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Durability of UHPC for Façade Elements with Self-cleaning Surfaces

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Abstract. This paper presents the development of ultra-high performance concrete (UHPC) for façade elements with self-cleaning properties. For creating self-cleaning surfaces two different approaches are proposed. One approach is based on the photocatalytic activation of the external UHPC shell by incorporation of TiO_2 particles. The second approach consists of the modification of the UHPC surface by micro structuring in combination with the application of hydrophobic agents to create durable super hydrophobicity. In the framework of the H-HOUSE project funded by the European Commission the experimental investigations were performed with UHPC based on Dyckerhoff Nanodur® technology. The special properties of this material enable the precise reproduction of any micro structure without flaws. The current results obtained from laboratory and outdoor weathering tests are promising and demonstrate the feasibility of the approaches.

Introduction

In comparison with steel reinforced concrete that presents high embodied energy and an important carbon footprint, ultra-high performance concrete (UHPC) elements can represent a promising alternative. Used in thin layer and with the replacement of Portland cement with less energy intensive supplementary cementitious materials (SCM), they show some advantages such as lower embodied energy, and thus reduced environmental impact. UHPC composite elements for building envelopes can have other benefits, such as increased service life, and optimized use of building area as well as economic transport and installation due to thinner light-weight elements.

In the framework of the ongoing European collaborative project H-House prototype façade elements comprising UHPC used for the external shell in combination with autoclaved aerated concrete (AAC) or cellular lightweight concrete (CLC) as insulation materials are developed. The very high density of the UHPC is of course beneficial to its durability. Numerous studies showed that due to the limited adsorption of moisture and negligible moisture transport the resistance of UHPC against any kind of deterioration mechanism is drastically increased compared to normal concrete. In the case of building envelopes, the excellent resistance against freeze-thaw attack and penetration of chloride ions in marine environments is a particular advantage [1-3]. UHPC was already applied successfully to building envelopes, such as lightweight roof constructions and façade elements [4-6].

In order to decrease the maintenance costs of the façade elements it is intended to provide self-cleaning properties to the surface of the external UHPC layer. The first approach is the application of TiO_2 photocatalysts that comprises two important effects related to the nature of photoactive TiO_2: a) the self-cleaning effect due to redox reactions promoted by UV radiation, which is promoting the disintegration of dirt, and b) the photo-induced hydrophilicity that enhances the self-cleaning effect by improved removal of dirt due to rainwater soaking between the dirt and the hydrophilic surface [7]. Although the self-cleaning properties of TiO_2 are known since the 1970s, its application in cementitious materials constructions started only since 2000 in a wider manner. Short, but comprehensive overview is provided by [7,8]. The most efficient way to use TiO_2 is its concentration at the concrete surface, e.g. as a coating, since TiO_2 particles located in the bulk of the concrete are not reached by UV radiation, and thus not available to active photocatalytic processes [9]. It is possible to realize such coating by incorporation of TiO_2 particles in the form release agent [10]. However, the durability of TiO_2 coatings might be limited. Therefore, in the presented studies TiO_2 was applied as bulk addition, which was not considered as severely uneconomic due to the small thickness of the external UHPC layer.

The second approach is to create a super hydrophobic UHPC surface. Super hydrophobicity is usually associated with contact angles of a water droplet ≥ 140-150° and is often referred to as Lotus effect. The special micro texture and the hydrophobic wax coating of the lotus leaf minimize the contact area between a water drop and the leaf. When a raindrop is hitting the leaf, it is easily running off and collecting dirt deposits from the surface. The same principle can be transferred to concrete. The use of technical fabrics as a relatively simple technique for micro-structuring of a concrete surface for the purpose of creating super hydrophobicity is reported in [11] and with UHPC it was possible to reproduce a micro texture very similar to that of the lotus leaf [12]. In both studies super hydrophobicity was achieved by applying a hydrophobic agent on the micro-structured surface of the hardened concrete.

Materials, sample preparation and test methods

The UHPC adopted is based on Dyckerhoff Nanodur® technology. Nanodur® Compound is a binder blend based on Nanodur® cement (CEM II/B-S 52.5 R) and contains ultrafine components (Portland cement, blast furnace slag, quartz, synthetic silica) smaller than 250 µm that are dry mixed intensively. In this way the homogeneity and dense packing of the particles is reliably achieved and the mixing process of the UHPC with a standard concrete mixer is simplified significantly [13].

For the activation of the photocatalytic effect, up to 5 wt.-% TiO_2 related to the total amount of solid components (binder compound and aggregates) was added, which required increasing the amount of superplasticiser significantly to maintain the workability, i.e. the flow characteristics and the self-compacting properties of the UHPC. The mixture compositions are listed in Table 1.

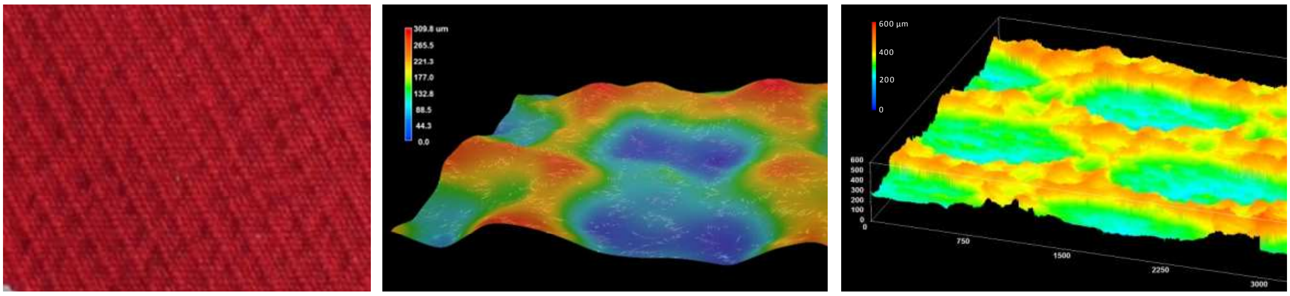
Table 1. UHPC compositions for evaluation of self-cleaning properties [kg/m³].

