Annexure I

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Use of recycled aggregate concrete for energy efficient buildings

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ABSTRACT

The rationale of the research presented in the paper is to use of construction and demolition waste (CDW) as a new resource for constructing sustainable nearly zero energy buildings (nZEBs). Research activities have been carried out in order to determine concrete mixture where recycled concrete and recycled brick aggregate would be used as a replacement of natural aggregate in significant quantity (40%, 50% and 60%). The properties of fresh and hardened concrete would need to satisfy requirements set for constructing buildings from prefabricated wall panel systems.
Based on conducted mechanical, durability and thermal testing of recycled aggregate concrete, replacement ratio of natural aggregate by 50% was determined as optimal. Concrete with compressive strength higher than 40 MPa was produced, which is satisfactory from the structural point of view for small buildings, and satisfactory durability properties (decrease of the elastic modulus was less than 8% for RBA concrete, and less than 4% for RCA concrete after 56 freeze-thaw cycles). Concrete mixtures containing RCA and RBA aggregates have 13–27% and 29–40% lower thermal conductivity than the reported literature values and 38 to 70% lower water vapor diffusion coefficient than the literature values. The monitoring results show that the panel attenuates the temperature very well with a time lag of 10h over a period of 25 hours in summer conditions, while in winter the time lag is approximately 6h over a period of 24 hours which noticeably decreases cooling and heating energy demand. Additionally, the monitoring shows significant influence of ventilated air layer on reducing temperature peaks during both winter and summer periods. The environmental impact of the ECO-SANDWICH wall panel is also shown.
Research resulted with development of an energy and resource efficient construction product ECO-SANDWICH - ventilated precast concrete sandwich wall panel with integrated formaldehyde-free mineral wool insulation. ECO-SANDWICH wall panel is a benchmark construction product that allows very low energy design buildings; therefore, it can be coupled with an exigent need to improve energy performance of the building stock in the EU member states. Storage of recycled materials from CDW in concrete and production of a new high quality construction product can add value to CDW and contribute to closing the loop of product lifecycles which is the basis of a circular economy.

Keywords: construction and demolition waste, recycled aggregate, nZEB, ECO-SANDWICH, environmental product declaration, thermal inertia.

INTRODUCTION

Today, construction sector is strongly challenged by the increasing demand on energy efficiency and natural resources conservation which are caused by the depletion of natural resources and energy poverty. Each year, large quantities of natural resources are extracted due to increasing demands and turned into primary aggregates and consequently into building materials. At a global level, civil works and building construction are using approx. 60% of the raw materials extracted from the lithosphere, while in Europe, the extraction of minerals for construction industry is about 4.8 t/anno/inhabitant (Simion, Fortuna, Bonoli, & Gavrilescu, 2013).

On the other hand, construction and demolition waste (CDW) contributes to one third of the waste generated in EU, which means about 180 million t/anno, approximated at 480 kg per person on average in all EU countries. It can be foreseen, that due to the continuous development, significant quantities of waste from construction, renovation and demolition sites will be produced by the construction sector. In general,

CDW consists of numerous materials, many of which can be recycled, including concrete, bricks, gypsum, wood, glass, metals, plastic, solvents and excavated soil.

Circular economy

Turning CDW into resource is particularly relevant for Europe and thus EU has set the legal framework and established the requirements that all Member States are obligated to fulfill regarding the management of construction and demolition waste (CDW) (European Parliament and the Council, 2008). The so called Waste Framework Directive (European Parliament and the Council, 2008) requires Member States to take any necessary measures to achieve a minimum target of 70% (by weight) of CDW by 2020 for preparation, for re-use, recycling and other material recovery, including backfilling operations using non-hazardous CDW to substitute other materials.

The circular economy aims to change the traditional way of doing business in which materials are produced, used and then disposed. Many research groups have thus focused their research efforts to develop new ideas and ways of embedding circular economy thinking into the built environment. When a material comes to the end of its service life it can be reused or regenerated into new products, rather than throwing it away. In other words, the material is viewed as a resource rather than waste. It is thought that comprehensive approach consisting of designing out and minimizing waste from root cause, incorporating reused and recycled materials into new enhanced construction products and managing the end of life reuse and recycling of assets will help achieve a circular economy (Hobbs, 2017). Additionally, circular economy offers EU an opportunity to boost global competitiveness, foster sustainable economic growth and generate new jobs (European Commission, 2015).

