Durability of ultra-high performance concrete – Experiences from a real-scale application

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Durability of ultra-high performance concrete – Experiences from a real-scale application

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Abstract. Ultra-High Strength Concrete or better Ultra-High Performance Concrete (UHPC) is finding increasingly more applications in real construction projects. However, mostly the focus is on the outstanding mechanical properties of this special concrete. But strength is just one side of this multifunctional material. Apart from that, it also comes along with distinguished durability properties which make it attractive to be used in construction projects despite a very high cost price. This paper refers to a real-scale application of UHPC used for the production of two bridge decks. The UHPC was produced in a ready-mixed concrete plant and delivered by concrete mixing trucks to a pre-cast plant. During the production, samples were made and later analysed regarding their mechanical properties and durability performance. This research is focusing on the latter and shows by means of porosity measurements, freeze-thaw resistance tests, carbonation tests and chloride diffusion and migration tests, that UHPC is a very dense and durable material that will allow for much longer service life periods and low maintenance and repair costs compared to structures made from conventional concrete.

Introduction

Modern advancements in concrete technology such as the introduction of superplasticizers, pozzolanic additives and fibres, development of concrete grading optimization approaches and better fundamental understanding of chemistry and mechanics of composite cement-based materials, led to the development of high and Ultra-High Performance Concrete (UHPC). Due to the very low water/cement ratio that is possible to be reached by using high performance superplasticizers, optimized grading, application of good quality cements and other reactive powders and fillers, the microstructure of hardened UHPC is very dense and compact. This results in outstanding mechanical properties and excellent durability due to reduced permeability. Addition of fibres improves the ductility and toughness and eliminates the brittleness, typical to plain concrete. Nevertheless, although known already for over two decades, UHPC still remains rather uncommon material in the building sector and its applications are rarely found. Despite the fact that the mechanical properties of UHPC are relatively well recognized already, there is still no widespread knowledge about the material’s durability, which in many cases could be even more important than just the compressive or tensile strengths. A more common application of UHPC into the building sector is hindered by several factors such as the high materials’ cost, production process that needs a strict control, lack of guidelines and codes for designing structures that make the full use of material’s potential and generally poor knowledge and experience with UHPC among the concrete technologists, structural engineers and architects.

Most investigations on UHPC described in the literature remain only laboratory research that is not implied for a larger scale concrete production. One of the reasons for this is the absence of relevant standards and lack of experience in interpreting the presented results, as there is no common agreement on the test procedures, geometry of tested samples, concrete age upon testing and curing conditions. Moreover, the UHPCs presented in the literature are often developed with
uncommon ingredients or with dry-mix proprietary and patent protected systems, which are most of the times composed only of binders and fine sand, thus are not fulfilling the proper definition of concrete, i.e. having coarse aggregates (> 4 mm). In fact, the commercially available UHPC-systems mainly represent the so-called “reactive powder concretes” (RPC), thus with sand as the coarsest granular material in the mixture. An additional factor causing that research still remains not linked to practical application is the fact that UHPC is very often developed using supplementary treatments, such as steam or heat curing, vacuum mixing or application of pressure on fresh concrete. Although the additional treatments increase the compressive strength of concrete (e.g. heat treated RPC can exceed 220 MPa), they also increase the production costs, prolong concrete production time, require additional equipment, control and experience and are applicable only in prefabrication plants. Thus, in order to facilitate the UHPC production and popularize its applications, there is a need to develop a UHPC with commonly available and rational ingredients, sensible mixing procedure and most importantly, to be able to produce it in conventional ready-mix concrete plants. At the same time, the UHPC properties should be maximized in order to offer wider application possibilities. Large scale production trials in concrete ready-mix plants are seldom performed and reported in the literature. The available publications show that the compressive strength of non-treated UHPC prepared with coarse aggregates does not exceed 175-185 MPa [1,2].

Taking into account all the above mentioned aspects, the aim of this study is to demonstrate the durability performance of a UHPC, that has been produced in a ready-mix concrete plant and applied in real-scale in two bridge decks. These decks were made for experimental and demonstration purposes and proof-loaded, as already presented in [3]. The concrete mixture is developed using coarse aggregates (up to 6 mm), with self-compacting properties and without any post-placeing treatments. It is produced in a conventional ready-mix concrete plant and delivered by concrete mixing trucks to a pre-cast plant where the bridge decks are cast. During the production a number of samples have been prepared for analyses regarding their mechanical properties and durability performance. This research is focusing on the latter and shows by means of the porosity measurements, freeze-thaw resistance tests, carbonation tests and chloride diffusion and migration tests, that UHPC is a very dense material that will most likely allow for much longer service life periods as well as reduced repair and maintenance costs compared to structures made with conventional or even high-strength concretes.

