UHPC-AAC/CLC composite panels with self-cleaning properties. Materials and production technology

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Abstract

The aim of this study is to show the development of a façade composite panel combining either an autoclaved aerated concrete or a cellular lightweight concrete insulation layer with a box-type external ultra-high performance concrete (UHPC) supporting layer.

The paper presents the materials characteristics of the different components and the production technology of the panel. The efficiency of surface modifications of the materials forming the external shell of the panel is reported. The activation of self-cleaning properties is described. The test results showed that the most efficient way to use the water-repellent agent is its application on the substrate before the concrete cast.

Concerning the production technology, the preliminary studies showed more advantages of a two-step manufacturing procedure of the UHPC boxes than a one-step procedure.

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 as a thin layer and with the replacement of Portland cement by less energy intensive supplementary cementitious materials (SCM), they show some advantages such as lower embodied energy and reduced environmental impact. Predictions suggest that UHPC composite elements for building envelopes could have other benefits such as an increased service life, optimised use of building area due to thinner elements and minimised maintenance due to the absence of reinforcement or use of non-corrosive reinforcing materials such as carbon fibres.

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 this framework the development of prototype façade elements comprising UHPC in combination with either autoclaved aerated concrete (AAC) or cellular lightweight concrete (CLC) is presented. UHPC exhibits extreme high strength and excellent chemical durability. The exceptional properties of UHPC are the result of a high packing density based on an optimised particle size distribution and significant reduction of water in the cement paste compared to ordinary concrete [1]. The workability of UHPC is adjusted by adding highly efficient superplasticisers and thus obtaining flowable mixes with self-compacting properties. The very high density of the material 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 [2], [3], [4]. UHPC was already applied successfully to building constructions, such as lightweight roof constructions, facade elements [5], [6], [7] and protection panels [8].

In this study two insulation materials were employed, lightweight AAC and CLC with a dry density of 90 kg/m^3 and 180 kg/m^3, respectively. These materials provide a low thermal conductivity in combination with mechanical properties adequate for the use as insulation layer in composite elements [9]. The major advantage compared to conventional solutions is that all components of the element are non-combustible.

A new typology of a composite UHPC-AAC/CLC element was developed. It is non-load bearing and it was conceived to be used for new buildings and for renovation of existing buildings. Small-scale elements were manufactured to assess the feasibility of the industrial production process.

2. Façade element components

The general idea is to realise the external UHPC shell as a box-shaped element. Due to the support from the edges of the 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. Moreover, the edges are forming a frame and improve the stiffness of the box-shaped element, allowing decreasing the thickness of the exterior UHPC layer [10]. In the corners, the cross section of the frame is broadened to include the assemblies for anchoring and transport/mounting. Fig. 1 and Table 1 give an overview of the geometry of the panels. The design was based on load assumptions required by Eurocode 2 [11]. In particular a wind speed of 44 m/s equivalent to a wind load of 1.66 kN/m^2 was considered.

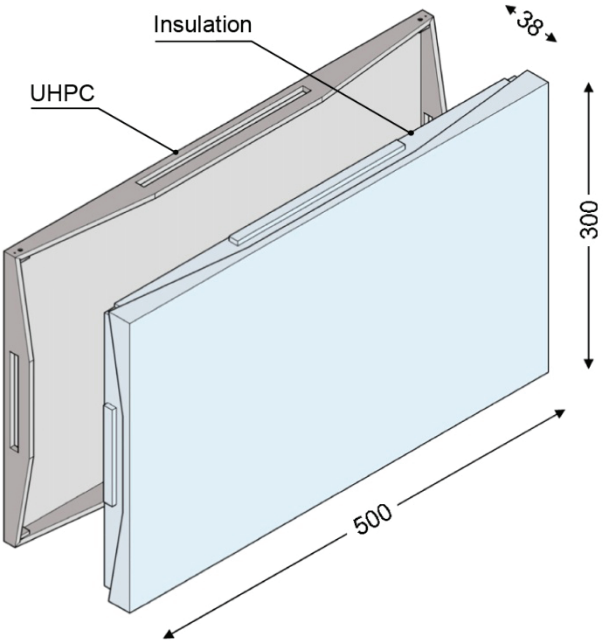

Fig. 1. Composite panel, non-load bearing: 5 m × 3 m.

Table 1. Geometrical parameters of composite panels.

Insulation	L × H (m)	UHPC ext. layer thickness (mm)	Insulation thickness (mm)	Total thickness (mm)	Total weight (kg)	Weight (kg/m²)
AAC	5 × 3	25	355	380	1620	108
CLC					2080	139

2.1 UHPC

Due to the extraordinary high strength and the high density of UHPC, it is possible to produce thin and durable façade elements. The use of UHPC for lightweight elements would reduce the environmental impact in relation to manufacturing, transport and installation processes.

