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Life cycle assessment of façade solutions made of durable reactive powder concrete

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Abstract. Reactive powder concrete (RPC) has become an important material for durable building envelope solutions in form of curtain walls or façade panels. RPC, also known as ultra-high performance concrete (UHPC), has a very dense micro structure and reaches compressive strength beyond 120 MPa. In conjunction with fibers or textile reinforcement it shows a 'quasi' ductile behavior. As a drawback it is often regarded as not so environmentally sustainable due to the high amount of cement used. This study investigates therefore the environmental aspects of façade panels consisting of RPC. Solutions with different mix proportions and reinforcement types will be analyzed and compared with elements made of standard steel reinforced concrete. The analysis will not only consider the results of the bulk material but also view it in the context of the entire façade elements. The life cycle assessment (LCA) does also approach the durability related aspects of the reactive powder concrete and alternative reinforcement materials.

Introduction

Since the 60's and 70's pre-fabricated modular concrete buildings dominated the city landscapes all over Europe. This was a reaction towards the increased demand for affordable housing. The pre-cast market for concrete building envelopes was dominated for a long time by standard steel reinforced concrete (RC) elements. The disadvantage of RC is the thickness of elements, which amounts usually to around 80 mm and is due to the necessary concrete cover on both sides of the reinforcement. Reinforcement corrosion due to carbonation and to a lesser degree due to chloride ingress is a frequent reason for limited durability of RC façades.

New materials that have been developed over the last 15 years enable a drastic reduction of the thickness and weight of pre-cast façade elements. This is accomplished by using alternative non-corroding reinforcement materials, thus eliminating minimum concrete cover thicknesses, in conjunction with cement based high performance and ultra-high performance materials. Examples of such materials are textile reinforced concrete (TRC) and fiber reinforced ultra-high performance concrete (FRUHPC). TRC and FRUHPC have been applied for façade elements in form of ventilated façade cladding [1] or as sandwich elements [2]. Increasingly more FRUHPC is used as a façade material since it shows extraordinary high strength and durability [3-5]. Prominent structures such as the Jean Bouin football stadium in Paris, France or the MuCEM in Marseille, France are both examples of FRUHPC perforated, partially structural, façade applications.

Reactive powder concrete (RPC) is a variant of ultra-high performance concrete, where the maximum aggregate size is usually 2 mm or below, whereas in UHPC the maximum aggregate size is usually 8 mm. Both concrete types exhibit compressive strengths greater than 120 MPa and a strongly reduced capillary porosity. Due to the high strength these materials are very brittle. To mitigate this, fibers or textile reinforcement are added in order to gain a quasi-ductile behavior (usually achieved by steel fibers) or to mitigate sudden failure by controlling cracking under strain hardening [6]. In façade applications steel fibers are less suitable due to the risk of corrosion of the fibers on the concrete's surface. This is not a structural defect but an aesthetical impediment in form of coin sized rust stains. To prevent this, additional coating of the concrete surface is required. Non-ferrous reinforcements such as carbon fiber textiles are therefore more suitable for façade applications. Glass fiber textiles seem to be less suitable due to the possibility of corrosion, even with so called alkali resistant glass fibers [7].

An important point concerning RPC/UHPC is their high powder content, and to be more specific, the high cement clinker content. The clinker content in RPC/UHPC is usually between 700 and 900 kg/m^3, which make the materials more expensive and seemingly less sustainable. The goal of this work was therefore to investigate sustainability aspects of façade sandwich elements, which are made from reactive powder concrete with carbon textile reinforcement. The study was performed on two RPC mixes which were developed within the transnational project SESBE (Smart Elements for Sustainable Building Envelopes), funded by the European Commission. The materials are benchmarked towards conventional materials (i.e. standard reinforced concrete). The results should illustrate under which conditions façade elements made with RPC are a more sustainable solution than standard reinforced concrete.

RPC Formulation

The extraordinary properties of reactive powder concrete are based on using a very low amount of mixing water, a high powder content and an optimization of the amounts of all components based on an ideal particle packing model. Minimization of the amount of mixing water is achieved by modern, high range water reducing admixtures, such as superplasticizers (SP) based on polycarboxylate ether (PCE) [8]. With SPs it is possible to reduce water binder ratios in RPCs below the value of 0.2. The powder content (i.e. all particles below 0.125 mm) is usually about 50 mass-% of the total mix, which is 1.5 to 2 times higher than in standard concretes.

