Development and Application of a Prefabricated Façade Panel Containing Recycled Construction and Demolition Waste

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Abstract

The construction sector, identified as one of the largest producers of construction and demolition waste (CDW) and one of the largest energy consumers, demands effective measures and applicable solutions to address sustainability challenges. The closed-loop recycling of CDW, integrated with the large-scale deployment of high energy performing buildings, represents a challenge for the whole construction sector, where the lack of waste efficient and energy efficient envelope systems is identified as one of the main barriers. The aim of this paper is to provide one possible solution to tackle the aforementioned issues – a highly insulated prefabricated ventilated façade panel with concrete layers produced using recycled CDW. The results of extensive research confirm that it is possible to replace a high percentage (50%) of natural coarse aggregate with recycled CDW and produce concrete with good mechanical, durability, and hygrothermal properties. Upscaling from initial research and optimisation at material level to an element level, i.e. development and testing of a ventilated façade panel, demonstrated that it is possible to produce a modular envelope system from recycled CDW that meets all performance requirements for certain construction product type (Declaration of performance and CE-marking). Moreover, the results of hygrothermal and energy consumption field monitoring at the whole building level suggest that the developed panel is suitable for use as a high-performing building envelope in real environmental conditions.

Keywords

Construction and demolition waste, recycling, high energy performing buildings, prefabricated ventilated façade panel, hygrothermal performance

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1 INTRODUCTION

The construction industry is one of the largest economic sectors in the world, while in Europe alone it employs 18 million people and generates approx. 9% of the European GDP (CECE, 2020). The impact of the intensive activities of the construction sector on our natural environment is an issue that is no longer subject to debate, as global effects of climate change and resource depletion unfold. The fact that in Europe nowadays 30% of all traffic, 40% of energy consumption, and 50% of material resources taken from nature are construction related; moreover, that 30 - 50% of European national waste production comes from the construction sector (Vyncke & Vrijders, 2016) is well known. (Self)-sustainability, both energy and environmental, has become a strategic priority of political and industrial actions. Through its Energy Performance of Buildings Directive – EPBD (European parliament, 2002; 2010; 2018a), the Directive on the promotion of the use of energy from renewable sources (European Parliament, 2018b) and the initiative to decarbonise the building sector by 2050 (European Commission, 2018), the building sector is undergoing a significant paradigm shift. High energy performing buildings, such as nearly zero-energy buildings (NZEB) have become imperative. According to EPBD, from 31 December 2020 in Europe all new buildings must be NZEB, which by definition means that they need to have a very high energy performance. This nearly zero, or very low, amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced onsite or nearby. The definition given by EPBD (European parliament, 2002; 2010; 2018a) is only theoretical, and each EU Member state is obliged to define its own NZEB requirements (annual primary energy, annual specific heating energy demand, etc.) in relation to national context, i.e. climate, building tradition, cost-optimal analysis, etc. Achieving high energy performing buildings requires a change in established principles in design and construction. This is only possible if the building is considered as a dynamic system that is in constant interaction with the external environment, and whose main aim is to provide a high level of comfort and a healthy indoor climate for building users. Additionally, changing established principles requires thinking about the environmental impact of a building and its operating costs throughout its life cycle, with particular emphasis on the durability of building materials, building envelope elements, thermo-technical systems, and the building itself (Banjad Pečur, Bagarić & Bomberg, 2020). The interaction of the building with the outdoor environment and the interior of the building takes place via the building envelope which, as an active participant in the processes of heat, air, and moisture transfer – HAM (hygrothermal performance), is directly exposed to environmental loads and thus must be both robust and resilient. When looking at the building envelope, 75 - 90% of all construction damage is caused by moisture (Milovanović & Mikulić, 2011), which further indicates the need to predict and ensure the optimal dynamic hygrothermal performance of the envelope in a timely manner, especially in the case of new envelope systems and materials.

By encouraging the reduction of the use of non-renewable natural energy sources, Europe strongly supports the reduction of waste generation, and its reuse and recycling, in a closed-loop system, which is one of the cornerstones of the circular economy (European Commission, 2015a). Reuse of waste usually implies using the same material or product more than once for the same or for some other function. If waste cannot be reused, recycling should be taken into consideration. In a closed-loop recycling system, recycled material can substitute for the original material and be used in identical types of products as before, thus reducing waste to a minimum. With regard to construction and demolition waste (CDW), the Waste Framework Directive (European Parliament & Council, 2008) set the target for preparation of 70% of waste for reuse, recycling, and other recovery by EU Member States.

By recycling construction waste and using it to produce a new construction product, waste becomes a resource, thus gaining new added value and remaining in the life cycle, i.e. kept in a closed cycle, and thus its landfilling can be avoided.

Concrete is the most widely used man-made product in the world. Approximately 4.7 tons of concrete is produced each year per capita (some 33 billion tons per year) (ISO, 2016) and this number is growing each year (Statista, 2020). Despite its advantages from a construction point of view, it has an enormous negative impact on our environment, resulting from cement production and resource excavation.

Aggregate accounts for 60 - 80% of the volume and 70 - 85% of the weight of concrete, and thus it is clear that there is tremendous potential for incorporating CDW into concrete. Concrete produced with aggregate from recycled CDW is called recycled aggregate concrete (RAC). In that sense, buildings built with RAC can be considered as material banks, which reduces the extent of excavation of natural resources and offers closed-loop solutions for CDW with added value. However, one must be aware that recycled aggregate can dramatically change the properties of concrete compared to the same composition concrete made with virgin aggregates. RAC has generally inferior mechanical and durability properties compared to conventional concrete (Bagarić, Banjad Pečur & Milovanović, 2020), and thus balancing between material properties and environmental benefits is crucial to obtain construction products of required quality. Even though RAC is considered to be a sustainable alternative to conventional concrete, and its mechanical and durability properties were the main objective of many extensive research activities (Behera, Bhattacharyya, Minocha, Deoliya, & Maiti, 2014; Marco, 2014; Pickel, 2014; Fraile-Garcia, Ferreiro-Cabello, López-Ochoa, & López-González, 2017; Banjad Pečur, Štirmer & Milovanović, 2015), its inferior properties and the lack of a proper specification, especially those that would enable performance based design, inhibits extensive use in concrete (Behera et al., 2014). For example, standard HRN EN 206:2016 (HZN, 2016) gives a recommendation for using only coarse aggregate (fractions with aggregate size larger than 4 mm) divided into two categories (A and B) depending on the classification of coarse aggregate components. For both coarse aggregate categories, the maximum allowable percentage for replacement of natural coarse aggregate is defined in relation to environmental exposure class. For category A, the allowable replacement percentage ranges from 50 % (X0) to 30% (XC1, XC2, XC3, XC4, XF1, XA1, XD1), while for category B from 50% (X0) to 20% (XC1, XC2), respectively. For all other environmental exposure classes, replacing natural coarse aggregate with recycled aggregate is not allowable.

One of the main obstacles for the massive use of recycled aggregate is also its variable quality, since the uniformity of the aggregate origin cannot always be guaranteed (Banjad Pečur & Štirmer, 2012). It is necessary to provide adequate plant for storage, processing, and quality control of the material that will be recycled. In fact, natural aggregate can be completely replaced with recycled, however, this kind of concrete would require a high amount of cement to achieve adequate mechanical and durability properties, which is not economically and environmentally feasible. Therefore, the optimal replacement percentage should be defined in a way that balances economical aspects, mechanical and durability aspects of RAC, as well as its environmental impact. While mechanical and durability properties of RAC have been extensively researched, to the best of the authors' knowledge, there are only fragmented research findings about RAC's hygrothermal properties at material level (Fenollera, Míguez, Goicoechea, & Lorenzo, 2015; Zhu, Dai, Bai, & Zhang, 2015; Bagarić et al., 2020).

Although the assessment of the hygrothermal performance of the whole system is crucial for overall performance, and for constructing high energy performing, durable, as well as moisture-safe buildings, there is a lack of such analyses for RAC envelopes at a large scale that are exposed to real environment conditions.

The presented study was driven by the research question that emerged from identified knowledge gaps – how does a building envelope containing RAC perform under real environment conditions from a hygrothermal point of view? In addition, is the building envelope system under consideration applicable to high energy performing buildings, such as NZEBs or some other low energy standard?

The goal of this paper is to broaden the current knowledge of possibilities and limitations of using RAC for a high energy performing, sustainable, durable, and moisture-safe building envelope. In the context of this research, the sustainability of the building envelope is reflected through the significantly reduced use of natural resources (natural aggregate), utilisation of recycled CDW that reduces waste disposal, and provides added value to CDW. Moreover, after the end-of-use, concrete layers of the panel can be crushed and used as a recycled aggregate for production of new panels.

