Tests of the innovative building materials used for external walls in a case-study construction objects

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Abstract. The article discuss performance of the innovative building materials used for external walls in a case study construction objects. Following the targets of EPBD directive all new constructions shall be nearly zero-energy buildings (NZEB). In this framework the goal of façade elements proposed is therefore to achieve or undercut a thermal transmittance of 0.20 W/(m²·K). An assessment of the thermal behaviour of the innovative composites elements was carried out considering the physical and thermal properties. The goal of investigation was to confirm that the results obtained in a laboratory can be successfully transferred to demo-case buildings taking into account thermal and mechanical behaviour of the façade elements. The results are presented in the paper.

1. Introduction
The materials and building components of modern buildings systems used in sustainable buildings to a society where environmental awareness and a high degree of living comfort are required. This is an actual research and development challenge faced by research centers from around the world including research projects done by ITB. Of particular importance are technical aspects such as mechanical performance, protection against moisture [1], heat loss in winter, overheating in summer and noise protection [1-2]. Components for the interior should be able to buffer heat and humidity peaks and also prevent pollutants and noise. The solutions currently in use are precast concrete wall panels [3]. Wall panels are structural elements subjected to in-plane action having negligible thickness compared to their length and breadth. In order to have sufficient strength to take in-plane loads, they may be reinforced with mild steel, steel fibers or steel fabric mesh. They are economical, not only from the structural design point, but also from the point of view overall construction. [4]. In this group of materials occur various types of concrete like Normal Strength Concrete (NSC), High Strength Concrete (HSC), Steel Fiber Reinforced Concrete (SFRC), Self-Compacting Concrete (SCC), Steel Fiber Reinforced Self Compacting Concrete (SFRSCC) Geo Polymer Concrete (GPC), Steel Fiber Light Weight Concrete (SFLWC), Hygrothermally Treated Ultra-High Performance Concrete (UHPC) in combination with autoclaved aerated concrete (AAC), textile reinforced concrete (TRC) or cellular lightweight concrete (CLC) [1-2, 4-5]. UHCP and other materials are promising alternatives with advantages such as lower energy consumption and reduced environmental impact. The materials used in the partitions shouldn’t additionally affect negatively the thermal comfort of users and the quality of the indoor air of buildings [6]. Predictions suggest sandwich elements for building envelopes have other benefits such as an increased service life, optimized use of building area due to thinner elements, and minimized maintenance due to non-corrosive reinforcing materials. Typical precast concrete sandwich wall panels consist of two concrete layers and a layer of insulation between them. The
Concrete layers may be conventionally reinforced or prestressed and the insulation layer may be made of extruded polystyrene (XPS) or expanded polystyrene (EPS) rigid foam insulation to provide high thermal resistance (R-value) for the wall panels [3].

The case study solutions are presented in the paper. The innovative sustainable façades are based on type of concrete as UHPC, TRF, AAC and FC, while partition walls are based on earthen materials, optimized cementitious materials with modified surfaces and wooden/cellulose materials. The demonstrator buildings made for H-House project (ID 608893, founded under FP7-NMP), applying available technics, i.e. heat-flow meter technique, were investigated during the winter time.

2. The object of the research.

The final exposure of project developed external and internal walls made of new materials were assembled at demonstration site at ITB premises at Warsaw, Poland, and at Buzzi-Unicem premises at Trino, Italy.

The Object of Research (demo-cases) at Warsaw were two separate buildings (5 m x 5 m) made of prefabricated TRC-FC and UHPC-AAC composite elements (Figure 1). Both buildings show different propositions for the developed systems, i.e. for construction of new buildings and renovation, as well as different element of assemblies. The UHPC-AAC demonstrator building consists of eight prefabricated elements (four wall elements and four corner elements, Figure 1). One of the UHPC-AAC wall element (its external side) has a super hydrophobic surface, while the other three UHPC-AAC wall elements have photocatalytic surfaces. The developed UHPC-AAC elements may be used both for a new building construction and a building renovation.

Figure 1. UHPC-AAC demonstrator building; left: view on super hydrophobic surface; right: view photocatalytic surface.

The TRC-FC demonstrator building is composed of five composite elements (Figure 2). Four of these are sandwich elements, consisting of external TRC layer, FC (Foam Concrete) insulation layer and internal load-bearing TRC layer, to be used for new construction. The fifth element is a half sandwich element, consisting of external TRC layer and internal FC insulation layer, to be used for renovation (element is non load-bearing and applied as curtain to the walls of an existing structure). The interior surface of the TRC-FC sandwich element is presented in figure 2.