The reactive powder concrete mix presented here was composed of the following starting materials: CEM II/A-V 52.5, class F fly ash, quartz filler, micro silica and 0-1 mm sand. Used was a highly effective PCE based superplasticizer. Two RPC formulas were used, RPC 3 and RPC 4, where RPC 4 has a slightly lower clinker content. The carbon fiber textile consisted of a mesh with a size of ca. 20 x 19 mm. Flexural and tensile strength tests on reinforced specimen were performed on 20 mm thick panels with two layers of textile reinforcement. The RPC mix was designed to be mixed in planetary and force action mixers as used in the laboratory and pre-cast plants. More details about mix design and early age properties of RPC can be found in Mueller et al. [9]. The structural details and performance of sandwich elements developed with RPC within the SESBE project are described in Flansbjer et al. [10,11] and are not further discussed here.

Mechanical and Durability Properties

The compressive strength, E-moduli, Poison ratio and tensile strength of two RPC mixes without reinforcement are shown in Fig. 1. Compressive strength was measured on standard mortar prisms following EN 1015-11 [12], and E-moduli according to EN 12390-13 [13]. The tensile strength was tested on cylinders (∅50 x 100 mm). The compressive strength development showed for the mix RPC 3 a value of ca. 60 MPa and for RPC 4 a value of ca. 30 MPa at 1 day of age. The lower value for RPC 4 results from the higher amount of fly ash replacement and a subsequent slower hydration of the binder. However, after 7 days both mixes show almost identical strength values, which represented ca. 80 % of the value at 28 d. The E-moduli for both mixes show the high value of 50 GPa, which explains the strong brittleness of the materials.

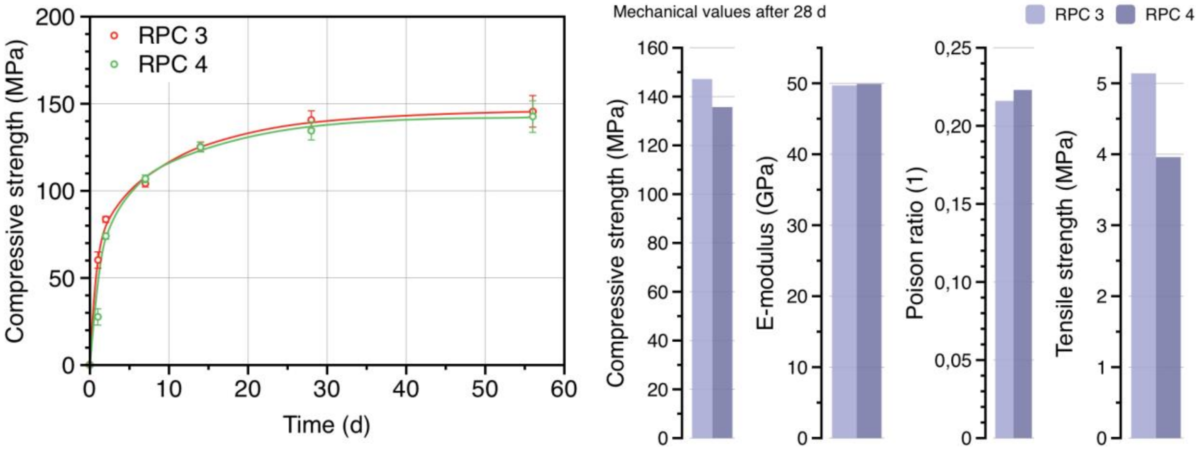

Fig. 1. Results of the mechanical tests for the RPC mixes 3 and 4.

The textile reinforcement increased the mechanical performance under flexural and tensile loads. This is shown in Fig. 2 in form of results of flexural tests in a 4-point bending mode [14], performed on panel specimens of 700 x 100 x 20 mm with two parallel carbon fiber grids. As it can be seen the first crack was initiated at load values of 0.1 to 0.6 kN. After that, the load increased under further cracking and strain hardening to values between 4.0 and 4.5 kN and to deflection values between 30 and 50 mm until complete failure. This is quite typical for textile reinforced concrete which indicates that a façade panel will not fail immediately after a first crack but will resist further load increase by a controlled cracking process.

