DURABILITY EVALUATION OF DIFFERENT TYPES OF UHPC

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Abstract

Ultra-high Performance Concrete (UHPC) offers the possibility to design exciting and innovative structures. This concrete type being relatively new in Belgium, some properties have still to be validated, more specifically for mixes made of local materials.

In order to evaluate the performances of UHPC exposed to different aggressive environments, the water porosity and the gas permeability of the concrete were measured and following accelerated tests were performed: resistance to carbonation, chloride diffusion, chemical attack, alkali-silica reaction and freeze-thaw cycling with and without de-icing salt. Compared to normal strength concrete, the duration of some tests had to be prolonged in order to get measurable values. Not only lab-produced concrete was tested but also concrete produced in precast factories.

The results indicate a spectacular improvement in durability compared to normal strength concrete and even high performance concrete, illustrating a clear gain in service life of structures and a possible need to review some design rules related to durability.

Résumé

Le Béton à Ultra-Hautes Performances (BUHP) offre la possibilité de concevoir des structures passionnantes et innovantes. Ce type de béton étant relativement récent en Belgique, certaines propriétés méritent encore d'être validées, en particulier pour des mélanges à base de matériaux locaux.

Dans le but d'évaluer les performances du BUHP exposé à différents environnements agressifs, la porosité à l'eau et la perméabilité au gaz du béton ont été mesurées et les essais accélérés suivants ont été réalisés : résistance à la carbonatation, à la diffusion des chlorures, à l'attaque chimique, à la réaction alcali-silice et aux cycles de gel-dégel (en présence ou non de sels de déverglaçage). Comparé au béton ordinaire, la durée de certains essais a été prolongée de manière à obtenir des valeurs mesurables. L'étude concerne aussi bien du béton produit en labo que du béton produit en usine de préfabrication.

Les résultats indiquent une amélioration spectaculaire de la durabilité en comparaison avec le béton ordinaire, et même le béton à hautes performances, illustrant ainsi un bénéfice évident en matière de durée de vie des structures et un éventuel besoin de revoir certaines règles de conception liées à la durabilité du béton.

1.   INTRODUCTION

Ultra-high performance concrete (UHPC), a concrete-family characterised by a compressive strength exceeding 130 N/mm², offers the possibility to design exciting and innovative structures. This concrete type being relatively new in Belgium, some properties have still to be validated, more specifically for mixes made of local materials.

During a large research project devoted to UHPC, several mixes were developed and tested. The most relevant properties for a wider application of UHPC (i.e. creep, shrinkage, stress-strain response, young modulus…) were investigated and compared to the design rules described in Eurocode 2. In addition, several durability parameters were evaluated using accelerated tests. In a final step, full-scale tests were conducted to determine the flexural behaviour of prestressed girders made with UHPC.

This paper reports the results related to the durability evaluation of UHPC. In order to evaluate the performances of UHPC exposed to different aggressive environments, the water porosity and the gas permeability of the concrete were measured and following accelerated tests were performed: resistance to carbonation, chloride diffusion, chemical attack, alkali-silica reaction and freeze-thaw cycling with and without de-icing salt. Lab-produced concrete as well as concrete from precast factories were tested.

The performances were compared with those of normal strength concrete and high performance concrete (HPC) to evaluate the possible gain in service life of UHPC-structures and the need to review some design rules related to durability.

2.   MATERIALS AND CURING

Three concrete mixes were subjected to the test program. The UHPC types M1, M2 and M3 represent different approaches of UHPC-design, ranging from compositions with larger aggregate size and minimal cement content (M1) to reactive powder concrete with high powder contents and complete removal of coarse aggregates (M3). The mix proportions and the properties of the fresh concrete mixes are given in table 1. Silica fume slurry and quartz powder are used to densify the matrix. The addition of high dosages of polycarboxylate based superplasticizer ensures a suitable fluidity, close to that of a self-compacting concrete.

