Recycled aggregate concrete –sustainable use of construction and demolition waste and reduction of energy consumption

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Abstract

The construction sector consumes vast amount of natural resources and produces significant quantity of construction and demolition waste (CDW), e.g. it counts for more than 30% of waste generated in the European Union (EU). By recycling and reusing CDW in concrete industry it would gain added value, thus it could open unexplored area of possibilities for improvement of concrete industry and its reorientation towards sustainability. This paper presents comprehensive research on recycled aggregate concrete, particularly on application of recycled concrete and brick aggregates as replacement of natural aggregates in concrete mixtures. Based on conducted mechanical, durability and thermal testing of recycled aggregate concrete, replacement ratio of natural aggregates by 50% was determined as optimal. Intensive research activities that have been carried out in recycling and reusing of CDW, have resulted with development of an energy and resource efficient product ECO-SANDWICH® - an innovative ventilated prefabricated concrete facade wall panel with integrated Ecose® mineral wool insulation.

ECO-SANDWICH® wall panel allows very low energy design and retrofit of buildings; therefore, it can be coupled with an exigent need to improve energy performance of the building stock in the EU and neighbouring countries. Exigent need derives from the fact that the most buildings are 'sub-standard' in terms of energy efficiency, comfort and health. Buildings account for the largest share of the total EU final energy consumption producing about 36% of greenhouse gas emissions during their service life.

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. Within this paper, future directions in research on recycled aggregate concrete, i.e. program of experimental monitoring of hygrothermal performance (combined heat, air and moisture transfer) of a building envelope constructed with presented panels will be indicated.

Keywords: construction and demolition waste (CDW), recycled aggregate concrete, energy efficiency, ECO-SANDWICH®, prefabricated concrete wall panel, hygrothermal performance

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Introduction

Construction sector is meeting the challenges of the 21st century. Efficient energy use and natural resources conservation are increasing demands on nowadays buildings. Sustainability has become a key in a competitive sector, especially in concrete industry. Only in Europe, over 750 million m^3 of concrete is produced annually, which rounds up to 4 tonnes of concrete per capita [1], thus it has significant impact on the environment. European Commission (EC) identified construction and demolition waste (CDW) as a priority waste stream since it represents approximately 34% - 49% [2, 3] of the total waste generation in the EU, which makes it dominated EU waste. EU policies are now aimed at significantly reducing the amount of waste generated, through new waste prevention initiatives, better use of resources, and encouraging a shift to more sustainable consumption and production patterns. 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 [4]. CDW could regain added value through the use as recycled aggregate concrete, extend its lifetime and open unexplored area of possibilities for improvement of concrete industry and its reorientation towards sustainability. Sustainable use of natural resources is defined also as 7th Basic requirement for construction work [5].
Another challenge facing construction sector today is energy economy and heat retention, since the most buildings are 'sub-standard' in terms of energy efficiency, comfort and health [6]. Energy efficiency is one of the most cost-effective way to stabilize the uncertainty of energy supplies and to reduce CO_2 emissions. The main prerequisite of energy efficient buildings is their energy efficient building envelope. EU strategy Europe 2020 [7], Energy Performance of Building (EPBD) Directive and its Recast [8] have established legal framework for energy efficiency in buildings through energy requirements for different building types. From all of the above, it is obvious that buildings are one of the biggest energy consumers and have a great impact on the environment. This paper presents research and development of ECO-SANDWICH® wall panel –a benchmark construction product that unites reduction of energy consumption and sustainable use of CDW. Also, the future directions in research on this kind of recycled aggregate concrete building envelope system will be indicated.

ECO-SANDWICH® panel

ECO-SANDWICH® satisfies mandatory targets of the EU EPBD Directive, its Recast EPBD II and WFD targets, and represents possible technological solution for fast construction of very low energy or passive house standard (A+) buildings on a large scale. Thereby, 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.