Recycled aggregate concrete (RAC) has been identified as sustainable alternative to conventional concrete. Its mechanical and durability behavior has already been widely acknowledged by many researchers (Behera, Bhattacharyya, Minocha, Deoliya, & Maiti, 2014; Bjegović, Štirmer, & Serdar, 2010; Fraile-Garcia, Ferreiro-Cabello, López-Ochoa, & López-González, 2017; Marco, 2014; McNeil & Kang, 2013; Miličević, Bjegović, & Siddique, 2015; Miličević, Štirmer, & Pečur, 2016; Pickel, 2014). The Portuguese study (Coelho & Brito, 2013) done on large scale CDW recycling plant shows that the energy and CO_2 savings can reach up to 8 times the burdens of the recycling operations in cases when the generated secondary materials clearly substitute primary materials and are effectively reused or recycled into new products.

Nearly Zero Energy Buildings

Energy efficiency and energy performance of buildings is an additional “hot” topic, being discussed the European Commission since 1970 and it has been widely recognized as an option to decrease primary energy use. According to Energy Performance of Building Directive - EPBD (2002-91 EC) and its Recast EPBD II (2010-31-EU) (European Parliament and the Council of the European Union, 2010) buildings account over 40% of total energy consumption in the EU with the sector expanding and increasing energy consumption (European Commission, 2016).

Europe has set the legal framework and established the requirements that all Member States are obligated to fulfill regarding the energy efficiency in building sector (European Parliament and the Council of the European Union, 2010), and through the so called Winter package (European Commission, 2016), it is putting energy efficiency first, which means: setting the framework for improving energy efficiency in general; improving energy efficiency in buildings; improving the energy performance of products (Ecodesign) and informing consumers (energy labelling); financing for energy efficiency with the smart finance for smart buildings proposal. As an encompassing element the European Commission proposed a binding EU-wide target of 30% for energy efficiency (reduction of energy consumption) by 2030 (European Commission, 2016). Article 9 of the EPBD II directive (European Parliament and the Council, 2010) indicates that EU Member States (MS) must ensure that by 2021 all new buildings, and already by 2019 all new public buildings, are nearly Zero Energy Buildings (nZEB), in other words high performance buildings with very low energy demand, were this demand is covered by renewable energy sources produced onsite or close to the building location.

ECO-SANDWICH PREFABRICATED WALL PANELS

The high production levels of concrete result in high material consumption globally: ~3.8 Gt of cement, ~17.5 Gt of aggregate, and over 2 Gt of water were used as material constituents in 2012 (Miller, Horvath, & Monteiro, 2018). Having in mind that aggregate accounts for 60-80% of the volume and 70-85% of the weight of concrete, it’s clear that there is a tremendous potential for incorporating CDW into concrete, thus creating a sustainable end use and reduce the demand for natural aggregate.

The Construction Industry Council (CIC) in the UK noted that prefabricated wall panels offer benefits over traditional approaches, like higher sustainability, better build quality, faster delivery, improved health

and safety, enhanced energy-in-use, lower whole-life carbon footprint and reduced transport pollution (Goulding & Arif, 2013).

Current influential construction trends, such as the increasing interest in lean construction, the rising use of BIM technologies and the growing influence of green construction have caused many construction companies to reconsider their appeal (McGraw-Hill Construction, 2011). (Jaillon, Poon, & Chiang, 2009) stated that prefabricated buildings reduce construction waste up to 52% compared to traditional methods, while (Quale, Eckelman, Williams, Sloditskie, & Zimmerman, 2012) showed that GHG emissions for modular constructions are 40 % lower than that for traditional on-site works.

At the University of Zagreb, Faculty of Civil Engineering, there is a longstanding tradition of concrete research, especially reuse of materials, use of recycled materials, and in past few years in the field of energy efficiency in buildings. The move towards circular economy was built upon this long standing knowledge, but the wish to combine these two seemingly different areas has challenged the research group. Two main difficulties arose. How to transform limitations of waste framework directive (European Parliament and the Council, 2008) and EPBD (European Parliament and the Council, 2010) directive into opportunities and advantages? Is it possible to add value to CDW and to use it as a resource for production of new construction products that will satisfy requirements of both directives, i.e. fit into the concept of sustainability and ensure lower energy consumption in buildings?