**Materials and concrete composition**

Based on a preliminary laboratory research, a UHPC composition was optimized aiming at the compressive strength of about 200 MPa and self-compacting properties (good stability, flowability and sufficient open time). Coarse aggregates up to 6 mm were used together with a fine sand 0-1 mm, Portland cement (CEM I 52.5 R, ENCI HeidelbergCement Benelux), silica fume slurry, limestone powder and short steel fibres. The characteristics of the ingredients is presented in Table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Characteristics</th>
<th>Specific density [kg/l]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM I 52.5 R</td>
<td>Portland cement</td>
<td>3.18</td>
</tr>
<tr>
<td>Limestone powder</td>
<td>-</td>
<td>2.75</td>
</tr>
<tr>
<td>Silica fume slurry</td>
<td>50 % wt.</td>
<td>1.98</td>
</tr>
<tr>
<td>Fine aggregate 0-1 mm</td>
<td>Calcined bauxite</td>
<td>3.49</td>
</tr>
<tr>
<td>Coarse aggregate 3-6 mm</td>
<td>Calcined bauxite</td>
<td>3.44</td>
</tr>
<tr>
<td>Steel fibres</td>
<td>Ø 0.3 mm x 12 mm</td>
<td>9.32</td>
</tr>
<tr>
<td>Superplasticizer</td>
<td>35 m.-%</td>
<td>1.07</td>
</tr>
<tr>
<td>Retarder</td>
<td>-</td>
<td>1.25</td>
</tr>
</tbody>
</table>
In the developed mix a polycarboxylate-based superplasticizer was used to adjust workability together with a setting retarder to extend the open time. The total amount of binder was 845 kg/m$^3$, the water/binder ratio 0.21 and the volumetric fibre content 1.5 %. About 9 % of the cement was replaced by silica fume. The grading of the UHPC ingredients was optimized applying the modified Andreasen & Andersen particle packing model \cite{4}, following the approach described earlier, e.g. in \cite{4,5}. The optimized particle packing results in a minimized void fraction, i.e. lower porosity, thus higher mechanical properties as well as reduced water demand of the mixture. The particle size distribution of the dry ingredients as well as the target and optimized packing curves for the developed mixture are presented in Fig. 1.

![Figure 1. Particle size distribution of individual granular materials, grading target curve and optimized mixture grading curve.](image.png)

**UHPC production in a ready-mix concrete plant**

The UHPC was produced in a ready-mix concrete plant (Mebin Utrecht, the Netherlands), using a twin-shaft mixer, in two batches of 1.5 m$^3$ each. The two batches were prepared on two different days, and due to some technical issues with the dosing unit, with different types and dosages of the setting retarders. Immediately after mixing for about 8 minutes, the charges were loaded into a concrete mixing truck, from which samples of about 120 l were collected for laboratory test on fresh and hardened concrete. Fig. 2 shows pictures taken during the UHPC production, including the silos, conveyor unit, loading of the concrete mixing truck and a UHPC sample collected for further testing. Subsequently, the concrete mixing truck departed to the site where the bridge decks were cast.
Fresh concrete properties

The slump-flow of fresh UHPC was determined using the Abrams cone as described in the EN 12350-8 [6]. The measurement was done on each produced batch, immediately after collecting fresh concrete samples from the trucks. Fig. 3 presents the fresh concrete flowability. For the two batches a flow diameter of 720 – 740 mm was determined, indicating an excellent flowability of the mixture. Moreover, no signs of segregation, paste halo or bleeding were observed. The UHPC mixture remained workable after the transportation and upon placing (in total about 1 hour after mixing).
Compressive strength development

A number of 15 x 15 x 15 cm³ cubes were cast from both UHPC batches in order to follow their compressive strength development in time. Immediately after casting, the samples were covered with a plastic foil to avoid water evaporation. One day after casting, the samples were de-molded and stored in a water batch (20 °C) until testing. The compressive strength tests were performed as described in EN 12390-3 [7], using a press with the maximum load of 5000 kN. At each test age two cubes were tested and the average values were calculated. The compressive strength development up to 28 days was determined for the first UHPC batch and up to one year for the second batch. The compressive strength development can be found in Fig. 4.