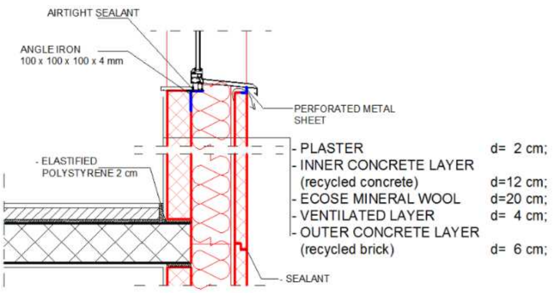
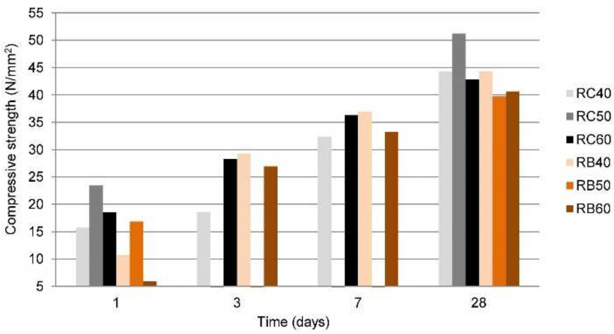


Figure 1: Composition of ECO-SANDWICH® wall panel

ECO-SANDWICH® consists of two prefabricated recycled aggregate concrete layers interconnected through stainless steel lattice girders, Figure 1. In inner (self-bearing) layer, 50% of the natural aggregate is replaced with recycled concrete, while in the outer façade layer the 50% of the natural aggregate is replaced with recycled brick. Incorporated 20 cm thick thermal insulation layer is mineral wool produced by innovative formaldehyde free Ecose® technology. To prevent possibility of water vapour condensation, 4 cm thick layer of ventilated air is placed between thermal insulation and outer façade layer.

Experimental work and test results

In order to optimize concrete mixes and determine the most favourable replacement ratio of natural aggregates with CDW, comprehensive research on mechanical, durability and thermal properties was performed. In the mixes, 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. All concrete mixes were produced with cement CEM II A/S 42.5 R. As aggregate, natural sand of the nominal size 0–4 mm from two sources was used: river sand and crushed aggregate together with recycled concrete (RC) and recycled brick (RB) aggregates 4–8 mm and 8–16 mm. For concrete mixes with 40% of recycled aggregate, natural crushed aggregate 4–8 mm was also used. RC aggregate was produced by crushing laboratory specimens, whereas RB was produced by crushing waste brick. Except for the aggregate, the proportion of other components was the same in all mixes: 400 kg of cement, water to cement ratio (w/c) 0.42 and air entraining plasticiser Melcret SPA 0.7% by weight of cement. Figure 2 show mechanical properties of tested mixes.



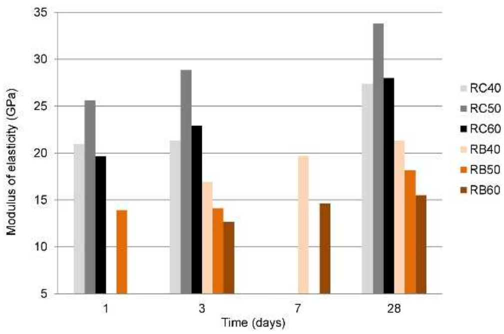


Figure 2: Mechanical properties of recycled aggregate concrete; Left: Compressive strength; Right: Modulus of elasticity

The analysis of the results was published elsewhere [9]. 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 [9]. Mixture with 50% of replacement of course aggregate was chosen as optimal for the ECO-SANDWICH® wall panels.

Relevant durability properties for prefabricated concrete wall elements are resistance to freezing and thawing as well as capillary absorption. Prefabricated wall elements should satisfy requirements for XF1 exposure class. To test freeze–thaw resistance, scaling was carried out on the concrete specimens with RB and RC with proportions of 40% and 60%. Specimens were tested up to 56 freeze–thaw cycles. On all tested specimens, the weighed cumulative scaled material per test area was less than 0.5 kg/m^2. From the results obtained, Figure 3, it can be concluded that concrete with aggregate from RB and RC is resistant to freezing and thawing with deicing salts and that the concrete satisfies requirements for XF2 (28 cycles) and XF4 (56 cycles) exposure classes, respectively. When comparing specimens produced with RC and RB, it can be seen that concrete with RB has a larger value of the scaled material per test area.