These were the guiding principles in extensive research that has been carried out within the ”ECO-SANDWICH Energy Efficient, Recycled Concrete Sandwich Façade Panel” project funded by CIP-Eco Innovation. Conducted research resulted with the development of ECO-SANDWICH (ES) panels with high degree of recycled materials obtained from demolition of existing buildings (concrete aggregates) and production process of construction materials (brick aggregates).

ES panel is a precast sandwich wall panel with integrated glass wool core insulation allowing very low energy design of new and retrofit of existing buildings. It consists of two concrete layers interconnected through stainless lattice girders and an all-important ventilated layer (Figure 1). Ventilated air layer enables water vapor diffusion, enables lower/higher surface temperatures on the outer surface of the insulation layer during summer and winter period respectively, which in turn results with lower cooling and heating demand of the whole building.

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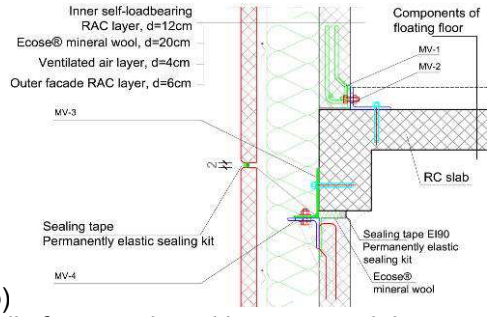
b) 

Figure 1. ES panel: a) model, b) detail of connection with concrete slab

CDW is being used as a resource for production of inner and outer concrete layers. The inner (self-load bearing) layer is made of recycled concrete aggregates (RCA) while the outer façade layer is made of recycled brick aggregates (RBA). ES represents possible technological solution for fast construction of very low energy or passive house standard buildings on a large scale, thus minimizing environmental impacts. During the project duration, the first step was to determine the most favorable replacement ratio of virgin aggregate with CDW in concrete mixes from the aspects of best balance between mechanical, durability and thermal properties. The second step was to deal with market uptake of the developed solution. Based on optimization, the replacement ratio of 50% of virgin coarse aggregate was chosen as optimal for the ES panels (Pečur, Štirmer, & Milovanović, 2015).

EXPERIMENTAL WORK

Thorough analysis of mechanical, durability and thermal properties was performed on six concrete mixtures which were prepared for laboratory testing. The aim was to determine which percentage of aggregates replacement (40%, 50% or 60%) would be most suitable for production of precast wall panels for constructing residential buildings and which of the proposed mixtures would satisfy current requirements for buildings during the whole life cycle.

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. Cement CEM II A/S 42.5 R was used to produce all concrete mixtures. Natural sand of the nominal size 0–4 mm from two sources was used: river sand and crushed aggregate together with recycled concrete (RCA) and recycled

brick (RBA) aggregates 4–8 mm and 8–16 mm. Natural crushed aggregate 4–8 mm was also used to produce concrete mixtures with 40% of recycled aggregate. The water absorption of CDW aggregates were 16.9% (4–8 mm) and 13.9% (8–16 mm) for the RCA aggregates and 17.8% (4–8 mm) and 18.4% (8–16 mm) for the RBA aggregates, respectively. Except for the aggregate, the proportion of other components was the same in all mixtures: 400 kg of cement, water to cement ratio (w/c) = 0.42 and air entraining plasticizer Melcret SPA 0.7% by weight of cement.