Material	Reference	1% TiO_2	3% TiO_2	5% TiO_2
Nanodur® Compound	1050	1028	984	940
TiO_2 powder [1)]	-	22	66	110
Sand 0/2 mm	1150	1150	1150	1150
Superplasticiser (PCE)	17.9	30.0	53.3	80.0
Water	178.5	178.5	178.5	178.5

[1)] Chrystal modification: anatase. Characteristic particle diameters (obtained using laser diffraction analysis): TiO_2 type 1: x_{50} = 1.4 µm, x_{90} = 2.9 µm; TiO_2 type 2: x_{50} = 1.8 µm, x_{90} = 3.6 µm. According to the manufacturer, the specific surface area is > 225 m²/g for both types of TiO_2.

The photocatalytic activity of two types of anatase TiO_2 products added to the UHPC was investigated by colour measurements on samples polluted with methylene blue following EN 1096-5 [14] and DIN 52980 [15]. For this purpose, (2.5 ± 0.5) mg/cm² of 1 wt.-% aqueous methylene blue solution was applied to the samples surface and evenly distributed. After pollution, the samples were subjected to artificial weathering consisting of two cycles of 24 hours of UV radiation (UVA-340, 40 W/m²) at 23 °C and 50% relative humidity (RH) and subsequent splashing of water with 2 bar pressure for 15 seconds. In the colour measurements, using a Minolta CM 2600d spectrophotometer, three parameters were determined that define a distinct point in the L*-a*-b* colour space: L* for lightness, and a* for blue-yellow and b* for red-green dimensions. Using these parameters, every change in colour of the sample surfaces due to pollution and self-cleaning was expressed as displacement in the colour space and the decrease of pollution was quantified as ratio of the colour displacement after self-cleaning to the colour displacement from original state to polluted state.

The challenge to create a permanent super hydrophobic concrete surface is the adequate and durable replication of a specific micro structure in combination with effective and durable chemical water repellence. In the presented studies, an elastane-polyamide fabric (Fig. 1a) was used as substrate for the UHPC cast to generate a micro structured imprint. Due to the self-compacting properties of the fresh concrete and the high packing density of the ultrafine particles of the Nanodur® based UHPC the micro structure of the fabric could be reproduced (Fig. 1b-c). The micro-structured UHPC surface was compared to the performance of a relatively smooth UHPC surface created using a PVC board as substrate for concrete cast.



(a) (b) (c)

Figure 1. (a) Fabric, (b) Micro structure of fabric, (c) Micro structure of UHPC surface cast on fabric. 3D micro structures were captured using a confocal laser microscope.

Investigations on water repellence were performed using seven types of chemical agents (six of them silane-based and one based on potassium methyl siliconate) by means of contact angle and roll-off angle measurements using a OCA-20 measurement system (DataPhysics Instruments). The volume of the water droplets was 22 µl. The measurement of the contact angles started 30 seconds after placing the droplet. Roll-off angles were measured using the tilting table function of the measurement device. When the table is tilted, the sample surface is rotated from the horizontal to the vertical, i.e. from 0° to 90°, and the rotation angle is registered when the water droplet is rolling off the sample surface. The lower the roll-off angle, tshe more pronounced is the water repellence. However, a large scatter of test results was observed in particular with the roll-off angle measurements. Thus, it is difficult to correlate directly the contact and roll-off angle measurements. Nevertheless, the fact that a sessile water droplet is rolling off or not, gives valuable information about the water repellence of the surface.

Following the approach introduced in [11] the micro-structured UHPC surface was impregnated with a water-repellent agent after initial hardening of the UHPC. This approach was advanced by application of the water-repellent agent on the fabric substrate shortly before the concrete cast. With both methods the water-repellent agents were applied with a paintbrush. The laboratory durability tests were performed with three test series where micro-structured UHPC surfaces created with fabrics were compared to a relatively smooth surface created using a PVC board:

– series 1: UHPC cast on fabric, impregnation 24 hours after demoulding;
– series 2: UHPC cast on PVC board, impregnation 24 hours after demoulding;
– series 3: Application of water-repellent agent on fabric before UHPC cast.

After preparation, the UHPC samples were stored at standard climate conditions and at elevated temperatures before they were exposed to UV radiation and to artificial weathering. After each of the intervals listed in Table 2 the contact angles and the roll-off angles of water droplets were measured to evaluate the water repellence of the UHPC samples.Table 2. Curing and weathering conditions for durability tests of water repellence.

Interval	Duration	Climate conditions
0	14 days	23 °C / 50% RH
1	7 days	30 °C without RH control
2	7 days	45 °C without RH control
3	7 days	UV(A) radiation (40 W/m²) at 60 °C without RH control
4	7 days	Artificial weathering with UV(A) radiation; 28 cycles consisting of - 4 hrs heating at 60 °C - cooling with splash water for 20 min at 10 °C - 2 hrs freezing at -5 °C
5	28 days	Artificial weathering as in interval 4

In addition to the accelerated artificial weathering tests in the laboratory, outdoor weathering of UHPC samples with surface modifications has started in May 2015. The samples (10 cm × 10 cm) are placed in sample holders, which are fixed on a rack on top of a building at BAM headquarters. This building is located close to a main road. The climate data (air temperature and relative humidity, wind speed and direction, air pressure and global solar radiation) are monitored.