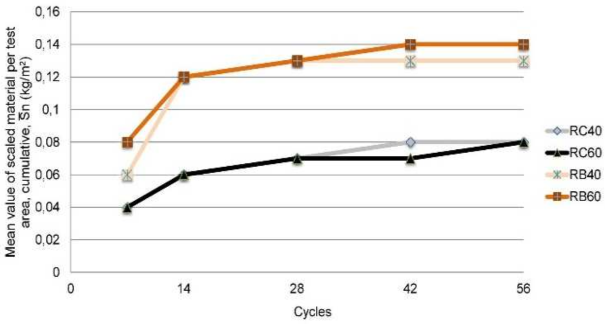


Figure 3: Durability properties of recycled aggregate concrete; freeze-thaw resistance

Table 1: Thermal conductivity of recycled aggregate concrete

Specimen	Density [kg/m^3]	Mean thermal conductivity $\lambda_{10,0}$ [W/mK]
RC40	2064.6	0.867
RC50	2105.0	0.858
RB40	1912.7	0.703
RB50	1971.0	0.746

Testing of thermal conductivity was carried out by means of guarded hot plate and the known thickness of the specimens used. Results of testing are shown in Table 1. It can be found from the literature that thermal conductivity of concrete can be in the range from 0.69 W/m K to 3.3 W/m K, depending on the type of aggregates used, the temperature and moisture content of concrete, together with its density [9]. For the concrete density of 1922 kg/m^3 and 2083 kg/m^3, ACI Committee 122 [10] gives thermal conductivities of 0.99 W/m K and 1.18 W/m K, respectively, for dry concrete made with limestone aggregates, while Gorse and Highfield [11] give thermal conductivity of 1.13 W/m K for the concrete with density of 2000 kg/m^3. It can thus be concluded that the concretes containing RC and RB aggregates have 13–27% and 29–40% lower thermal conductivity than the reported literature values for the dry concrete with approximately the same density. It should be noted here that concrete made with natural aggregates with a density of 2400 kg/m^3, which is usually being used for prefabricated sandwich panels, has the thermal conductivity of 2.00 W/m K [12].

Environmental benefits

One of the most significant environmental benefit of ECO-SANDWICH® panel is the vast amount of CDW that can be incorporated into concrete, thus reducing the amount of landfilled CDW. If we take into account that in tested mixes total amount of 1759 kg of aggregate was used per 1 m^3 of concrete, then 879.5 kg per 1 m^3 of concrete was recycled aggregate. Regard to the annual concrete production in Europe of 750 million m^3, there is a potential for sustainable management of 659.6 billion kg of CDW per year. In other words, it would mean 659.6 billion kg of natural resources less excavated, and consequently decreased environmental footprint. According to the available data, in South Africa more than 4.7 million tonnes of CDW were generated in 2011, but only 16% was recycled [13]. There is possibility to use those amounts of CDW as a replacement of natural resources for production of recycled aggregate concrete.

ECO-SANDWICH® has a surface density of 458 kg/m^2 and the building constructed using such panels can be classified as a heavyweight building. Concrete heavyweight structure can greatly influence, thanks to the thermal mass property, on the annual heating and cooling energy demand. Comparison of different structures varying from very lightweight to very heavyweight was performed in order to evaluate the influence of effective thermal capacity on energy performance of a building [9]. The results expressed as a specific heating and cooling energy demand for the analysed building are shown in Figure 4, plotted against the specific effective thermal capacity, where the percentage variations are calculated with reference to the heavyweight building. It is shown that very lightweight structures such as wooden structures and structural insulated panels consume 20% more heating and cooling energy annually than heavyweight structures [9]. Concrete can provide a level of internal temperature stability that is simply not attainable with lightweight construction.

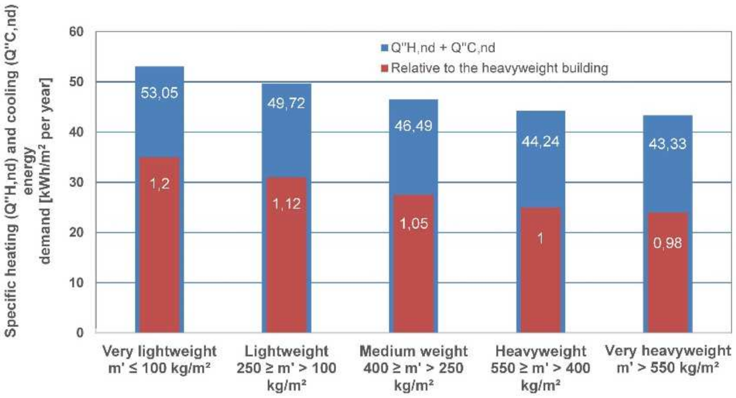


Figure 4 Influence of effective thermal capacity on specific heating and cooling demand [9]