In addition to the lab-production, UHPC type M2 was produced in three Belgian precast factories using conventional equipment (batches of 1 to 2 m³). 1 vol. % steel fibres were added, consisting of a mix of 70 % microfibers (6 mm length) and 30 % macrofibres (30 mm length). No difficulties were encountered, but a slighty longer mixing period was required compared to conventional concrete in order to achieve a good dispersion of the steel fibres. Figure 1 shows a test production of a fibre reinforced UHPC girder in a precast factory.

All concrete specimens were demoulded 24 hours after casting and then stored at $20 \pm 2°C$ and more than 95 % RH until testing (up to an age of 90 days for the specimens used for durability testing). No heat treatment was applied.

Figure 1 : Production test of fibre reinforced UHPC type M2 in a Belgian precast factory.

Table 1: Mix design of M1, M2 and M3 and properties of the fresh concrete mixes.

		M1	**M2**	**M3**
CEM I 42.5 R HSR LA (c)	kg/m³	500	830	777
Silica fume (sf)	kg/m³	100	166	156
Quartz sand 0/0.5 mm	kg/m³	786	335	1060
Quartz powder (d_{50} = 12 μm)	kg/m³	50	83	211
Basalt 1/3 mm	kg/m³	510	0	0
Basalt 5/8 mm	kg/m³	386	0	0
Porphyry 2/4 mm	kg/m³	0	776	0
Mixing water (w)	kg/m³	150	178	162
Superplasticizer (SP, con. 30%)	kg/m³	15	24	28
Steel fibres (6 and 30 mm length)		[0 - 1 vol.%]		
(w/c)-ratio (SP included)		0.32	0.23	0.23
(sf/c)-ratio		0.20	0.20	0.20
Slumpflow	mm	650 - 750	700 - 800	700 - 800
Fresh density	kg/m³	2490	2420	2430
Air content	vol.%	2.5	2.0	3.5

3.   MECHANICAL PROPERTIES AND MICROSTRUCTURE

The compressive strength was obtained by testing cubes with an edge length of 100 mm (see table 2). Other mechanical properties of the UHPC mixes are provided in [1] and [2].

The total water absorption was measured by immersing concrete cores (70 mm diameter). A water porosity ratio was calculated (see table 2) using the following expression:

$$P = \frac{m_{ssd} - m_d}{m_{ssd} - m_{susp}} \times 100 \ \textit{(vol.\%)}$$
(1)

where m_{ssd} is the mass of water saturated surface dry concrete (in g), m_d is the mass of concrete oven-dried at 105°C (in g) and m_{susp} is the mass of concrete suspended in water (in g). Typical values for normal strength concrete range from 12 to 16 vol. % [3, 4].

Similar results were reported for fibre reinforced UHPC type M2 produced in the precast factories: around 160 MPa for the mean 28-day compressive strength and 5 vol. % for the water porosity ratio.

As a supplemental durability indicator, the oxygen permeability was also measured by using the AFREM recommendation entitled "Gas permeability of hardened concrete" [3]. The test involves measuring the steady-state volumic flowrate of gases passing through a sample under a constant pressure gradient, and then deducing its permeability to gas (in this case, oxygen) using Darcy's law. The results given in table 2, corresponding to the material in its dry state, are very close to the detection limit of the method (10^{-19} m²) and seem to be in accordance with the French Guidelines for UHPC [4]. Typical values for normal strength concrete range from 10^{-15} to 10^{-16} m² [3, 4].

Table 2: Compressive strength and porosity of the tested UHPC mixes

		M1	**M2**	**M3**
Mean 28-day compressive strength	MPa	130 - 140	140 - 160 (*)	140 - 160 (*)
Water porosity ratio (P)	vol.%	*N.D.*	6	5
Oxygen permeability (k_{app})	10^{-19} m²	2	9	*N.D.*

(*) up to 180-200 MPa for heat treated specimens.