The UHPC adopted is based on Dyckerhoff Nanodur® technology. Nanodur compound 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 wet mixing process of the UHPC with a standard concrete mixer is simplified significantly (Table 2). Nanodur cement is a CEM II B-S 52.5 R according to EN 197-1, 2011 [12].

Further reduction of embodied energy was achieved by replacement of Portland cement with less energy intensive SCM originating also from industrial residuals. In order to increase the performance of UHPC, hydrothermal treatment (autoclaving) is applied [13], a technique used for the industrial production of AAC elements. Solutions are referred to minimum compressive strength of 100 N/mm² for non-load bearing applications and high quality of the UHPC surface.

Table 2. Composition of UHPC mixtures and obtained density.

Material	Nanodur® Compound	Sand 0/2 mm	Superplasticiser	Water	Dry density
(kg/m^3)	1050	1150	17.9	178.5	2440

Self-cleaning properties are based on the interaction of the specific micro structure and the chemical (water-repellent) nature of the surface that makes a water droplet taking off pollutions from the surface when it is easily rolling off. Super hydrophobicity is usually associated with contact angles of a water droplet ≥ 140-150° (when the contact angle is < 90°, the surface is hydrophilic). A second important parameter is the roll-off angle, i.e. the angle at which a water droplet on the sample surface is rolling off during rotation from the horizontal to the vertical. The lower the contact angle is, the more pronounced is the water repellence and the associated self-cleaning effect. The challenge to create a permanent super hydrophobic concrete surface is therefore the adequate and durable replication of a specific micro structure in combination with effective and durable chemical water repellence (Fig. 2).

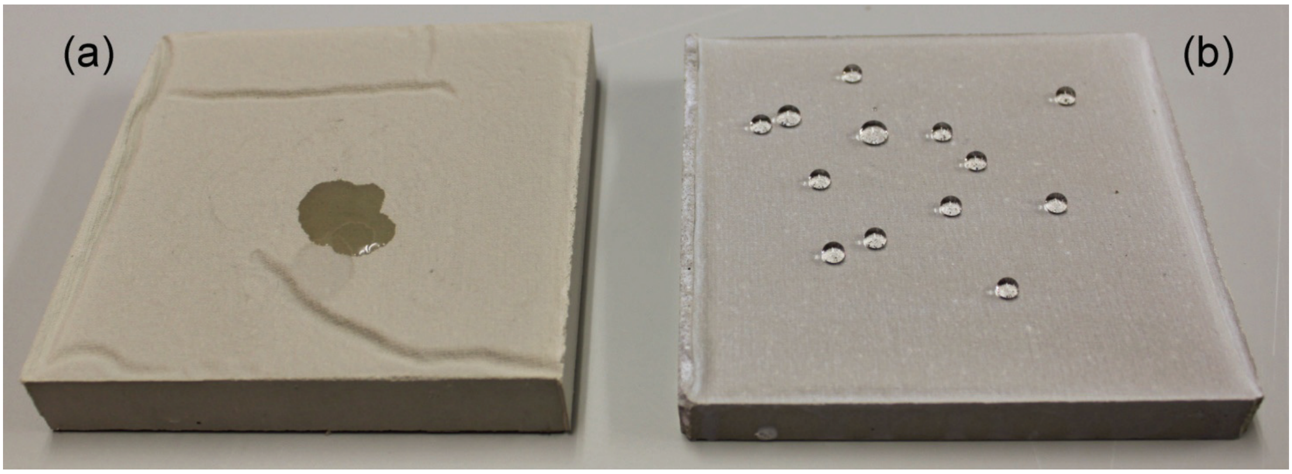

Fig. 2. Surface of UHPC samples. (a) Structured only. (b) Impregnated with water-repellent agent after demoulding.

Fabrics were used as substrate for the UHPC cast to create a micro structured surface. Tests with micro structured UHPC surfaces aimed to evaluate the influence of two different application techniques of the chemical agents on the water repellence. The first technique consisted of impregnation of the hardened UHPC with the chemical agents, which is commonly used on buildings for restoration and maintenance purposes or in concrete precast plants to equip concrete elements with water repellence before transport to the construction site. The second technique was based on the idea to incorporate the chemical agent in the fresh UHPC by its application on the substrate in the formwork shortly before the UHPC cast, and thus to ease the production process. After demoulding and impregnation, respectively, the samples were stored for 14 days at 23 °C and 50% RH.

