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Design of UHPC-AAC light-weight composite façade elements for refurbishment

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Abstract. The aim of this study was to develop a lightweight composite façade element for refurbishment of existing façades. It was crucial to minimize the thermal bridges and to undercut the thermal requirement of the system existing façade new element. The awareness of the environmental impact of the building sector is increasing. In this context, ultra-high performance concrete (UHPC) materials are shown to be promising alternatives with 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, optimized use of building area due to thinner elements and minimized maintenance due to the absence of reinforcement or use of non-corrosive reinforcing materials such as carbon fibers. In this framework, composite elements have been developed combining an autoclaved aerated concrete insulation layer with an external UHPC supporting layer. The results show that the lightweight composite element has a good performance in term of thermal transmittance and minimization of thermal bridges.

1. Introduction

The purpose of an adequate building envelope is protection against moisture ingress, heat loss in winter, excessive heating in summer and noise. Components for the interior should be able to buffer heat and humidity peaks and prevent pollutants and noise. Solutions for components for building envelope have to be durable, energy-efficient and affordable. In this framework the development of façade elements for refurbishment comprising ultra-high performance concrete (UHPC) in combination with autoclaved aerated concrete (AAC) are presented. The use of a mineral heat insulation material allows increasing the fire resistance of the composite elements in comparison to the performance provided by the insulation in expanded polystyrene insulation (EPS). The aim was to develop a non-load bearing element to be applied to an existing façade able to undercut the current thermal requirements. The main design criteria were related to the minimization of the thermal bridges, reaching a thermal transmittance of 0.15 $W/(m^2 \cdot K)$ (existing wall + façade element for refurbishment) in order to be marketable also in the long term. The exceptional properties of UHPC are the result of a high packing density based on an optimized particle size distribution and significant reduction of water in the cement paste compared to ordinary concrete [1][2]. The workability of UHPC is adjusted by adding highly efficient plasticisers, obtaining mixes capable to flow or even 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 [3][4][5]. UHPC was already applied successfully to building constructions, such as lightweight roof constructions, façade elements [6][7][8] and protection panels [9]. In this study, light weight AAC with a dry density between 85 and 95 kg/m^3 was employed. This material provides a low thermal conductivity in combination with mechanical properties adequate for the use as insulation layer in composite elements [10]. In the first part of this study the characteristics of the main components together with the key phases of the production technology are presented. In the second part the thermal behavior of the façade element was assessed.

2. Façade element components

The general idea is to realise the external UHPC shell as a box-shaped element (Fig. 1). Due to the support from the edges of the box no shear forces are generated in the UHPC-AAC interface during transport and service life. Thus, no additional connectors are necessary, provided that the bond between UHPC and AAC 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. In the corners, the cross section of the frame is broadened to include the assemblies for anchoring and transport/mounting. Table 1 gives an overview of the geometry of the façade element. 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. Details of the structural behavior of the façade element are reported elsewhere [12].

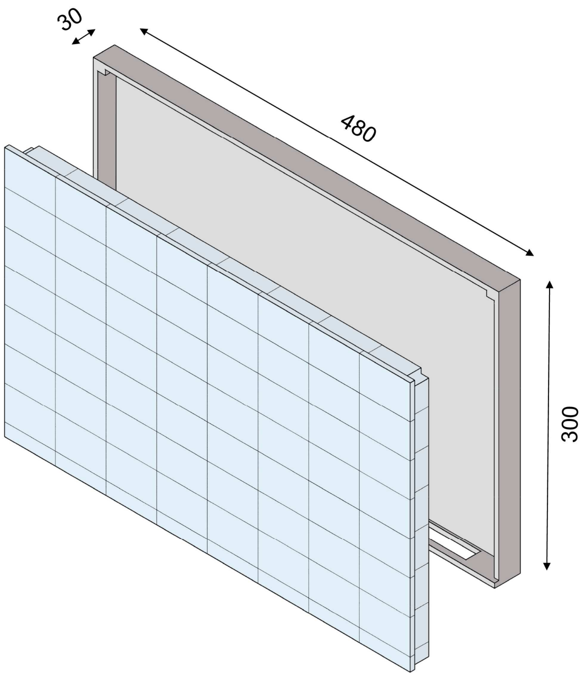


Fig. 1. Non-load bearing façade element for refurbishment (size in cm).