The paper consists of 6 sections. After the first section (Introduction), the research methodology is presented in Section 2. Section 3, with its sub-sections, outlines all activities conducted within the frame of this research and their results, including the RAC mix optimisation and testing at material level, panel development and testing at an element level, elaboration of construction details, as well as investigation of thermal mass. Section 4 presents the whole building level, i.e. the first implementation of the panel followed by the field monitoring of the panels' hygrothermal performance and numerical HAM simulations. For the building under consideration, annual energy consumption was also monitored and analysed (Section 5). The last section offers conclusions and presents plans for future work.

2 METHODOLOGY

To confront the challenges imposed on buildings to reduce energy consumption and on the entire construction sector to achieve a high level of recycling of CDW, the research methodology, as presented in Fig. 1, has been proposed.

The conducted research consists of five main phases. The first phase (State-of-the-art review) sets out the motivation and the research problem that derived from the knowledge niche identified by overlapping two specific research areas: i) heat, air, and moisture transfer with a focus on ventilated façades; ii) recycled aggregate concrete with a focus on its use as a heavyweight building envelope system. In the second phase (RAC laboratory testing at material level), the optimisation process was conducted to identify the most favourable replacement ratio of recycled aggregate in concrete. The most favourable replacement ratio implied the balance between mechanical, durability, and hygrothermal properties. During the third phase, the innovative prefabricated façade panel was developed at element level. After setting up the pilot production in a precast factory, all testing required for issuing the Declaration of Performance and CE-marking were performed. To evaluate the environmental impact of the developed panel, the life cycle analysis was also performed. As part of the third phase, two applications at the whole building level were realised: 3-storey family house and kindergarten. Both were designed as high energy performing buildings. A 3-storey family house, as the first application of the developed innovative panel, was selected for further research activities (Phase 4). A field monitoring was carried out in order to evaluate the hygrothermal performance of the panel in real operating conditions, as well as whole building energy performance. Numerical HAM simulations are also a part of this phase, and they were validated with results of the monitoring. The fifth phase summed up the results from all research levels, which provides a wider perspective on RAC and performance of the specific envelope system. Directions for future research are also formulated in this last phase.

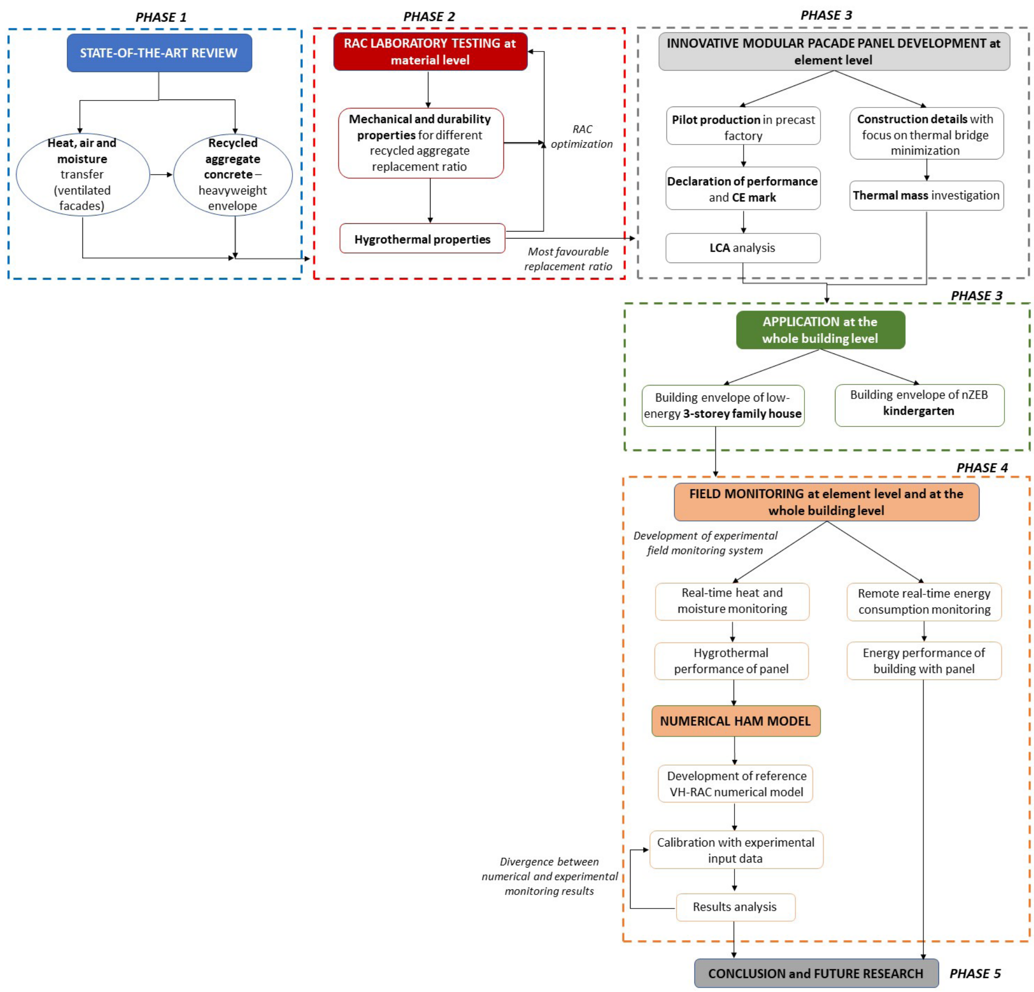


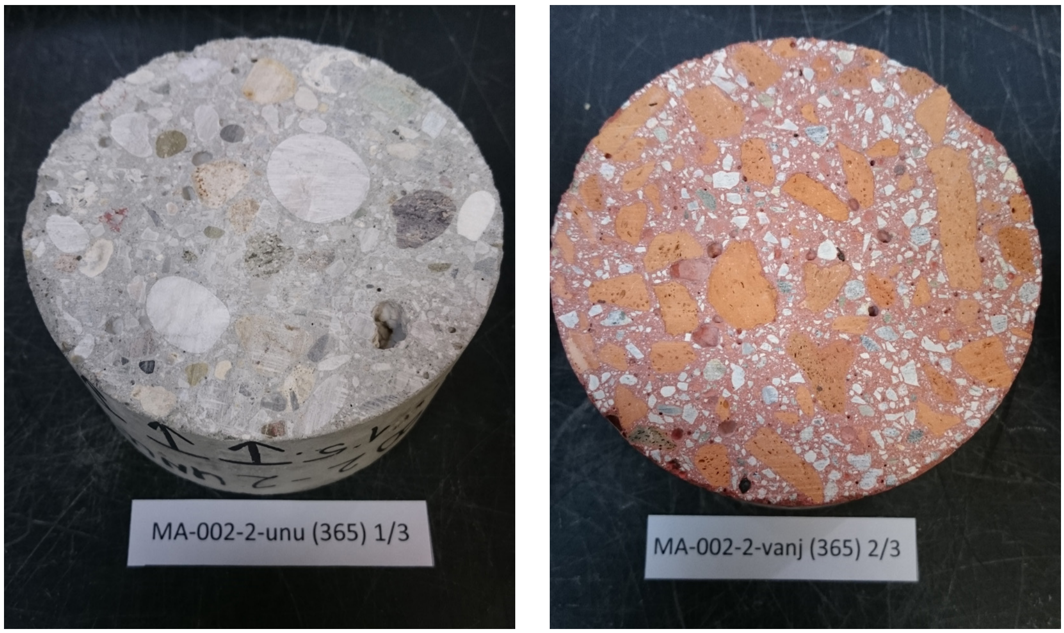
FIG. 1 Graphical representation of the research methodology

3 DEVELOPMENT OF PREFABRICATED FAÇADE PANEL

A highly thermally insulated façade system from a prefabricated ventilated sandwich panel comprising concrete from recycled CDW was developed at the Faculty of Civil Engineering, University of Zagreb (ECO-SANDWICH®, 2012).

3.1 CONCRETE OPTIMISATION AND TESTING – MATERIAL LEVEL

Two different types of RAC were investigated – one with recycled aggregate from old demolished concrete structures (RAC-Concrete) and the other with recycled brick from brick manufacturing waste (RAC-Brick) (Fig. 2).



a b

FIG. 2 Recycled aggregate concrete: a) old crushed concrete as recycled aggregate; b) crushed brick as recycled aggregate

Optimisation of concrete mixtures was performed by varying the replacement ratio of natural with recycled aggregate (40%, 50%, 60%). From a mechanical and durability perspective, the replacement ratio of 50% was deemed to be the most favourable for both types of RAC, as shown in Banjad Pečur, Štirmer, & Milovanović (2015). Table 1 shows some of the main mechanical, durability, and hygrothermal properties of tested RAC types. Based on experimental results, both RAC-Concrete and RAC-Brick can be classified in compressive strength class C 30/37. Generally, RAC-Brick exhibited lower compressive strength compared to RAC-Concrete. Both concretes satisfy requirements for XF4 (56 cycles of freezing and thawing with de-icing salts) environmental exposure class. In comparison to conventional concrete made with natural aggregates (density of approximately 2400 kg/m^3), recycled aggregate concretes are lighter, but they have maintained good mechanical and durability properties. If there are no specific requirements and no significantly high loads are expected, then compressive strength class C 30/37 is suitable for most construction applications. Regarding thermal properties, RAC-Concrete and RAC-Brick have 13 - 27% and 29 - 40% lower thermal conductivity than the reported literature values for the dry concrete with approximately the same density. The water vapour diffusion coefficient for these concretes is 38 to 70% lower than the literature values for similar wet concrete (Banjad Pečur et al., 2015). These results indicate that recycled aggregate has a positive influence on the hygrothermal properties of concrete by improving thermal performance and contributing to more vapour-open performance.

