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## **Preliminary monitoring results of ventilated heavyweight building envelope from recycled aggregate**

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### **ABSTRACT**

Potential of recycled aggregate concrete (RAC) has already been acknowledged by many researchers, but the focus was primarily on its mechanical and durability properties at material level. If the focus is shifted to element and whole building level, then the question can be raised; how building envelopes made from RAC behave when exposed to real environment? The present paper describes an experimental set up to monitor hygrothermal behaviour of one three-storey family house built with prefabricated ventilated sandwich wall panels made from recycled concrete and recycled brick aggregate. This type of building envelope can be classified as a heavyweight envelope. In ground-floor flat a wall in the living room facing south is analysed in terms of internal temperature evolution and humidity distribution. Conditions of indoor and outdoor environment were monitored as well. Time lag and decrement of temperature extremes were observed and these benefits can be attributed to the presence of thermal mass. Ventilation of air in cavity ensured acceptable humidity level in all characteristic layers of wall panel. Summer overheating occurred due to insufficiently shaded large transparent openings. Further step is validation of numerical model and assessing the suitability of presented envelope type to different climates. This paper indicates the great potential of RAC application in energy efficient and moisture safe building envelope design.

### **KEYWORDS**

Recycled aggregate concrete, prefabricated ventilated sandwich panels, heavyweight building envelope, field monitoring, hygrothermal behaviour

### **INTRODUCTION**

Recycled aggregate concrete (RAC) has been identified as sustainable alternative to conventional concrete. Its mechanical and durability behaviour has already been widely acknowledged by many researchers (Behera et al. 2014; Fraile-Garcia et al. 2017; Marco 2014). Contrary to that, its hygrothermal behaviour as an important aspect of overall performance, has only been scarcely investigated. There are fragmented research findings on thermal and hygric properties of different types of RAC at material level (Banjad Pečur et al. 2015; Fenollera et al. 2015; Zhu et al. 2015). Having in mind the influence that building envelope's hygrothermal behaviour has on buildings energy needs, service performance, indoor thermal comfort and air quality which is directly related to the health of occupants (Feng and Janssen 2016), obviously there is a strong need to predict hygrothermal behaviour of RAC at component and ultimately at entire building level. To establish trustworthy numerical model, experimental results are desirable for model validation. This paper investigates transient hygrothermal behaviour of ventilated heavyweight building envelope constructed with RAC prefabricated panels under real variable climate conditions and occupants' behaviour.

## DESCRIPTION OF MONITORED BUILDING AND EXPERIMENTAL SET-UP

The subject of this study is a 3-storey family house (approx. 268 m<sup>2</sup>) built within socially – supported housing program in City of Koprivnica, Republic of Croatia (Figure 1a) as very low energy (A+) standard.

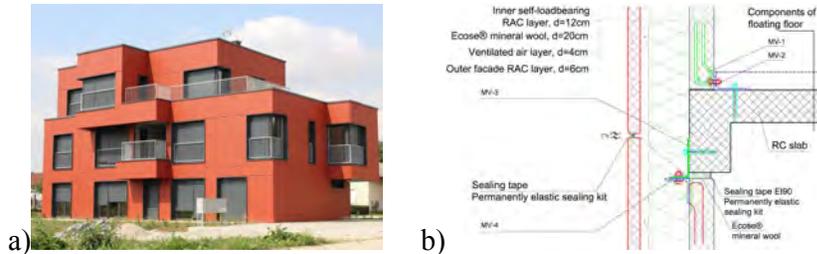


Figure 1. a) View of monitored building; b) Cross section of prefabricated ventilated RAC wall panel

Its building envelope consist of 42 cm thick prefabricated ventilated sandwich wall panels made from recycled aggregate. With surface mass of 458 kg/m<sup>2</sup>, building constructed with this type of envelope system can be classified as a heavyweight building. Based on thorough research of mechanical and durability properties (Banjad Pečur et al. 2015), replacement ratio of 50 % natural aggregate with recycled one deemed as the most favourable. As shown in Figure 1b), observed panel consists of four characteristic layers: outer RAC facade layer (6 cm), ventilated air cavity (4 cm), thermal insulation (20 cm), and inner self-loadbearing RAC layer (12 cm). The thermal transmittance of panel is approx. 0.16 W/(m<sup>2</sup>K).