Figure 2. TRC-FC demonstrator building; left: external view on TRC-FC sandwich elements; right: interior FC layer.
The development of internal walls was based on natural materials (wood, wood fibre boards, straw boards and cellulose boards, earth plasters, etc.) which are exhibited in both demonstrator buildings, as shown in figure 3. In the UHPC-AAC demonstrator building the partition wall constructed (Figure 3, left) was based on timber studs anchored to floor and roof construction. Wood fibre insulation was placed between the timber studs. The stud structure was covered with wood fibre boards that are finished with an earth adhesive with integrated flax fibre and earth plaster final coat. The TRC-FC demonstrator building includes a partition wall made out of solid straw boards covered with cellulose boards (Figure 3, right). The finishing layer consists of an earth filler, reinforced with a glass fibre reinforcement mesh. The interior surface of the TRC-FC sandwich element is presented in finished with an earth plaster final coat with integrated flax fibre reinforcement mesh (Figure 3, right).

![Figure 3. Internal walls in the UHPC-ACC (left) and TRC-FC (right) case-study buildings. Components and materials of the external and internal walls](image)

### 3. Methods- technical performance assessment

#### 3.1 Thermal performance.

Determination of thermal conductivity $\lambda$ of the developed in the project materials was done in steady-state conditions by one–sample heat flow meter apparatus type FOX 314 or FOX 50 with horizontal orientation and hot plate situated on underside of sample, according to PN-EN 12667:2002 [8] and PN-EN 12664:2002 [9], respectively in ITB. Measurements were performed in mean specimen temperature of $10^\circ$C, temperature difference over sample thickness $20\,\text{K}$, heat movement vertically up, in environment temperature about $20^\circ$C. Before measurements the samples were conditioned at $23^\circ$C and 50% relatively air humidity till the stable masses of the samples were obtained. For each material, at least 5 samples have been tested and the mean thermal conductivity value was determined. On the basis of the measurement results the thermal transmittance in steady-state conditions of developed external walls was done applying 3D numerical modelling (Physibel, Solido) according to PN-EN ISO 6946:2008 [10] and PN-EN ISO 10211:2008 [11].

For the case-study objects during the winter period (2017/2018) the thermal performance tests were done applying the heat-flow meter technique for on-site measurements of thermal resistance, $R$, according to the standards of ISO 9869:1994 [7]. The measurements of $R$ were based on simultaneous time averaged measurement of heat flux $\Phi$ and differential temperature, $\Delta T$, (using two temperature sensors on each on a different side of the wall). During these tests the infrared thermal mapping was also performed to inspect the developed panels construction and locate in the building defects such as thermal linear and point bridges, missing insulation, delaminating render or condensation problems. For each of the two separate buildings (Figures 1and 2) the thermal imaging mapping were performed using FLIR-T62101 thermal imaging camera.
3.2 Mechanical tests.

The durability of the developed products i.e. TRC-FC and UHPC-AAC panels intended to be used in the building envelope was assessed by testing them in various sequences following the EOTA protocol i.e. ETAG 004, Guideline for European Technical Approval of External thermal Insulation Composite Systems (ETICS) with Rendering [12], applied directly and/or modified in ITB. The components were tested in the temperature range between -20° C and +70° C. Deterioration, cracking, blistering etc. of the components during the tests were closely observed.

The following tests of durability performance were performed:

3.2.1 Heat - rain cycles

Before the tests, samples were conditioned for 4 weeks at the temperature between 10°C and 25°C and relative humidity (RH) of about 50%. The tested sample was subjected to a series of 80 cycles, containing the three following stages:

1st - heating the sample surface up to 70°C (temperature rising within 1 hour) and maintaining at (70 + 5)° C and at RH 10-30% for 2 hours (total heating of 3 hours),
2nd – spraying-on water for 1 hour (water temperature (+15 ± 5)° C, water flow rate of 1 l/m² min),
3rd – sample drying for 2 hours.

After every 4 cycles the sample surface was investigated, i.e. any deterioration, cracking, blistering, declaration, etc. of the sample surface occurring during the tests were closely observed. To illustrate the changes (if visible/noticed) photographs of the exposed sample surface were taken.