TABLE 1 Main mechanical, durability, and hygrothermal properties of tested RACs for different replacement ratio

RAC-CONCRETE			
	40%	50%	60%
Dry density [kg/m^3]	2064.60	2105.00	2243.33
Compressive strength at 1 day [MPa]	15.76	23.43	18.51
Compressive strength at 28 days [MPa]	44.33	51.20	42.82
Tensile strength by bending at 28 days [MPa]	5.77	6,36	5.41
Elasticity modulus at 28 days [GPa]	27.38	33.80	27.99
Dry thermal conductivity at +10°C [W/(mK)]	0.867	0.858	/*
Water vapour diffusion resistance [-]	26	37	/*
Freeze/thaw class with de-icing salts	XF4	XF4	XF4
Capillary absorption [kg/(m^{2}h$^{0.5}$)]	1.29	1.0	0.80
RAC-BRICK			
	40%	50%	60%
Dry density [kg/m^3]	1912.70	1971.00	2099.67
Compressive strength [MPa] at 1 day	10.76	16.85	5.87
Compressive strength [MPa] at 28 days	44.33	39.74	40.66
Tensile strength by bending at 28 days [MPa]	5.83	5.94	5.19
Elasticity modulus at 28 days [GPa]	21.30	18.16	15.55
Dry thermal conductivity at +10°C [W/(mK)]	0.703	0.746	/*
Water vapour diffusion resistance [-]	18	29	/*
Freeze/thaw class with de-icing salts	XF4	XF4	XF4
Capillary absorption [kg/(m^{2}h$^{0.5}$)]	1.26	0.9	0.60

[*Not tested.]

3.2 PANEL DEVELOPMENT AND TESTING – ELEMENT LEVEL

Even though quite satisfactory mechanical, durability, and hygrothermal properties of RAC have been achieved by replacing a high amount (50%) of coarse natural aggregate with recycled CDW, the idea was to develop a robust and resilient façade system whose overall performance will not be compromised by material properties of RACs. Therefore, choosing a self-load-bearing façade system, i.e., a system that doesn't function as an active structural building element, combined with prefabrication, i.e., production in a precast factory, was confirmed as a promising solution. Prefabrication is a well-known construction technology in which construction elements are produced in controlled conditions that enhance their quality. After production, construction elements are transported to the construction site and fixed to a load-bearing structure. This speeds up the construction process, minimises labour at the construction site, and reduces the overall construction costs. Despite its obvious advantages, prefabricated façade elements experienced stagnation in comparison to other façade systems and components, such as windows, thermal insulation materials, thermally enhanced bricks, etc. A paradigm shift in the construction industry is characterised by its re-orientation towards sustainability, resources, and energy efficiency.
A ventilated prefabricated façade panel from RAC, originally conceived in 2012, tackled sustainability by incorporating 50% recycled aggregate from CDW in concrete production and formaldehyde-free mineral wool thermal insulation, as well as introducing a naturally ventilated air layer which is not characteristic of conventional concrete sandwich façade panels. The latest development in prefabricated concrete panels are carbon concrete façade elements with aerogel-based insulating

materials, presented in 2019 (C3 project, 2020). Their innovation lies in utilising carbon-reinforced concrete and aerogel-based insulating panels, which results in a smaller thickness of concrete and insulation layers, and thus a lower overall panel weight, as well as less material use, which supports sustainability. The first implementation has not yet been realised, and thus, their influence on the dynamic energy performance of buildings, as well as overall dynamic hygrothermal performance at a large scale remains unknown. Therefore, it can be concluded that the utilisation of recycled CDW for production of concrete layers, as well as a naturally ventilated cavity, remain as specific characteristics of the ventilated prefabricated RAC façade panel that is the subject of this paper.

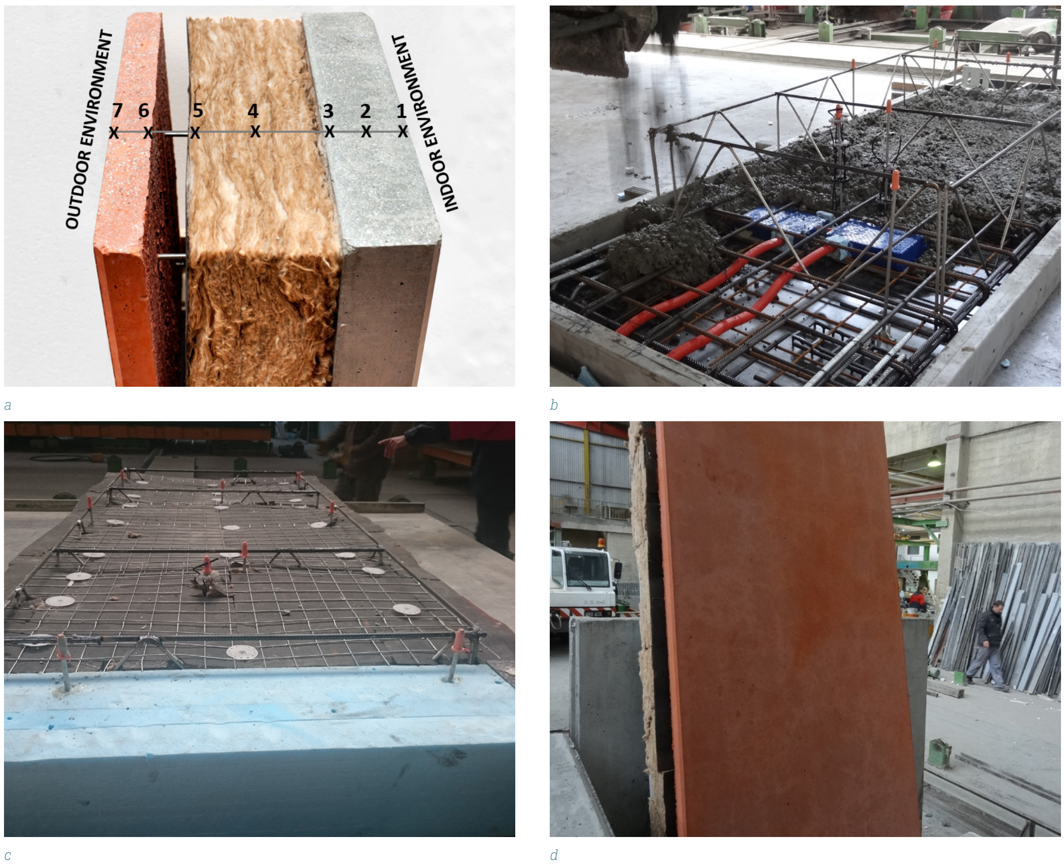


FIG. 3 Prefabricated RAC façade panel: a) model; b)-d) production phases in precast factory

A self-load-bearing prefabricated façade panel produced in a precast factory (Fig. 3) consists of four characteristic layers interconnected with stainless steel girders and steel truss connectors: i) inner concrete layer (12 cm), ii) thermal insulation layer (20 cm), iii) air cavity (4 cm), iv) outer concrete cladding (6 cm). The inner concrete layer has the role of bearing the outer concrete cladding, and thus its thickness is derived from structural analysis calculations. The thickness of thermal insulation was defined to provide a thermal transmittance of a minimum 0.2 W/(m^{2}K), while the air cavity thickness was assumed according to the current rules of practice. The outer concrete cladding thickness was limited by environmental exposure class requirements, reinforcement arrangement, and the panel's production technology (ensuring an air cavity).

The specificity of the panel lies in utilising recycled CDW as aggregate for the production of concrete layers, naturally ventilated cavity, and formaldehyde-free thermal insulation. The inner concrete layer is produced from RAC-Concrete, while RAC-Brick is used for the outer concrete cladding. The naturally ventilated air cavity is foreseen to prevent the possibility of water vapour condensation, as well as to reduce heat gains in the summer period thanks to the passive cooling mechanism of the ventilated façade. Formaldehyde-free thermal insulation comprises glass wool with a weather-resistant protective barrier. At the end of the building's life cycle, a panel can be removed from the load-bearing structure and its characteristic layers can be separated. Concrete layers can be crushed and used as recycled aggregate for new concrete (de Brito, Gonçalves & Ramos dos Santos, 2006). Reinforcement and stainless-steel girders can also be recycled and used for steel production. Glass wool that is used as thermal insulation is also recyclable, and thus, for the panel under investigation the loop is closed with minimum waste generation.