4.   DURABILITY PROPERTIES

4.1   Accelerated carbonation test

The resistance against carbonation was determined on three prisms having a cross-section of 100×100 mm². Prior to the test, the prisms were oven-dried at 50°C during 14 days and then placed in a climate chamber at 20 ± 2°C and 60 ± 5 % RH during 7 days. The prisms were then stored in a 1 %-CO_2 atmosphere and the depth of the carbonation front was regularly measured by spraying a phenolphtaleine acid/base indicator solution on a fresh fracture. It should be noted that the carbonation front is sometimes difficult to observe due to the darker colour of UHPC compared to concrete without silica fume.

The results of these measurements are plotted in figure 2. After a one-year exposure to a 1 %-CO_2 atmosphere (the duration of this test is generally limited to 56 days), a carbonation depth of only 1.5 to 2 mm was reached. Similar results were reported for the UHPC type M2 produced in precast factories.

A coefficient of carbonation can be calculated (see figure 2 and table 3) using the following equation:

$$x_c = k_c \cdot \sqrt{t} \qquad\qquad\qquad (2)$$

where x_c is the carbonation depth at time t (in mm); k_c is the coefficient of carbonation which represents the carbonation rate under accelerated conditions (in mm/$\sqrt{day}$) and t is the exposure period (in days).
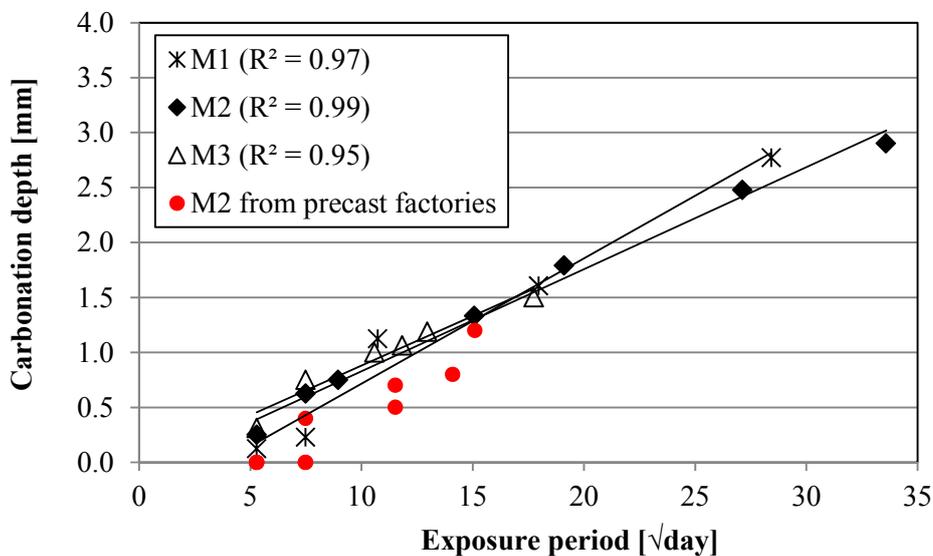

Figure 2: Carbonation depth vs. exposure period to 1 %-CO_2 atmosphere for fibre reinforced UHPC mixes.

From a practical point of view, this coefficient can be used as input data in predictive approaches like the DuraCrete Model [5] to estimate the carbonation depth in real conditions as a function of time. In order to compare the performances of an ordinary concrete (k_c = 1.5 mm/$\sqrt{day}$), a HPC (k_c = 0.6 mm/$\sqrt{day}$) and a UHPC (k_c = 0.1 mm/$\sqrt{day}$) in the same conditions (see also [6]), we can for example calculate the minimum concrete cover needed to reach a lifetime (towards carbonation induced rebar corrosion) of 100 years. We obtain values of 65 mm for ordinary concrete, 25 mm for HPC and less than 5 mm for UHPC.