For production of outer RAC façade layer (RAC-B), recycled brick from waste generated during manufacturing brick process was used, while recycled aggregate from demolition of old concrete structure was used for production of inner self-loadbearing RAC layer (RAC-C). Thermal insulation is formaldehyde-free glass wool with integrated wind barrier. Air cavity is placed between thermal insulation and outer façade layer, with aim to prevent possibility of water vapour condensation. The water-repellent coating was applied on outer façade surface. Main hygrothermal properties of target recycled aggregate concrete are shown in Table 1.

Table 1. Hygrothermal properties of RAC-C and RAC-B

	RAC-C	RAC-B
Dry density [kg/m <sup>3</sup> ]	2204.96	1948.22
Open porosity [%]	16.67	19.27
Thermal conductivity $\lambda_{dry,+10^{\circ}C}$ [W/(mK)]	0.944	0.745
Water vapour resistance factor $\mu$ [-]	41	28

to approx. 44% lower  $\lambda$  when concrete is used and approx. 56% when brick is used as recycled aggregate. It is suggested to use  $\mu$ -value for normal concrete as a constant value of 150. From Table 1, it can be seen that  $\mu$ -factors for RAC-C and RAC-B concrete are up to 80% lower compared to value suggested for normal concrete. This basic hygrothermal parameters indicate that more energy efficient building design can be achieved with RAC without compromising mechanical requirements – 43.3 MPa was mean cube compressive strength of RAC-C and 38.7 MPa of RAC-B, respectively.

Conventional concrete made completely with natural aggregates with a density of 2300 kg/m<sup>3</sup> has  $\lambda$ -value of approximately 1.7 W/(mK).

Replacement of 50% contributed

In ground-floor flat a wall panel in the living room facing south (marked red in Figure 2a) is analyzed in terms of internal temperature evolution and humidity distribution. Panel is 128.5×297 cm, with the first set of sensors centrally positioned 86 cm from the panel's bottom and second set of sensors 100 cm, respectively.

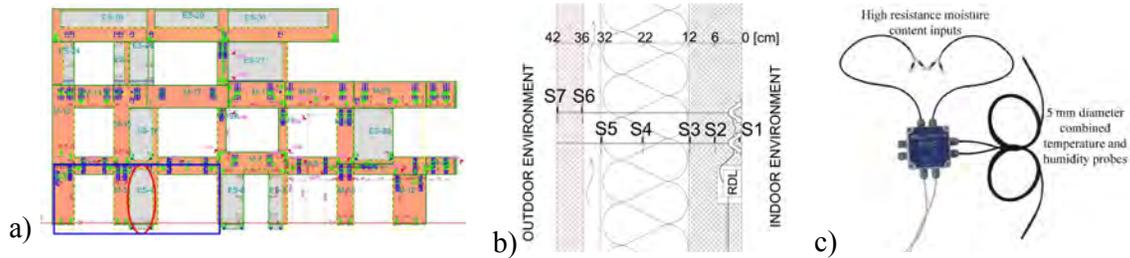


Figure 2. Measurement location: a) Position plan for southern façade; b) Arrangement of T-H sensors within panel layers; c) RDL Client-THR system

Temperature (T) and humidity (H) distribution was monitored in all four characteristic layers of presented wall panel, in total seven positions S1-S7 (Figure 2b), using the RDL Client-THR system from Caption Data Limited (Figure 2c). Installation of T-H sensors was carried out in precast factory during the moulding of panels (Figure 3). Presented monitoring system



Figure 3. Installation of T-H sensors

is a combination of wire-based and wireless measurement system. Sensors (S1-S7) at south measurement location are wired connected to

the central measurement unit in building's entrance hall, where sensors readings are recorded every hour and then sent by Internet on a dedicated server. The data can be accessed via custom Brightcore computer system. Further analysis of measured data was performed with Microsoft Excel software. Boundary conditions in terms of indoor and outdoor environment were also monitored. Indoor climate is dependent on the occupants' behaviour – young couple with small child. TFA Klimalogg Pro Thermo-Hygro-Station data logger was used for monitoring and recording the air temperature and relative humidity in living room of the house every 15 minutes. Basic meteorological data were measured every 5 min at nearest available meteorological station Herešín. These data are taken as representative for the Cfb climate of City of Koprivnica (Köppen climate classification).