Contact and roll-off angle measurements were performed using seven types of water-repellent agents (commercial products). In general, the application of the water-repellent agents on the substrate in the formwork resulted in higher contact angles compared to the impregnated UHPC samples (Fig. 3a) and with three agents (silane-siloxane-based products A, B and G) obtaining contact angles ≥ 140°. The good performance of these agents in combination with their application on the substrate is demonstrated also by the results of the roll-off angle measurements in Fig. 3b, where the high contact angles correlate well with low roll-off angles (products A, B, F and G). As for the impregnated samples, in only one case (product G) was possible to measure the roll-off angle; in all other cases the water droplets did not roll off even at vertical position (90°) of the sample surface.

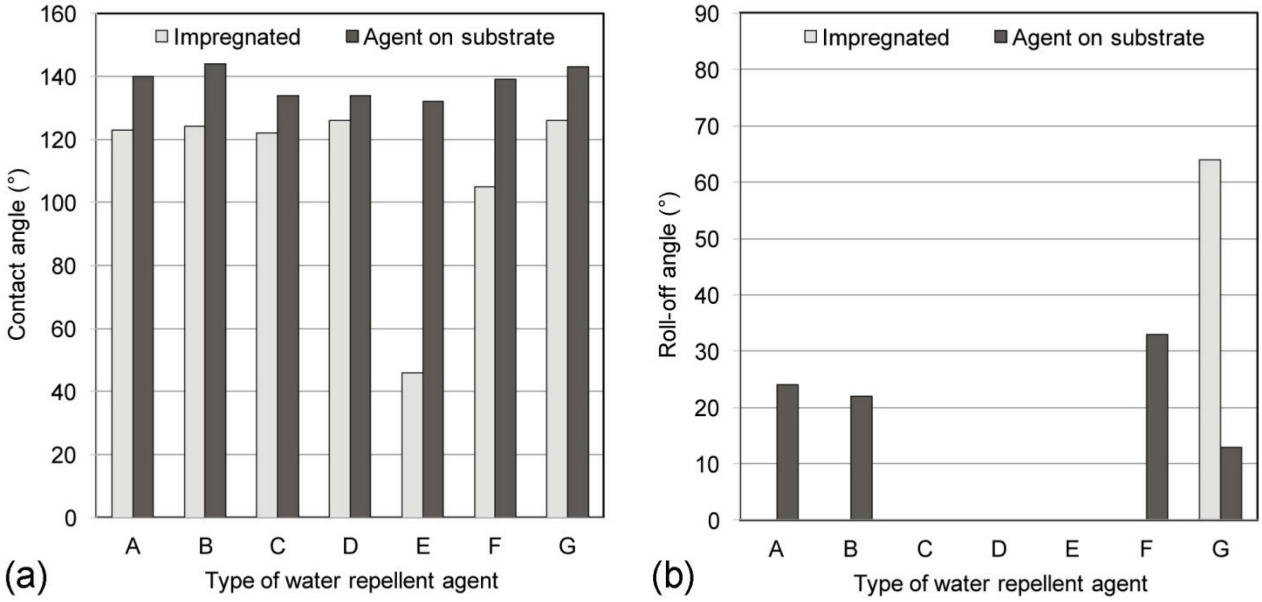

Fig. 3. Results of contact angle (a) and roll-off angle (b) measurements.

2.2 Insulation materials

2.2.1 AAC

The material structure of AAC is characterised by a solid skeleton and aeration pores being formed during the aluminium-driven expansion of the cementitious slurry. The solid skeleton consists of hydrothermally synthesized crystalline calcium-silicate-hydrates (thereof mainly tobermorite) and, moreover, minor contributions of unreacted sand. The foam-like structure of AAC, with its solid skeleton acting as partitioning walls between the aeration pores [14], leads to an optimum correlation between weight and compressive strength. Millions of aeration pores lead to a low thermal conductivity making AAC a highly thermal insulating building material.

Thermal conductivity depends on temperature, density, structure and chemical nature of the material. In AAC, it is largely a function of density and moisture content [15], [16], [17].

For this reason, improvements of the thermal performance of AAC had been mainly achieved by reducing the dry density (Fig. 4a). Although the strength of the remaining solid skeleton could be steadily improved in the last decades, decreasing the dry density by trend leads to losses in the compressive strength (Fig. 4b). In other words, the material 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. For AAC, the lowest range of lambda-values (declared thermal conductivities = 42 to 47 mW/(m·K)) [9], [18] was accomplished at dry densities between 85 and 115 kg/m^3. Due to its extremely low mass, such light-weight-AAC is a pure insulation material without any load bearing capacity (see Table 3). The difference is only the dry density, being achieved by altering the amount of aluminium (the more aluminium the lower the dry density).