4.2   Accelerated chloride diffusion test

The resistance against chloride diffusion was determined on drilled cores of 90 mm diameter by accelerated testing in non-steady state conditions, according to the Nordtest method NT Build 443 (1995). In this test, a $Ca(OH)_2$ saturated surface is exposed to a chloride solution, obtained by dissolving 165 g of dry NaCl in one litre of water, while the other surfaces are coated with epoxy resin. After an exposure period of at least 35 days (in

this case extended to 90 days), thin successive layers (1 mm thick) are ground off parallel to the exposed surface. The acid-soluble chloride content of each layer is then determined by potentiometric titration.

According to the test results (see chloride ingress profiles in figure 3), the chloride penetration after 90 days of accelerated testing is restricted to the outer 2 to 3 mm. Similar intrusion depths were observed by Scheydt et al. [7] for UHPC subjected to real-time testing. A chloride diffusion coefficient (D_{app}) can be calculated using a mathematical model based on the Fick's second law of diffusion. This coefficient is found to be as low as 0.1×10^{-12} m²/s (see table 3), while typical values for normal strength concrete are in the range from 5×10^{-12} to 50×10^{-12} m²/s [3, 4]. The presence of steel fibres in the concrete produced in precast factories prevented the grinding of thin layers from the concrete surface. Results obtained on thicker layers clearly indicate that no chloride has penetrated beyond the first 5 mm after 90 days of accelerated testing.
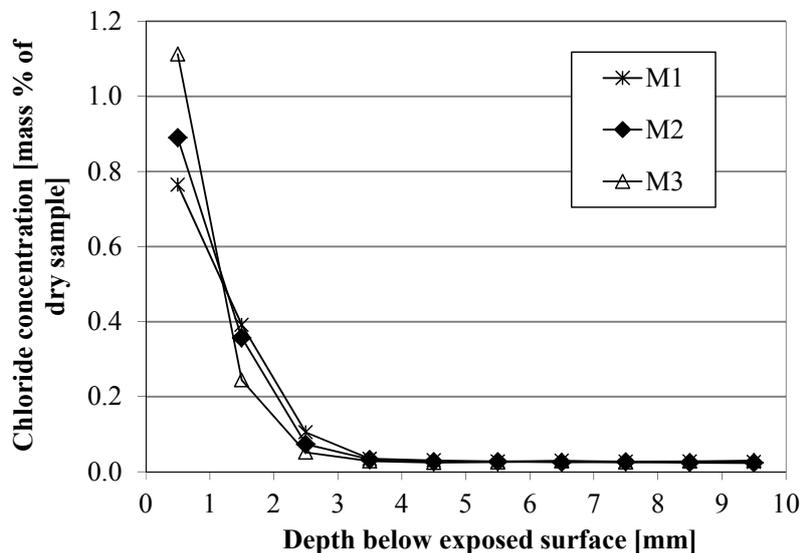

Figure 3: Chloride ingress profiles of UHPC mixes after 90 days of exposure to a saline solution.

4.3   Freeze-thaw attack (Slab test)

The frost resistance of UHPC was tested according to the reference method (Slab Test) described in the technical specification CEN/TS 12390-9 (Freeze-thaw Resistance – Scaling, 2006). In this test, four concrete cores (113 mm diameter, 50 mm long) are subjected to a freeze-thaw attack in presence of a 3 mm deep layer of de-ionised water or 3 % sodium chloride (NaCl) solution. All surfaces of the specimens except the test surface are coated and insulated according to the test set-up in figure 4. The freeze-thaw resistance is evaluated by measuring the mass of scaled material (in kg/m²) from the concrete slab after 56 freeze-thaw cycles (i.e. 56 days). In this case, the duration of the test was extended to 112 cycles.