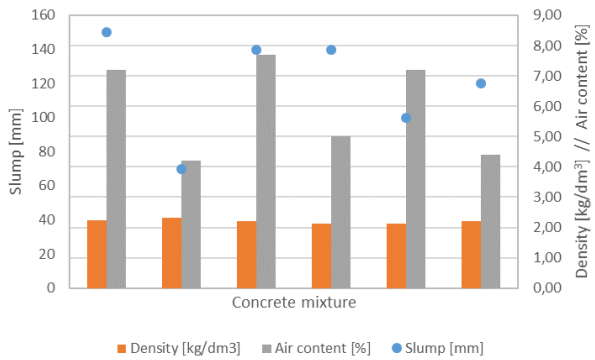


Figure 2. Properties of fresh concrete

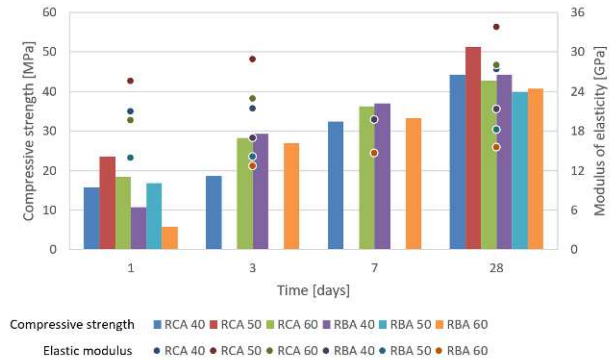


Figure 3. Mechanical properties: compressive strength; modulus of elasticity

The properties of fresh concrete are shown in Figure 2. The reduced workability of fresh concrete mixtures was noted both for recycled concrete and recycled brick due to the high water absorption of RAC and RBA, which was in accordance with the expectations of initial workability loss. The workability loss was taken into account and did not affect significantly the casting of the wall panels since they were produced in a precast concrete factory where an adequate compaction could be achieved.

Mechanical properties

Compressive strength was tested according to the standard EN 12390-3 after 1, 3, 7 and 28 days. It can be seen from Figure 3 that concrete with 50% recycled concrete (RCA 50) has the largest 1 day compressive strength, as well as at the age of 28 days, which is obviously caused by smaller air content (4.2%). In general, concrete produced with RCA has higher compressive strength than concrete with RBA.

When comparing results of mechanical properties testing, it can be concluded that an increase of the RBA amount from 40% to 60% decreases compressive strength by approximately 10%, Figure 3. For RCA, there is a similar trend for 28-day compressive strength, but concrete with 60% recycled aggregate has faster strength development. It can be seen that 28 day compressive strength is higher than 40 MPa (Figure 3), which is satisfactory from the structural point of view for small buildings and this kind of self-bearing wall panels. If necessary, the reduction in compressive strength due to the addition of recycled aggregate can be controlled by changing various factors of the concrete mix, such as adjusting the w/c ratio, changing the mixing procedure, treating the aggregate and using a mineral addition. The literature reports that modifications in the concrete mixing procedure are the key step to develop a good quality concrete containing any type of CDW aggregate (de Brito & Saikia, 2013).

Durability properties

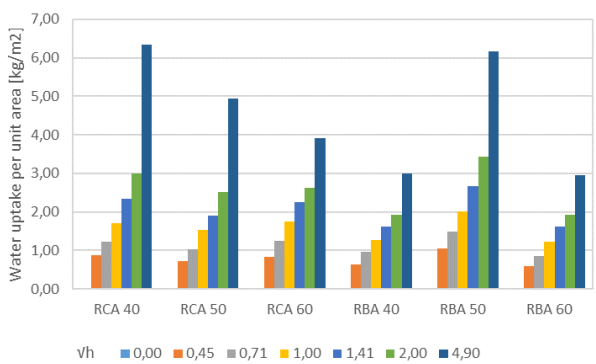


Figure 4. Capillary absorption

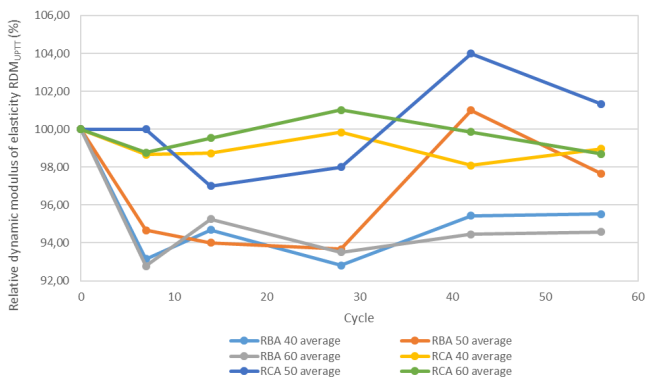


Figure 5. Freeze–thaw resistance – dynamic modulus

Relevant durability properties for prefabricated concrete wall elements are resistance to freezing and thawing and capillary absorption. Prefabricated wall elements should satisfy requirements for XF1 exposure class. Results of testing capillary absorption are shown in Figure 4, where all mixtures except RBA 40 and RBA 60 have high absorption.