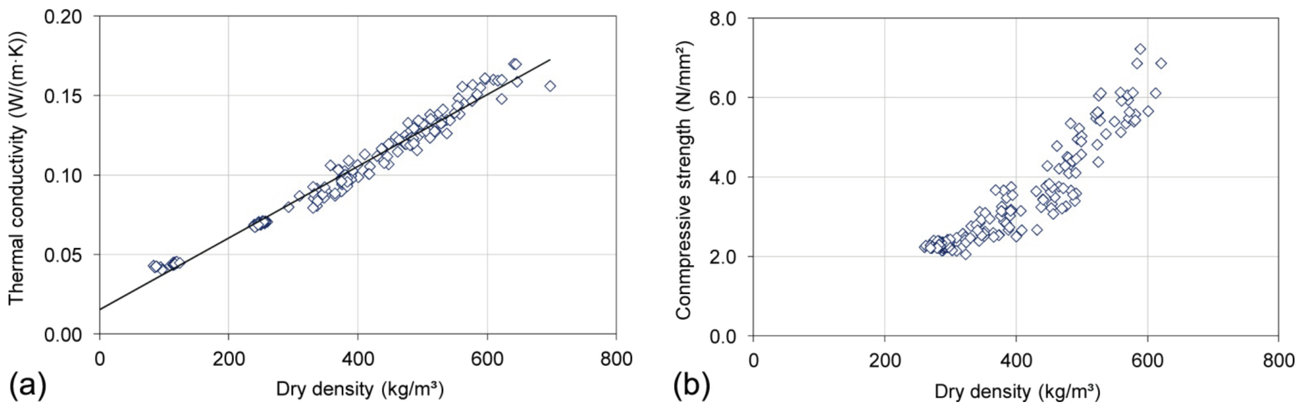

Fig. 4. Correlation between AAC dry density and: thermal conductivity (a); compressive strength (b).

Table 3. AAC. Range of mix proportions tested and obtained densities.

Material	Cement	Sand	Quick lime	Anhydrite/ Gypsum	Mineral aggregate	Aluminium [a]	Dry density
(kg/m^3)	250-500	250-400	50-250	30-70	100-200	5-8	85-115

[a] used as porosing/blowing agent.

2.2.2 CLC

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 30-35 mW/(m·K) at a density around 150 kg/m^3. 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 was chosen as binder, which sets much faster when compared to Portland cement. Table 4 lists the range of mix compositions tested with respective target and obtained densities. Initial tests had for objective to evaluate the compressive strength and thermal conductivity of a series of samples to be used as a benchmark for further development.

Table 4. CLC. Range of mix proportions tested and obtained densities.

Material	Cement	Sand	SP	w/c	V_F (l)	Density		
						Target	Wet	Dry
(kg/m^3)	72-303	76-258	0.4-1.8	0.25-0.5	737-952	155-637	165-958	175-734

SP = superplasticizer; V_F = volume of foam.

The results in Fig. 5a show that, at low densities, very low values of compressive strength are obtained; in addition, the scatter is also large. This is typical for CLC in which the mechanical properties are very much dependent on the homogeneity of the air void distribution.

The results from thermal conductivity measurements (Fig. 5b) are quite promising; at a density of about 300 kg/m^3, the λ-value is around 70 mW/(m·K). Given the good linear correlation with density, a λ-value below 45 mW/(m·K) can be expected for the target density of the research.

