Composite UHPC façade elements with functional surfaces

Patrick Fontana[1], Lorenzo Miccoli[1], Ricardo Kocadag[1], Nelson Silva[2], Dirk Qvaeschning[3], Oliver Kreft[4], Christer Cederqvist[5]

1: Bundesanstalt für Materialforschung und –prüfung (BAM), Berlin, Germany
2: CBI Swedish Cement and Concrete Research Institute, Borås, Sweden
3: Dyckerhoff GmbH, Wiesbaden, Germany
4: Xella Technology and Research, Kloster Lehnin, Germany
5: Aercrete Technology AB, Bankeryd, Sweden

This paper presents an innovative way to combine an external ultra-high performance concrete (UHPC) supporting layer with an insulation layer of autoclaved aerated concrete (AAC) or cellular lightweight concrete (CLC) to create light-weight façade elements, which are improved in functionality and in energy efficiency. The durability of the façade elements is improved by developing UHPC with self-cleaning properties. 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 water-repellent agents to create durable super hydrophobicity. The current results obtained from laboratory testing are promising and demonstrate the feasibility of the approaches.

Keywords: Composite UHPC elements, photocatalysis, super hydrophobicity, self-cleaning, autoclaved aerated concrete, cellular lightweight concrete

1 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 optimised use of building area as well as economic transport and installation due to thinner light-weight elements.

The purpose of an adequate building envelope is protection against moisture ingress, heat loss in winter, excessive heating in summer and noise. The building envelope has to be durable, energy-efficient and affordable. 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 preliminary design is focussed on non-load bearing elements for new construction and for refurbishment. One major advantage compared to conventional solutions is that all components of the element are non-combustible.

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 realise 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 minimise 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.

2 Façade elements

Element design

The current design of the elements is based on the assumption of a model residential building with a floor height of 3 m. The maximum element length is supposed to be 5 m (Fig. 1). The general idea is to realise the external UHPC shell as a box-shaped element and to produce the insulation layer by simply cast the AAC/CLC into the UHPC box. In the case of the combination of UHPC and AAC, a joint autoclaving of both layers is intended, which is limiting the maximum size of the elements to approx. 3 m × 2 m due to the restricted size of the autoclaves used in AAC industry. The thickness of the insulation layer is calculated according to the materials characteristics and a target U-value of 0.15 W/(m²·K). The design of the UHPC layer is based on load assumptions required by Eurocode 2 [13].

Due to the support from the edges of the UHPC box no shear forces are generated in the UHPC-AAC/CLC interface during transport and service life. Thus, no additional connectors are necessary, provided that the bond between UHPC and AAC/CLC is sufficiently high to prevent from detachment of the layers when the composite element is tilted after demoulding and during transport. The edges are forming a frame and improve the stiffness of the element, allowing decreasing the thickness of the external UHPC layer. Moreover, the frame is providing a minimum protection to the weak insulation material during handling of the elements. In the corners, the cross section of the frame is broadened to include the assemblies for anchoring and transport/installation. The shape of the edges was optimised reducing the section height near the corners and placing openings in correspondence of the middle parts. These measures allowed the reduction of weight without compromising their structural performances. Details on production technology are reported in a previous study [14].

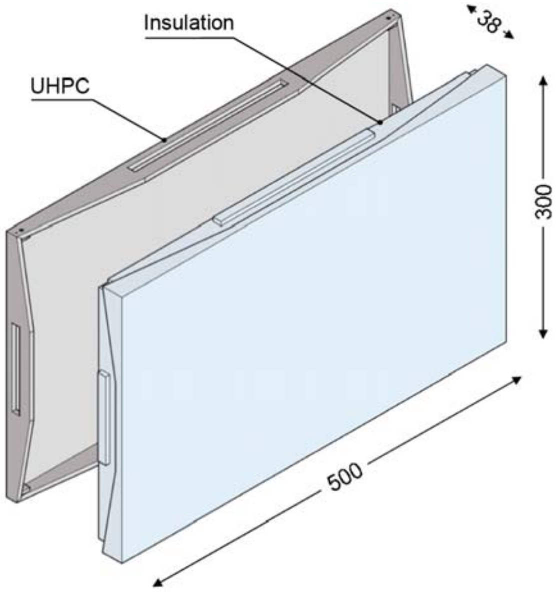


Figure 1: Basic element design (dimensions in cm).