Freeze thaw resistance without deicing salts was tested according to CEN/TR 15177 where internal structural damage was determined by measuring the relative change of dynamic modulus of elasticity. It can be seen from the results in Figure 5 that the maximum relative decrease of the elastic modulus during 56 cycles of testing is less than 8% for RBA concrete, while for RCA concrete the maximum relative decrease is less than 4%. Here, average was calculated out of measurement results on 3 specimens, where ultrasonic pulse transit time (UPTT) was measured. The results of the tests of freeze-thaw resistance with de-icing salts were published elsewhere (Pečur et al., 2015). Moreover, other relevant durability properties such as resistance to freezing and thawing with de-icing salts, water permeability, gas permeability and chloride migration were tested and the results were published in (Pečur et al., 2015).

It can be concluded from the durability testing results that even though freeze-thaw resistance is satisfactory, gas and water permeability properties of all specimens is average at best, while resistance to chloride penetration is unsatisfactory and that tested concrete types would not be suitable for structural elements in a marine environment or they should be additionally protected when used in a harsh environment.

Thermal and water vapor diffusion properties

Testing of thermal conductivity was carried out by means of guarded hot plate (GHP) according to (HZN, 2002a) and (HZN, 1998). Results of testing are shown in Figure 6.

Literature review shows that thermal conductivity of concrete can vary significantly, depending on the type of aggregates used as well as its density. For the concrete (ACI Committee 122, 2002) gives thermal conductivity values of 0.99 W/m K and 1.18 W/m K for densities of 1922 kg/m^3 and 2083 kg/m^3, respectively, (dry concrete made, limestone aggregates), while (Gorse & Highfield, 2009) give thermal conductivity of 1.13 W/m K for the concrete with density of 2000 kg/m^3. On the other hand, concrete which is usually being used for this kind of application in structural concrete insulated panels (SCIPs) has the thermal conductivity of 2.00 W/m K (Willems, Dinter, & Schild, 2006) (natural aggregates, density of 2400 kg/m^3).

It can thus be concluded that the concretes containing RCA and RBA aggregates have 13–27% and 29–40% lower thermal conductivity than the reported literature values for the dry concrete with approximately the same density.

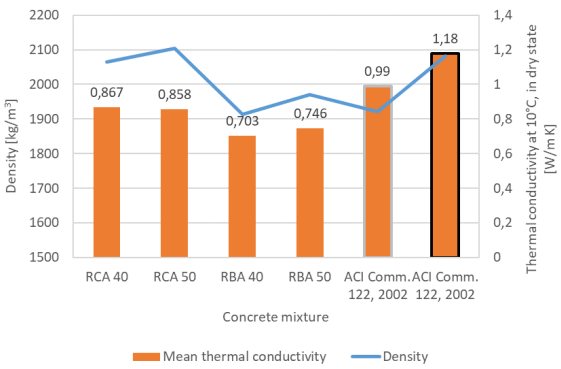


Figure 6. Thermal conductivity testing results, compared to ACI Committee 122

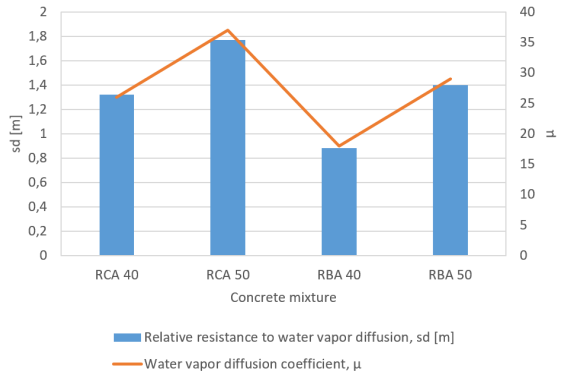


Figure 7. Results of testing water vapor diffusion coefficient

Testing of water vapor diffusion coefficient was carried out according to (HZN, 2002b). It can be seen (Figure 7) that concrete produced with RCA and RBA aggregates has 38 to 70% lower water vapor diffusion coefficient than the literature values for concrete with the density of 2000 kg/m^3, (μ = 60 or 100, in wet and dry state), respectively (Willems et al., 2006).