Table 1. Geometrical parameters of the façade element for refurbishment.

Length [cm]	Height [cm]	UHPC ext. layer thickness [cm]	AAC insulation thickness [cm]	Total thickness [cm]	Weight [kg]	Weight [kg/m²]
480	300	3.5	26.5	30.0	1880	125

2.1 UHPC

Due to the extraordinary high strength and the high density of UHPC, it is possible to produce very thin and durable façade elements. The use of UHPC for light-weight 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 the standards [13].

Table 2. Composition of UHPC mixtures and obtained density.

Nanodur® Compound 5941 [kg/m^3]	Sand [kg/m^3]	Superplasticiser [kg/m^3]	Water [kg/m^3]	Dry density [kg/m^3]
1050	1150	17.9	178.5	2440

Further reduction of embodied energy was achieved by replacement of Portland cement with less energy intensive types of cement or supplementary cementitious materials (SCM) originating also from industrial residuals. Solutions are referred to minimum compressive strength of 100 MPa for non-load bearing applications and high quality of the formed UHPC surface. With screening tests three superplasticizers were identified for optimum workability of the fresh UHPC. Shrinkage of the UHPC was identified as potential problem with regard to bond behaviour and large sizes of composite elements. With the use of a shrinkage-reducing admixture promising results were obtained.

2.2 AAC

The material structure of AAC is characterized by a solid skeleton and aeration pores being formed during the aluminum-driven expansion of the 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 good thermal insulating material. Thermal conductivity depends on temperature, density, structure (porosity) and chemical nature of the material. In AAC, it is largely a function of density and moisture content as shown in [15]. For this reason, improvements of the thermal performance of AAC had been mainly achieved by reducing the dry density (Fig. 3a). 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. 3b). 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. The lowest range of thermal conductivity (declared values, $\lambda_{10,dry}$, in the range of 0.042–0.047 W/(m·K) [10][16] 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 (Table 3). The difference is only the dry density, being achieved by altering the amount of aluminum (the more aluminum the lower the dry density).

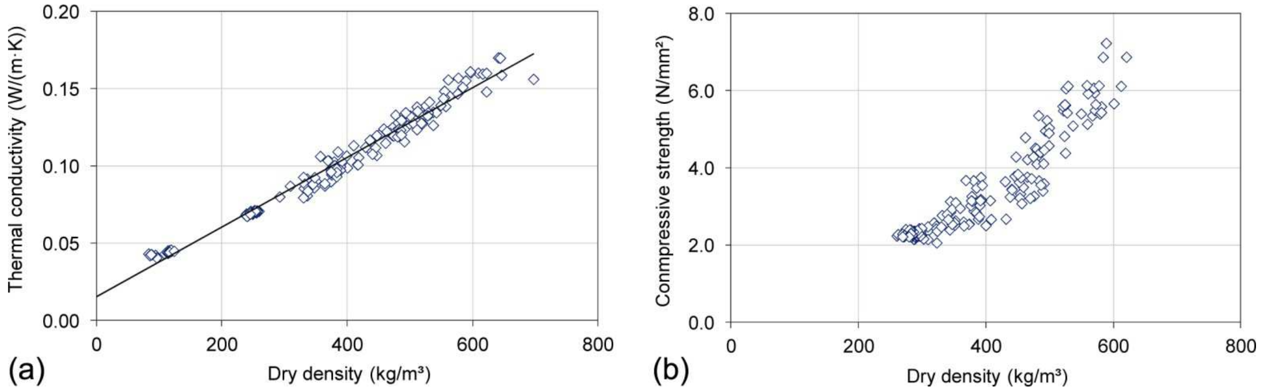


Fig. 2. Correlation between AAC dry density and: thermal conductivity (a); compressive strength (b).