Several standard durability tests were performed in the laboratories in order to evaluate the further reduction of Portland cement by several supplementary cementitious materials (SCM). Appropriate SCM and UHPC mixture compositions were referred to minimum compressive strength of 50 N/mm² after 1 day and 100 N/mm² after 28 days as major boundary conditions (tested according to EN 196-1 [16]). The tests included four different types of Portland cement CEM I (denoted as type A-D). In total a selection of nine different binder blends were used (Table 4). Some of them are not defined in the currently valid EN 197-1, 2011 [17]. The composition of the UHPC mixtures that were prepared for the standard durability tests using the binder blends according to Table 3 are given in Table 4.

Table 3. Composition of the tested binder blends.

Cement blend	No.	Composition [wt.-%]	
		CEM I	Total of SCMs
CEM II/B-S	II-a	70 (type A)	30
	II-b	70 (type B)	30
CEM V/A	V-a	55 (type C)	45
	V-b	55 (type B)	45
CEM II/C-M (S-LL) 1)	III-a	55 (type A)	45
	III-b	55 (type D)	45
CEM X (S-LL) 2)	III-c	40 (type B)	60
CEM X (S-V-LL) 2)	III-d	50 (type C)	50
	III-e	50 (type C)	50

1) prEN 197-1:2014 [18].
2) Tentatively labeled with ‘X’ since not defined in EN 197-1, 2011 [17].

Table 4. Mix design for UHPC prepared for durability tests.

Component	Content [kg/m³]
Cement/Binder	620
Quartz powder	430
Sand 0/2 mm (air-dry)	1150
Water	167
PCE superplasticiser	17.8

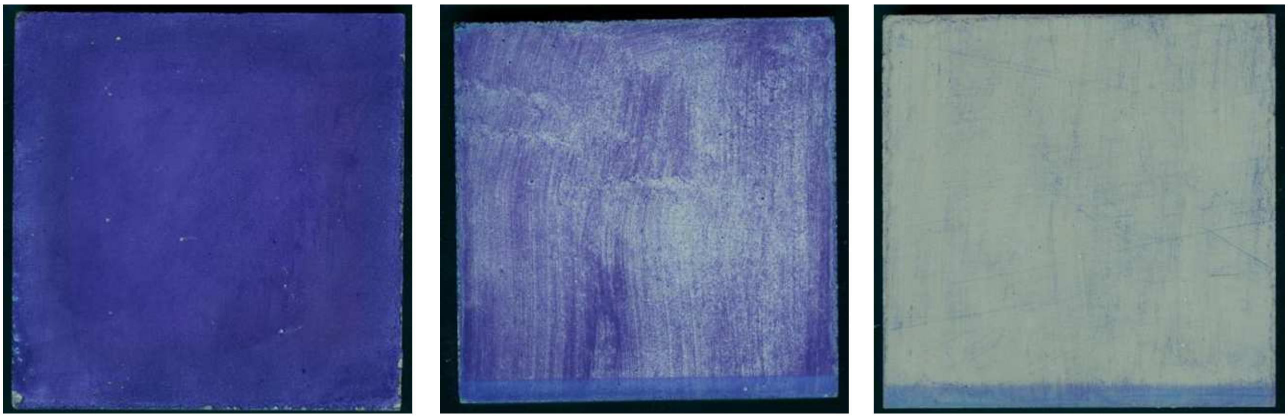
The freeze-thaw resistance of the UHPC samples was tested following the CDF test procedure according to the RILEM Recommendation TC 117-FDC [19] where the specimens are immersed in 3 wt.-% NaCl solution during the test and the assessment is based on the weight of the material that has scaled from the concrete samples. UHPC specimens (15 cm × 11 cm × 7.5 cm) were manufactured and stored after demoulding for 6 days in tap water at 20 °C. Afterwards the specimens were stored for 21 days in a climate chamber at 20 °C and 65% RH. In the last week of the storage in the climate chamber the sides of the specimens were sealed with solvent free epoxy resin. After storage, the specimens were pre-saturated for 7 days by capillary suction of the NaCl solution followed by the freeze-thaw-exposure. For the assessment of the CDF test, the dry mass of the scaled material from the surface of the test specimens was determined after 4, 14, 18, 24, 28 and 56 freeze-thaw cycles.

The resistance of the concrete to chloride penetration was tested according to the Code of Practice Chloride Penetration Resistance issued by the German Federal Waterways Engineering and Research Institute (BAW) [20], which was developed referring to the Nordtest Method (NT Build 492) [21]. With this method the intrusion of chloride ions into a concrete sample is supported by an external electrical field. After a certain test duration, the samples are split and the penetration depth is measured with the aid of a silver nitrate indicator solution. The chloride migration coefficient is calculated by the penetration depth and other parameters like applied voltage, test duration and chloride concentration in the catholyte solution. The test samples were cast in a cylindrical mould with a diameter of 100 mm and cut after demoulding into pieces of 50 mm thickness. The specimens were stored in tap water at 20 °C until the performance of the test at the age of 28 days.