Thermal properties of RCA and RBA concrete have thus proven to be significantly better than those for conventional concrete. Combined with sustainable thermal insulation materials, this facilitates easier and more economical achievement of required heat transfer values in very low-energy buildings and nZEBs.

The analysis of thermal inertia of buildings constructed using different effective thermal capacities has been published in (Pečur et al., 2015), where it was concluded that the weight of ES (458 kg/m^2) has a positive effect on energy consumption and indoor climate, especially in climates with a large diurnal temperature range. In this paper, the monitoring results of the within the cross-section of the ES wall panels installed in a nZEB building in Croatia (Figure 8a). The monitoring system (Figure 8b) was positioned on the southern façade of the building thus measuring the influence of thermal inertia on the most critical side of the building. It has to be said here, that the nZEB building in Croatia (Figure 8a) was constructed using ES wall

panels with RCA 50 and RBA 50 where out of 1759 kg/m^3 of total amount of aggregates in the concrete mixture, 879.5 kg (50%) was recycled aggregate.

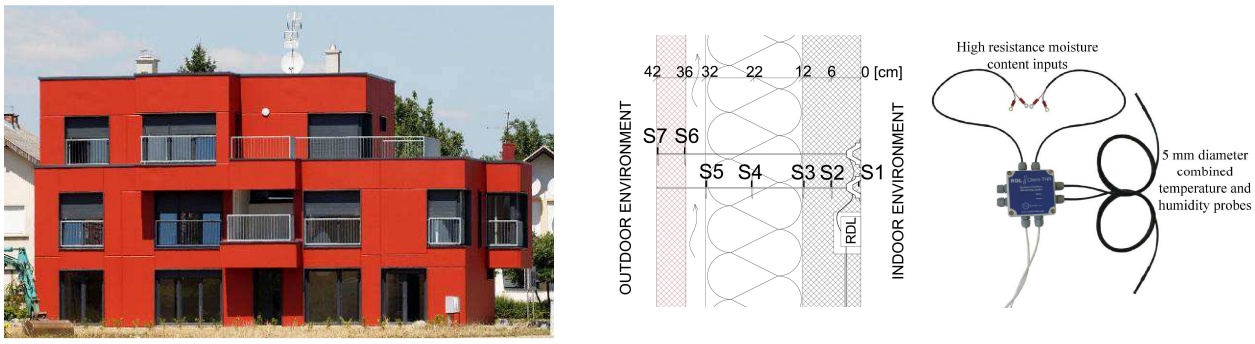


Figure 8. Measurement location: a) nZEB building under monitoring; b) Arrangement of temperature sensors within panel layers and the monitoring system installed

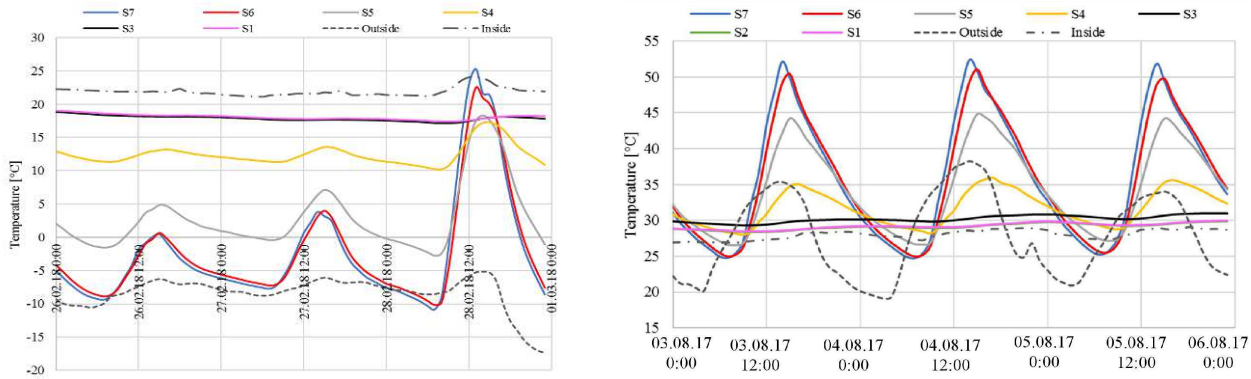


Figure 9. Temperature responses within the panel for: a) three coldest days of the winter period; b) three hottest days in the summer period