The results indicate that the mass losses of the specimens (i.e. the mass of scaled material) after 112 cycles are extremely low, even with the NaCl solution. The values are limited to 0.3 kg/m² (see table 3) and seem to be in good agreement with those obtained by

Cwirzen et al. [8]. For comparison, values between 0.5 and 2 kg/m² after 30 cycles are generally accepted for road applications.
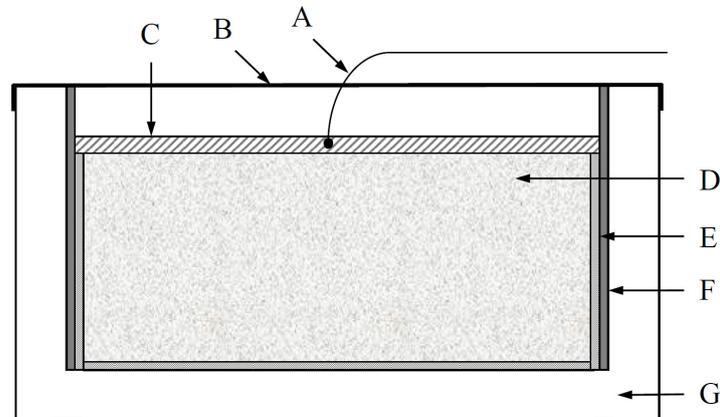

Figure 4: Slab Test set-up. A = Temperature measuring device, B = Evaporation protection, C = Freezing medium, D = Concrete specimen, E = Epoxy resin, F = PVC tube, G = Thermal insulation.

4.4   Alkali-silica reaction

The cement and silica fume content in UHPC mixes is very high. For this reason, it is necessary to evaluate the risk of damage due to alkali-silica reaction (ASR) even if a cement with a low alkali content is used [9]. It is generally accepted that no deleterious ASR is generated when the water soluble alkali content (Na_2O_{eq}) of the concrete is less than 3 kg/m³ [10]. For UHPC type M2, the total alkali content is estimated to be more than 4 kg/m³.

In this study, an "Oberholster test" [11] based on the modified ASTM C1260 test applied to concrete was used for M2. Three cylinders (50 mm diameter, 160 mm long) were hot-cured at 80°C for 24 hours and the initial length was determined. Subsequent length measurements were taken daily for 20 days while the prisms were immersed in hot (80°C) 1 N NaOH solution. The acceptable expansion limit is set at 0.1%. The results indicate no expansion or deterioration after this severe test. Based on previous experience, it can be concluded that there is no risk of ASR for this concrete mix.

4.5   Sulphate attack

The sulphate resistance was evaluated based on the CUR Recommendation 48 (The Netherlands, 1999). Three prisms of 40 x 40 x 160 mm³ are immersed in a sodium sulphate solution (Na_2SO_4, 16 g SO_4^{2-} per litre) and the length variation is regularly measured. The results indicate no expansion or deterioration, even after 500 days of immersion.

Table 3: Summary of the durability results for M1, M2 and M3.

		M1	**M2**	**M3**
Coefficient of carbonation at 1% CO_2 (k_c)	mm/√day	0.12	0.10	0.09
Apparent chloride diffusion coefficient (D_{app})	10^{-12} m²/s	0.11	0.09	0.07
Surface scaling after 56 cycles (freeze-thaw) with water	kg/m²	0.16	0.02	0.04
112 cycles	kg/m²	0.22	0.03	*N.D.*
Surface scaling after 56 cycles (freeze-thaw) with NaCl sol.	kg/m²	0.17	0.10	0.06
112 cycles	kg/m²	0.27	0.12	*N.D.*
Length variation after 20 days in 80°C 1 N NaOH solution	%	*N.D.*	0	*N.D.*
Length variation after 365 days in a sulphate solution	%	0	0	0

4.6   Sulphuric acid attack (TAP test)

The resistance of UHPC type M2 against sulphuric acid (H_2SO_4) attack was evaluated using a test equipment for accelerated degradation (TAP) developed by De Belie et al. [12]. Three cylinders (230 mm diameter, 70 mm long) are subjected to a cyclic procedure of immersion in a 0.5 % sulphuric acid solution (initial pH 0.9-1.0) and drying by air. The cylinders, fixed on a horizontal axle, turn with a speed of 1 revolution per hour through separate recipients (see figure 5). Each point of the outer circumference is submerged during 1/3rd of the rotation time. After each cycle, which lasts for 14 days, the cylinders are brushed with rotary brushes to remove weakly adhering concrete particles. The corrosion of the concrete is quantified by measuring the change in dimensions of the test specimens with laser sensors.