## RESULTS AND DISCUSSIONS

Period of almost one year was monitored (March 9, 2017 – February 28, 2018). In winter months outside temperature was occasionally under  $0^{\circ}\text{C}$  with peak of  $-17.3^{\circ}\text{C}$  at the end of February 2018. Five days in a row was the longest continuous period of temperature under  $0^{\circ}\text{C}$  with mean value of  $-6.6^{\circ}\text{C}$ . Max value was  $38.3^{\circ}\text{C}$  in August 2017 and its average monthly value was  $22.5^{\circ}\text{C}$ . Inside air temperature (living room) was in range from  $19.5$  to  $29.1^{\circ}\text{C}$ . It needs to be noted that in this paper humidity distribution will be presented only in terms of relative humidity (RH). Used moisture content sensors are electrical resistance-based sensors with readings in [kohm] and establishment of correlation curves for both type of RAC is still in process. Those results will be published elsewhere. Figure 4a) and 4b) show the measured T and RH values within the panel. While the exterior surface T (S7) vary in a wide range (from  $-10.8$  to  $55.4^{\circ}\text{C}$ ) following the pattern of outdoor climate, T variations through inner RAC layer (S1 – S3) are more stable and limited from  $17.18$  to max  $31^{\circ}\text{C}$ . RH sensors at positions S1 – S3 (inner RAC layer) did not send any information (Figure 4b).

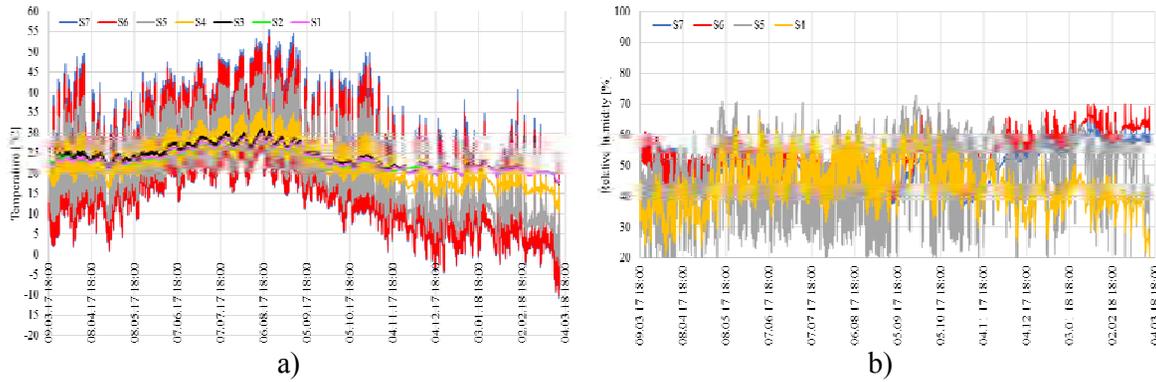


Fig 4. One-year monitoring data: a) Temperature b) Relative humidity

Figure 5 presents the measured RH in the mineral wool (MW) and RAC outer facade layer for period December 1, 2017 – February 28, 2018. MW is of big interest due to its thermal insulation function, while RAC outer façade layer presents the most humid area of the panel in winter by being directly submitted to wind driven rain. Despite high outdoor RH values (above 90%), for external surface of RAC façade layer RH oscillates mostly around 60%. This can probably be attributed to the water-repellent coating.

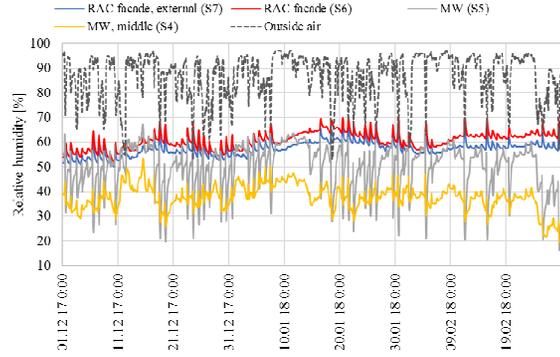


Figure 5. RH inside RAC outer façade and MW layer of monitored panel during winter

It appears that the RH is mostly, except the few occasional peaks, under 60 % at the surface of MW layer (S5). In the middle of MW (S4), RH is almost always under 50 % and mostly fluctuating around 40% which indicates the positive effect of air ventilation in cavity. To gain a deeper understanding of hygrothermal behaviour of observed south-facing panel, monitoring results are presented hereafter for the three coldest days of the winter period (February 26-28, 2018) and the three hottest days of the summer period (August 3-5, 2017), respectively.