As shown in Figure 9, in winter months outside temperature was under 0°C with peak of -17.34°C at the end of February 2018. Five days in a row was the longest continuous period of temperature under 0°C with the mean value of -6.63°C. On the other hand, in August 2017 maximum temperature value was 38.27°C and with its average monthly value of 22.49°C. In February 2018, indoor air temperature varies between 21.13 and 25.45°C with a mean of 22.9 °C. During August 2017, indoor air temperature varies in a wider range from 29.05 to 23.73°C, with a mean of 26.22°C.

The exterior surface temperature (S7) of observed south-facing panel follows the pattern of behavior 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 (RCA inner layer). Besides attenuation of T amplitude, a time shift between the peaks can be observed.

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 (Kontoleon and Giarma, 2016). February 27, 2018 is analyzed for winter conditions and August 4-5, 2017 for summer conditions, respectively.

In summer conditions, between sensors S7 and S1 a damping of 56.99 % is measured. The panel attenuates the temperature very well with a time lag of 10h over a period of 25 hours. For the winter conditions, with min. exterior surface temperature (-7.70°C) and min. interior surface temperature (17.80°C) are analyzed. In this case, time lag is approximately 6h over a period of 24 hours. This noticeably decreases heating and cooling energy, but the results of the analysis will be published elsewhere. In particular, benefits can be achieved when the window size is great and the building is well insulated, which is the case in nZEBs, where utilization of the solar gains is one of the basic design principles.

It can be also seen from Figure 9 that the temperature on the outer layer of thermal insulation (S5) is quite significantly different (more than 5°C in peak temperatures) both in winter and summer period than the temperature on the outer surface of the panel (S7). In winter period for example when S7 temperature was fluctuating between -10 °C and +4 °C the S5 temperature fluctuated between -2 °C and 7 °C. This is significant since it is concrete evidence that ventilated air layer has an influence on energy consumption not only in summer period (reduced cooling demand) but also in winter period with reduced heating demand of the building. This is important since in the thermal transmittance calculation, the effect of the ventilated layer is being neglected, and the buildings are calculated as if the external air temperature and ventilated air

temperature are the same. This effectively means that the actual performance of a building made with ES panels may be better than designed, in particular if the building is carefully designed executed.

ENVIRONMENTAL PRODUCT DECLARATION

The life cycle assessment study of ES panels was performed from cradle to grave. This means that all activities throughout the life cycle of each panel were included in the assessment, that is: the product stage, installation into the building (nZEB building in Croatia, Figure 8a), use and maintenance, replacements, demolition, waste processing for re-use, recovery, recycling and disposal, and disposal.

All specific data is measured directly at the only production site of the wall panels. As a result, both the technological and geographical representativeness are very good. The measurements took place in the last years and thus the time related representativeness is also good. The generic data was selected based on the best geographical match to the actual situation, which in most cases resulted in an average for either Croatia or Europe. The geographical representativeness therefore varies. In most cases a good technological match was found, though in some cases an average production process, such as 'average metal working' had to be used. In those cases, the technological representativeness is lower. The product life cycles were modelled using the LCA software SimaPro, where generic data was taken from the ecoinvent database, version 3.1, which was released in 2014 (most recent at the time of assessment), while the specific data has been collected recently and is not older than 3 years.

All inputs and outputs for which data was available were included in the calculation. Data gaps were filled with conservative assumptions with average (generic) data. For end-of-life allocation, the cut-off approach is used, which means that at the end of life, the benefits and burdens of recycling of the ECO-SANDWICH wall panel will not be taken into account. This approach is applied consistently throughout both the foreground and background data.