Table 3. Composition of AAC mixtures and obtained density.

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

[a] Used as porosing agent/blowing agent.

3. Production technology

3.1 Manufacturing of UHPC boxes

The purpose of this section is to present the product technology used for producing UHPC-AAC composite elements. First trials were dedicated to the one-step production of the box-shaped UHPC elements, 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). One day after the cast of the exterior layer the upturning edges were cast. The UHPC was poured into the gap between the rigid frames of the formwork at one corner of the formwork. The UHPC was easily flowing around. More details of this procedure are reported in a previous study [17].

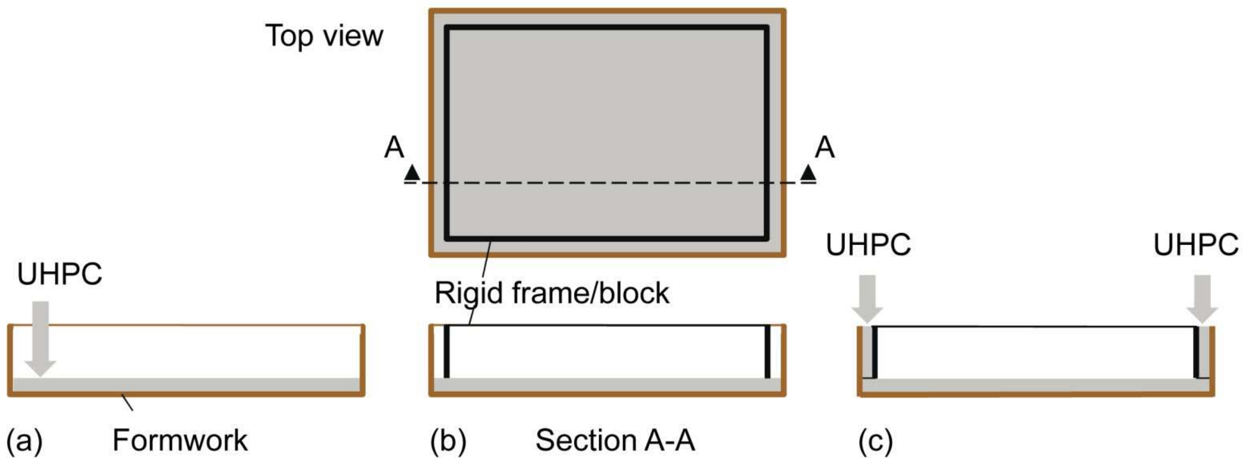


Fig. 3. Procedure for two-step production of box-shaped UHPC elements: (a) cast of exterior layer; (b) placement of a rigid frame as internal formwork on hardened exterior layer; (c) cast of upturning edges.

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.

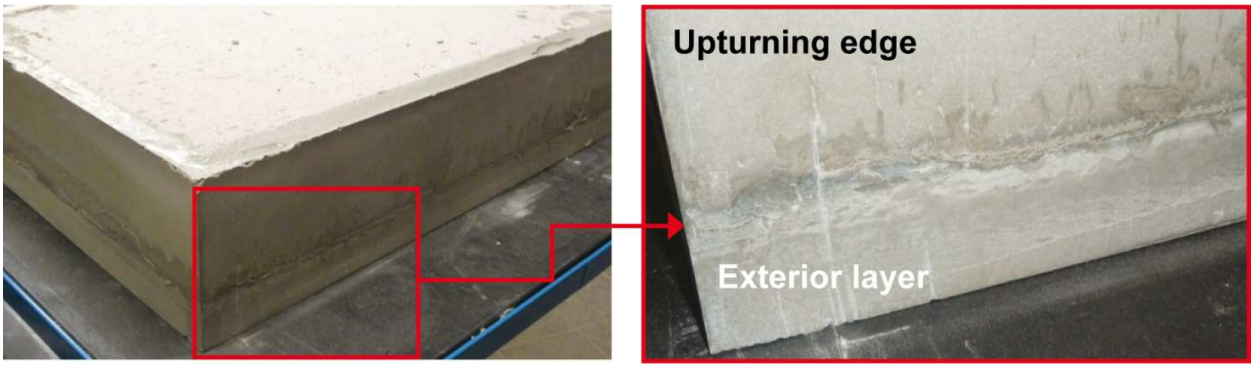


Fig. 4. UHPC box manufactured with the two-step procedure: joint between exterior UHPC layer and upturning edges.

