Application of developed facade panel from recycled CDW: A case study

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Abstract. Using waste materials for production of sustainable exterior façade panel, that can be recycled at the end of its life cycle as part of a circular economy model, can significantly reduce environmental footprint of buildings and help preserve natural resources. The envelope system under consideration is a ventilated prefabricated wall panel from recycled construction and demolition waste (CDW). In this paper, hygrothermal simulations together with field monitoring of hygrothermal performance, energy consumption, indoor comfort and air quality in real environment conditions have been presented. Results show that developed panel is a robust, moisture-safe panel suitable for constructing energy high performing buildings. Thermal discomfort in summer is related to the architectural design of the building.

1. Introduction
This paper is focused on facade system which reflects two key objectives of European and world strategic activities: (i) reduction, reuse and recycling of construction and demolition waste (CDW) as a cornerstone of closed-loop circular economy; (ii) enhancing energy performance of buildings and indoor comfort of occupants. Despite the fact that the potential for the use of recycled aggregates has been widely addressed and concrete with recycled aggregates (RAC) has been recognized as an alternative to conventional concrete in sustainable construction practice, its inferior properties and lack of proper specification inhibit its massive use in concrete [1]. To overcome this gap, a prefabricated facade panel was developed, Figure 1, whose distinctive feature is that 50 % of the natural coarse aggregate is replaced by recycled CDW to produce two concrete layers [2-5]. The thermal transmittance (U-value) of panel is 0.16 W/m²K, which makes the panel suitable for constructing energy high performing buildings.

Figure 1. Ventilated wall panel from CDW.

Figure 2. Family house with VH-RAC (1st full-scale application of developed panel).
Inner concrete layer is made from demolished concrete structures while recycled brick manufacturing waste is used for outer concrete cladding. With surface mass of 458 kg/m² (including concrete cladding) the panel can be classified as a heavyweight. At the end of the life cycle, the panels can be deconstructed with materials separated and recycled. A naturally ventilated air cavity is not common in conventional concrete sandwich panels, which is an additional specificity of panel under consideration. Utilization of recycled CDW improved thermal and hygric properties of concrete, and those results are presented in detail in [3-5]. The goal of this paper is to broaden the current knowledge of possibilities of full-scale implementation of RAC by assessing the suitability of the panel in construction of nearly zero energy buildings. The main aim is to determine and understand how ventilated heavyweight building envelope from RAC (VH-RAC) performs when exposed to real environment conditions and occupied by real tenants.

2. Preliminary hygrothermal simulations
The influence of VH-RAC on indoor air temperature and relative humidity has been investigated for free-floating conditions with geometry of exemplary building calculated according to EN ISO 52016-1 [6]. Calculations have been performed with WUFI® Plus using the measured meteorological data for Zagreb. The wind-dependent ACH model [7] was used to simulate the ventilation in the air cavity. When compared to medium weight envelope (brick walls with ETICS) and lightweight envelope (timber frame walls) of same thermal transmittance values, the results suggest that the most stable indoor temperatures are present for building with the highest thermal mass, i.e. VH-RAC contributed to the lowest daily temperature amplitude (Figure 3). The same pattern is observed for relative humidity.

![Figure 3. Influence of different façade massiveness on daily temperature profile in free-floating conditions for extreme winter day (left) and extreme summer day (right).](image)

3. Field monitoring of hygrothermal performance – element level
The first full-scale application of developed panel was a 3-storey family house located in the city of Koprivnica, Croatia (Cfa climate according to Köppen classification). In the ground floor apartment, hygrothermal performance of three panels was monitored (Figure 2). For the sake of brevity, results are shown only for south panel M1 adjacent to conditioned living room and north panel M3 adjacent to unconditioned stairway. In each characteristic layer (Figure 1) of selected panels temperature and relative humidity (RH) sensors were installed to monitor heat and moisture transfer on hourly basis.
Figure 4. Comparison of monitored RH in thermal insulation layer with RH\textsubscript{crit} for south-oriented panel M1 (left) and north-oriented panel M3 (right).