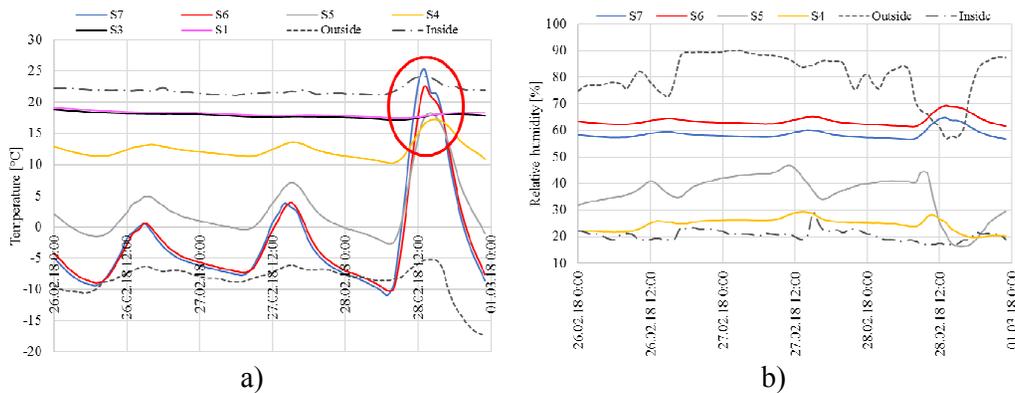


Figure 6. Hygrothermal responses within the panel for three coldest days: a) T; b) RH

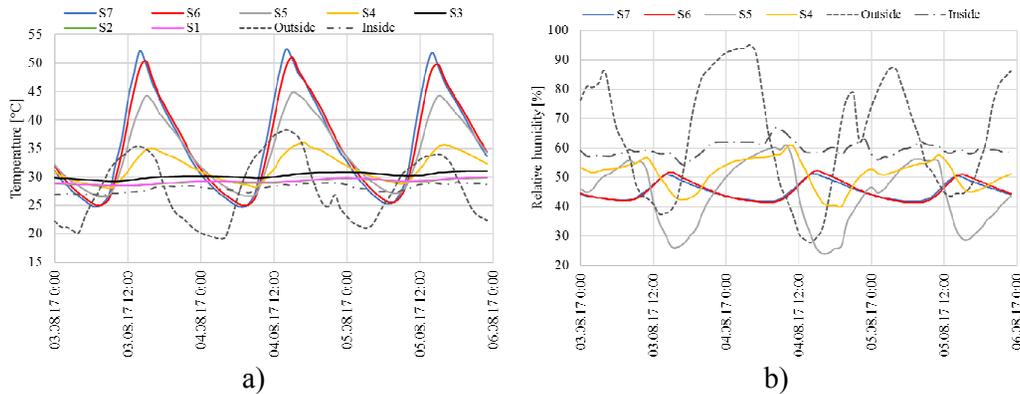


Figure 7. Hygrothermal responses within the panel for three hottest days: a) T; b) RH

In February 2018, indoor air temperature varies between 21.1 – 25.5°C with a mean of 22.9 °C. Values of RH vary between 41.3 – 77 % with a mean of 53.3 %. During August 2017, indoor air temperature varies in a wider range from 29.1 – 23.7°C, with a mean of 26.2°C, while values of RH vary between 69.3 – 37.3 % with a mean of 53.3 %. The fluctuations of indoor temperature are limited by heating system (mechanical ventilation with recuperation system and radiators as additional heating system in winter but without additional cooling system in summer). The exterior surface temperature (S7) of observed south-facing panel follows the pattern of behaviour of the outdoor temperature reaching a high peak at 14:00h in summer conditions due to the solar exposure. The same pattern is followed by S6 – S4 but with decreased amplitude. Further and more progressive attenuation of T amplitude is present in S3 – S1 (inner layer). In winter period, high peak occurs on February 28 reaching 25.3°C at panel's exterior surface at 13:00h. This specific peak is most likely induced by increased solar radiation at clear winter day compared to previous days (Figure 8). Unfortunately, there was occasional interruption of measurement and some hourly solar radiation data are missing.