After the truss connector was optimised from the structural point of view and the first prototypes were produced, testing at element level proceeded. The declared airborne sound insulation R_w of the whole panel is 53 dB, and the tested fire resistance is equal to class EI90, while the calculated thermal transmittance (U-value) is approx. 0.16 W/m^{2}K. Based on the material properties of individual layers shown in Table 1 and the main requirements of panel itself, the Declaration of Performance and CE mark were issued by the panel manufacturer (BETON-LUČKO Ltd., 2015). According to Bjegović et al. (2014), the developed façade panel is a non-load-bearing wall panel without structural purpose (standard EN 14992 *Precast concrete products – Wall elements)*, and thus the performance of its essential characteristics must be declared according to AVCP 4 system (AVCP – assessment and verification of constancy of performance) (European Commission, 2015b). AVCP 4 system states that the manufacturer is responsible for factory production control and assessment of performance. By declaring all essential characteristics and issuing the CE mark, the newly developed prefabricated panel was placed on the construction market, which made possible the first full scale implementation.

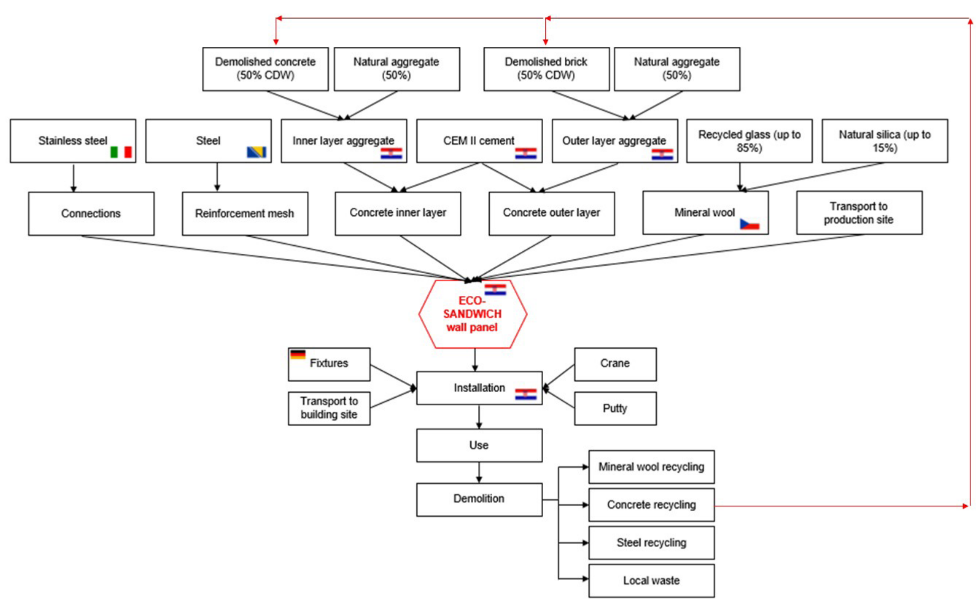


FIG. 4 Simplified flow chart of the life cycle of developed panel

Additionally, the environmental impact of the developed prefabricated façade panel from RAC was determined according to EN 15804 standard (EN 15804, 2013) and the environmental hotspots in its life cycle were identified. All activities throughout the life cycle of the panel were included in the assessment, from raw material extraction through to manufacturing, distribution, use of the panels and maintenance, replacements, demolition, waste processing for re-use, recovery, recycling, and the end-of-life disposal. A simplified flow chart of the panel's life cycle is shown in Fig. 4.

TABLE 2 Different recycling scenarios

RECYCLING SCENARIO	RECYCLING RATE [%]			LANDFILL	REFERENCES
	Mineral wool	**Concrete**	**Steel**		
SCENARIO 1: Current waste recycling rate [%] in Croatia	51	46	100	100 % of waste that is not recycled	EUROSTAT 2015; Calvo, Varela-Candamio & Novo-Corti, 2014; Monier et al., 2011
SCENARIO 2: Current waste recycling rate [%], average EU-27	79	46	100	100 % of waste that is not recycled	
SCENARIO 3: Future waste recycling rate [%] – Best case scenario	100	100	100	100 % of waste that is not recycled	Assumption

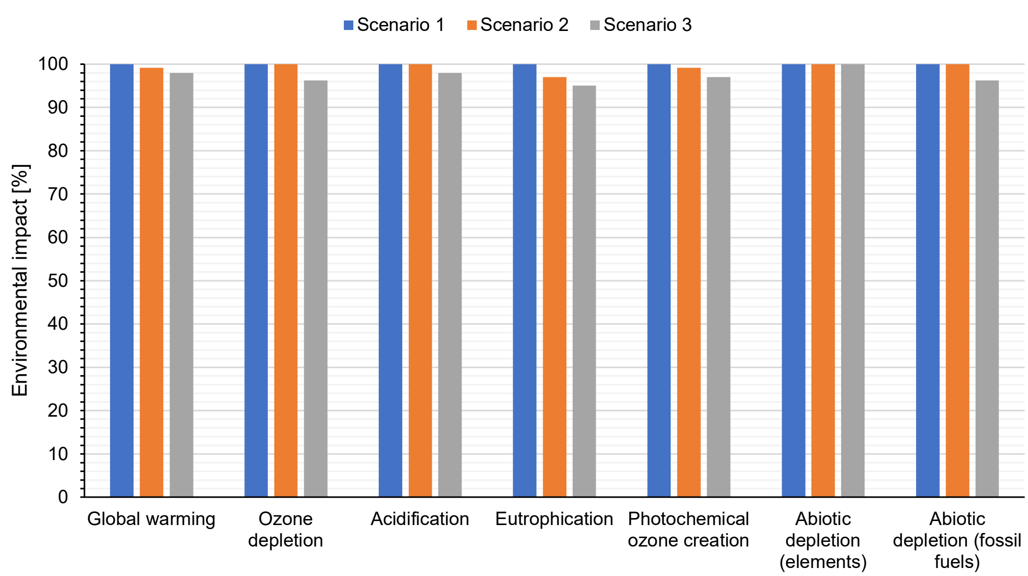


FIG. 5 The influence of different recycling scenarios on environmental impact

A detailed list of all inputs and outputs of the system can be found in Štirmer, Banjad Pečur & Milovanović (2015). The product life cycles were modelled using LCA software SimaPro, developed by PRéConsultants. The environmental impact of the panel is predominantly determined by the product itself. The total contribution of life stages such as raw materials, transport, production, and assembly ranges from 48% for the impact category Abiotic depletion (elements) to 84% for Global warming. Regarding the total contribution of transport to building site and installing of the wall panel, the lowest contribution is found for Global warming (13%) and the highest for Abiotic depletion (elements) (51%). The contribution of the waste treatment in the end of life ranges from 0% for Abiotic depletion (elements) to 7% for Eutrophication. The life cycle stages use and operation do not contribute to the environmental impact, since no processes and/or emissions occur (Štirmer et al., 2015). Different recycling scenarios provided in Table 2 show that higher recycling percentages for mineral wool, concrete, and steel can have a positive effect on the results, especially where Eutrophication is concerned (Fig. 5).

3.3 CONSTRUCTION DETAILS

Some of the most common construction details have been built on the principles of minimising thermal bridges, achieving high airtightness of the building envelope, and ensuring adequate air flow in the cavity by designing cavity inlets and outlets (Fig. 6).