Materials

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 [15].

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 mixture compositions (in kg/m³).

Material	Reference	1% TiO_2	3% TiO_2	5% TiO_2
Nanodur® Compound	1050	1028	984	940
TiO_2 powder	-	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

Further reduction of embodied energy was achieved by replacement of Portland cement with SCM originating also from industrial residuals. Appropriate SCM and UHPC mixture compositions were referred to minimum compressive strength of 100 N/mm². In the case of joint autoclaving of external UHPC and AAC insulation layers, the increased use of SCM is even more reasonable since their reactivity is significantly enhanced, leading to an appreciable contribution to the hydration processes in autoclaved UHPC [16].

The structure of AAC is characterised by a solid skeleton and aeration pores being formed during the aluminium-driven expansion of the slurry. The solid skeleton consists mainly of hydrothermally synthesized crystalline calcium-silicate-hydrates (thereof mainly tobermorite) and minor contributions of unreacted sand. The foam-like structure of AAC, with its solid skeleton acting as partitioning walls between the aeration pores [17], leads to an optimum correlation between weight and compressive strength. On the other hand the properties of AAC always represent a compromise of mechanical and thermal properties. In case of a certain minimum mechanical requirement, options for reducing the thermal conductivity are limited. The AAC adopted is based on Xella Multipor® technology [18]. The lowest range of thermal conductivity (λ = 42-47 mW/(m·K)) was accomplished at dry densities between 85 and 115 kg/m³ (Fig. 2a). Due to its extremely low mass, such light-weight AAC is a pure insulation material without any load bearing capacity.

In order to be used as a high performance insulation material, very low density CLC must be developed. The goal is to achieve a thermal conductivity of λ = 30-35 mW/(m·K) at a density around 150 kg/m³. Given the high volume of foam, the main challenge is to guarantee that the cementitious matrix sets fast enough to sustain the porous structure without collapse of the foam. For this purpose, calcium sulfoaluminate cement was chosen as binder, which sets much faster compared to Portland cement. Initial tests showed that at low densities, similar to AAC, the compressive strength of CLC is very low. The results from thermal conductivity measurements (Fig. 2b) are quite promising. At a density of about 300 kg/m³, the λ-value is around 70 mW/(m·K). Given the good linear correlation with density, λ < 45 mW/(m·K) can be expected for the target density of the research. Additional improvement of the thermal performance can be expected by the incorporation of aeogels based on the Quartzene® technology. Typical bulk densities of the Quartzene® materials fall in the range 40-150 kg/m³, the specific surface area (BET) is up to 750 m²/g, and the thermal conductivity is presently 22-27 mW/(m·K).

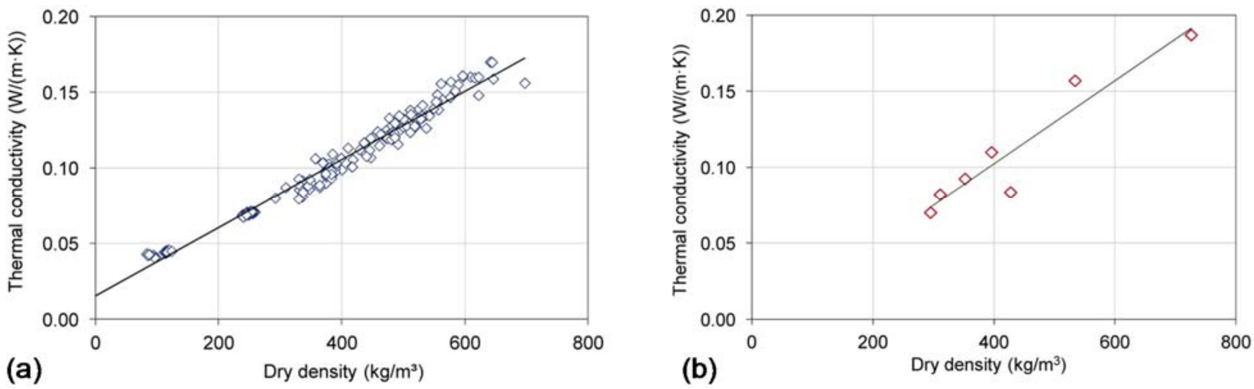


Figure 2: Correlation between thermal conductivity and dry density. (a) AAC; (b) CLC.