3.2 Manufacturing of insulation

Two different approaches for the application of the insulation were applied. The first one involved casting AAC onto prefabricated UHPC layer, whereas the second one was based on gluing prefabricated AAC blocks (60 cm × 40 cm × 18 cm) onto UHPC surface by using mineral base mortar as an adhesive. In the first approach the UHPC boxes were filled with fresh AAC slurries so that the swelling process induced by the reaction of the aluminium and the set of the AAC occurred inside the UHPC boxes. After 24 hours the elements were autoclaved. After autoclaving two AAC composites samples 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 façade element is not suitable for AAC with dry densities ≥ 175 kg/m^3. It is assumed that the observed cracks both in the AAC and in the UHPC box are a consequence of a restrained thermal dilation of the material in particular during the cooling phase of the autoclaving process, resulting in tensile stresses. The autoclaving of the UHPC-AAC composite elements showed disadvantages related to: weak bond between UHPC and AAC; detachment of the external UHPC layer (cast in the first step) from the upturning edges (cast in the second step); a diffused colour change (not uniform) on the UHPC surface after autoclaving. For these reasons the production technology focused on a more reliable production process based on AAC blocks (Table 4) glued on the UHPC layer. The AAC blocks are glued on the back side of the exterior UHPC layer with a rapidly hardening mineral-based adhesive with low shrinkage. The tests confirmed a good adhesion between AAC blocks and the UHPC layer.

Table 4. Material properties of light weight AAC blocks 042 according to [10].

Parameter	Dry density [kg/m^3]	Declared thermal conductivity $\lambda_{10,dry}$ [W/(m·K)]	Compressive strength [MPa]	Water vapour diffusion resistance coefficient [-]	Water absorption [kg/m^2]	Water absorption [kg/m^2]
Standard	EN 1602 [18]	EN 12667 [19]	EN 826 [20]	-	EN 1609 [21]	EN 12087 [22]
Value	85–95	0.039	> 0.2	2	≤ 2	≤ 3

4. Thermal performance

Following the targets of the European Commission related to the primary energy demand for buildings by 31st December 2020 all new constructions shall be nearly zero-energy buildings (NZEB). In this framework the goal of façade elements here proposed is therefore to achieve or undercut a thermal transmittance of 0.15 W/(m^2·K). A first assessment of the thermal behaviour of the composites elements was carried out considering the physical and thermal properties reported in Table 5. The goal of thermal modelling was to calculate the thermal behaviour of the façade element, i.e. overall thermal transmittance. The thermal transmittance of the façade element was calculated according to EN ISO 6496 [23] applying 3D Physibel software [24]. The temperature distribution (isotherms) for the façade element is presented in Fig. 5. The values of thermal transmittance are reported in Table 6.

Table 5. Physical and thermal properties of the materials used.

Component	Function	Dry density [kg/m^3]	Thermal conductivity [W/(m·K)]
UHPC	Structural	2440	1.5
AAC	Insulation	90	0.042[a]

[a] The thermal conductivity of 0.042 W/(m·K) was used as design value; it corresponds to declared dry thermal conductivity $\lambda_{10,\,dry} \leq 0.0392$ W/(m·K) [10].