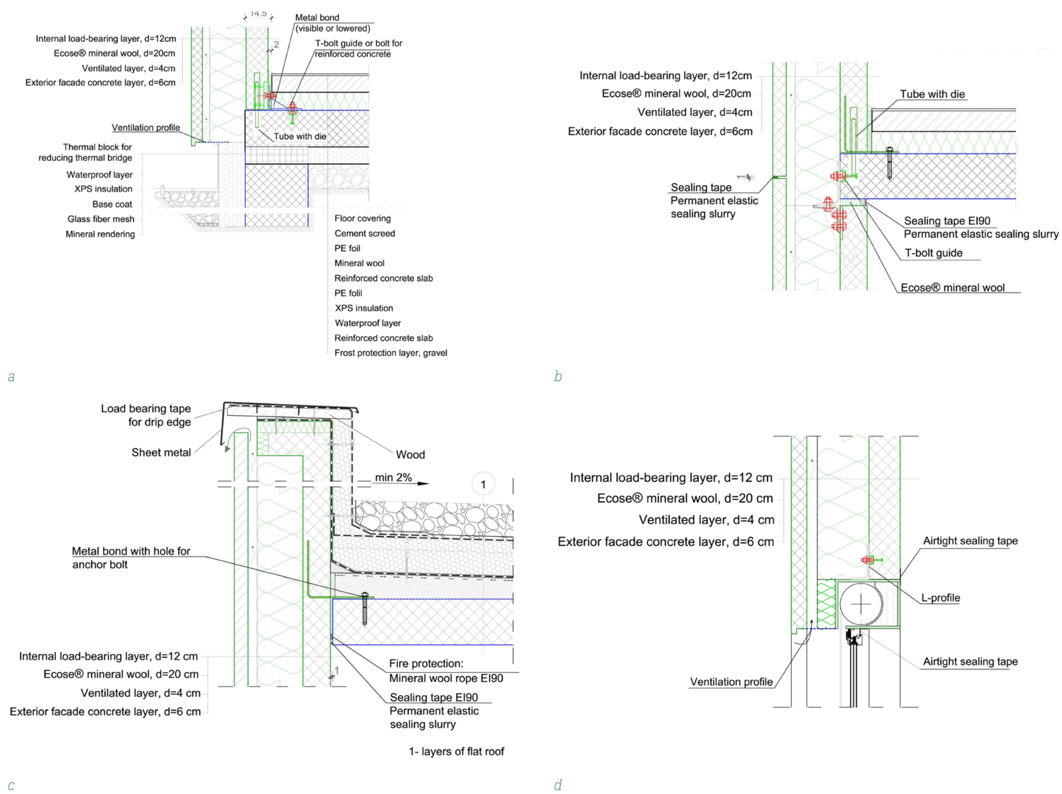


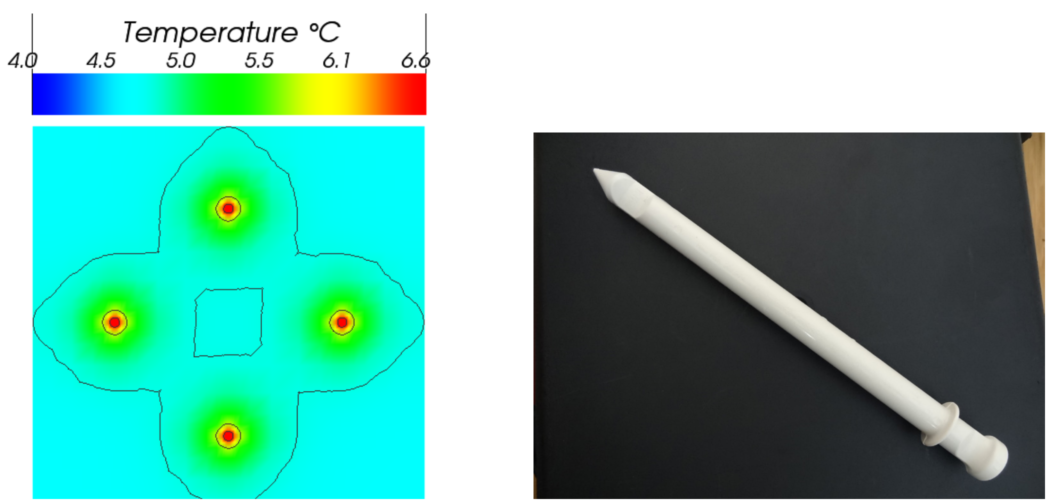
FIG. 6 Construction details: a) Vertical section of slab foundation; b) Vertical section of intermediate floor slab; c) Vertical section of flat roof; d) Vertical section of connection with upper part of the window (detail with the roller blind box)

The developed envelope system is modular and based on prefabrication, which allows a certain degree of architectural flexibility (Ku & Cardenas, 2008; Correia, 2017; Scuderi, 2019). The maximum panel dimensions of 8 × 4 m are limited by transportation possibilities. After mounting the panels to a load-bearing structure, panels need to be properly sealed from the interior side (joints between the inner concrete layer and load-bearing structure) in order to ensure continuity of the thermal envelope, adequate airtightness, and fire resistance of panels. Joints are sealed using mineral wool, autoclaved aerated concrete, and fire-resistant permanently elastic putty (Fig. 7).

FIG. 7 Sealing joints of panel and load-bearing structure

3.3.1 Point Thermal Bridges

The stainless steel girders (Ø=8 mm) connecting all characteristic layers of the panel act as point thermal bridges which can increase heat losses (Fig. 8). Since the exact type of stainless steel is not known, as well as its thermal conductivity, numerical analyses have been performed for two different values λ = 15 W/mK and λ = 50 W/mK and different boundary conditions. For the metal girders with λ = 50 W/mK and set of boundary conditions (interior surface of RAC-Concrete 20,58°C, outer surface of RAC-Brick 3,99°C). Fig. 8a shows the presence of point thermal bridges with a temperature difference of 2.54°C between the metal girder and the thermal insulation. This temperature difference increases with harsher boundary conditions, i.e. the influence of point thermal bridges becomes more pronounced.



a

b

FIG. 8 Girders: a) point thermal bridges caused by metal girders; b) polymer girder

One of the main design principles of NZEB, and generally all high energy performing buildings, is the minimisation of thermal bridges. Therefore, the possibility of replacing metal girders with polymer girders (Fig. 8b) was investigated. Numerical analysis has confirmed that it is possible to reduce point thermal bridges if metal girders (assumed λ = 16 W/mK) are replaced by polymer girders with low thermal conductivity (λ = 0.35 W/mK). The achieved reduction is approximately 91% for assumed boundary conditions of 20°C and -10°C (Martinić, Pogačić & Marić, 2019). Moreover, this investigation has revealed that when using polymer girders, an optimisation of the arrangement of girders is necessary to ensure the panel's stiffness. The reorganisation of the arrangement of girders that results in minimal vertical and horizontal translations, compared to the original arrangement, is proposed (Martinić, Pogačić & Marić, 2019). In addition, polymers can be recycled, which supports their use from the sustainability perspective.

3.4 THERMAL MASS

The main difference between dynamic (transient) and steady-state performance of building elements and a building as a whole is energy storage. The ability to absorb, store thermal energy, and later release it to the environment, depending on the temperature difference of the immediate surroundings, is called thermal mass. Showed quite simplified in Eq. (1), heat energy storage can be described as a difference between the energy that enters building elements and the energy that "exits" from building elements.

$$\frac{dE_{storage}}{dt} = \frac{dE_g}{dt} + \frac{dE_{in}}{dt} - \frac{dE_{out}}{dt} \neq 0 \qquad [1]$$

Where ($dE_{storage}/dt$) states the rate of change of total energy, (dE_g/dt) is the rate of energy generated (e.g. internal gains), (dE_{in}/dt) is the rate of heat transfer in (e.g. solar gains) and (dE_{out}/dt) stands for the rate of heat transfer out (e.g. transmission and ventilation losses). From the Eq. (1) it is evident that the dynamic behaviour is a time-based problem.

A building envelope with a high thermal mass will respond to external changes, e.g. a sudden increase or decrease of outdoor temperature, with certain time delays and amplitude attenuation. This pattern of dynamic behaviour is defined as the thermal inertia of a building. A conventional approach in building design supports high thermal mass as beneficial for reducing energy consumption and maintaining indoor thermal comfort in both summer and winter periods. One should take into account that thermal mass is largely influenced by the arrangement of layers in a multi-layered construction element (Evangelisti, Battista, Guattari, Basilicata & de Lieto Vollaro, 2014), as well as insulation thickness. For example, an element that has a high thermal mass but is thermally insulated from interior will dynamically behave more like a lightweight element. A building envelope with high thermal mass acts like a "heat sink", i.e. it must first be "filled" with heat, so it can further release it to the indoor environment. Elements with high thermal mass and an excessive thickness of the thermal insulation layer, despite being very effective from the steady-state point of view (reducing heating energy need in winter), can cause overheating and thermal discomfort in summer.

Two concrete layers have contributed the most to the high thermal mass of the prefabricated panel. The panel has a surface mass of 458 kg/m^2 which classifies a building built with this envelope system as a heavyweight. The impact of the panel's high thermal mass on building energy need for two different Croatian climates (littoral and continental) and three different system operating modes (one continuous and two intermittent) was analysed according to EN ISO 52016-1 Standard (EN ISO 52016-1, 2017). Simulations of an exemplary building (Bagarić et al., 2020) covered only opaque façade elements with high thermal mass (dynamic calculations) and without any capacity to store heat (static calculations). The hourly calculation procedure according to new Standard EN ISO 52016-1 showed that the thermal mass of the envelope system has a significant influence on the building's dynamic energy performance, whereas it cannot be analysed independently of the system operating mode and climate conditions. In the case of intermittent occupancy, a heavyweight building will require more heating energy but less cooling energy in comparison to the static scenario without heat storage capacity. When prolonging working hours of systems (continuous mode), high thermal mass will be beneficial from both heating and cooling energy demand aspects.

Even though the new Standard EN ISO 52016-1 has officially replaced EN ISO 13790 (EN ISO 13790, 2008), most European countries are still using procedures from EN ISO 13790 to calculate the energy performance of their buildings during this transition period. The comparison of the heavyweight exemplary building with other massiveness categories (very lightweight, lightweight, medium weight, very heavyweight) using the calculation procedure from EN ISO 13790 revealed that, for the continuous mode, a heavyweight building will consume somewhat less heating and cooling energy. This applies for both Croatian climates (littoral and continental). Contrary to that, for the intermittent mode, a heavyweight building can consume up to 6% more heating energy compared to a very lightweight building, but it will still require less cooling energy (up to 21%), respectively. Those results are valid for the exemplary building without transparent openings and all assumption made by authors (Bagarić, Banjad Pečur, Milovanović & Hozmec, 2019). Nevertheless, one must be aware that windows can have a dominant role in the energy balance of the whole building. Therefore, when designing a building with a prefabricated façade panel from RAC, in order to take advantages of its thermal mass, special attention should be given to defining the size and arrangement of windows.