3 Self-cleaning surfaces

Photocatalytic activity

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 [19] and DIN 52980 [20]. 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 (40 W/m²) at 23 °C and 50% relative humidity (RH) and subsequent spraying of water with 2 bar pressure for 15 seconds. The degradation of the methylene blue caused by the UV radiation is obvious from the sample images in Fig. 3. The disadvantage of the standard tests adopted, or more in general, the disadvantage of the methylene blue and other types of dye, might be 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 was noted already in [7].

(a) (b) (c)

Figure 3: 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. 4 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.

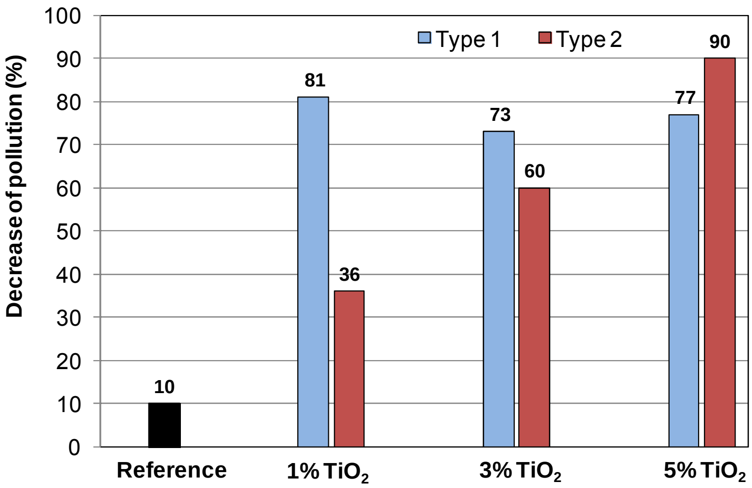
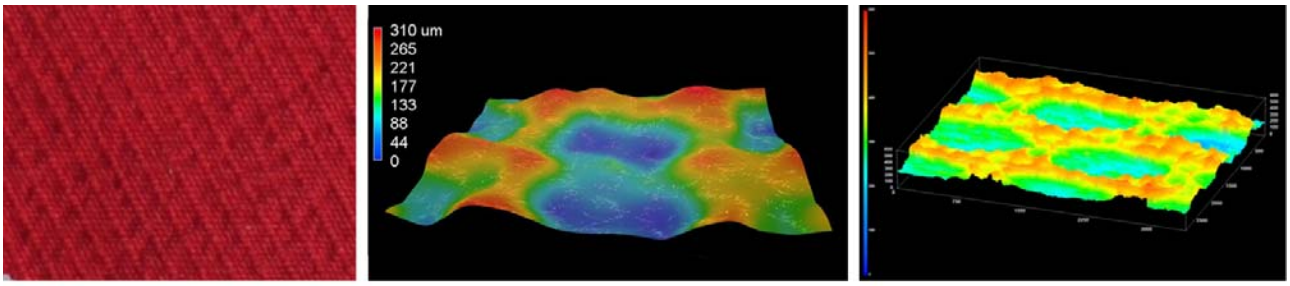


Figure 4: Influence of TiO_2 in UHPC on the decomposition of methylene blue (decrease of pollution) after 48 hours UV radiation.

Water repellence

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. 5a) was used as substrate for the UHPC cast to generate a micro structured imprint. Due to the excellent fresh concrete properties and the high packing density of the ultrafine particles of the Nanodur® based UHPC the reproduction of micro structure was almost perfect (Fig. 5b-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 5: (a) Fabric, (b) Micro structure of fabric, (c) Micro structure of UHPC surface cast on fabric.

As already stated in [11], concrete surfaces without any hydrophobic treatment, even if micro-structured, are hydrophilic (Fig. 6a). Hydrophobic concrete surfaces are obtained only by application of water-repellent agents (Fig. 6b).