Carbonation tests were performed according to EN 13295 [22]. The test procedure requires storage of the prismatic specimens (4 cm × 4 cm × 16 cm) in enriched CO_2 atmosphere (1% CO_2) and (60±10)% RH for a period of 56 days. After the storage, the specimens are broken into two pieces and the carbonation depth is assessed using a solution of phenolphthalein sprayed on the freshly broken cross sections. Phenolphthalein is an indicator that turns to pink in a pH range from about 8 to 13, which is the case of non carbonated concrete. Below pH = 8 phenolphthalein is colourless, i.e. when in contact with carbonated concrete. In this way the carbonation depth of concrete can be easily determined by measurement of the area that is not pink coloured.

Results and discussion

Photocatalytic activation. The degradation of the methylene blue caused by the UV radiation is obvious from the sample images in Fig. 2. The disadvantage of the standard tests adopted, or more in general, the disadvantage of the methylene blue and other types of dye, is their instability when exposed to UV radiation. In order to distinguish between the photocatalytic effect and the decomposition of the methylene blue caused by the UV radiation itself, it was necessary to include a polluted reference sample in the test series that was not modified with TiO_2, as noted already in [7].



(a) (b) (c)

Figure 2. UHPC sample (10 cm × 10 cm) polluted with methylene blue in the initial state (a), after 24 hours UV radiation (b) and after48 hours UV radiation (c).

In the colour measurements, using a Minolta CM 2600d spectrophotometer, three parameters were determined that define a distinct point in the L*-a*-b* colour space: L* for lightness, and a* for blue-yellow and b* for red-green dimensions. Using these parameters, every change in colour of the sample surfaces due to pollution and self-cleaning was expressed as displacement in the colour space and the decrease of pollution was quantified as ratio of the colour displacement after self-cleaning to the colour displacement from original state to polluted state.

Fig. 3 presents the evaluated test results. The reference sample without addition of TiO_2 showed a decrease of pollution of 10%, which is attributed exclusively to the decomposition of the methylene blue caused by the UV radiation. With addition of TiO_2 the decomposition of the methylene blue (decrease of pollution) was significantly higher due to the photocatalytic effect. The results demonstrate a higher efficiency of the TiO_2 Type 1 at moderate dosages.

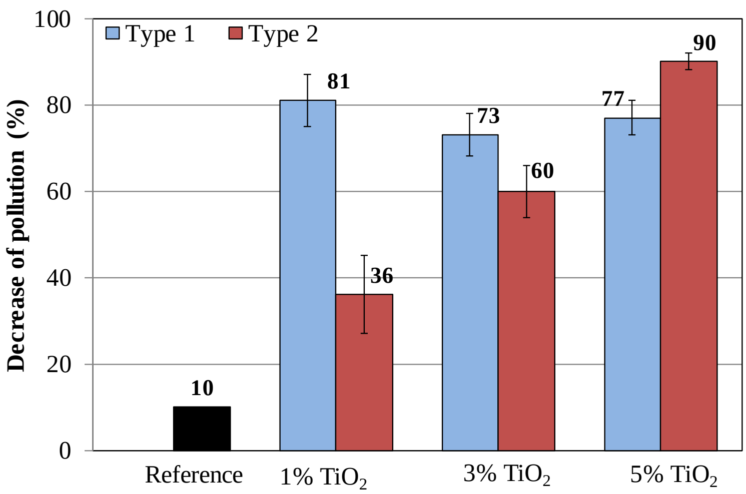
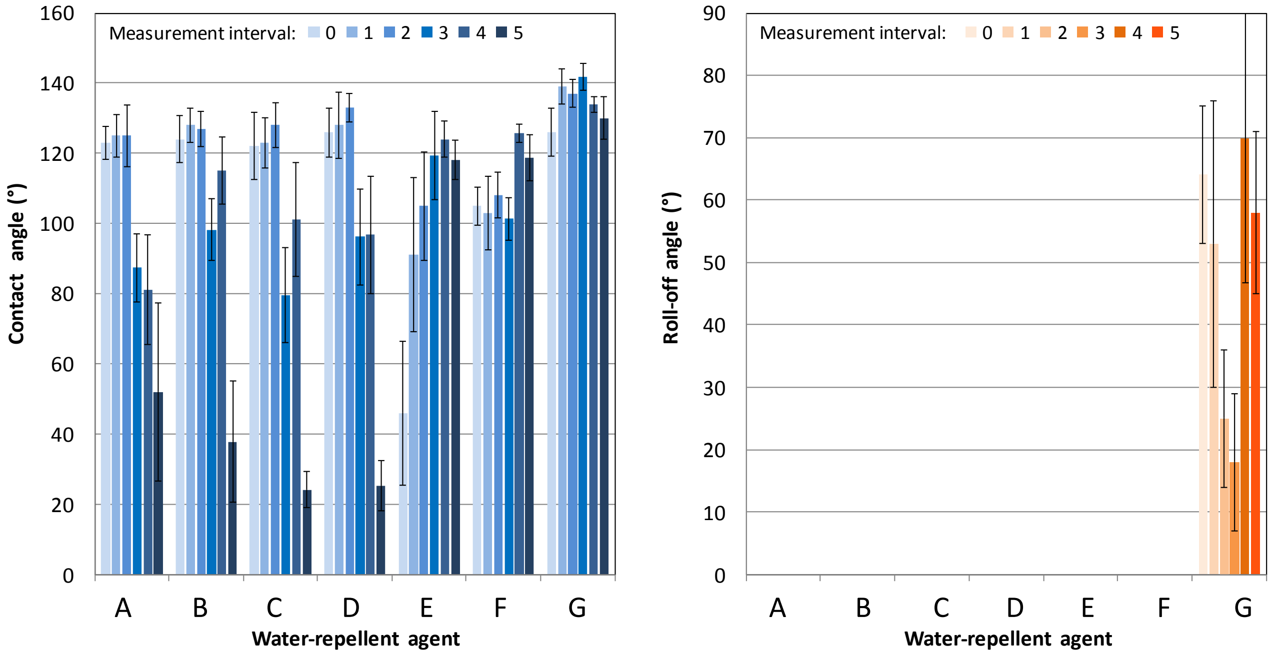


Figure 3. Influence of TiO_2 in UHPC on the decomposition of methylene blue (decrease of pollution) after 48 hours UV radiation (average values, standard deviations indicated by error bars, standard deviation in case of reference samples was 18%).