4 APPLICATION OF PREFABRICATED PANELS

The first full scale application of a prefabricated RAC panel was a family house built in the city of Koprivnica, Croatia. Since the application of the panel was realised within the European research project ECO-SANDWICH (ECO-SANDWICH®, 2012) within which it was conceived and developed, the house was named "First ECO-SANDWICH® house" (Fig. 9a). The second application was NZEB kindergarten "Ribica" near the city of Osijek, Croatia (Fig. 9b).

a *b*

FIG. 9 First implementation of prefabricated modular façade panel from RAC: a) family house "First ECO-SANDWICH® house"; b) kindergarten "Ribica" (Cist racun, 2017)

4.1 "FIRST ECO-SANDWICH® HOUSE"

"First ECO-SANDWICH® house" is a 3-storey family house built within a socially supported housing programme of the city of Koprivnica, Croatia. Since the house was designed in 2015, when there were no regulations or requirements related to NZEB, its design principles followed passive house standards. These principles indicate large transparent openings to the south (Fig. 10a) and minimal transparent openings on the north façade, as well as mechanical ventilation with a heat recovery system. Thermal breaks from the neoprene pads (Fig. 10b) were installed to prevent thermal bridges due to anchoring systems. To ensure airtightness and fire resistance of panels, joints were properly sealed using autoclaved aerated concrete, mineral wool, and permanent elastic sealing slurry (Fig. 7). The main geometric characteristics of the house are shown in Table 3. As a first full-scale implementation of the prefabricated RAC panel in real environmental conditions and occupied by tenants, "First ECO-SANDWICH® house" was selected as a case study for investigating the panel's dynamic hygrothermal performance and energy consumption of the whole building.

a

b

FIG. 10 "First ECO-SANDWICH® house": a) south façade; b) thermal break for anchoring systems

TABLE 3 Main characteristics of the "First ECO-SANDWICH® house"

	GROUND FLOOR APARTMENT	1ST FLOOR APARTMENT	2ND FLOOR APARTMENT	UNHEATED STAIRWELL
Useful heated floor area [m2]	95.69	101.44	67.47	/
	Total 264.60			
Net volume of heated air [m3]	258.36	273.89	182.17	/
	Total 714.42			
Shape ratio [-]	0.77			
Useful unheated floor area [m2]	/	/	/	41.52
Net volume of unheated air [m3]	/	/	/	144.50
Number of occupants	2 adults with 2 children (< 5 y.o.)	2 adults with 2 children (< 15 y.o.)	2 adults with one child (< 3 y.o.)	/

5 MONITORING OF FIELD PERFORMANCE – ELEMENT AND WHOLE BUILDING LEVEL

Extensive research activities have been conducted at a material level (Banjad Pečur et al., 2015) (Banjad Pečur & Štirmer, 2012) (Milovanović, Bagarić, Banjad Pečur & Štirmer, 2018) (Bagarić et al., 2019) and essential characteristics of the panel have been tested at element level (Bjegović et al., 2014) (BETON-LUČKO Ltd., 2015) (Štirmer et al., 2015) (PRéConsultants bv, 2015). However, despite the importance of understanding the dynamic hygrothermal performance of the developed RAC panel under variable climate conditions and occupants' behaviour on a large scale, it remains an under-researched area. To the best knowledge of the authors, there is still a gap between research and large scale practical applications of RAC (de Brito, Poon, Zhan, 2019), and thus a strong need to evaluate RAC's suitability for constructing building envelopes that are robust and resilient in a holistic manner: energy performance, moisture behaviour, durability, and sustainability.

5.1 HYGROTHERMAL PERFORMANCE AT THE ELEMENT LEVEL

Field monitoring of hygrothermal performance of the "First ECO-SANDWICH® house" envelope was commissioned on March 9th, 2017. In a ground floor apartment, three panels were selected for monitoring, as shown in Fig. 11. Those panels differ by orientation and indoor conditions (south-oriented M1 adjacent to conditioned living room, east-oriented M2 adjacent to conditioned bedroom and north-oriented M3 adjacent to unconditioned stairwell). In each characteristic layer (Fig. 3a) of selected panels, temperature and relative humidity (RH) sensors were installed to monitor heat and moisture transfer on an hourly basis. For the sake of brevity, results are shown only for south and north panels.

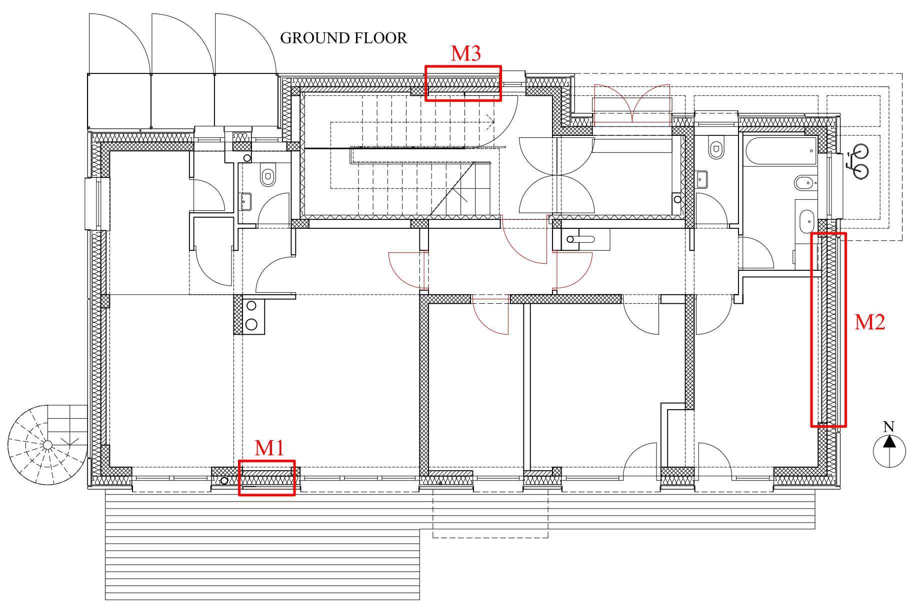


FIG. 11 Location of panels selected for hygrothermal monitoring

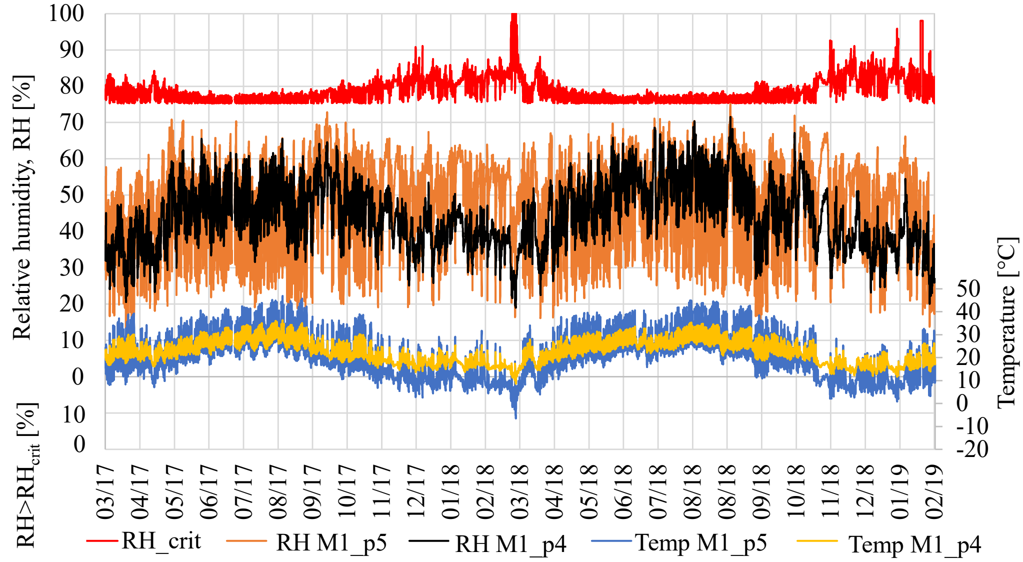


FIG. 12 Comparison of monitored RH at positions p5 and p4 in thermal insulation layer with RHcrit for south-oriented panel M1