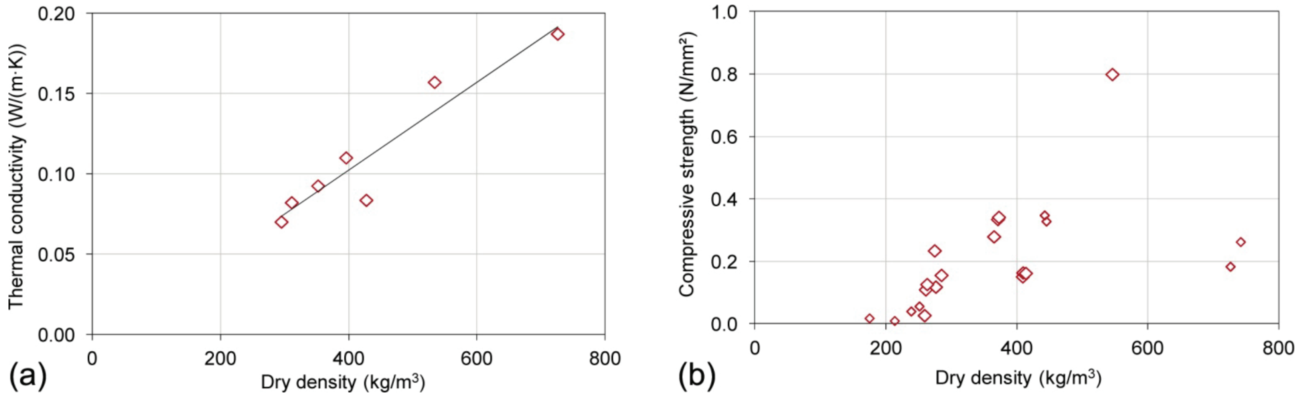

Fig. 5. Correlation between CLC dry density and: thermal conductivity (a); compressive strength (b).

3. Production technology of composite UHPC-AAC/CLC

3.1 Manufacturing of UHPC boxes

First trials were dedicated to the one-step production of the box-shaped UHPC elements (60 cm × 40 cm), i.e. the exterior UHPC layer and the upturning edges are cast with a single concrete batch.

For this purpose a ‘floating body’ was adopted. The protection of the floating body against buoying upwards requires accurate measures when full hydrostatic pressure is considered. In the case of full-scale elements, where the buoyancy may reach high values, it might be too complex to accurately fix the floating bodies. Therefore, in a second approach, further trials were dedicated to a two-step production procedure of the UHPC box with the upturning edges of the box being cast on top of the exterior layer after initial hardening (Fig. 6).

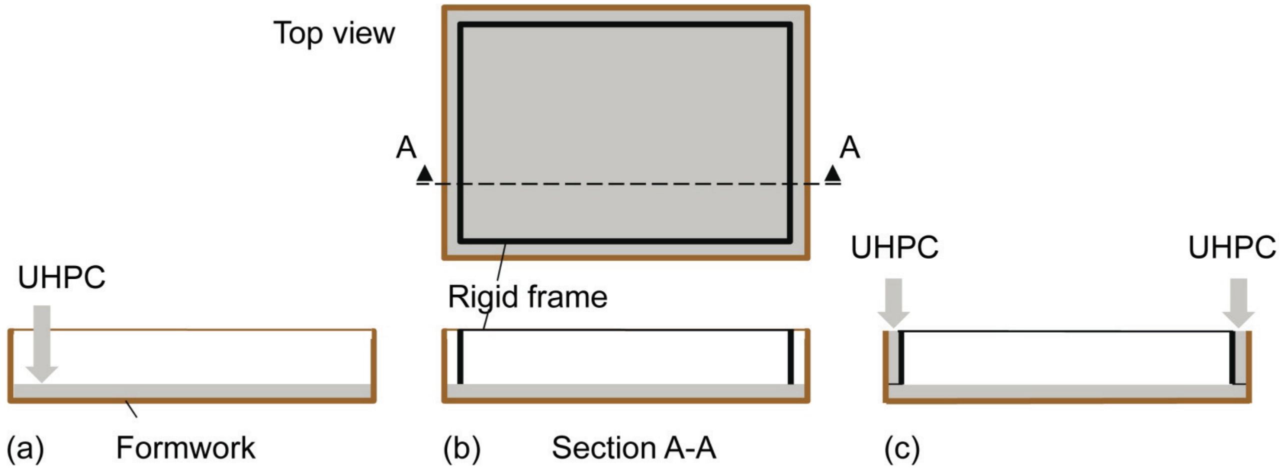

Fig. 6. Procedure for two-step production of box-shaped UHPC elements. (a) Cast of exterior layer. (b) Placement of a rigid frame as internal formwork on hardened exterior layer. (c) Cast of upturning edges.

In the first trials a hardened AAC block was used as internal formwork. One day after casting of the exterior layer the block was placed on its top without fixation and the upturning edges were cast. The UHPC was poured into the gap between formwork and block at one corner of the formwork. The UHPC was easily flowing around the block filling the gap completely without generating any buoyancy; i.e. during the cast the block was simply held in place manually and the UHPC was not penetrating under the block, even though the rear side of the exterior layer was not perfectly smooth.

Due to the two-step manufacturing procedure the UHPC boxes cannot be regarded as monolithic like in the case of the one-step manufacturing. In fact, a distinct layering was observed, visible as a joint between exterior UHPC layer and upturning edges (Fig. 7). In order to evaluate the bond strength between the two UHPC layers, preliminary shear and pull-off tests were performed.