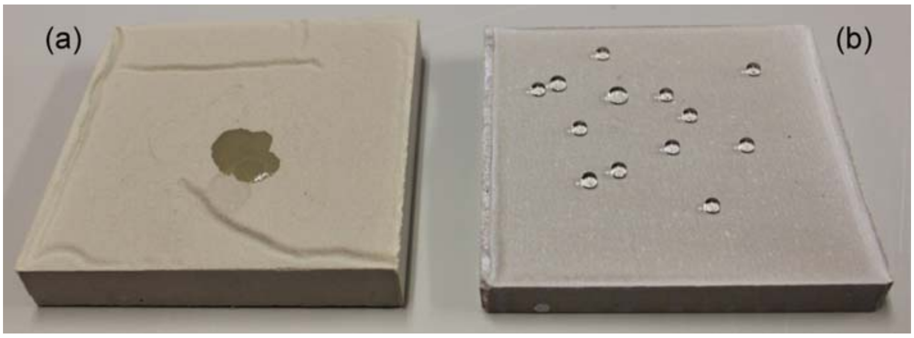


Figure 6: Surface of UHPC samples. (a) Micro-structured only. (b) Micro-structured and impregnated with water-repellent agent after demoulding.

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 automatically when the water droplet is rolling off the sample surface. The lower the roll-off angle, the more pronounced is the water repellence.

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 measurements were performed after storing the samples for 14 days at 23 °C and 50% RH. From the results of the contact angle measurements shown in Fig. 7a it is evident that in general the best performance, i.e. the highest water contact angles, were obtained with the samples where the water-repellent agents were applied on the fabric before the cast of the UHPC. The lowest contact angles were obtained when the UHPC was cast on the PVC and impregnated with the water-repellent agents after initial hardening. Intermediate results were obtained when micro structured UHPC surface was impregnated. The best results were obtained with the products A, B and G with contact angles ≥ 140°, and the product F.

The results of the roll-off angle measurements are presented in Fig. 7b. Roll-off angles were measured only with the products A, B, F and G when the water repellent agents were applied, with which the highest contact angles were measured, and with the product G when it was applied on the micro-structured UHPC surface. No roll-off angles are indicated when the samples were rotated up to 90° (vertical position) and the water droplets were still sticking to the sample surface and not rolling off.

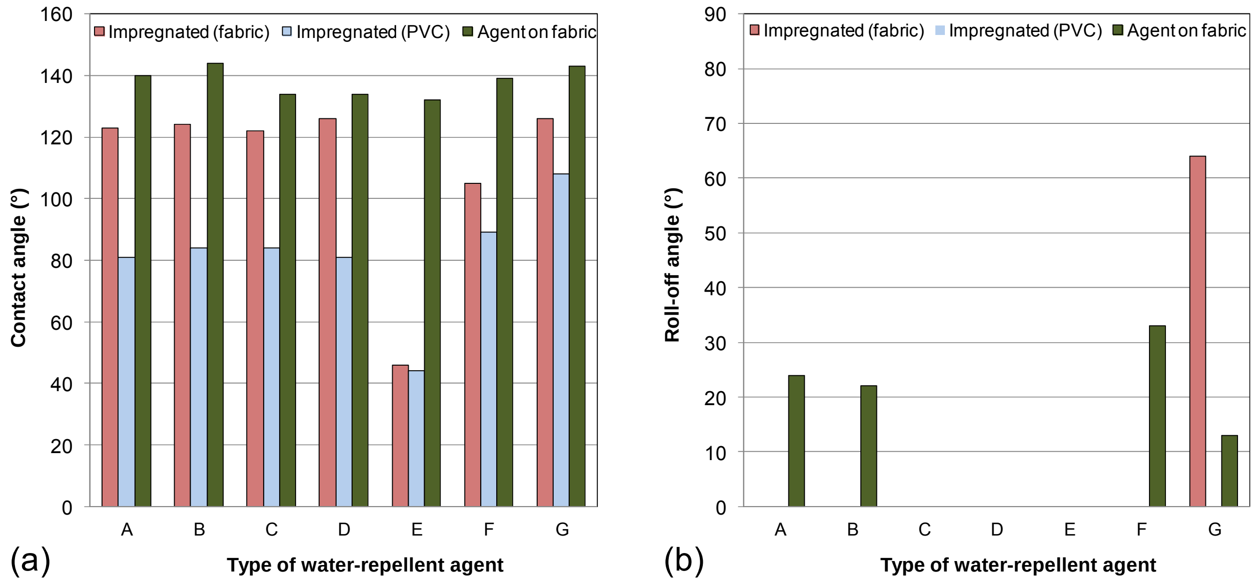


Figure 7: Results of contact angle (a) and roll-off angle (b) measurements.