Monitored RH values are displayed using Folos 2D visual mold chart [8], in Figure 4, which shows developed temperatures and RH, calculated RH\textsubscript{crit} and calculated RH>RH\textsubscript{crit} difference. During two-year monitoring period, RH in thermal insulation layer of south-oriented panel M1 never exceeded critical values. For north-oriented panel M3, RH>RH\textsubscript{crit} occurred 107 h in total at position S4 in thermal insulation layer. This was due to lower solar radiation intensity on the north façade and thus lower drying capacity. However, if time distribution of RH>RH\textsubscript{crit} events is analysed, it shows that there is no longer continuity of critical conditions, and no mould can occur. Therefore, it can be concluded that north-oriented panel is also safe from degradation. Additional numerical simulations performed using WUFI® Pro tool, confirmed that naturally ventilated air in cavity has positive impact on moisture conditions in developed panel, especially in case of unexpected leakages (e.g. poor window installation, etc.). The same wind-dependent ACH model [7] was used as for the simulations described in Section 2.

4. Field monitoring of energy consumption, hygrothermal comfort and IAQ – building level

For the same building with VH-RAC (Figure 2) total energy consumption (electricity, natural gas) was monitored, as well as indoor hygrothermal comfort (temperature, RH) and indoor air quality (CO\textsubscript{2}) in living room of each apartment. Building’s main characteristics are shown in Table 1.

| Apartment 1 (Ground floor) | 95.69 | 258.36 | 2 adults with 2 children |
|-----------------------------|-------|--------|-------------------------|
| Apartment 2 (1st floor)     | 101.44| 273.89 | 2 adults with 2 children |
| Apartment 3 (2nd floor)     | 67.47 | 182.17 | 2 adults with one child  |
| TOTAL HEATED                | 264.60| 714.42 |                         |
| UNHEATED stairway           | 41.52 | 144.50 |                         |

Shape ratio [-] 0.77

Figure 5 and Figure 6 present the time distribution of the comfort classes from EN 15251 [9]. Monitoring on an hourly basis covered one whole year (01/2019 – 01/2020).
Figure 5. Room temperature comfort classes in winter period (left) and in summer period (right).

The total annual primary energy of the whole building (using Croatian factors for primary energy) is $E_{\text{prim}} = 119.77 \text{ kWh/m}^2$. For building under consideration final energy consumption has been measured (heating, mechanical ventilation, lighting, cooking, all devices used by occupants, etc.). Having in mind that no renewable energy sources have been installed and technical systems are freely operated by occupants (no building management systems installed), it can be said that the actual energy consumption suggests high energy performance of building under consideration.

Figure 6. IAQ classes during whole period.

Analyses of indoor temperature indicated summer overheating periods in all three apartments, which was confirmed by occupants who expressed their dissatisfaction with comfort during summer months. Additional shading of transparent openings and/or mechanical cooling system should be installed. The lowest air quality is measured in 2nd floor apartment, whereby 16.81% of time CO$_2$ concentrations exceeded 1000 ppm limit and 3.52% of time 1250 ppm, respectively. Higher CO$_2$ concentrations suggest inadequate operation of mechanical ventilation, which is freely operated by occupants, but these are the occupants that have not been trained on how to use the ventilation system.

5. Conclusion

Upscaling from laboratory investigation of material properties to a full-scale product implementation requires a proof-of-concept. For the presented wall panel made from recycled CDW, holistic hygrothermal simulations showed that panel’s high thermal mass ensured most stable indoor air temperature and relative humidity in free-floating conditions. Field monitoring results of hygrothermal performance suggest moisture-safe performance for south and north orientation panel in continental climate of Croatia. At the whole building level, remote monitoring confirmed high energy performance, which is reflected through primary energy of 119.77 kWh/m$^2$. This $E_{\text{prim}}$ covers complete energy consumed by occupants, and without any contribution of renewable energy sources. Significant summer discomfort is detected, and it derived from architectural design of building (window-to-wall ration on south façade 0.69) and absence of mechanical cooling. High IAQ is present in all three apartments, with slightly worse quality in Apartment 2 due to inadequate operation (occupants haven not been trained on how to use the ventilation system). The developed ventilated wall system from CDW confirmed its applicability for moisture-safe, sustainable and energy high performing building. However, to avoid
compromising positive characteristics of panel, careful architectural design must be applied, and occupants should be educated how to behave in high energy performing building in order to achieve its full potential.

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