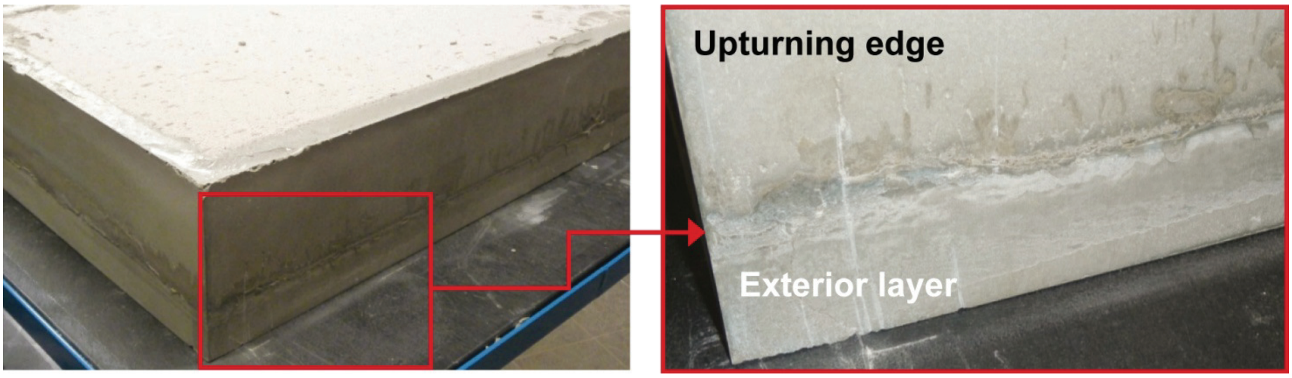

Fig. 7. UHPC box (60 cm × 40 cm) manufactured with the two-step procedure: joint between exterior UHPC layer and upturning edges.

A rigid frame as internal formwork on top of the exterior UHPC layer is supposed to be more efficient for the cast of the upturning edges than a block. A frame consisting of several parts will be more flexible and easier to install as well as to remove when the element is demoulded after hardening of the UHPC.

In Fig. 8 the phases of a laboratory scale box-shaped UHPC element production (1.6 m × 0.60 m) are shown. First, the micro structured substrate was placed in the formwork and the water-repellent agent was applied on top with paint rollers (Fig. 8a). Subsequently the exterior UHPC layer was cast on top of the substrate (Fig. 8b-c), the external part of the formwork for the upturning edges was mounted (Fig. 8d) and transport anchors were fixed to the formwork (Fig. 8e). After initial hardening of the exterior UHPC layer, the internal frame was placed and fixed thoroughly to the external part of the formwork (Fig. 8f) and the second UHPC batch was filled into the gap between internal and external parts of the formwork at one corner of the element (Fig. 8g). The UHPC was flowing inside the gap to the opposite corners of the formwork without using additional compaction (self-levelling/self-compacting). After hardening of the UHPC the formwork was removed (Fig. 8h) and UHPC-box lifted (Fig. 8i).