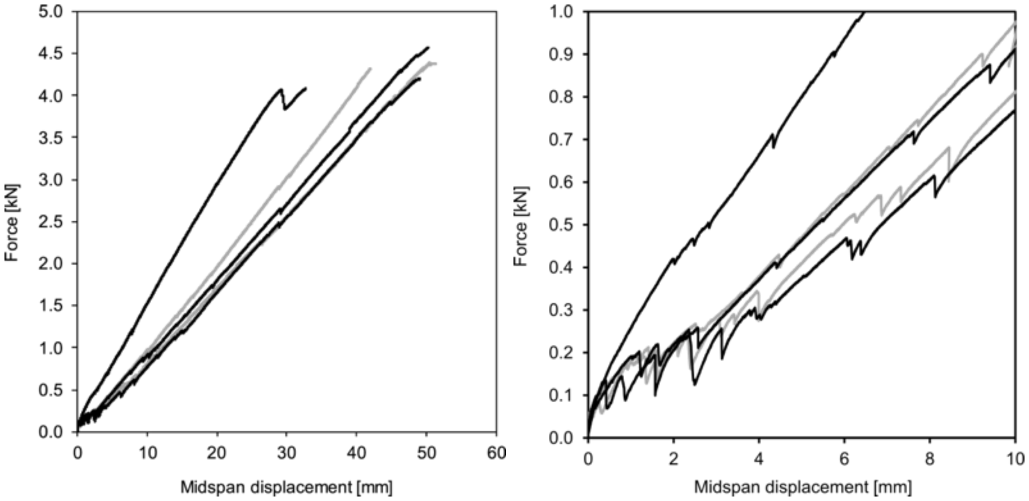

Fig. 2. Results of 4-point bending tests on the RPC 3 mix. The right figure is a detail of the graph on the left, illustrating the crack formation and strain hardening under load.

The durability properties of one mix, RPC 3, were exemplarily determined in form of frost resistance and chloride migration. Even though both processes have less significance for façade applications, they give a good indication of general durability. The frost test was performed according to the slab test described in CEN/TS 12390-9 [15]. The chloride migration was tested according to the Nordtest method NTBuild 492 [16].

Fig. 3 illustrates the frost resistance towards scaling of mix RPC 3. The mix exhibited an air void volume between 1.5 and 2.5 vol.-% but no additional air entrainment was applied. Even after 112 cycles the scaling of RPC 3 specimen was under 0.1 kg/m^2. This is far below standard concrete without air entrainment, which usually shows scaling above 1 kg/m^2.

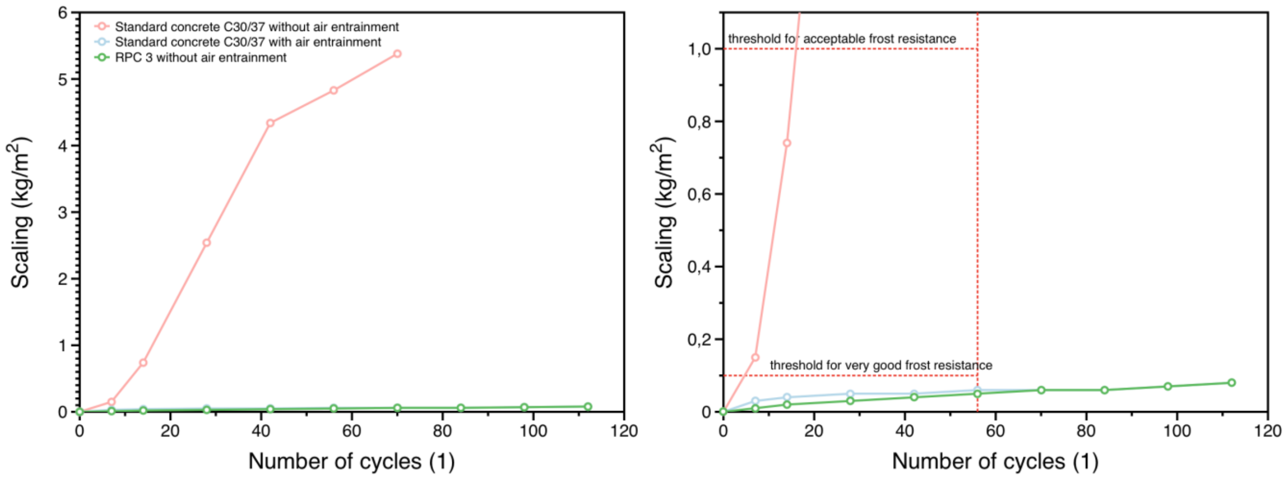

Fig. 3. Performance of RPC 3 in the freeze-thaw test according to CEN/TS 12390-9 [15] compared to a C30/37 standard concrete. The right graph is a detail of the left one. The threshold values for scaling are according to the Swedish standard SS 137244 [17].