![Compressive strength development of UHPC](image)

It can be observed in Fig. 4 that the setting of concrete from batch 1 was much faster compared to batch 2. The 1 day strength of concrete batch 1 was about 107 MPa while the concrete batch 2 reached only 4 MPa after 3 days. This difference is caused by the different type and dosage of setting retarders, as mentioned earlier. The compressive strength of concrete batch 1 reached 188 MPa after 28 days. Despite the delayed early strength development, batch 2 concrete reached 194 MPa of the compressive strength after 91 days, and over 200 MPa after 1 year of water curing. It is worth emphasizing that such an outstanding compressive strength has been obtained by producing concrete in a ready-mix concrete plant, without using any additional treatments such as vacuum mixing or steam/heat curing.

Porosity

The water-permeable porosity was determined for the UHPC mixture on four samples (two plates 15 x 15 x 1.5 cm³ and two prisms 4 x 4 x 16 cm³). The plates were extracted from cast cubes by cutting while the prisms were cast in molds. In order to determine the porosity, 28 days after casting the samples were firstly saturated with water under vacuum and weighted in air and in water (hydrostatically), then dried in an oven (105 °C) to a constant mass and subsequently weighted again. The saturation of the samples with water was performed under vacuum conditions, as this technique is reported to be the most efficient among other saturation techniques [8]. The saturation was performed following the procedure as described ASTM C 1202 [9]. Finally, the water-permeable porosity was calculated using Eq. (1). The results are shown in Table 1.
\[ \varphi_w = \frac{m_s - m_d}{m_s - m_w} \cdot 100\% \]  

where: \( \varphi_w \) – water-permeable porosity of UHPC, \( m_s \) – surface-dry mass of the water-saturated sample in air, \( m_w \) – mass of water-saturated sample in water and \( m_d \) – mass of the oven-dried sample.

### Table 1. Water-permeable porosity determination.

<table>
<thead>
<tr>
<th></th>
<th>( m_s [g] )</th>
<th>( m_w [g] )</th>
<th>( m_d [g] )</th>
<th>( \varphi_w [%] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prism 1</td>
<td>746.8</td>
<td>486.1</td>
<td>740.4</td>
<td>2.4</td>
</tr>
<tr>
<td>Prism 2</td>
<td>733.8</td>
<td>476.6</td>
<td>727.1</td>
<td>2.6</td>
</tr>
<tr>
<td>Plate 1</td>
<td>1023.4</td>
<td>633.6</td>
<td>1008.9</td>
<td>3.7</td>
</tr>
<tr>
<td>Plate 2</td>
<td>1224.0</td>
<td>793.0</td>
<td>1208.7</td>
<td>3.6</td>
</tr>
</tbody>
</table>

It can be observed in Table 1 that the determined porosities depend strongly on the geometry of the test sample, i.e. are lower for the prisms than for the plates. This can be explained by a lower saturation efficiency for the prisms (especially in their core) due to their geometry compared with the flat plates of low thickness and higher surface area. It can be expected as the UHPC has a very tight and dense microstructure. Another possible explanation for the difference in the measured porosities is the influence of the sample preparation technique, as the plates were extracted from the cubes by cutting (diamond saw), which could induce microcracks and result in a higher total porosity compared to the prism samples which were not further treated.

The water-permeable porosity takes into account both the micro- and macro-porosities, i.e. capillary pores as well as air voids (including the entrained air), therefore it is always much higher than air content in fresh concrete. For conventional concrete the permeable-porosity accounts for about 15% of volume [10], while for a high strength self-compacting concrete with nano-silica additions it is about 12 % [11]. At the same time, Yu et al. [12,13] reported a permeable porosity of about 10% for UHPCs with low binder contents. The data presented here in Table 1 reflect much lower porosities than reported elsewhere. Such a low porosity corresponds well with the high compressive strength, and can be explained by the low water/binder ratio, self-compacting (self-de-airing) fresh concrete properties, optimized particle packing (less air voids) as well as the utilization of silica fume which further densifies the microstructure (it acts as a fine micro-filler and also reacts with Ca(OH)\(_2\) to produce fine C-S-H gel). The very low porosity of the UHPC developed here would significantly limit the intrusion of aggressive substances into the concrete and thus extend its potential service lifetime. This will be validated in this study by performing carbonation and chloride intrusion tests.