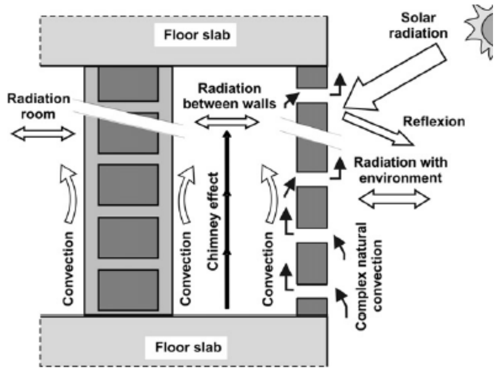


Figure 5: Principles of passive cooling in OJVF [14; 15]

Well insulated building envelope and thermal mass of concrete make ECO-SANDWICH® suitable for cold climate areas. Besides, due to 4 cm of a ventilated air layer and open joints between individual panels, ECO-SANDWICH® performs as an open-joint ventilated façade (OJVF) and hence it is also suitable for the hot climate areas. OJVF is a passive conditioning system. The solar radiation on the outer façade layer heats them him and activates convection inside the air layer, thus generating ventilation with an ascending air current that enters and exits the cavity through the open joints, Figure 5. When this current leaves the cavity by the upper gaps, it extracts thermal energy. In that way, the temperature of the inner wall and the heat flow towards the interior of the building is reduced, cutting down the energy required for cooling. As this ventilation is produced by solar radiation, the OJVF is particularly interesting for areas where the peak of energy demand happens during the summer [14].

Technical and technological benefits

Building with prefabricated construction elements, i.e. modular construction is a familiar way of construction but in today's era of energy efficiency, it has a great capability. Modular construction offers great advantages such as safer, quicker and cheaper buildings. With modular construction, construction is practically moved to the factory into controlled conditions. Afterwards the panels are transported to the construction site and installed into load bearing structure, Figure 6. Prefabricated buildings have to satisfy all requirements of mechanical resistance and stability as traditionally built buildings, i.e. on-site construction, and they can be at least equally energy efficient as buildings built on-site. Therefore, the main difference is the construction technology. It can be said that energy efficient buildings built with prefabricated panels are structural revolution if we observe final product in terms of time, money, natural resources, sustainability and achieved level of energy efficiency of the building [16].

Figure 6 Production and transportation of ECO-SANDWICH® to the construction site

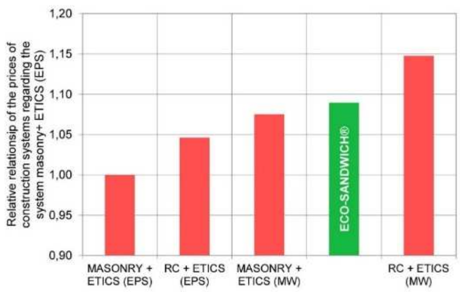
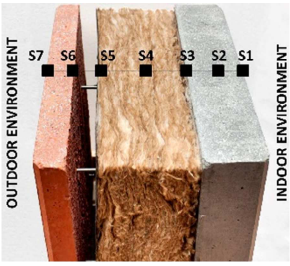


Figure 7 Cost comparison of different building envelope systems

Depending on the modular elements and their pre-planned sequence of installation, the construction time can be cut by 30 to 50% compared to the on-site construction [17]. Faster construction means the project reaches hand-over more quickly, and the client can occupy or let the building earlier. Consequently, there are savings in land, labour, rents, overheads and financing costs, and a faster return on investment [18]. If all costs of modular and on-site construction are taken into account, summarized and compared, then the relative relationship of the prices for ECO-SANDWICH® and different External Thermal Insulation Composite System (ETICS) on different substrates can be outlined. Figure 7 represents cost comparison made for constructing a building envelope for family house, with the surface area < 400 m2, using different construction systems. It can be concluded from Figure 7 that ECO-SANDWICH® is a competitive system on a market of energy efficient and sustainable building envelopes. In addition, it needs to be highlighted that presented cost comparison does not include time as a parameter that can greatly influence on a total construction costs. Additionally, ETICS with EPS is the cheapest solution for thermal enhancement of building envelope among systems compared in Figure 7, and it counts for approximately 85% of all ETICS installed in Europe [19]. Unfortunately, EPS is a combustible material and its application has limitations due to possible poor fire performance of that kind of a building envelope [20]. In parallel, fire performance of ECO-SANDWICH® shows its advantage over ETICS with EPS. Fire resistance of ECO-SANDWICH® was conducted according to the standard HRN EN 1364-4 [21] for curtain walling. Results indicate fire resistance class EI90, i.e. ECO-SANDWICH® can provide over 90 minutes fire resistance [22].