Water repellence. For test series 1 (UHPC cast on fabric and impregnation of hardened UHPC, Fig. 4) the samples with most of the water-repellent agents showed average contact angles below 130° and/or significant decrease of the contact angles when exposed to UV radiation and artificial weathering. Moreover, the roll-off angle could not be measured, i.e. the water droplets did not roll off the UHPC surface even when the table was tilted by 90°. Only exception was the sample impregnated with the product type G where the average contact angles exceeded 130° and the droplets rolled off at approx. 70° in average after weathering. Interestingly, the roll-off angles improved (decreased) until the measurements after interval 3 and degraded (increased) after weathering.



(a) (b)

Figure 4. Test series 1 (impregnated UHPC cast on fabric). Results of contact angle (a) and roll-off angle (b) measurements (average values, error bars indicate standard deviation).

For samples of test series 2 (UHPC cast on PVC and impregnation of hardened UHPC, Fig. 5) the results were even worse. Samples with six out of the seven products showed contact angles after weathering lower than or close to 90° (hydrophilic). Again, best results were achieved with the product type G with contact angles after weathering of approx. 110°. In no case the water droplets were rolling off the UHPC surfaces.

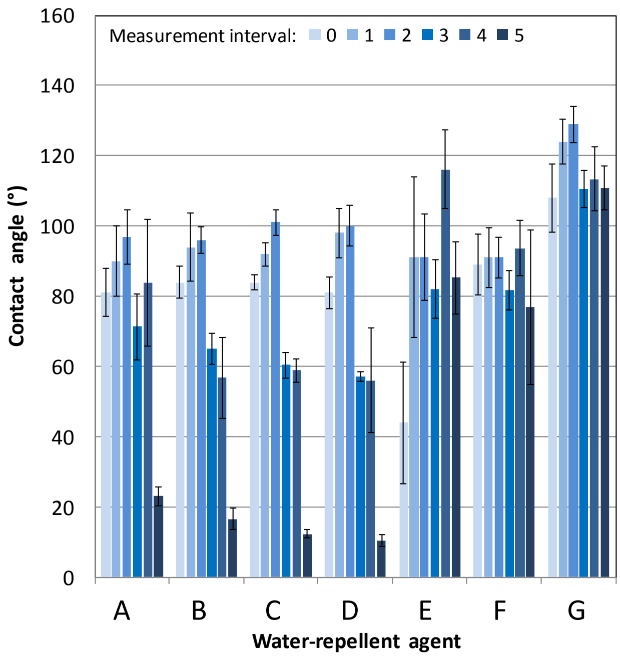
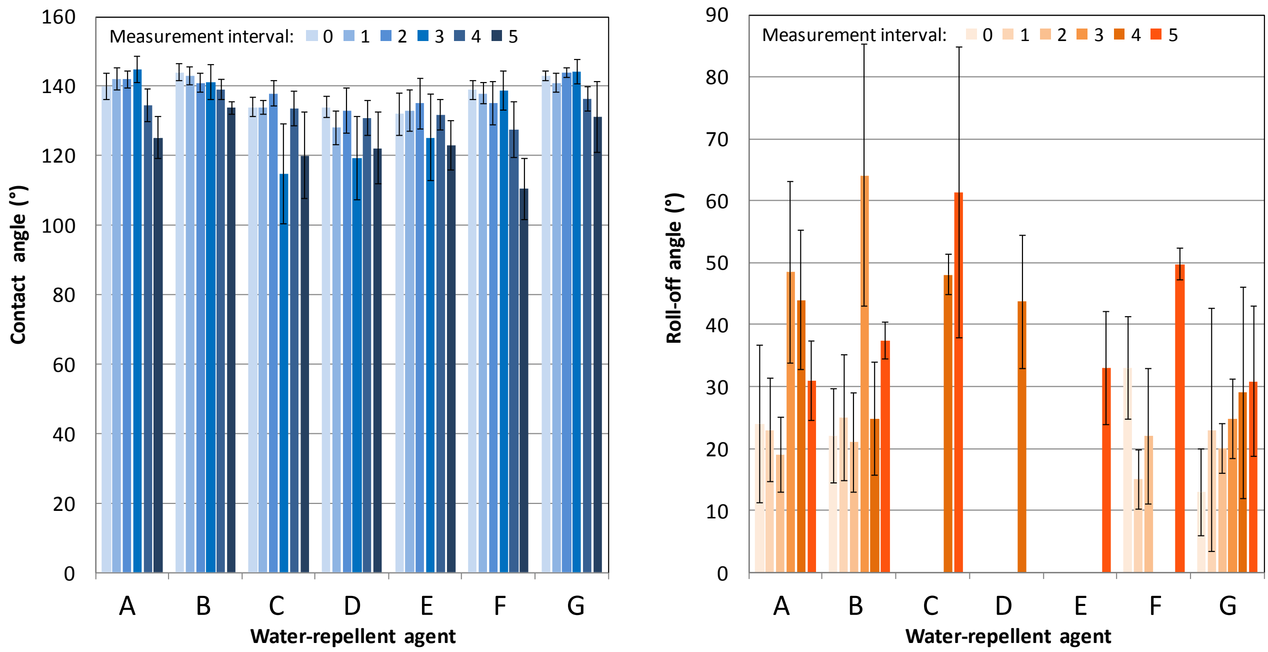


Figure 5. Test series 2 (impregnated UHPC cast on PVC). Results of contact angle measurements (average values, error bars indicate standard deviation).