The results indicate a relatively low resistance of UHPC against sulphuric acid. After 6 attack cycles (i.e. 12 weeks), the average radius change of the cylinders due to the chemical reaction of the concrete (expansion) was 0.8 mm, while the average radius change due to chemical action of brushing the cylinders (material loss) was 1.3 mm. As a consequence, severe damage was reported (see figure 5). For comparison, ordinary concrete containing blast furnace slag cement shows very good results: expansion of only 0.1 mm and no material loss after brushing [13]. This aspect still needs to be further investigated before allowing the use of UHPC in specific applications such as sewer pipes and water storage tanks.
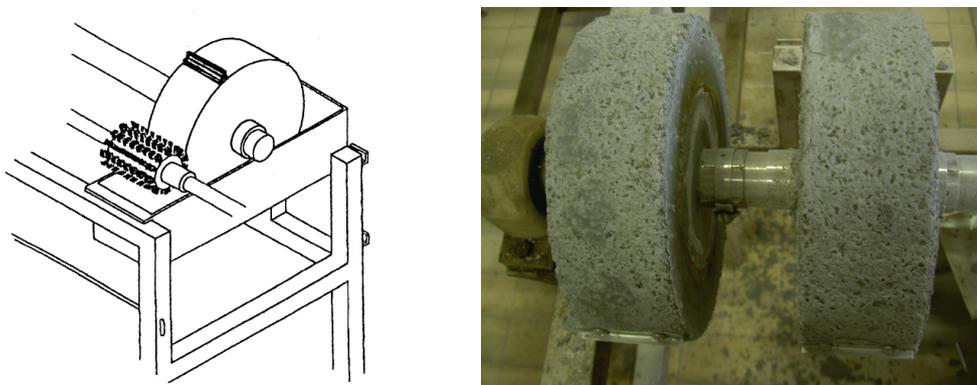

Figure 5: Schematic representation of the TAP (left) [12] and observed damage in UHPC type M2 due to chemical attack (right).

5.   CONCLUSIONS

In this study, the durability parameters of three concrete mixes using local materials (Belgium) were investigated, covering a broad range of UHPC types. The results indicate a spectacular improvement in durability compared to normal strength concrete and even HPC. No significant difference was observed between the tested UHPC mixes, even though mix M1 has a rather limited powder content and a (w/c)-ratio above 0.30.

The resistance to carbonation of the UHPC mixes being very high, steel rebars and reinforcing fibres are much longer protected from carbonation induced corrosion then in ordinary concrete mixes. However, the possible corrosion of steel fibres directly at the concrete surface could be a problem for aesthetic considerations. The UHPC mixes also show an excellent resistance to freezing and thawing, alkali-silica reaction and against ingress of aggressive substances such as chloride ions and sulphates. These results are in good agreement with previous studies and existing recommendations [4, 14].

The highly dense hardened state of UHPC, caused by a very low w/c-ratio and high powder contents, is the primary reason for this enhanced durability. The porosity could be reduced even more by applying a specific heat treatment, especially for the mixes M2 and M3 (for example, curing the concrete at 2 days for about 4 days at 90°C).

Contrary to what is expected considering the results of all the other considered durability parameters, UHPC seems to have a relatively low resistance against sulphuric acid (determined using the TAP test). Further investigation is necessary in order to confirm and explain this anomaly and to draw up guidelines for the use of UHPC in specific applications like sewer pipes.

This study also showed that fibre reinforced UHPC can easily be produced in precast factories using conventional equipment. Similar performances were obtained compared to lab-produced concrete.

From a practical point of view, the mechanical and durability properties of UHPC allow for the design of slimline concrete structures and components with high structural capacities and a very long service life. The minimum requirements for the concrete cover with regard to durability for reinforcement steel, as currently specified in the Eurocode 2 (EN 1992-1-1 and national annexes), do not consider UHPC structures. This study could be used as an impulse to review this aspect of said standard.