The environmental impact was calculated using impact categories from Institute of Environmental Sciences (CML) of the Faculty of Science of Leiden University.

The environmental impact of an ECO-SANDWICH wall panel is predominantly determined by the product itself (Figure 10). The total contribution of life cycle stages A1-A3 (i.e. raw materials, transport to production, and assembly) ranges from 48% (Abiotic depletion - elements) to 84% (Global warming). Regarding the total contribution of A4-A5 (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 B1-7 (i.e. use and operation) do not contribute to the environmental impact, since no processes and/or emissions occur.

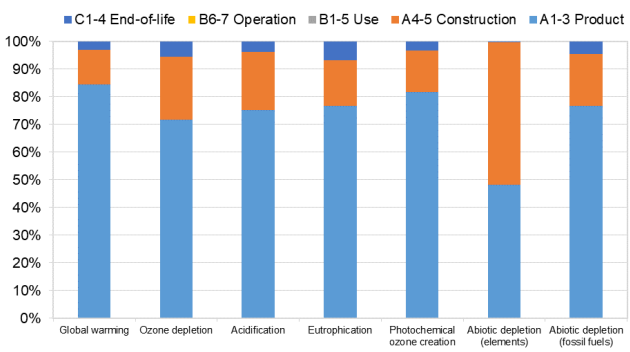


Figure 10. Graph of characterized results for ES

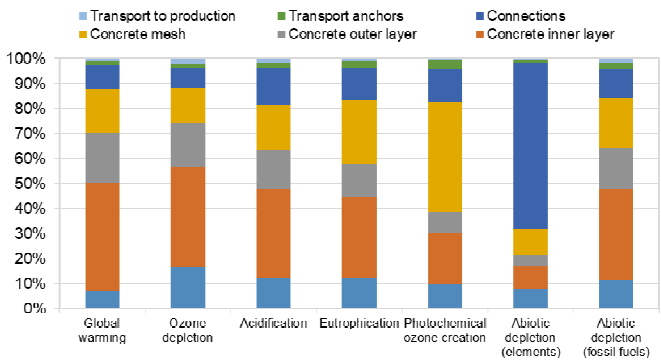


Figure 11. Characterized results A1-3

Module A1-3 has the highest impact for all product categories, but it can be seen from Figure 11 that it varies which part of the LCI is causing it. For example, inner concrete layer of the panel is causing 43% of the impact on global warming, as well as on several other impact categories, while for abiotic depletion of elements, the connections cause 66% of the impact.

CONCLUSIONS

This paper presents research results and efforts needed to create dynamic and flexible construction products which demonstrate the circular way, using less virgin resources and reducing CDW while at the same time creating nZEBs. As expected, the research results showed that recycled aggregates and

particularly, recycled concrete aggregate substantially affect the properties and mix design of concrete both at fresh and hardened states, lower density and strength, and other durability related properties.

Even though the use of recycled aggregates in concrete structures is still limited to low strength and non-structural applications due to their lower durability and mechanical properties requirements, it is show in this paper that buildings can offer a great opportunity to incorporate a large amount of CDW. Existing buildings can also act as a materials bank, providing valuable resource in the form of inert CDW after their future dismantling and/or demolition.

If one looks at the built environment as a material bank, i.e. as a storage of future resources, then it is evident that in the future lower amount of natural resources would be extracted from the lithosphere. But in order to be able to achieve this, more research and development is needed to develop and introduce products like ECO-SANDWICH into construction industry. As shown in this paper, these products would need to exploit all the advantages of CDW used (i.e. thermal mass or thermal conductivity, etc.) but would be, at the same time, fit for their intended purpose (i.e. taking into account their lower compressive strength, lower durability properties, heterogeneous nature of the material etc.).

This paper shows that energy efficiency and sustainability parameters of recycled aggregate concrete can be coupled with an exigent need to improve energy performance of the building thus facilitating a move towards reaching the goals of nZEB (European Parliament and the Council, 2010) and Waste Framework Directive (European Parliament and the Council, 2008).

ECO-SANDWICH panel is an example of possible ways of embedding circular economy thinking into the built environment, where practical application resulting from scientific research is the key towards future widespread application of similar products.

ACKNOWLEDGEMENT

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