### Carbonation

The carbonation test is performed on two 10 x 10 x 50 cm\(^3\) beams cast from batch 2 UHPC. After casting, the beams were covered with a plastic foil to avoid water evaporation, de-molded after one day and subsequently wrapped in tight plastic foil. At the age of 28 days the test beams were transferred to a climate room (RH 60 ±5%, 20 °C, 0.035% CO\(_2\)). After a period of 91 days and 1 year, the outermost 5 cm of both the beams were split and sprayed with 1% phenolphthalein in 70% ethanol solution to determine the carbonation depth. The resulting colouration of concrete samples is shown in Fig. 5.
As can be noticed in Fig. 5, no carbonation front can be observed on the presented photos, even after 1 year of exposure. This reflects on a great concrete resistance against the CO$_2$ ingress and corresponds with the measured total porosity of UHPC, which is much lower compared to other concrete types.

**Accelerated chloride ingress (Rapid Chloride Migration test)**

In order to quantify the UHPC resistance against chloride ingress, the accelerated Rapid Chloride Migration test (RCM) is performed, following NT Build 492 [14]. As an electric field is applied in this test to accelerated chloride ingress, no steel fibres can be present in the test sample because they would disturb the electric field distribution and immediately start to corrode, thus influence the test results. Therefore, the cubes prepared in this study for the RCM test were not cast with the concrete produced at the ready-mix concrete plant, but on a small scale (15 l) in the laboratory. Here, three concrete cubes (15 x 15 x 15 cm$^3$) were cast and cured in a water bath (20 °C) until the age of 27 days. Then, cores of 10 cm diameter were extracted from the cubes by drilling. Subsequently, the outermost layer of about 1 cm was removed and a disc of 5 cm height was cut from each core. In this way, a total number of three RCM test cylinders was prepared. Subsequently, the cylinders were surface-dried and placed in a desiccator container for vacuum-saturation treatment. The negative pressure of about 20 mbar (2 kPa) was maintained for three hours to the samples in the container, and then, with the vacuum pump still running, the container was filled with limewater. The vacuum was maintained for an additional hour before allowing air to re-enter the container. Thereupon, the samples were stored in limewater for about 20 h. Next, the samples were sealed in a non-conductive rubber sleeve with metal clamps and placed on an inclined support. Two stainless-
Steel electrodes were installed on both exposed sides of the sample. The cathode was immersed in a 10% NaCl solution while the anode in a 0.3 M NaOH solution. Subsequently, an initial DC voltage of 30 V was applied between both electrodes and the resulting initial current was measured. Based on the value of this current, the duration of the RCM test and the voltage level applied during testing were determined, following [14,15]. After applying the voltage for a pre-defined duration, the samples were removed from the rubber sleeves and split opened by applying force. The fracture surfaces of the samples were then sprayed with a colorimetric indicator for chlorides (0.1 M AgNO₃ solution), so that the chloride penetration depth in the sample could be measured. Using the value of the average measured chloride penetration depth, the 28 days chloride migration coefficient $D_{RCM}$ was computed, following the formula given in [14]. Table 2 presents the RCM test conditions, the measured chloride penetration depths as well as the calculated $D_{RCM}$ values.

Table 2. RCM test conditions and test results for UHPC at 28 days, where $I_0$ – initial current measured at 30 V, $I_i$ – initial current measured at 60 V, $I_e$ – end current, $T_i$ – initial temperature measured in the NaOH solution, $T_e$ – end temperature measured in the NaOH solution, $U$ – applied voltage, $t$ – test duration, $x_d$ – average chloride penetration depth and $D_{RCM}$ – 28 days chloride migration coefficient.