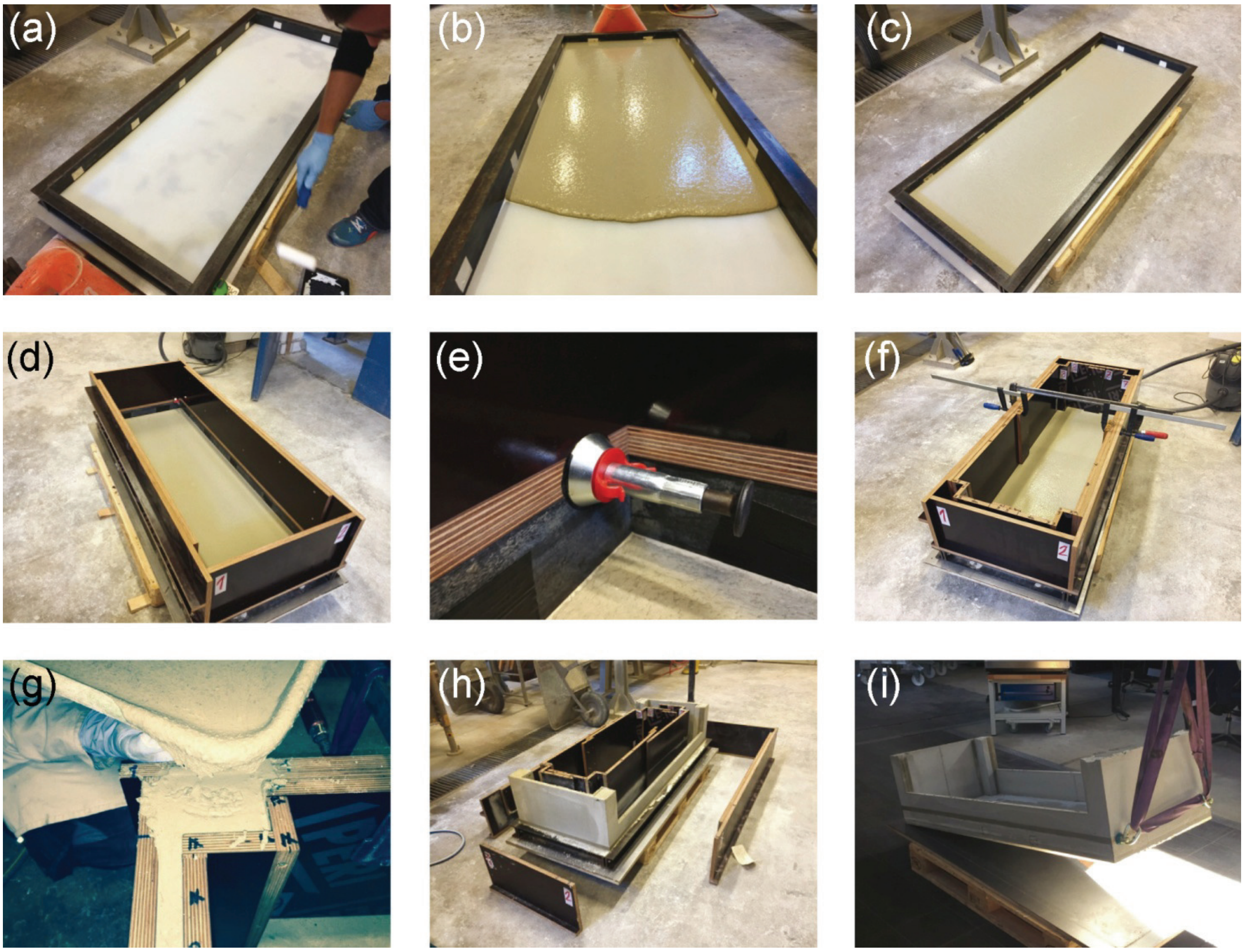

Fig. 8. Laboratory scale UHPC elements manufactured with the two-step procedure.

3.2 Manufacturing of insulation

Monolithic small-scale box-shaped UHPC elements (60 cm × 40 cm) as shown in Fig. 9a were prefabricated at Dyckerhoff laboratories and were shipped to Xella and CBI for the manufacturing of composite panels using AAC and CLC respectively. After sufficient hardening of the UHPC, the developed AAC/CLC was cast directly into these elements to realise the insulation layer.

In the case of AAC the UHPC boxes were filled with fresh slurries so that the swelling process induced by the reaction of the aluminium and the set of the AAC occurred inside the UHPC boxes (Fig. 9b,c). Three types of AAC with different densities were used.

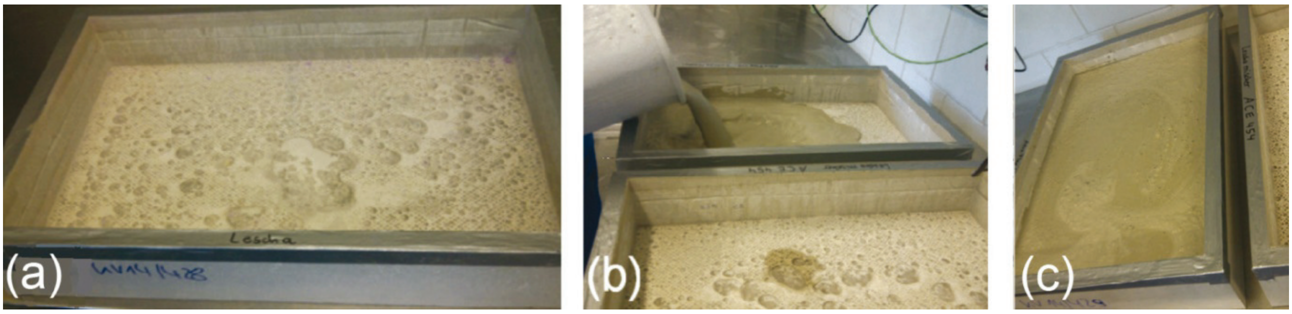

Fig. 9. Manufacturing of small-scale UHPC-AAC elements. (a) Empty UHPC box with highly porous internal surface; (b) Cast of AAC slurry; (c) Swelling process of the AAC slurry driven by the aluminium reaction.