Future directions in research

Presented comprehensive research conducted on a material level (mechanical, durability and thermal properties) and on a building element level (fire resistance) will be upgraded with research on a whole building level. Material properties of a recycled aggregate concrete and properties of a building element are determining performance of a building envelope, which can be fully assessed and understand only if observed on a whole building level. Together with the characteristics of a building envelope, climate conditions directly influence the dynamics of the process of combined heat, air and moisture transfer through envelope, thus they directly influence the hygrothermal performance of a building as a whole [23]. 75-90% of all damage in building envelope are caused by the moisture [24]. Moisture transfer through building envelope is correlated with heat transfer and they manifest as temperature and moisture content change within the layers of building envelope. Hygrothermal performance of ventilated facades is quite recent research topic. By literature review, it has been noted that all the research was done on lightweight ventilated structures [25-28] or medium-weight ventilated structures [29-31]. There is not a lot of available papers on the research on hygrothermal performance of a concrete sandwich panels. Al-Neshawy [32] investigated hygrothermal performance of a concrete sandwich panel with incorporated thermal insulation. However, correlation cannot be drawn between this panel and ECO-SANDWICH®, because ECO-SANDWICH® is made from recycled aggregate concrete and it has a layer of ventilated air. So, there is an unexplored area of hygrothermal performance of a ventilated prefabricated recycled aggregate concrete panels, which can be determined by continuous experimental monitoring and by numerical simulations using HAM models. Figure 8 show experimental set-up for continuous monitoring of hygrothermal performance of a family house (A+ energy class) constructed within socially-supported housing program in Koprivnica, Republic of Croatia. Three panels with different sun orientations were selected as measurement locations and marked as M1-M3, Figure 8b). At every measurement location, within all characteristic layers of ECO-SANDWICH®, sensors needed for hygrothermal monitoring were positioned and marked as S1-S7, Figure 8a). Every position has a set of temperature, relative humidity (RH) and moisture content (MC) sensor, Figure 8c). Experimental monitoring of temperature and moisture variations in all layers of ECO-SANDWICH® will provide an deeper insight in dynamic hygrothermal performance of building constructed with presented panels under real terms of using, i.e. people living inside, and exposure to the real outdoor conditions.



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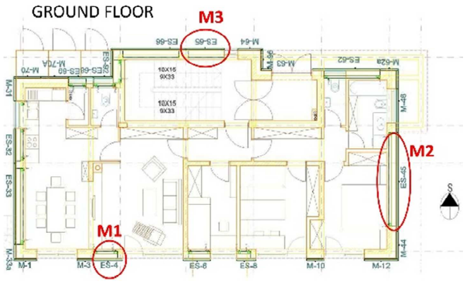

b)

c)

Figure 8: Experimental set-up for hygrothermal monitoring; a) Arrangement of sensors within layers; b) Measuring locations; c) Set of temperature, RH and MC sensor

By controlling its hygrothermal performance, building envelope can be, together with HVAC systems, actively involved in regulation of consumption of heating and cooling energy.
In addition, hygrothermal monitoring can provide monitoring of a material degradation, which is significant since it can be shown that moisture is a key factor when service performance and durability issues are concerned [33]. Knowing the degradation process of a material, it could ensure that timely and suitable rehabilitation of a building is performed, i.e. the service life of a monitored building could be extended.

Conclusion

Recycled aggregate concrete utilizes CDW, which is in Europe identified as a priority waste stream. In order to achieve the best ecology-to-quality ratio considering materials, appropriate selections should be made. In this paper it is shown that both, recycled brick and recycled concrete can be successfully used for high-grade application in amount 50% of recycled aggregate. The ratio of replacement by 50% was determined based on comprehensive research. Presented ECO-SANDWICH® panels incorporate environmental, technical and technological advantages compared to the traditionally built concrete sandwich panels, and also represent an improvement of existing prefabricated sandwich wall panel product, aligning with mandatory targets of EU strategies and directives. Being suitable for hot and cold climate areas, makes it applicable on a worldwide market. Construction with presented panels provides user a high quality, affordable, energy saving and aesthetically attractive recycled aggregate concrete building on principles of ''turnkey'' construction. Nevertheless the fact that its properties at material and building element level are investigated, presented recycled aggregate concrete panels offer possibilities for further scientific research at a whole building level. At the moment, experimental set-up for monitoring of hygrothermal performance is established, thus deeper insight in dynamic performance regarding the heat, moisture and air transfer will be obtained.

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