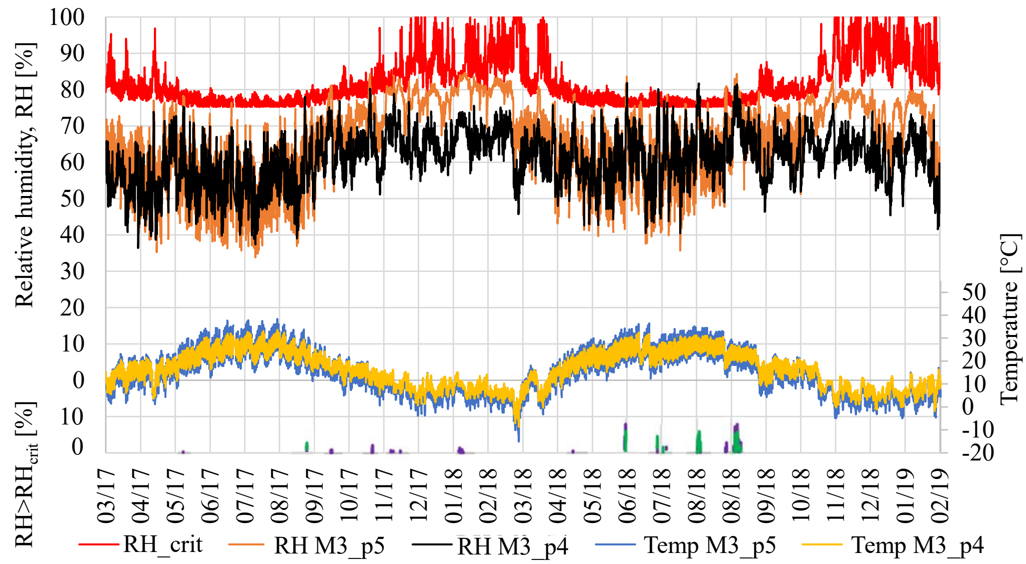


FIG. 13 Comparison of monitored RH at positions p5 and p4 in thermal insulation layer with RHcrit for north-oriented panel M3

Monitored RH values are displayed using Folos 2D visual mould chart (Mundt-Petersen, 2015), (Figs. 12 – 13) which shows developed temperatures and RH, calculated $RH_{crit,}$ and calculated $RH>RH_{crit}$ difference. Conditions at any specific time are visible, whereas of particular interest are the periods during which the RH exceeds RH_{crit} and their duration. Critical conditions depend on the prevailing RH and temperature, where a low temperature gives a higher RH_{crit}. More about Folos 2D chart and calculation of RH_{crit} can be found in the reference, Mundt-Petersen (2015). As can be seen from Fig. 12, during the two-year monitoring period, RH in the thermal insulation layer of south-oriented panel M1 never exceeded critical values. For the complete opposite orientation (north-oriented panel M3 presented in Fig. 13), occasional RH > RH_{crit} occurs at positions p5 and p4 in the thermal insulation layer. This can be attributed to the lower solar radiation intensity on the north façade and thus lower drying capacity. However, if time distribution of $RH>RH_{crit}$ events is analysed (Table 4), it suggests that there is no longer continuity of critical conditions and no mould can occur (Sedlbauer, 2001). Therefore, it can be concluded that north-oriented is also moisture-safe.

TABLE 4 Time distribution of RH > RHcrit within thermal insulation layer of north-oriented panel M3

	POSITION P5	POSITION P4
05/2017	2	/
08/2017	3	5
09/2017	17	/
10/2017	18	/
11/2017	10	/
01/2018	25	/
04/2018	3	/
06/2018	32	17
07/2018	2	4
08/2018	73	36
09/2018	106	45
TOTAL [h]	**291**	**107**

5.2 NUMERICAL SIMULATIONS OF HYGROTHERMAL PERFORMANCE

To investigate if natural ventilation influences the thermal performance of the prefabricated façade RAC panel, the numerical model was developed using WUFI® Pro 5.2. WUFI® Pro is a tool capable of predicting one-dimensional transient heat, air, and moisture transfer through building elements. The numerical model was calibrated by monitoring results (Bagarić et al., 2020) and used to compare the prefabricated ventilated façade panel with the non-ventilated façade panel and ETICS system. The non-ventilated panel was modelled with the same geometry and material characteristics as the ventilated one, except for the cavity ventilation, which was omitted from the calculations. ETICS system was modelled with mineral wool insulation applied to the inner RAC-Concrete layer of same thickness, as in case of the ventilated and non-ventilated façade panel. The thermal transmittance of all three façade systems is comparable. In the case of the ventilated façade panel, cavity ventilation was modelled as a varying air change rate using a simplified Nore's model (Hägerstedt & Harderup, 2011).

When the south orientation is observed, the lowest heat gains during summer are present in the case of the ventilated façade RAC panel, and when compared to other systems the differences are in range from 29.07% (non-ventilated façade panel) up to 50.65% (ETICS system). In the winter period, heat losses through the ventilated panel are practically the same as for non-ventilated, but they are still slightly lower than for ETICS system (8.72%). For the completely opposite orientation, i.e. north, results suggest that during the winter period, the ventilated and non-ventilated façade RAC panels exhibited more favourable thermal behaviour than ETICS. In summer, for the north oriented envelope systems under consideration, the highest heat losses are attributed to the ventilated façade RAC panel. It needs to be highlighted that those summer thermal losses are very low for all analysed façade systems. By comparing heat losses through north and south oriented façade systems in winter, it can be seen that they are less pronounced on the north side. Most probably this can be explained by the unconditioned stairwell subjected to façade systems facing north, and hence a lower temperature difference governing the heat exchange between stairwell and outdoor environment. Results from Table 5 confirm a generally more favourable thermal performance of the ventilated façade RAC panel compared to the non-ventilated and ETICS systems, especially for the south orientation, which makes this façade system suitable for hot climates. It can be concluded that naturally ventilated air in the cavity passively cools down the external surface of thermal insulation, and thus reduces heat gains.

TABLE 5 Total heat flow through analysed façade systems (flow from the outside to the inside of building is considered positive)

SOUTH ORIENTATION	August 2017 (summer period)		February 2018 (winter period)	
	Monthly [Wh/m2]	Average daily [Wh/m2]	Monthly [Wh/m2]	Average daily [Wh/m2]
Ventilated façade panel	331.72	10.70	-2122.17	-75.79
Non-ventilated façade panel	427.86	13.81	-2088.68	-74.60
ETICS system	499.84	16.12	-2307.11	-82.40
NORTH ORIENTATION	August 2017 (summer period)		February 2018 (winter period)	
	Monthly [Wh/m2]	Average daily [Wh/m2]	Monthly [Wh/m2]	Average daily [Wh/m2]
Ventilated façade panel	-27.60	-0.89	-1158.09	-41.36
Non-ventilated façade panel	-18.28	-0.59	-1150.80	-41.10
ETICS system	-12.06	-0.39	-1348.08	-48.15

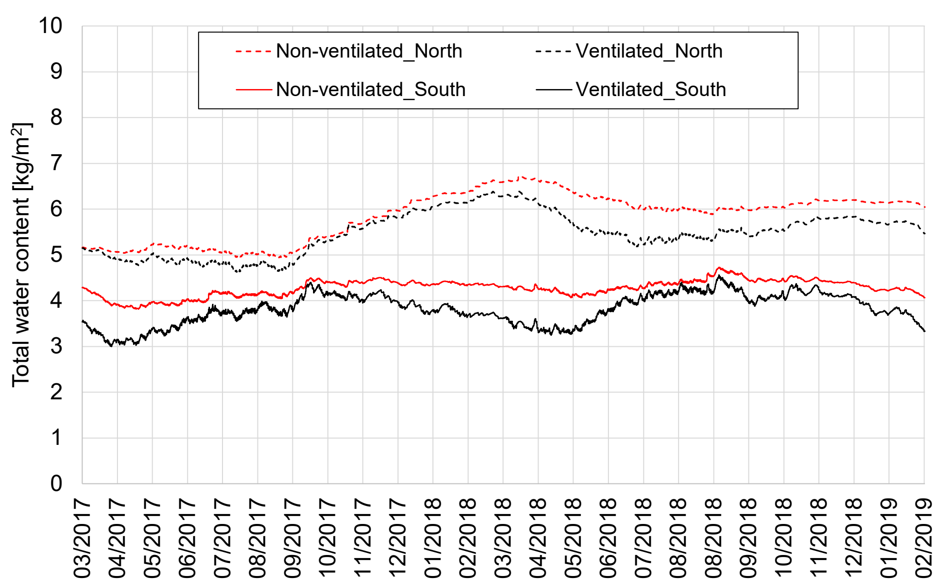


FIG. 14 Total water content in ventilated and non-ventilated panels for unexpected leakages scenario

The influence of naturally ventilated air in the cavity on the hygric performance was also investigated in case of unexpected leakages. Unexpected leakages may occur as a result of poor workmanship or poor design (e.g. wind-driven rain penetrating through cladding joints, joints between window and panels, etc.). The same numerical models of ventilated and non-ventilated panels, as presented above, were used for this investigation. For the purpose of simulating unexpected leakages, the penetration through the façade was assumed to be 1% of the amount of wind-driven rain and this amount was added as a moisture source in the middle of the thermal insulation layer. For both analysed orientations, south and north, the non-ventilated panel contains more water content than the ventilated panel (Fig. 14). Results suggest that naturally ventilated air in the cavity helped to dry out excessive moisture caused by leakages. Fig. 15 indicates that this drying efficiency (reduction of total water content in comparison to the non-ventilated panel of the same orientation) is more pronounced for the south-oriented ventilated panel (10.75%) than for north-oriented ventilated panel (6.33%).