After 24 hours the elements were autoclaved. After autoclaving no damage was visible on the low density ACC types 1 and 2 (86 kg/m³ and 114 kg/m³, respectively) of the composite elements (Fig. 10a-b). By contrast, the AAC type 3 with the highest density of 175 kg/m³ (Fig. 11c) revealed severe crack formation, presumably as a consequence of differences in thermal strain between the AAC insulation layer and the encasing UHPC box. The observed results suggest that the pursued strategy of manufacturing UHPC/AAC composite panels is not suitable for AAC with dry densities ≥ 175 kg/m³.

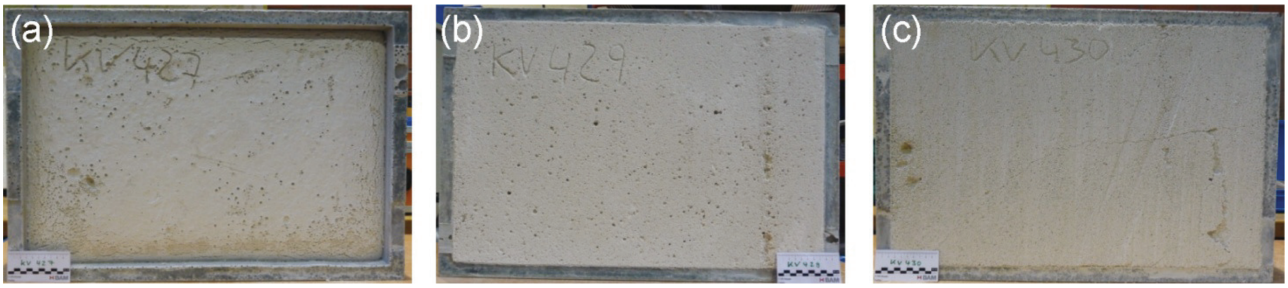

Fig. 10.Small-scale UHPC-AAC elements after autoclaving. (a) AAC type 1; (b) AAC type 2; (c) AAC type 3.

So far, small-scale samples (Fig. 11) were prepared using CLC with a density about 300 kg/m³. After hardening, the CLC generally maintained its original dimensions. Mainly around the edges, cracking and detachment of the CLC from the UHPC was observed but without compromising the integrity of the panel.

Fig. 11.Manufacturing of small-scale UHPC-CLC elements. (a) Cast of CLC; (b) Distribution of CLC in the UHPC box; (c) CLC after finishing.

Concerning the manufacturing of CLC there are, however, two main aspects that need to be considered: thorough wetting of the internal surfaces of the UHPC before casting to avoid CLC collapse and decrease shrinkage; and after casting, enough time should be given in order to allow the CLC to dry and thus avoid excessive moisture to be entrapped in the insulation.

4. Conclusions

The experimental investigations aimed at identifying appropriate ways to obtain self-cleaning surfaces showed the suitability of fabrics for the manufacture of micro structured UHPC surfaces. The combination with a water-repellent agent may generate super hydrophobicity. Several fabrics were used. However, no conclusion can be drawn yet on the most efficient micro structure.

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, assuming that the active substances of the agent are incorporated better in the fresh concrete than in the hardened UHPC.

Contact and roll-off angle measurements on several water-repellent agents were carried out. Excellent results are related to silane-siloxane-based products when applied on the fabric substrate before concrete cast.

The box-shaped concept is a simple and robust solution for the façade elements; besides the good structural performance, the concept enables efficient protection of the insulation material 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.

The preliminary studies showed more advantages of a two-step manufacturing procedure of the UHPC boxes than a one-step procedure. In this framework the bond between UHPC layers plays a key role with the production of non-monolithic UHPC elements. The bond strength between the UHPC substrate and the UHPC top layer was evaluated by shear tests and pull-off tests with promising results. However, future activities need to include more systematic investigations, in particular with regard to the surface properties of the UHPC substrate.

In the manufacturing of small-scale UHPC-AAC composite elements a satisfying bond between the UHPC and the AAC was observed. However, the investigations of the thermal deformation behaviour of the composite elements will be part of future activities.

Before casting the insulation layer thorough wetting of the UHPC substrate is recommended to avoid collapse and harmful shrinkage of the CLC. Special attention has to be paid to the drying of the CLC to avoid excessive moisture entrapped in the insulation layer after mounting of the façade elements.

The hardening process of CLC seems compatible with panel configuration. The CLC generally maintained its original dimensions. Only minor damages were observed without compromising the integrity of the panel. Future activities will include quantification of the bond strength of the UHPC-CLC interface and focus on the incorporation of fibres and aerogels. The first is expected to contribute to an increase in the mechanical stability of the CLC whilst the second will considerably lower the thermal conductivity to values in the range of 30-35 mW/(m·K).

Acknowledgements

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