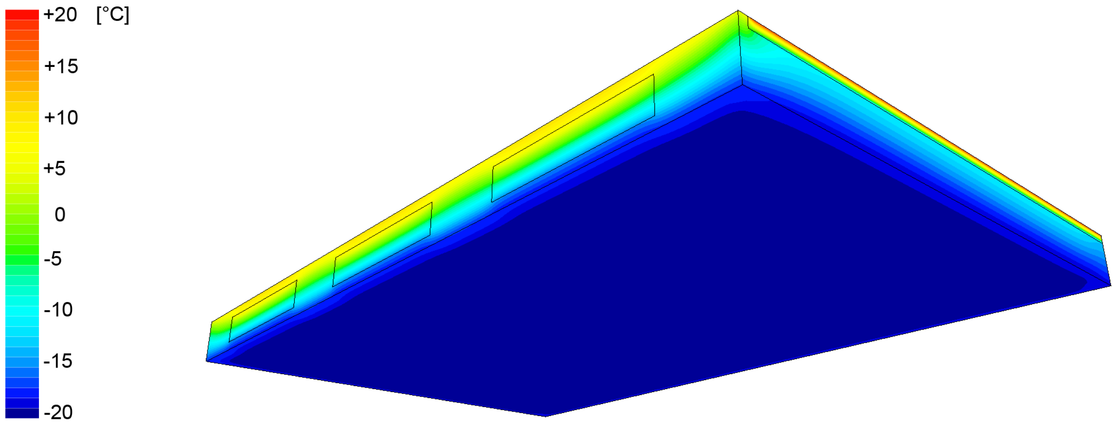


Fig. 5. Temperature distribution of the façade element.

Table 6. Values of thermal transmittance of the façade element for refurbishment.

Total thermal transmittance [W/(m^2·K)]	Thermal transmittance in the central part [W/(m^2·K)]	[a]ΔU [W/(m^2·K)]
0.23	0.15	0.08

[a] The difference ΔU is due to the heat lost at the edges of the façade element.

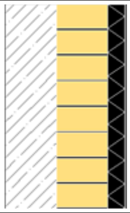
To validate the efficiency of the thermal solution developed on the existing façade it was compared the thermal behaviour of typical wall types in Poland (years of construction 1970–1995) before and after a potential intervention using the UHPC-AAC composite element. According to polish regulations newly constructed buildings need to minimize their energy consumption down to 90–120 kWh/m^2 per year and meet a thermal transmittance for external walls of 0.30 W/(m^2·K) (Table 7). However, from the 1st of January 2014 polish building regulations [25] gradually decreasing these values to achieve respectively 65 kWh/m^2 per year and thermal transmittance of 0.20 W/(m^2·K) in 2021.

Table 7. National requirements for values of thermal transmittance depending on the construction time of buildings.

Time of construction	National standards and guidelines	Thermal transmittance for external wall [$W/(m^2 \cdot K)$]	Average energy consumption per year [kWh/m^2]
Jan 2014–Dec 2016	Updated technical standards for the buildings	0.25	105
Jan 2017–Dec 2020	Updated technical standards for the buildings	0.23	85
> Jan 2021	Updated technical standards for the buildings	0.20	65

Below a selection of typical external wall types of buildings, which need to be refurbished, are presented and characterized (Tables 8–10). The results show that in both cases the use of the UHPC-AAC composite element allows to undercut considerably the thermal requirements. In all cases the refurbished façade reached a value of thermal transmittance of 0.12 $W/(m^2 \cdot K)$. These results allowed an improvement in the range of 72–79% in comparison to the initial values before refurbishment.

Table 8. Existing wall type 1 in Poland.

Year of construction		**Building overview**		**Externall wall sketch**
1970–1985				
Technology of construction				
Building constructed in an industrialized prefabricated technology. Materials used are: foam concrete blocks, gravel concrete, EPS and plaster.				
Before intervention				
No.	Material type	Thickness [cm]	Thermal conductivity [$W/(m \cdot K)$]	[b] Wall thermal transmittance [$W/(m^2 \cdot K)$]
1	Internal layer of plaster	1.0	0.82	0.52
2	Gravel concrete blocks	15.0	1.3	
3	Cellular lightweight concrete	15.0	0.35	
4	EPS	5.0	0.042	
5	External finishing layer of cement-lime plaster	1.0	0.82	
After intervention				
1	Internal layer of plaster	1.0	0.82	0.12
2	Gravel concrete blocks	15.0	1.3	
3	Cellular lightweight concrete	15.0	0.35	
4	EPS	5.0	0.042	
5	External finishing layer of cement-lime plaster	1.0	0.82	
6	UHPC	3.5	1.5	
7	AAC	26.5	0.042	

[b]The linear and point thermal transmittance are not included in the wall U values. $R_{si} = 0.13\ m^2 \cdot K/W$; $R_{se} = 0.04\ m^2 \cdot K/W$ according to [23].