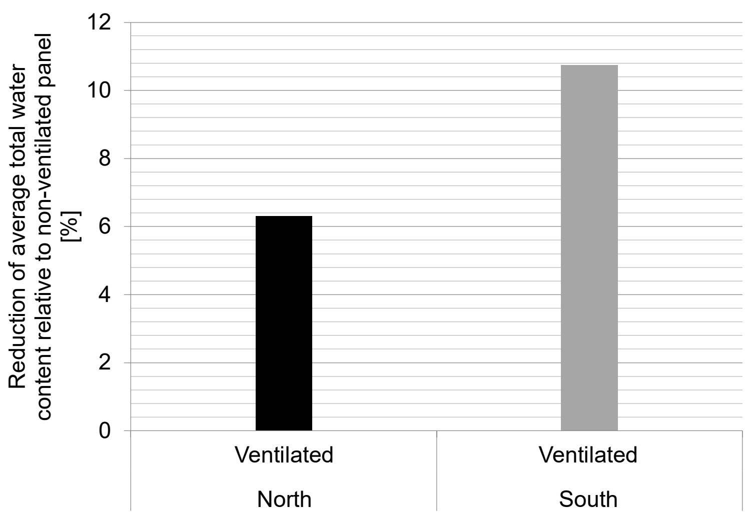


FIG. 15 Efficiency of ventilated panels in terms of reducing total water content when exposed to unexpected leakages, compared to non-ventilated panels

5.3 BUILDING'S ENERGY CONSUMPTION

The "First ECO-SANDWICH® house" was designed in 2015 as a very low-energy house with an annual specific energy demand for heating $Q_{H,nd}''$ = 14.95 kWh/m^2 and cooling $Q_{C,nd}''$ = 10.86 kWh/m^2, respectively. At the time of project design, Croatian legislation and methodology for calculating energy performance of buildings required only specific energy needs, and thus, for the building under investigation no design values of delivered and/or primary energy are available. For each apartment, energy consumption (electrical energy and natural gas) is being monitored, as well as electrical energy in the common area (unheated stairwell). All data can be accessed and analysed through a computer system for real-time remote energy supervision called ESCO Monitor® (HEP ESCO, 2018). Table 6 shows the energy consumed by the occupants for a one-year period (01.01.2019 – 01.01.2020). For different energy resources, Republic of Croatia had defined different values of primary energy factors f_{prim} (MGIPU, 2014) for conversion of delivered energy E_{del} into primary E_{prim}. Using those values (f_{prim} = 1.614 for electrical energy and f_{prim} = 1.6095 for natural gas), annual primary energy of "First ECO-SANDWICH® house" was calculated (Table 7).

TABLE 6 Measured delivered energy E_{del}

DELIVERED ENERGY E_{DEL}	Electrical energy [kWh]	Natural gas [kWh]
Ground floor apartment	3113.03	10896.50
1st floor apartment	1668.95	4750.00
2nd floor apartment	1146.57	8236.50
TOTAL HEATED	**5928.55**	**23883.00**
Unheated stairwell	584.92	/
TOTAL HEATED + UNHEATED	**6513.47**	**23883.00**

TABLE 7 Annual primary energy E_{prim} calculated based on measured delivered energy E_{del}

PRIMARY ENERGY E_{DEL}	[kWh]	[kWh/m^2]
Heated part of building (apartments, useful floor area 264.60 m^2)	35720.56	134.99
Common area (unheated stairwell, useful floor area 41.52 m^2)	944.06	22.74
TOTAL	**36664.62**	**119.77**

According to the Croatian legislation (MGIPU, 2018), the annual primary energy for a new residential building (family house) in a continental climate needs to be less than 115 kWh/m^2, while for a NZEB family house it needs to be less than 45 kWh/m^2. However, it must be noted that according to the current Croatian legislation, the primary energy for a family house covers only the energy needed for heating, domestic hot water, and mechanical ventilation (if installed). For the building under consideration, monitoring of overall energy consumption was conducted, which also implies energy for lighting, cooking, home devices, cooling, etc. without the contribution of renewable energy sources. Moreover, methodology for energy calculations assumes certain indoor temperature conditions and working hours of technical systems, which in reality, completely depends on occupants' habits and comfort perception. Based on the monitoring results, it can be concluded that it is possible to construct a family house with ventilated prefabricated RAC façade panels that will consume less than 120 kWh/m^2 of the total primary energy annually, covering all energy sources used by occupants. It can be assumed that with other thermo-technical systems and with integration of renewable energy systems, the total primary energy consumption could be additionally reduced.

6 CONCLUSION

This paper discusses the development and application of an innovative ventilated façade system from recycled construction and demolition waste (CDW). A comprehensive methodological approach consisted of upscaling the research from material level (initial research activities focused on material properties) to the element level (optimisation and production of prototype panel) and finally to the whole building level (application of panel in real environmental conditions and performance monitoring).

The extensive research activities at the material level confirmed the possibility of using crushed brick and recycled concrete from CDW as a partial replacement of natural aggregates in concrete production. The high replacement ratio of coarse natural aggregate (50%) with recycled aggregate from CDW resulted in two types of recycled aggregate concrete (RAC). Their mechanical, durability, and hygrothermal properties showed to be satisfactory and acceptable for producing a prefabricated self-load bearing façade panel. Both RAC-Concrete and RAC-Brick can be classified in compressive strength class C 30/37, and they satisfy requirements for XF4 (56 cycled of freezing and thawing with de-icing salts) environmental exposure class. A high percentage of recycled aggregate resulted in up to 13 - 27 % (RAC-Concrete) and 29 - 40 % (RAC-brick) lower thermal conductivity than the reported literature values for the dry concrete with approximately the same density. The water vapour diffusion coefficient for these concretes is 38 - 70% lower than the literature values for similar wet concrete.

Besides incorporating a high amount of CDW, the main specificity of the developed prefabricated façade system is a cavity with naturally ventilated air, which is not common for conventional concrete sandwich wall panels. Prefabrication ensured the production of the panel in controlled conditions, which increases product quality and reduces construction time. The Declaration of Performance and CE mark were issued by manufacturer after testing all essential characteristics at material and element level (AVCP 4 system). This enabled the panel to be put on the market and confirmed that it is possible to produce a high quality envelope system by incorporating high amount of recycled CDW.

The first application of the developed panel in real environmental conditions served as a case study to evaluate panel's suitability for constructing high energy performing, durable, and moisture-safe building envelope. For the 3-storey family house in the city of Koprivnica (Croatia), results from two years of monitoring confirmed that the naturally ventilated air layer helps to maintain acceptable humidity conditions in the thermal insulation layer, whereas the south orientation is completely moisture safe. For the north oriented panel there are certain periods in which relative humidity exceeds critical values (in total 291 hours at the surface of thermal insulation adjacent to the air cavity and 107 hours in the middle of thermal insulation). However, these periods are quite short (a few hours per day) and thus, not long enough for mycelia germination and degradation of thermal insulation.

Furthermore, numerical simulation results indicate the presence of a passive cooling mechanism for the ventilated façade panel, and thus its positive impact on reducing heat gains. Summer heat gains through the ventilated façade panel were up to 29.07% lower than the non-ventilated façade panel and up to 50.65% lower than the ETICS system, respectively. This confirms the suitability of the developed panel for hot climates. A ventilated air cavity was also shown to be beneficial when drying of extensive moisture from the unexpected leakages is observed. This drying efficiency (reduction of total water content in comparison to the non-ventilated panel of the same orientation) is more pronounced for the south-oriented ventilated panel (10.75%) than for the north-oriented ventilated panel (6.33%).

The panel's high thermal mass, depending on the climate and system operating mode, can have a positive impact on a building's heating and cooling energy needs. However, the size and location of transparent openings need to be carefully considered during the design phase. For the family house under consideration, the total annual primary energy consumption was less than 120 kWh/m^2, but it encompasses the total energy consumed by occupants and no contribution from renewable energy sources.

It can be concluded that the developed prefabricated ventilated façade panel is a robust and resilient façade system, which offers a closed-loop solution for CDW with lower environmental impact and contributes to reducing energy needs in the building sector. Therefore, it can certainly foster the breakthrough of RAC in high energy performing and healthy buildings, as well as their large-scale deployment.

Further research will include the specific design of air cavity openings and its influence on cavity ventilation. A climate-dependent analysis will be performed to evaluate the applicability of the developed panel for different conditions in practice. Different cladding materials and the possibility of integrating photovoltaics will be analysed, whereby building envelope and mechanical service would be integrated, and thus, the applicability for NZEB buildings increased. Moreover, the long-term monitoring of indoor comfort parameters in "First ECO-SANDWICH® house" will be performed.

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