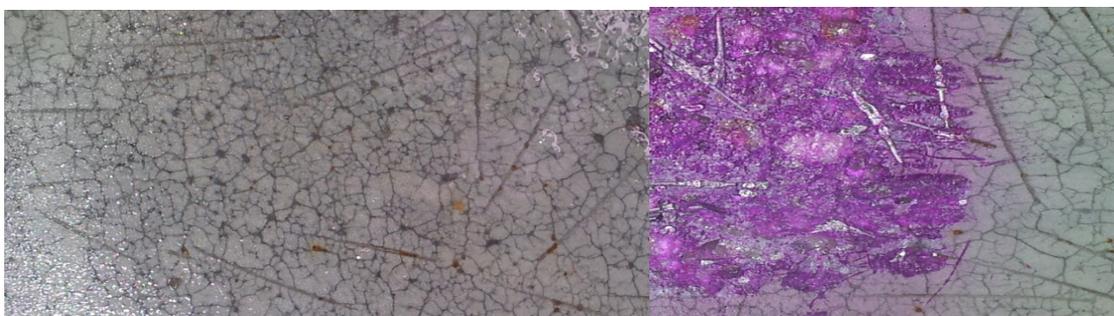


Figure 6: Phenolphthalein test which shows that below less than 1 mm from the external surface the concrete remains alkaline and the fibers exhibit (right part) free of any rust.

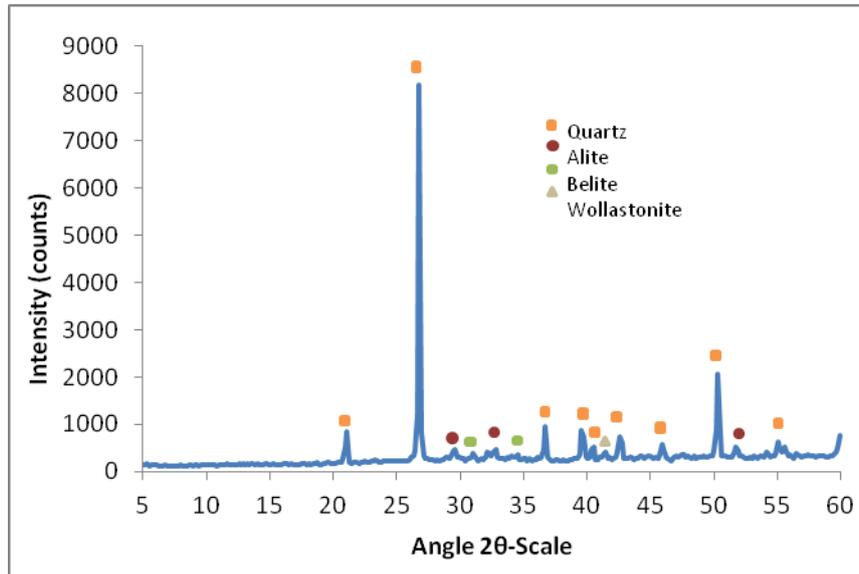


Figure 7: XR Diffractogram of the CRC beam held outdoors

The DRX performed on the powder obtained from the scratching around less than 1mm of the surface of the beam held outdoors indicates as given in figure 7: a) the presence quartz from the aggregates, b) of anhydrous particles and c) has not noticed the presence of calcium carbonate.

#### 4. DISCUSSION

The results obtained of absence of corrosion in the reinforcing bars with only 1 cm of cover depth can be justified because the material remains alkaline from around 1 mm cover depth, either maintained indoors or outdoors. The CRC seems to preserve the alkalinity for at least the period tested and then, it seems that it will be able to maintain much longer. This alkalinity also maintain passive the added fibers and their corrosion in the concrete surface do not induce particular defects. The aesthetic impression of the corroded surface fibers remains to be solved although it does not represent a risk.

In the preliminary studies performed there were several open questions about the long term performance of CRC. In particular related to the carbonation resistance, it was questioned the impact on how the pozzolanic reaction of the high proportion of silica fume is going to influence the pH value of the pore solution and also how the cracks could facilitate the carbonation due to the low cover depth at which the reinforcement is placed. Present results seem to confirm the most optimistic assumptions that the cracks do not enable depassivation of the bars, and that the material keep the alkalinity in a value high enough to give the red color with the Phenolftalein, from around 1 mm in cover depth.

The fact that no carbonates were detected in the XR diffractogram is even more interesting because enables to deduce that the carbonation is produced only in the pore solution but that carbonation does not affects the CSH gel as in standard concretes, result which confirms that there is almost lack of capillary water and then, this absence prevents the CSH to dissolve and decalcify, at the partial pressure of the atmospheric carbon dioxide.

It can then be deduced that, as predicted, the CRC is a material with so low porosity that the carbon dioxide gas almost does not diffuse inside and that this low porosity also explains the lack of capillary water to allow the penetration of the carbonation front.

## 5. CONCLUSIONS

The conclusions that can be deduced indicate that Compact reinforced composite (CRC) having around 6% of metallic fibers, high proportions (20-25 %) of microsilica and low w/c ratios (0.2-0.15),

- Is remaining very resistant to the penetration of the carbonation front after 16 years of been exposed indoors and outdoors in Madrid climate.
- The results also show that the reinforcing bars remain in passive state in spite of the microcracks induced by the deflections imposed by a frame at constant load.
- The corrosion of the fibers protruding from the concrete is very slight not inducing surface disruptions or important defects. The fully embedded fibers remain passive at 1 mm of cover depth.

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