3.2.2 Heat-cold cycles

Before the tests the sample was conditioned, at least 48 hours, at temperatures between 10°C and 25°C and RH ≥ 50%. The tested sample was exposed to 5 heat/cold cycles, each of 24 hours, including two following stages:

1st – sample exposure to temperature (50 ± 5)° C (temp. rising within 1 hour) at maximum RH of 30% for 7 hours (total of 8 hours),
2nd – sample exposure to temperature (-20 ± 5)° C (temp. falling within 2 hours) at RH of (50 ± 5)% for 14 hours (total of 16 hours). At every cycle during the heat/cold cycles, observations relating to a change in characteristics or performance (blistering, detachment, crazing, loss of adhesion, formation of cracks, deceleration, etc., of the sample were recorded.

For the heat-rain cycles and heat-cold cycles tests the dimension of the UHPC-AAC panel was 0.6 m x 1.6 m x 0.38 m (width x height x thickness) and of the TRC-FC panel of a size 0.6 m x 1.3 m x 0.23 m. To avoid wetting of the panel sides during the heat-rain cycles its inner layers were protected by a waterproof emulsion as shown in figure 4.

3.2.3 Freeze-thaw behavior.

Before the tests the samples were conditioned for 28 days at (23 + 2)° C and (50 + 5)% RH. The samples were handled manually, the size was about 200 mm x 200 mm and 300 mm x 300 mm. The samples were subjected to a series of 30 cycles including the following stages:

1st – sample exposure to water for 8 hours at initial temperature of (23 ± 2)° C by immersion of the sample in a water bath (max. immersion till 8 mm)
2nd – sample freezing at temperature (- 20 ± 2)° C for 16 hours.

Figure 4. The view of the UHPC-AAC panel (left) and TRF-FC panel (right).
When the test was interrupted, i.e. because the samples were handled manually and there were stops during weekends or holidays, the samples were always maintained immersed in water between the cycles. At the end of the tests, observations relating to a change in characteristics of the sample surface i.e. distortion, deceleration, cracking etc. were recorded.

4. Tests results

4.1. Thermal performance.

The thermal conductivity of tested materials are presented in Table 1 (uncertainty of thermal conductivity measurement is 3%). The values of thermal transmittance of the façade element calculated according to PN-EN ISO 6946:2008 [10] and PN-EN ISO 10211:2008 [11] and measured on-site on the demo-cases are reported in Table 2 (uncertainty of heat flux measurement is 5%). The temperature distribution (isotherms) for the façade element obtained during the calculation method and during in-situ infrared measurements are presented in Figure 5.

| Component                                      | Density (kgm\(^{-3}\)) | Thermal conductivity (Wm\(^{-1}\)K\(^{-1}\)) |
|------------------------------------------------|-------------------------|---------------------------------------------|
| UHPC-Ultra-High Performance Concrete           | 2200                    | 1.5                                         |
| AAC-autoclaved aerated concrete                 | 120                     | 0.042                                       |
| TRC-textile reinforced concrete                 | 1800                    | 1.3                                         |
| FC-foamed concrete                              | 200                     | 0.040                                       |

| Component                                      | Calculated U value in the central part of the panel (Wm\(^{2}\)K\(^{-1}\)) | Measured on-site U value in the central part of the panel (Wm\(^{2}\)K\(^{-1}\)) |
|------------------------------------------------|--------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| UHPC-AAC-Ultra-High Performance Concrete (UHPC) | 0.15                                                                     | 0.13                                                                         |
| in combination with autoclaved aerated concrete (AAC) |                                                                          |                                                                              |
| TRC-FC Textile Reinforced Concrete (TRC) with a combination with low density foamed concrete (FC) | 0.30                                                                     | 0.29                                                                         |

(heat flux - uncertainty of measurement 5%)

The temperature distribution (isotherms) of the UHPC-AAC panel as 3D model (bottom) and the infrared mapping of the tested samples are presented in figure 5.
4.2 Durability result results.
After the mechanical testing “no damage” i.e. distortion or cracking on the surface of the tested panels was recorded. Only small deceleration was observed, mainly near, along edges of the sample what was probably due to insufficient samples sides protection, as shown in figure 6.

**Figure 5.** The view of the UHPC-AAC panel of the demo side (left) and infrared mapping (right) and 3D model of temperature distribution (bottom).
Summary
Durability and thermal tests of prefabricated elements built on the basis of innovative material solutions have been carried out. The obtained test results presented in tables and figures indicate that developed within the H-House project two innovative panels i.e. UHPC-AAC and TRC-FC can be proposed as solutions for building external walls. Thermal and durability analyses made for the developed within the H-House project demo-cases supported the idea that the prefabricated TRC-FC and UHPC-AAC composite elements can be used in climate zone as it is in Poland. Performed thermal analyses showed that the installed panels achieve the thermal transmittance values and infrared imaging supported didn’t show any changes in the structure during the tests.

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