Best results were generally achieved with the samples of test series 3 (UHPC cast on fabric with previous application of water-repellent agents on the fabric, Fig. 6). In two cases (products type B and type G) the contact angles exceeded 130° after weathering and with four products (Types A, B, E and G) the droplets rolled off at relatively small angles (< 40°). Interestingly, with the products type C, D and E, roll-off angles could be measured only after interval 4, i.e. after starting artificial weathering. The use of (silane-based) products type A, B and G in further development seems most promising.

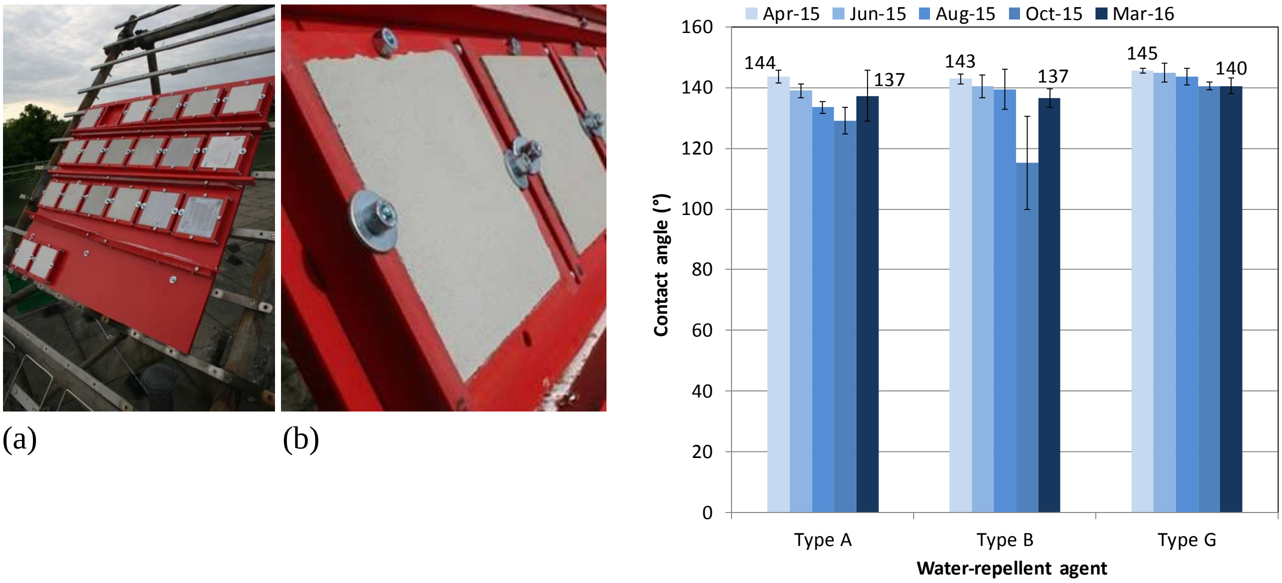


(a) (b)

Figure 6. Test series 3 (application of water-repellent agent on fabric before UHPC cast). Results of contact angle (a) and roll-off angle (b) measurements (average values, error bars indicate standard deviation).

After more than one year of exposure to outdoor weathering no change in the appearance of the UHPC samples is visible to the eye (Fig. 7). However, the colour measurements reveal slight, but distinct differences. The reference and the hydrophobic UHPC samples tend to become darker (decreasing lightness L*) when the water-repellent agent type G was used. Interestingly, the hydrophobic samples do not change in colour or tend to become even brighter (increasing lightness L*) when the water-repellent agents type A and B were used. This is also the case with the UHPC samples containing the two types of photoactive TiO_2 powder where the lightness is steadily increasing.