<table>
<thead>
<tr>
<th>Sample number</th>
<th>$I_0$ (at 30V) [mA]</th>
<th>$I_i$ [mA]</th>
<th>$I_e$ [mA]</th>
<th>$T_i$ [°C]</th>
<th>$T_e$ [°C]</th>
<th>$U$ [V]</th>
<th>$t$ [h]</th>
<th>$x_d$ [mm]</th>
<th>$D_{RCM}$ [10⁻¹² m²/s]</th>
<th>$D_{RCM}$ - average [10⁻¹² m²/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.97</td>
<td>1.96</td>
<td>1.48</td>
<td>19.7</td>
<td>20.1</td>
<td>60</td>
<td>168</td>
<td>3.7</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.97</td>
<td>1.97</td>
<td>1.55</td>
<td>19.7</td>
<td>20.1</td>
<td>60</td>
<td>168</td>
<td>4.1</td>
<td>0.12</td>
<td>0.11</td>
</tr>
<tr>
<td>3</td>
<td>1.02</td>
<td>2.07</td>
<td>1.66</td>
<td>19.7</td>
<td>20.1</td>
<td>60</td>
<td>168</td>
<td>3.8</td>
<td>0.11</td>
<td></td>
</tr>
</tbody>
</table>

The initial current measured at 30 V for all the samples amounts to about 1 mA. This is extraordinarily low for the RCM test, which reflects the concrete quality (dense structure). For such an initial current NT Build 492 [14] prescribes 4 days RCM test at 60 V. Nevertheless, a Dutch annex to the RCM test [15] prescribes a test duration of 168 hours (7 days) at 60 V for the initial current $I_0 < 2$ mA. In this study the latter test conditions were used to secure a sufficiently deep chloride penetration depth. Despite the extended test duration, the measured chloride penetration depths were still very shallow ($x_d$ of about 4 mm, an example is shown in Fig. 6), as can be seen in Table 2. The average 28 days chloride migration coefficient $D_{RCM}$ determined here is very low, and amounts to 0.11·10⁻¹² m²/s. This is far lower than for any other normal- or high-strength concrete, for which the $D_{RCM}$ values in the range of 1–10·10⁻¹² m²/s are typical, strongly depending on the binder composition and water/cement ratio [10]. Nevertheless, the data available in the literature on the $D_{RCM}$ for UHPC systems is very scarce, as this test cannot be performed for concrete with steel fibre additions. Hence, it is concluded that the UHPC developed in this study exhibits very shallow chloride penetration depths (about 4 mm after 7 days at 60 V) and extremely low 28 days $D_{RCM}$ values of 0.11·10⁻¹² m²/s. This value is expected to decrease further, as the microstructure of UHPC continues to develop after the 28 days of curing, which will be validated in the future.

Figure 6. Chloride penetration depth measured in the UHPC sample (chloride indicated by the white precipitation, in the top side)
Natural chloride ingress (Chloride bulk diffusion test)

The natural chloride diffusion test performed in this study was based on the procedure described in NT Build 443 [16]. Three cubes (15 x 15 x 15 cm$^3$) were cast from batch 2 UHPC. After 25 days of curing in a water bath (20 °C), cores of 10 cm diameter were extracted from the cubes by drilling. Subsequently, the outermost layer of about 1 cm was removed and a disc of 5 cm height was cut from each core. In this way, a total number of three diffusion test cylinders was prepared. Subsequently, the cylinders were saturated in vacuum with limewater, as explained in the previous section. After the saturation, all external faces of the samples were coated with an epoxy resin except for one flat surface, left uncovered to allow the chlorides to penetrate the samples just from that side. Then, the samples were placed back in limewater for one day, to avoid capillary action. Next, at the age of 28 days, the samples were immersed in a sodium chloride solution (concentration of 165 g/l), at 20 °C, in a sealed container, with the uncoated surface on top. After the exposure periods (3 months and 1 year), each time one sample was dry-ground in thin layers for the determination of the chloride concentration profiles. The obtained powder was collected for the determination of the total chloride concentration profiles, following the procedure described in [10]. An automatic potentiometric titration unit was used for the Cl$^-$ concentration measurements, employing a 0.01 M AgNO$_3$ as the titrant. In order to estimate the apparent chloride diffusion coefficient ($D_{app}$) and the surface total chloride concentration, the solution of Fick’s 2nd law was fitted to the measured total chloride concentration profile, following the description given in [16]. The chloride concentration profile as well as the determined apparent chloride diffusion coefficient are presented in Fig. 7.