Table 9. Existing wall type 2 in Poland.

Year of construction		Building overview		External wall sketch
1970–1985				
Technology of construction				
Buildings constructed in the system industrialized prefabricated system (W-70) were performed from the large scale, finished, prefabricated elements.				
Before intervention				
No.	Material type	Thickness [cm]	Thermal conductivity [W/(m·K)]	[b] Wall thermal transmittance [W/(m²·K)]
1	Internal layer of plaster	1.0	0.82	0.56
2	Structural layer of reinforced concrete	15.0	2.2	
3	Mineral wool insulation	6.0	0.040	
4	External finishing layer of concrete	6.0	1.2	
After intervention				
1	Internal layer of plaster	1.0	0.82	0.12
2	Structural layer of reinforced concrete	15.0	2.2	
3	Mineral wool insulation	6.0	0.040	
4	External finishing layer of concrete	6.0	1.2	
5	UHPC	3.5	1.5	
6	AAC	26.5	0.042	

[b]The linear and point thermal transmittance are not included in the wall U values. R_{si} = 0.13 m^2· K/W; R_{se} = 0.04 m^2·K/W according to [23].

Table 10. Existing wall type 3 in Poland.

Year of construction		Building overview		External wall sketch
1985–1995				
Technology of construction				
Multi storey, multi-family residential building constructed with large-dimensions elements - cellular concrete blocks.				
Before intervention				
No.	Material type	Thickness [cm]	Thermal conductivity [W/(m·K)]	[b] Wall thermal transmittance [W/(m²·K)]
1	Internal layer of plaster	1.0	0.82	0.43
2	Cellular lightweight concrete blocks	43.0	0.21	
3	External finishing layer of cement-lime plaster	1.0	0.82	
After intervention				
1	Internal layer of plaster	1.0	0.82	0.12
2	Cellular lightweight concrete blocks	43.0	0.21	
3	External finishing layer of cement-lime plaster	1.0	0.82	
4	UHPC	3.5	1.5	
5	AAC	26.5	0.042	

[b]The linear and point thermal transmittance are not included in the wall U values. R_{si} = 0.13 m^2· K/W; R_{se} = 0.04 m^2·K/W according to [23].

Conclusions

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 two-step casting is a reliable technique to produce the composite elements. The structural behaviour of the façade elements is mainly influenced by the presence of the upturning edges that are able to increase the stiffness of the element and to reduce the thickness of the external layer. The insulation material has no influence on the structural behaviour of the UHPC boxes. In conclusion, the quality of the bond between the external layer and the upturning edge is a key parameter to define the bearing capacity of the element. The production technology, based on the two-step manufacturing of UHPC boxes and 'gluing' of AAC blocks on hardened UHPC was found to be the best option. The one-step manufacturing of full-scale UHPC boxes appears too complex and will not be investigated further. For the façade element for refurbishment a limited thermal transmittance value of about 0.23 $W/(m^2 \cdot K)$ was observed. No point thermal bridges were detected. The influence of the edges as potential thermal bridges should be also considered. However, the possible heat loss can be minimized applying insulation materials and anchoring systems. The validation of the efficiency of thermal solution was assessed considering a potential refurbishment intervention on existing walls. The results show that the application or the UHCP-AAC façade element allows undercutting the value of thermal transmittance of more than 70%. The value of thermal transmittance obtained is considerably below the threshold that will be introduced in Poland for the buildings in 2021.

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