Young Researchers' Forum III
Innovation in Construction Materials
12 April 2016

Paper Number XX

Experimental investigation of hygrothermal performance of recycled aggregate concrete

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ABSTRACT

Increasing demand on energy efficiency and natural resources conservation is challenging the construction sector. Construction and demolition waste can gain added value through its reuse as aggregate in concrete, thus it could contribute to the natural resources conservation. Prefabricated ventilated concrete wall panel, produced by using recycled aggregate, is a benchmark construction product that unites reduction of energy consumption and sustainable use of construction and demolition waste. How building envelope built with this kind of panels perform when exposed to the real weather conditions and real conditions of use, i.e. people living inside the building, defines its hygrothermal performance (combined heat, air and moisture transfer). Hygrothermal performance of a building envelope is reflected in temperature and moisture content variations within the building assemblies, thus directly affecting the energy consumption, durability of building envelope and comfort of inhabitants. Since there is no experimental confirmation on hygrothermal performance of prefabricated ventilated concrete wall panels, produced using the recycled aggregate, experimental set-up for hygrothermal monitoring was designed in order to provide a deeper insight in heat, air and moisture transfer through this kind of panels.

1. INTRODUCTION

Construction sector is facing two main challenges of the 21st century: energy poverty and depletion of natural resources. Efficient use of energy and natural resource conservation, reflected in 6th and 7th Basic requirement for construction work (European Parliament, 2011), are the prerequisite for achieving sustainability and innovation in construction sector.

Since the most buildings are ''sub-standard'' in terms of energy consumption, EU strategy Europe 2020 (European Commission, 2010), Energy Performance of Buildings Directive and its Recast (European Parliament, 2010) have established legal framework for energy efficiency in buildings through strictly defined energy requirements for different type of buildings. The first step towards energy efficient buildings is design and construction of energy efficient building envelope.

The second challenge that construction sector, but also the whole Europe, is facing to is natural resource conservation. European Commission (EC) identified construction and demolition waste (CDW) as a priority waste stream since it represents approximately 34% - 49% (Eurostat, 2014; Sáez et al, 2011) of the total waste generation in the EU, which makes it dominated EU waste. EC established the legislative framework for waste management through The Waste Framework Directive (WFD). WFD requires Member States to take any necessary measures to achieve a minimum target of 70% (by weight) of CDW by 2020 for preparation for reuse, recycling and other material recovery, including backfilling operations using non-hazardous CDW to substitute other materials (European Parliament, 2008). CDW could gain added value through its use for the production of recycled aggregate concrete.

With the aim to develop benchmark construction product that unites reduction of energy consumption and sustainable use of CDW, extensive research has been carried out by the research group at Department of Materials, Faculty of Civil Engineering, University of Zagreb. Conducted research resulted with the innovative prefabricated ventilated ECO-SANDWICH® (EC®) wall panels.

For detail understanding on the behavior of building envelope, its hygrothermal performance have to be known. In case of prefabricated ventilated wall panels, i.e. for the same type of sandwich wall panels as EC® panels, dynamic hygrothermal performance is only assumed, but not experimentally confirmed.

2. ECO-SANDWICH® panel

EC® panel is innovative prefabricated ventilated wall panel with integrated formaldehyde-free core insulation allowing very low energy design and retrofit of buildings. It consist of two recycled aggregate concrete layers interconnected through stainless lattice girders, Figure 1.

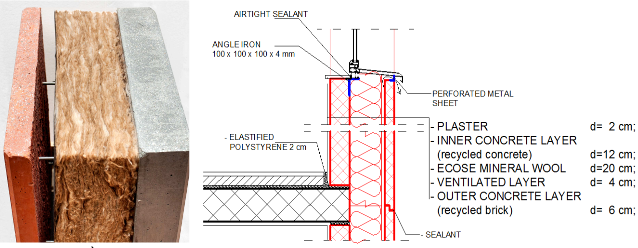


Figure 1. EC® wall system: a) Model; b) Cross section

The inner (self-load bearing) layer is made of recycled concrete aggregates while the outer façade layer is made of recycled brick aggregates. Replacement ratio of natural aggregate in both concrete layers is 50%. To prevent possibility of water vapour condensation, layer of ventilated air is placed between layer of thermal insulation and outer façade layer. Therefore, EC® combines both functions, the one of ventilated façade and the other one of external wall.