![Figure 7. Chloride concentration profiles determined after 91 days and 1 year of exposure to a chloride solution.](image_url)

It can be found in Fig. 7 that the chloride penetration profile after 91 days of exposure was not possible to be accurately determined due to a shallow chloride penetration depth (only about 1.5 mm). Therefore, the 91 days chloride diffusion coefficient has not been determined in this study. After 1 year of exposure to the chloride solution, the penetration of chloride into the UHPC sample reached about 3 mm in depth. This was sufficient to estimate the 1 year chloride diffusion coefficient $D_{app}$, which amounts to $0.05 \cdot 10^{-12}$ m$^2$/s. Such an excessively low value demonstrates the
excellent UHPC resistance against chloride ingress. For normal strength concrete the $D_{app}$ holds in the range of $5$-$50 \cdot 10^{-12} \text{ m}^2/\text{s}$, as reported in [17] and for another type UHPC about $0.23 \cdot 10^{-12} \text{ m}^2/\text{s}$ after 3 months of exposure to chlorides [17]. Similarly to the $D_{RCM}$ coefficient, the $D_{app}$ values are expected to further decreased over time, due to the progressing hydration. This will be verified in the future.

**Freeze-thaw resistance**

The freeze-thaw resistance of the developed UHPC mixture was tested according to the slab test method, described in EN 12390-9 [18], using a 3% NaCl solution. Firstly, two cubes (15 x 15 x 15 cm$^3$) were cast, de-molded after 1 day and cured in a water bath (20 °C). After 7 days, the cubes were removed from water and placed in a climate room (20 °C, 60% RH). At the age of 21 days, two 5 cm thick slices were extracted from each cube, giving in total 4 test samples. Then, at the age of 25 days, rubber sheets were glued around the samples, except for the test surface, and sealed on the sides with silicone at the age of 26 days. At the age of 28 days, a 3 mm layer of de-mineralized water was poured on the samples to saturate the exposed surfaces with water. Next, at the age of 31 days, a 3 mm layer of 3% NaCl solution was replaced on the test samples, which were then transferred to a climatized chamber, programmed to follow the freezing-thawing temperature profile, as specified in [18] (one freezing cycle per day). The surface scaling of the test slabs was analysed after 7, 14, 28, 42 and 56 days (cycles) and the obtained results are presented in Fig. 8.

![Figure 8. Surface-scaling development of UHPC samples exposed to freeze-thaw cycles.](image)

In general, concrete can be classified as having good resistance against freeze-thaw attack when the surface scaling is less than 0.5 kg/m$^2$ [19]. The surface scaling values obtained for the UHPC developed here are over 10 times lower than this limit (average of 0.04 kg/m$^2$), which reflects that this material has an excellent freeze-thaw attack resistance. The scaling for normal and high strength, non-air entrained concrete of 1.5-6 kg/m$^2$ is reported in [11]. The scaling values obtained here correspond well to the literature, as e.g. [17] reported the scaling of 0.06-0.17 kg/m$^2$ for UHPC.
Summary and conclusions

This study is executed to promote the UHPC applications by demonstrating that a material of an excellent performance can be produced in a conventional concrete plant. Although the mechanical properties of UHPC are relatively well recognized already, there is still no widespread knowledge about the material’s durability, which in many cases could be even more important than just the compressive or tensile strengths. Therefore, the aim of this study is also to demonstrate the durability performance of a UHPC mix produced in a real scale, in a ready-mix concrete plant, using a conventional mixing process.

A self-compacting concrete is successfully produced in two batches of 1.5 m$^3$ each, transported and placed. The developed UHPC mix is prepared with coarse aggregates, which distinguishes it from the most commonly produced UHPCs in a form of Reactive Powder Concretes. Moreover, no additional special treatments such as vacuum mixing or steam/heat curing are applied, which is a solid technological and cost advantage. The determined material’s characteristics is outstanding, including the compressive strength (188 MPa after 28 days and 200 MPa after 1 year) and durability performance. Here, the porosity, carbonation resistance, accelerated and natural chloride diffusion as well as freeze-thaw resistance are examined. All these durability performance indicators are by far better than for conventional and high strength concretes, indicating a great service lifetime potential of the UHPC. It is expected that in the future such a material be more often applied in practice as it provides more possibilities to structural engineers and architects. On top of that, the durability performance indicators of UHPC will assure maintenance- and repair-cost free concrete elements/structures with a greatly extended service lifetime.

References