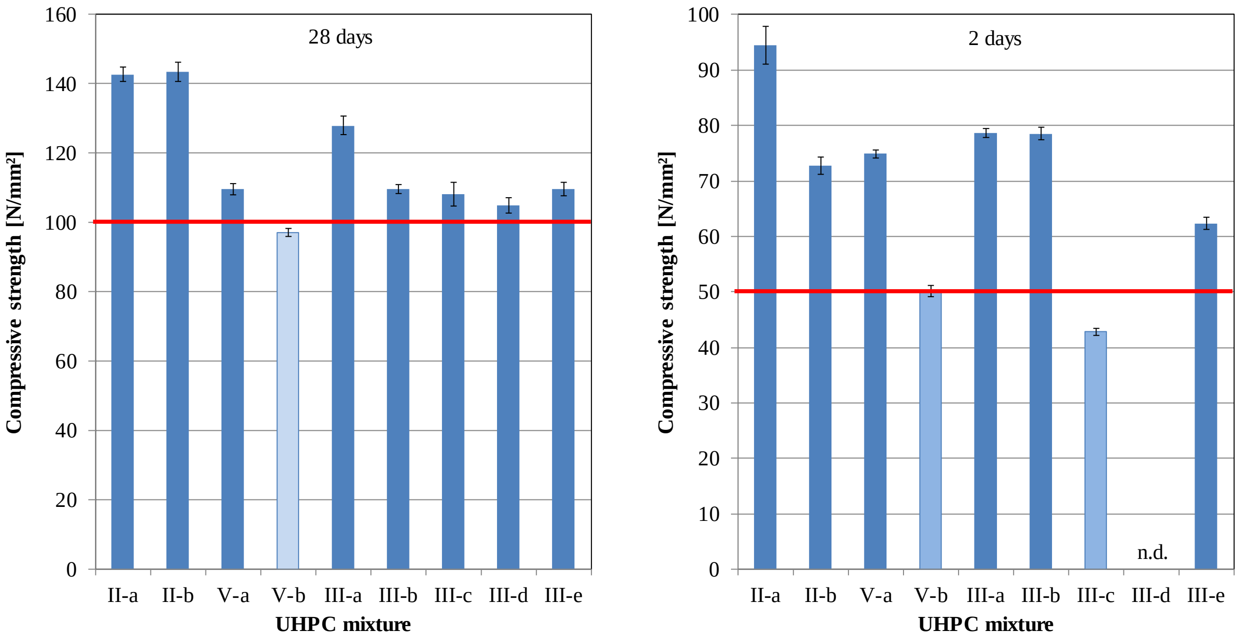
In consistence with the laboratory tests, the best results with hydrophobic surfaces were observed when the UHPC was cast on the fabric with previous application of water-repellent agent on the fabric. In comparison with the original state (measured in April 2015) the water contact angle was decreasing steadily in the first six months of exposure (Fig. 7c). In this period the total precipitation height (rain) was 235 mm, the daily average RH was between 40% and 99%. The highest air temperature was +38 °C in July 2015 and lowest air temperature was around the freezing point (-0.2 °C) once in October 2015. The total sunshine duration was approximately 1100 hours with a total global radiation of approximately 700 kWh/m² (climate data from [23]). The degradation was more pronounced with the products type A and B. Interestingly, the water repellence was recovering subsequently while there was almost no reduction in water repellence with the product type G. From October 2015 to March 2016 the daily average RH was between 64% and 99%, air temperature ranged from -12 to +15 °C with changes exceeding the freezing point on 38 days. The sunshine duration was around 260 hours with a total global radiation of 107 kWh/m² (climate data from [23]).



(c)

Figure 7. UHPC samples subjected to outdoor weathering. (a) Sample holders fixed to a rack; (b) detail of sample holders; (c) Results of contact angle measurements (UHPC cast on fabric with water-repellent agent); average values, error bars indicate standard deviation.

Mechanical properties. Results of the strength tests are reported in Fig. 8. With exception of the UHPC mixtures prepared with the binders no. V-b and III-c the requirements on the compressive strength were fulfilled by all UHPC mixtures.



(a) (b)

Figure 8. Mechanical properties of UHPC. Compressive strength after 28 days (a) and 2 days (b); average values, error bars indicate standard deviation.

Freeze-thaw resistance. In Fig. 9 the total scaling accumulated after 56 cycles is compared to the requirements of RILEM recommendations [19]. The results demonstrate that all types of UHPC can be regarded to have excellent freeze-thaw resistance. In the case of the UHPC mixtures no. II-a/b and III-a/b no scaling was observed at all.

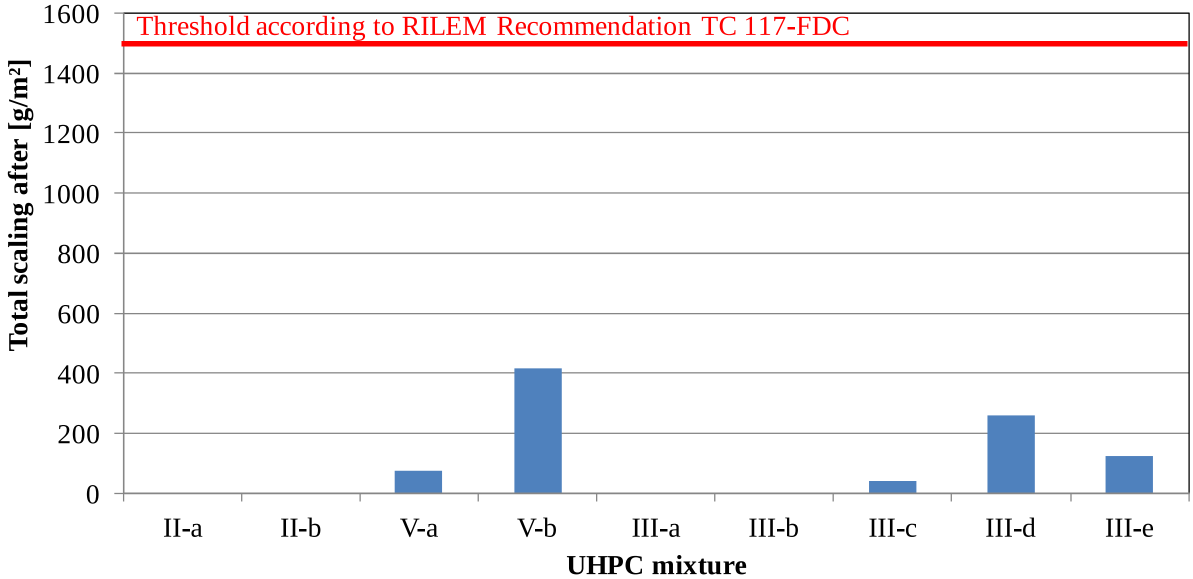


Figure 9. Results of the freeze-thaw resistance test of UHPC samples after 56 freeze-thaw cycles.