The measured chloride migration coefficient was in the range of 1.2 to $1.7\cdot10^{-13}$ m^2/s with a mean value of $1.5\cdot10^{-13}$ m^2/s, which is essentially one order of magnitude lower than the values for a standard concrete (Fig. 4). The results from the freeze-thaw and chloride migration tests showed the extreme compactness of the mix RPC 3, which is essentially due to the very low amount of capillary pores and the high amount of gel pores, which slow down diffusion processes and prevent freezing of water in such pores except under very low temperatures.

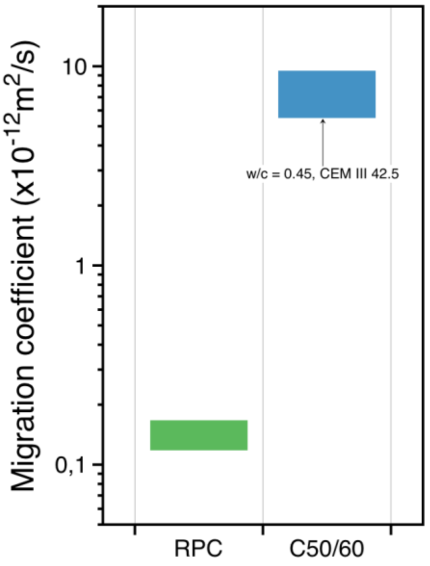

Fig. 4. Ranges of chloride migration coefficients of the RPC 3 mix and a standard concrete C50/60 (prepared with a CEM III 42.5).

Under normal conditions within a building envelope system these properties ensure a long lasting performance for façade panels made with RPC. Negative impacts on durability of panels due to corrosion of reinforcement are excluded by utilizing corrosion resistant carbon fiber textiles. By using carbon fiber based reinforcement products and taking advantage of the exceptional mechanical performance of RPC, panels can be made much thinner compared to the ones made of standard reinforced concrete.

LCA of Façade Panel made of RPC

Concrete is the world’s second most consumed material after water. Due to the high volumes, concrete has a significant effect on the climate of which cement has been identified as the main contributor. Not only does the cement production process consume a large amount of fossil fuels, part of which might be secondary fuels, but it also emits carbon dioxide in the calcination step [18,19]. While a substantial effort is being made to reduce the climate impact of this production, there are also other ways for minimizing the environmental burden of concrete. Malhotra and Mehta presented three proposals in “High-performance, high-volume fly ash concrete”; (1) To consume less amount of concrete by developing innovative structural design and highly durable materials. (2) To consume less Portland cement by specifying a 56 or 91-day concrete strength in structural elements and also by optimizing the aggregate size and grading and thereby reducing the amount of paste. (3) And finally to reduce proportion of clinker in the cement by replacing parts of it with complementary cementing materials. Examples of such materials are granulated blast furnace slag, fly ash, silica fume and rice-husk ash. By following these three steps the authors expect the global carbon dioxide emitted from the concrete to be reduced by 55% within 20 years if the same amount of concrete or less is consumed during this period [20].

In this study the first and third proposals are mainly implemented where the amount of concrete is reduced and the durability is increased while at the same time reducing the clinker content with the use of supplementary cementitious materials (SCM). The environmental impact of RPC will be evaluated using a LCA approach. The RPC will be compared with regular concrete for façade application and another type of UHPC. Façade panels with the chosen concrete mixes will be compared and put in a context of a non-loadbearing sandwich panel.

Methodology. The methodology of the LCA is based on the ISO 14000 series and *SS-EN 15804:2012+A1:2013 Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products* [21,22]. The chosen impact categories in this study are global warming potential (GWP) and primary energy (PE). The GWP is calculated based on IPCC (Intergovernmental Panel on Climate Change) 2013 100a and the PE, both renewable and non-renewable, is based on the cumulative energy demand method in the LCA software SimaPro version 8. This is in line with the key indicators for addressing the European Commission’s key objectives for the so called “20-20-20 goal” [23].

The life cycle stage included in the analysis is the production stage which includes the upstream processes; extraction and transport of raw materials and manufacturing at the factory plant. The production is assumed to be a prefabricated process. The infrastructure processes, e.g. the manufacturing plant, and the long term emissions are not included in this analysis. The production site is assumed to be someplace in Sweden. In this study the concrete design mix is being assessed and therefore the production site is of less importance. All concrete mix designs are assumed to have the same energy input.