Fig. 8 shows images of the samples (10 cm × 10 cm) with the best results related to contact angle and roll-off angles measurements. The images were captured three weeks after demoulding and subsequent storage at 23 °C and 50% RH. Using the paste-like products A and B (Fig. 8a-b) brush marks were clearly visible, whereas with the liquid product G the surface was much more homogeneous in colour (Fig. 8c).

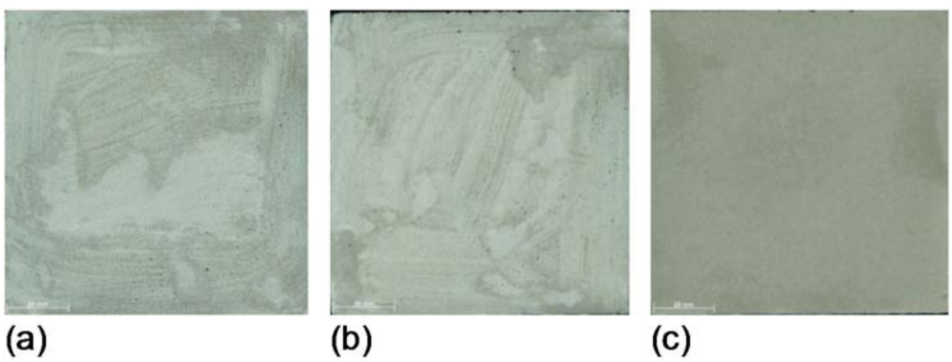


Figure 8: Images of samples prepared with water-repellent agents applied with a paintbrush on fabric substrate before concrete cast.

4 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 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 test results have shown that 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 three silane-based products However, while the liquid product did not influence the surface quality of the UHPC, it was impaired when the paste-like products were used. Possibly, the performance of the agents can be improved by adjusting the products more liquid and/or by other application techniques instead of brushing, e.g. spraying or using paint rollers.

Preliminary results of artificial weathering tests revealed consistently good performance of the water repellence in the case of the aforementioned silane-based products when applied on the fabric substrate before the concrete cast. The tests included 140 heating and freeze-thaw cycles with a total UV-A radiation of approximately 145 MJ/m². However, UHPC samples with water-repellent and with photocatalytic surfaces are currently exposed to urban environment at BAM premises being located close to a main road to evaluate the performance of the functional surfaces in the long-term by means of water contact angle and roll-off angle measurements as well as colour and gloss measurements. The efficiency of photocatalytic concrete surfaces based on the use of TiO_2 might be impaired by soiling as reported in [21] where the efficiency of the photoactivity was recovered to a large extent after manual cleaning of the surfaces.

The concept of a box-shaped UHPC structural layer is a simple and robust solution for the composite façade elements. Besides the good structural performance, the concept enables efficient protection of the insulation layer during transport, installation and use. Additionally, due to the absence of reinforcement and connectors through the insulation, the production technology does not involve major labour-intensive tasks, which is desirable for scale-up, and the thermal performance of the elements is not impaired. With the current design the U-value of the composite elements was numerically estimated to < 0.15 W/(m²·K) considering a thermal conductivity of the mineral insulation layer of λ = 45 mW/(m·K).

Acknowledgements

This research study was made possible with the support of the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no. 608893 (H-House, www.h-house-project.eu).

References

[1] Ahlborn, T.M.; Misson, D.L.; Peuse, E.J.; Gilbertson, C.G.: Durability and Strength Characterization of Ultra-High Performance Concrete under variable Curing Regimes. Proc. 2nd Int. Symp. on Ultra High Performance Concrete, Kassel 2008, pp.197-204.