Chloride migration. The German Code of Practice [20] requires a maximum chloride migration coefficient of 5×10^{-12} m²/s for concrete that is exposed to corrosion induced by chlorides from deicing and to chlorides from sea water (exposition classes XD3 and XS3 according to EN 206 [23]). The migration coefficients of the UHPC samples obtained from the tests were significantly lower than that threshold value (Fig. 10).

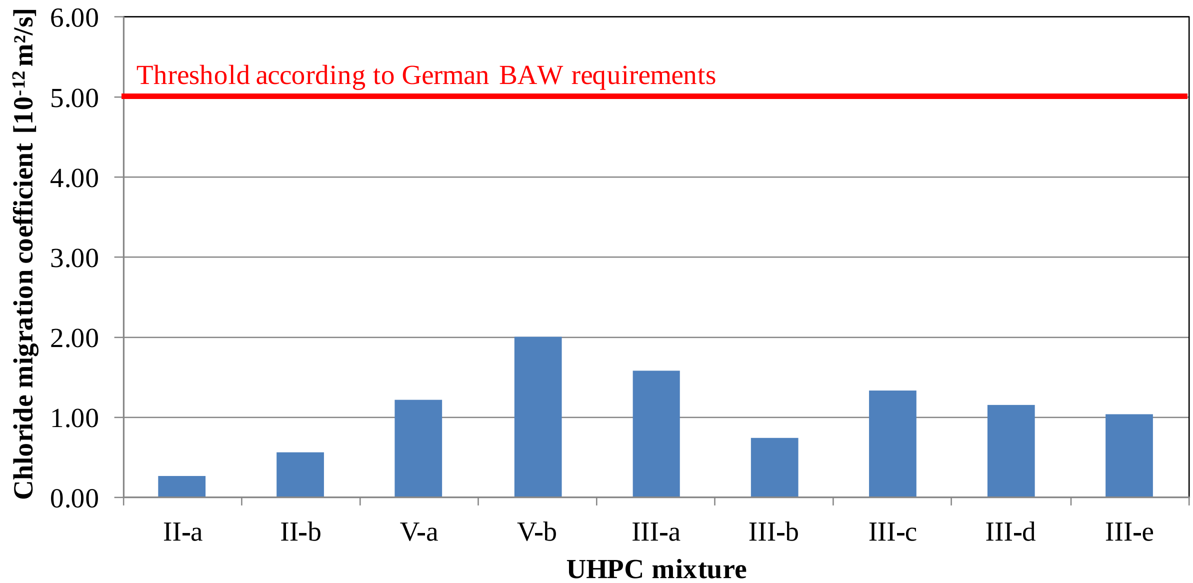


Figure 10. Chloride migration coefficients of the UHPC samples.

Carbonation. None of the UHPC samples showed noteworthy carbonation after 56 days indicating their very dense and impermeable structure. Fig. 11 is showing images of samples where the complete area of the cross sections appeares pink after contact with the phenolphthalein solution. Carbonation took place only at the surface of the specimens.

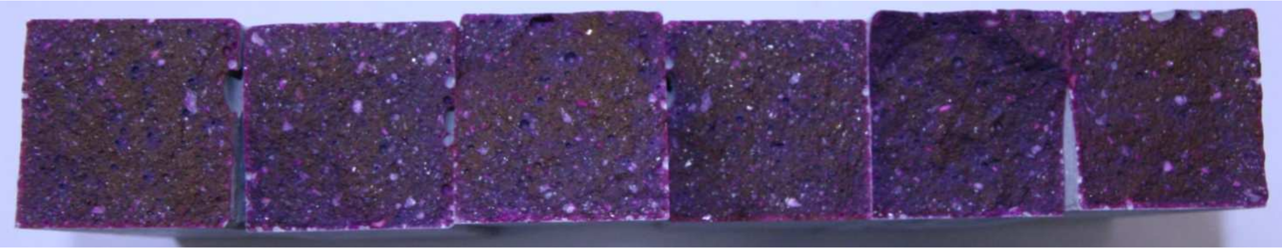


Figure 11. UHPC samples (V-a) after 56 days storage in enriched CO_2 atmosphere. Pink coloured phenolphthalein indicates non carbonated concrete.

Conclusions

The experimental investigations presented in this paper aimed at identifying appropriate ways to obtain self-cleaning surfaces that might be adopted in an industrial production of durable precast UHPC façade elements. The results revealed the suitability of fabrics for the manufacture of micro-structured UHPC surfaces, which in combination with a water-repellent agent may generate super hydrophobicity. The most efficient way to use the water-repellent agent is its application on the fabric substrate before the concrete cast. It is assumed that the active substances of the agent are incorporated better in the fresh UHPC than in the hardened UHPC when the UHPC is impregnated and the penetration of the agent might be reduced by the high density of the hardened UHPC.

Excellent test results by means of contact and roll-off angle measurements were obtained with silane-based products. Possibly, the performance of the agents can be improved by adjusting the viscosity of the products and/or by other application techniques instead of brushing, e.g. spraying or using paint rollers.

The results of the durability tests on UHPC samples produced with several binder compositions confirmed the excellent resistance of UHPC against environmental impacts and have shown that the best overall performance was obtained with the binder compositions no. III-a and no. III-b with acceptable results in the strength tests. Thus, further reduction of embodied energy was achieved by replacement of Portland cement with supplementary cementitious materials (SCM). Currently the Portland cement content can be reduced to approximately 30 wt.-% of the binder, which is equivalent to 190 kg/m³ in the UHPC. The exact composition of the binder is dependent on the quality of the SCM.

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