EC® represents possible technological solution for fast construction of very low energy or passive house standard (A+) buildings on a large scale. It tackles three major environmental problems: reducing greenhouse gas emission by enhancing energy efficiency of buildings, increased resource efficiency through the use of CDW in panel manufacturing and minimising the use of regulated chemicals like phenol and formaldehyde from the insulation material production process.

In order to optimize concrete mixtures and determine the most favourable replacement ratio of natural aggregates with CDW, comprehensive research on mechanical, durability and thermal properties was performed. In the mixtures, proportions of the recycled aggregate of 40%, 50% and 60% were used, as they were deemed to hold the best balance between environmental, structural, durability and thermal requirements. Mixture with 50% of replacement of coarse aggregate was chosen as optimal for the EC® wall panels (Alagusic et al, 2016; Banjad Pečur et al, 2015).

3. Hygrothermal performance

When considering the building envelope, 75 - 90% of all construction damage is caused by moisture (Milovanović and Mikulić, 2011). Moisture transfer (water vapour contained in the air and/or liquid moisture) through the building envelope cannot be fully prevented and it takes place simultaneously with the heat transfer. Moisture and heat transfer reflect by changes in temperature and moisture content within the characteristic layers of the building envelope. Thereby, hygrothermal performance of the building envelope implies a combined heat, air and moisture transfer through the envelope, which occurs due to differences between the external environment and the interior of the building (internal environment). Primarily it refers to the different temperature conditions and different conditions of relative humidity, i.e. different partial pressures of water vapour in air, of the external and internal environment. These conditions represent the boundary conditions of the building envelope. The outer boundary conditions of the envelope are determined by the climate that shows the repeatability for the particular building location. The influence of weather on the building is therefore taken into account by choosing representative meteorological data for a particular building location. The inner boundary conditions are determined by the use type of the building and the user habits. In the average household 10 liters of water is generated as water vapour per day. It is necessary to control the amount of moisture inside the buildings in such way that the excess moisture is brought outside the building (natural ventilation or mechanical ventilation), in order to ensure comfort and hygienic conditions and to prevent the occurrence of construction damage.

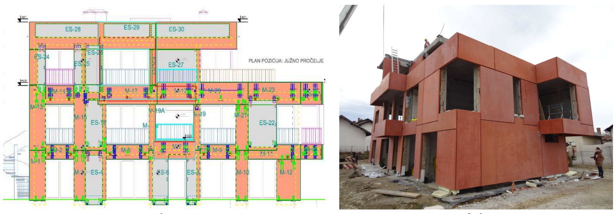
Building envelope is a ''skin'' of the building and it is exposed to the external loads from the environment, both the mechanical and hygrothermal ones. Through the ''skin'', i.e. its envelope, building resists loads and strive to establish a balance in terms of mechanical stability and resistance and in terms of dynamic hygrothermal balance. In addition to the external and inner boundary conditions, significant role in hygrothermal performance have the properties of characteristic layers of building envelope. The characteristic layers with its physical, mechanical and hygrothermal properties considerably affect the dynamics of the heat, air and moisture transfer, thereby defining hygrothermal performance of the building as a whole (Künzel and Holm, 2009).

So, the appropriate moisture control is a prerequisite for the design of energy efficient buildings and buildings without damage. Investigation on hygrothermal performance of ventilated facades is an active field of actual research. Review of the literature has revealed that all studies regarding the hygrothermal performance of ventilated facades have been conducted on the wooden ventilated facades which is common type of building in North America and Northern Europe (Salonvarra et al, 2007; Künzel et al, 2008; Grau and Rode, 2006; Tichy and Murray, 2007) or on ventilated facades with brick walls (Van Belleghem et al, 2015; Karagiozis and Künzel, 2009; Hens and Janssens, 2007). Al-Neshawy (Al-Neshawy, 2013) conducted a study on hygrothermal performance of prefabricated concrete sandwich panels with a core of thermal insulation, however, this kind of sandwich system has no ventilated layer and cannot be compared with EC® panels. Currently there is no available research dealing with hygrothermal performance of previously described prefabricated ventilated wall panels made of recycled aggregate concrete. Künzel et al. (Künzel et al, 2008) emphasize the necessity of knowing the hygrothermal properties of concrete since the moisture is a key factor influencing the pathology of building elements made of concrete. Also, moisture is a key factor influencing the behaviour of concrete from the aspects of energy efficiency during its service life.