[2] Thomas, M.; Green, B.; O'Neal, E.; Perry, V.; Hayman, S.; Hossack, A.: Marine performance of UHPC at Treat Island. Proc. HiPerMat 2012, 3rd Int. Symp. on UHPC and Nanotechnology for High Performance Construction Materials, Kassel 2012, pp. 365-370.

[3] Piérard, J.; Dooms, B.; Cauberg, N.: Evaluation of Durability Parameters of UHPC Using Accelerated Lab Tests. Proc. HiPerMat 2012, 3rd Int. Symp. on UHPC and Nanotechnology for High Performance Construction Materials, Kassel 2012, pp. 371-376.

[4] Acker, P.; Behloul, M.: Ductal® technology: A large spectrum of properties, a wide range of applications. Proc. Int. Symp. On Ultra High Performance Concrete, Kassel 2004, pp. 11-23.

[5] Behloul, M.; Batoz, J.-F.: Ductal® applications over the last Olympiad. Proc. 2nd Int. Symp. on Ultra High Performance Concrete, Kassel 2008, pp. 855-862.

[6] Rebentrost, M.; Wight, G.: Experiences and applications on Ultra-high Performance Concrete in Asia. Proc. 2nd Int. Symp. on Ultra High Performance Concrete, Kassel 2008, pp. 19-30.

[7] Folli, A.; Pade, C.; Hansen, T.; De Marco, T.; Macphee, D.E.: TiO_2 photocatalysis in cementitious systems: Insights into self-cleaning and depollution chemistry. Cement and Concrete Research 42, pp. 539-548, (2012).

[8] Pacheco-Torgal, F.; Jalali, S.: Nanotechnology: Advances and drawbacks in the field of construction and building materials. Construction and Building Materials, 25, pp. 582-590, 2011.

[9] Diamanti, M.V.; Ormellese, M.; Pedeferri, M.: Characterization of photocatalytic and superhydrophilic properties of mortars containing titanium dioxide. Cement and Concrete Research 38, pp. 1349-1353, 2008.

[10] European patent specification EP 2 156 932 “Concrete separator”, 2011.

[11] Malaga, K.; Lundahl, A.; Kargol, M.A.: Use of technical textile to obtain sustainable easy to clean concrete surface. Proc. Hydrophobe VI, 6th Int. Conf. on Water Repellent Treatment of Building Materials, Rome 2011, pp. 181-188.

[12] Horgnies, M.; Chen, J.J.: Superhydrophobic concrete surfaces with integrated microtexture. Cement & Concrete Composites 52, pp. 81-90, 2014.

[13] EN 1992-1-1 (2004), Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings.

[14] Miccoli, L.; Fontana, P.; Silva, N.; Klinge, A.; Cederqvist, C.; Kreft, O.; Qvaeschning, D.; Sjöström, C.: Composite UHPC-AAC/CLC facade elements with modified interior plaster for new buildings and refurbishment. Materials and production technology. Journal of Facade Design and Engineering 3 (1), pp. 91-102, 2015.

[15] Deuse, T.; Hornung, D.; Möllmann, M.: From Mikrodur to Nanodur technology - Standard cement for practice-oriented manufacture of UHPC. BFT International 75 (5), 2009.

[16] Fontana, P.; Lehmann, C.; Müller, U.; Meng, B.: Reactivity of mineral additions in autoclaved UHPC. Proc. Int. RILEM Conference on Material Science (MatSci), Vol. III, Additions Improving Properties of Concrete (ADIPoC), Aachen 2010, pp. 69-77.

[17] Alexanderson, J.: Relations between structure and mechanical properties of autoclaved aerated concrete. Cement and Concrete Research 9 (4), pp. 507-514, 1979.

[18] European Technical Approval ETA-05/0093, Multipor thermal insulation panel, 2011.

[19] EN 1096-5 (2011): Glass in building - Coated glass - Part 5: Test method and classification for the self-cleaning performances of coated glass surfaces.

[20] DIN 52980 (2008): Photocatalytic activity of surfaces – Determination of photocatalytic activity by degradation of methylene blue.

[21] Diamanti, M.V. et al.: Long term self-cleaning and photocatalytic performance of anatase added mortars exposed to the urban environment. Construction and Building Materials 96 (2015), pp. 270–278.