Other important issues related to the durability evaluation of UHPC such as the risk of delayed ettringite formation and the fire behaviour (risk of explosive spalling) are not detailed here. The influence of the fibre reinforcement could also be investigated.

ACKNOWLEDGEMENTS

REFERENCES

[1] Cauberg, N., Remy, O., Parmentier, B., Piérard, J. and Van Itterbeeck P., 'Shrinkage Behavior and Cracking Tendency of UHPC', Proceedings of the 9th International Symposium on High Performance Concrete – Design, Verification and Utilization, Rotorua, New Zealand, 2011.

[2] Cauberg, N., Piérard, J. and Van Itterbeeck, P., 'Case study: Flexural Behaviour of Prestressed Beams in Fibre Reinforced Ultra High Performance Concrete', Proceedings of the RILEM-fib-AFGC International Symposium on Ultra-High Performance Fibre-Reinforced Concrete (UHPFRC 2013), Marseille, France, 2013.

[3] Baroghel-Bouny, V. & al., 'Conception des bétons pour une durée de vie donnée des ouvrages – Maîtrise de la durabilité vis-à-vis de la corrosion des armatures et de l'alcali-réaction – Etat de l'Art et Guide pour la mise en œuvre d'une approche performantielle et prédictive sur la base d'indicateurs de durabilité' (in French), Association Française de Génie Civil (AFGC), France, July 2004, 252p.

[4] 'Ultra-High Performance Fibre-Reinforced Concretes: Interim Recommendations', AFGC/SETRA, France, January 2002, 98p.

[5] 'DuraCrete: General Guidelines for Durability Design and Redesign', EU-Project (Brite EuRam III), 2000, 109p.

[6] Piérard, J., Cauberg, N., Remy, O., 'Evaluation of Durability and Cracking Tendency of Ultra-High Performance Concrete', Proceedings of the 8th International Conference on Creep, Shrinkage and Durability of Concrete and Concrete Structures (CONCREEP 8), Ise-Shima, Japan, 2008, p.695-700.

[7] Scheydt, J.C., Herold, G. and Müller, H.S., 'Long Term Behaviour of Ultra High Performance Concrete Under the Attack of Chlorides and Aggressive Waters', Proceedings of the 2nd International Symposium on Ultra High Performance Concrete, Kassel, Germany, 2008, p.231-239.

[8] Cwirzen, A., Habemehl-Cwirzen, K. and Penttala V., 'The effect of heat treatment on the salt freeze-thaw durability of UHSC', Proceedings of the 2nd International Symposium on Ultra High Performance Concrete, Kassel, Germany, 2008, p.221-230.

[9] Möser, B. and Pfeifer, C., 'Microstructure and Durability of Ultra-High Performance Concrete', Proceedings of the 2nd International Symposium on Ultra High Performance Concrete, Kassel, Germany, 2008, p.417-424.

[10] CUR Recommendation 89 'Maatregelen ter voorkoming van betonschade door alkali-silicatereactie (ASR)' (in Dutch), 2nd edition, 2006, 48p.

[11] MET Recommendations: 'Béton – Spécification, performances, production et conformité' (in French), Circulaire n° 42-3-06-05 (01), 2006.

[12] De Belie, N., Monteny, J., Taerwe, L., 'Apparatus for accelerated degradation testing of concrete specimens', Materials and Structures, Vol. 35, 2002, p.427-433.

[13] Monteny, J., De Belie, N., Taerwe, L., 'Resistance of different types of concrete mixtures to sulphuric acid', Materials and Structures, Vol. 36, 2003, p.242-249.

[14] Uchida, Y & al., 'Review of Japanese Recommendations on Design and Construction of Different Classes of Fiber Reinforced Concrete and Application Examples', Proceedings of the 8th Symposium on Utilization of High-Strength and High-Performance Concrete, Tokyo, Japan, 2008, p.92-100.