Currently, there is a lack of knowledge on how recycled aggregate concrete and how ventilated prefabricated sandwich wall panels behave when exposed to the weather and real use conditions, i.e. there is a lack of knowledge on their hygrothermal performance. To gain a deeper insight into hygrothermal performance of EC® panels, a program of experimental monitoring on hygrothermal performance of a building envelope constructed with EC® panels is designed.

4. Experimental set-up

At the moment, a 3-storey family house (A+ energy class) is being constructed with EC® panels within socially - supported housing program in Koprivnica, Republic of Croatia (Figure 2). House is planned for sale, which provided the unique opportunity to install a monitoring system for hygrothermal performance of a building envelope in real conditions of use, i.e. people living inside the house.



a) b)

Figure 2. EC® house: a) Position plan for southern façade; b) Construction site in March 2016

The objective of this experimental research is to gain a deeper insight in heat and moisture transfer through the building envelope built with EC® panels, i.e. to obtain temperature and moisture content distribution and variation within all characteristic layers of prefabricated ventilated wall systems in a long-term period.

Monitoring system for hygrothermal performance consists of a set of temperature (T), moisture content (MC) and relative humidity (RH) sensors (Figure 3a). The set of T-MC-RH sensors is fixed on a girder and positioned through the all characteristic layers of EC® panel. Positions of set of T-MC-RH sensors are marked as S1-S7, Figure 3c.

Figure 3. a) Set of T-MC-RH sensors; b) Installation of sets of T-MC-RH sensors on girders; c) Arrangement of T-MC-RH sensors within EC® layers

Since the building envelope consists of a large number of EC® panels, measurement locations had to be selected and reduced. Three panels in ground floor, with different sun orientations, were selected as measurement locations and marked as M1-M3, Figure 4. As it was previously mentioned, at every measurement location, sensors needed for hygrothermal monitoring were positioned within the all characteristic layers of EC®.

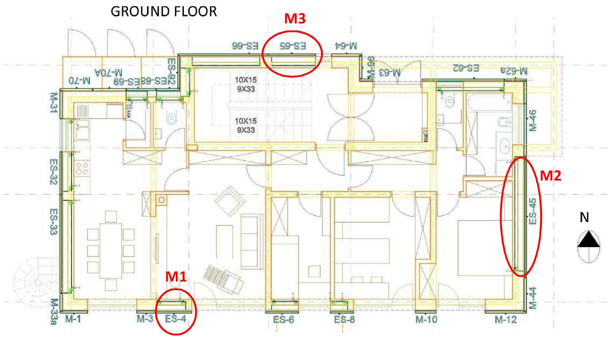


Figure 4. Measurement locations

Presented monitoring system is a combination of wire - based measurement system and wireless system. Every set of sensors (S1-S7) at every measurement location (M1-M3) will be connected to the central measurement unit, where sensors readings will be recorded. Data will be stored in online database, so that the information could be accessed via a web access.

5. Conclusion

It is expected that experimental monitoring of temperature and moisture variations in all characteristic layers of EC® panels will provide a dynamic real-time hygrothermal performance of building envelope constructed with the presented panels under the real terms of use, i.e. people living inside the building, and exposure to the real outdoor conditions.

By controlling its hygrothermal performance, building envelope together with HVAC systems, through the smart building automatization system, can be actively involved in a regulation of consumption of energy needed for heating and cooling.

In addition, hygrothermal monitoring can provide monitoring of a material degradation, which is significant since 75 - 90 % of all damage in building envelope are caused by the moisture. Knowing the degradation process of a material, it could ensure that timely and suitable rehabilitation of a building is performed, i.e. the long term performance and thus the service life of a monitored building could be extended.

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