Besides attenuation of T amplitude, a time shift between the peaks can be observed. These appearances are due to the thermal inertia of RAC panel. Thermal inertia is evaluated in terms of time lag and attenuation of heat wave amplitude while propagating from the outer surface to the inner surface. February 27, 2018 is analysed for winter conditions and August 4-5, 2017 for summer conditions, respectively. In summer conditions, between S7 – S1 a

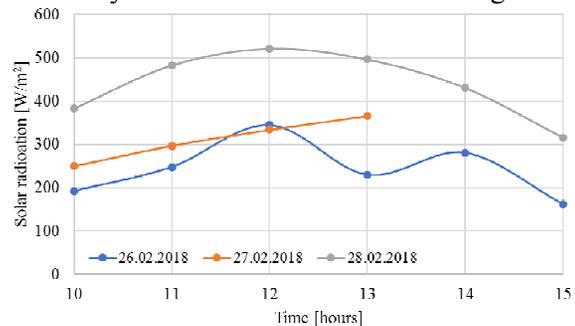


Figure 8. Solar radiation data in February 2018

damping of approx. 57 % is measured. The panel attenuates the temperature very well with a time lag of 10h over a period of 25 hours. These two observations indicate that the panel has a good thermal inertia. For completely opposite boundary conditions, i.e. winter conditions, the min exterior surface temperature (-7.7°C) and min interior surface temperature (17.8°C) are analysed. In this case, time lag is approximately 6h over a period of 24 hours. High façade surface temperatures (> 50°C) in the summer indicate there may be periods of overheating that potentially could compromise thermal comfort of occupants. Living room has large transparent openings (marked blue in Figure 2a) oriented to south which ensures considerable solar heat gains. In Figure 9 coincidence of the measured psychrometric data in living room and the summer comfort zone is presented for period of June 1 to September 1, 2018. Used summer comfort limits are the ones defined for living spaces in residential buildings, Category II (HZN 2008). During summer, T and RH were in the comfort zone 57.7% of time.

Actually, RH exceeds the upper threshold (60%) only 17.5% of the time, while T exhibited significant violation of upper threshold (26°C). This overheating is related to architectural design of building, where large transparent openings at south are not adequately shaded. To avoid installation of additional air-conditioning systems, application of adequate shading devices or/and external greenery should be considered. That would undoubtedly decrease operating temperatures in summer period.

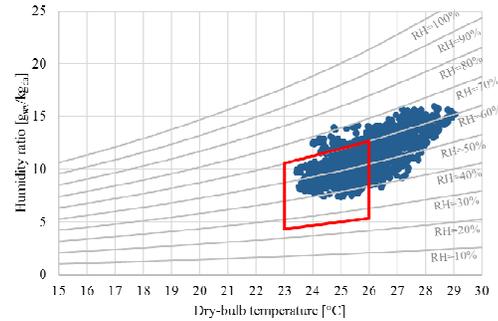


Figure 9. Internal psychrometrics data vs. HRN EN 15251 summer comfort limits

## CONCLUSIONS AND FURTHER RESEARCH ACTIVITIES

The first in-situ monitoring results of family house constructed with prefabricated ventilated sandwich wall panels from recycled aggregate concrete (RAC) were analysed. Hygrothermal behaviour under real variable climate conditions and real use of occupants was experimentally monitored during one year. The south-oriented RAC panel exhibited a good thermal inertia - high damping capacity (>50 %) and time shift up to 10 hours in summer period. Air ventilation maintained relative humidity levels in mineral insulation under 60 % during winter months. Even though these results are preliminary results, they can already confirm that it is possible to upscale RAC from laboratory material experiments to full-scale construction product implementation and design sustainable, energy efficient and moisture-safe buildings. Special attention should be on preventing summer overheating. Further research steps are: i) analysis of west- and north-oriented (more shady) facades and their comparison with presented south panel; ii) numerical simulation of panels and validation with experimental results (assessing the panel's suitability for different climates); iii) continue with monitoring for at least next two years – possibility to confirm pattern of RAC's hygrothermal behaviour.

## ACKNOWLEDGEMENT

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