The declared unit in the primary study is 1 m^2 of reinforced façade panel and sandwich element made of prefabricated concrete.

The result of the LCA is dependent on several factors. To include possible scenarios in the result the following sensibility analysis are performed. (1) Type of reinforcement for the façade panels. Carbon fiber grid without coating, glass fiber mesh without coating and steel reinforcement is compared based on climate change. (2) GWP and PE of insulation types for the sandwich elements. The insulating materials for comparison are: EPS, glass wool, rock wool, extruded polystyrene (XPS) and polyurethane (PU).

In this study average data for the raw materials are adequate since it is the concrete mix design which is to be compared and the same technical properties are assumed to be achieved with different producers for the same product. Most of the data for cement, water, aggregates, reinforcement and energy, are gathered from the ecoinvent version 3 database. Inventory data for admixtures are gathered from an environmental product declaration (EPD) by European Federation of Concrete Admixture Associations (EFCA). In the case of carbon fiber grid, there is no comprehensive data in ecoinvent version 3 or any other LCA database in SimaPro. The only available data is the carbon fiber precursor, PAN (polyacrylonitrile), in the ELCD database. Therefore the PAN data were complemented with literature values from an article by Das et al. [24].

There is a variation in environmental data for some raw materials due to manufacturing processes. For reinforcement, for example, there is a big difference depending on scrap rate and energy source [25]. In this study a worst case scenario with ecoinvent data is considered for the reinforcement. Table 1 shows the materials used in this study.

Fly ash, which is used in some of the concrete mixes in this study, is the by-product of a coal power plant. To see if there is any environmental burden allocated to the fly ash an economic evaluation was performed based on German data and energy prices for year 2015. The result of this evaluation showed that the revenue of fly ash is less than 1 % of the total revenue in the coal combustion process and is therefore considered as very low according to EN 15804. This means that there is no environmental burden allocated to fly ash. The silica fume is also considered to be burden free.

Transport of raw materials is calculated with ecoinvent processes. The average transport distance in the “market” datasets are used for all ecoinvent datasets. In case of carbon grid, fly ash and admixtures a default transport distance is set at 200 km.

The energy consumption at the concrete factory is assumed to be according to a building product declaration of prefabricated elements from a specific producer [26]. The required energy is 5 kWh/m^2 electricity and 10 kWh/m^2 district heating. This energy is consumed for a full sandwich element with two panels. For one panel only half the energy is assumed to be enough.

Formwork is excluded from the analysis since it is reused many times and may therefore not have a big overall environmental impact.

Table 1. Inventory of materials and energy used in this study.

Resource	Reference/Database	Primary study	Sensitivity analysis
CEM II/A-V	Ecoinvent 3	X	
CEM II/A-LL	Ecoinvent 3	X	
CEM I	Ecoinvent 3	X	
Water	Ecoinvent 3	X	
Crushed aggregates	Ecoinvent 3	X	
Sand	Ecoinvent 3	X	
Super plasticizer	EPD	X	
Quartz filler	ELCD	X	
Carbon grid	ELCD, [24]	X	X
Steel reinforcement	Ecoinvent 3	X	X
Glass reinforcement	Ecoinvent 3		X
EPS	Ecoinvent 3	X	X
Glass wool	Ecoinvent 3		X
Rock wool	Ecoinvent 3		X
XPS	EPD		X
PU	EPD		X
Electricity, Swedish mix	Ecoinvent 3	X	
District heat, european	Ecoinvent 3	X	

Façade Panels made of Different Mix Designs. This study investigates two kinds of RPC mix designs (RPC-3 and RPC-4), both developed by CBI. The difference between the two mix designs is the lower clinker content and compressive strength in RPC-4. RPC-3 has a compressive strength of 160 MPa while the RPC-4 has a compressive strength of 140 MPa. Façade concrete is exposed to harsher climate than indoor concrete and requires therefore a higher quality with a low water cement ratio [27]. The mix design for the standard concrete is therefor based on an ecoinvent version 3 dataset for concrete with a compressive strength of 50 MPa. The dataset is based on an actual mix design. The alternative UHPC, which has a compressive strength of 160 MPa, is only based on silica fume as SCM unlike RPC-3 and RPC-4 which also contain fly ash. The concrete mix designs used in this analysis are presented in Fig. 5.

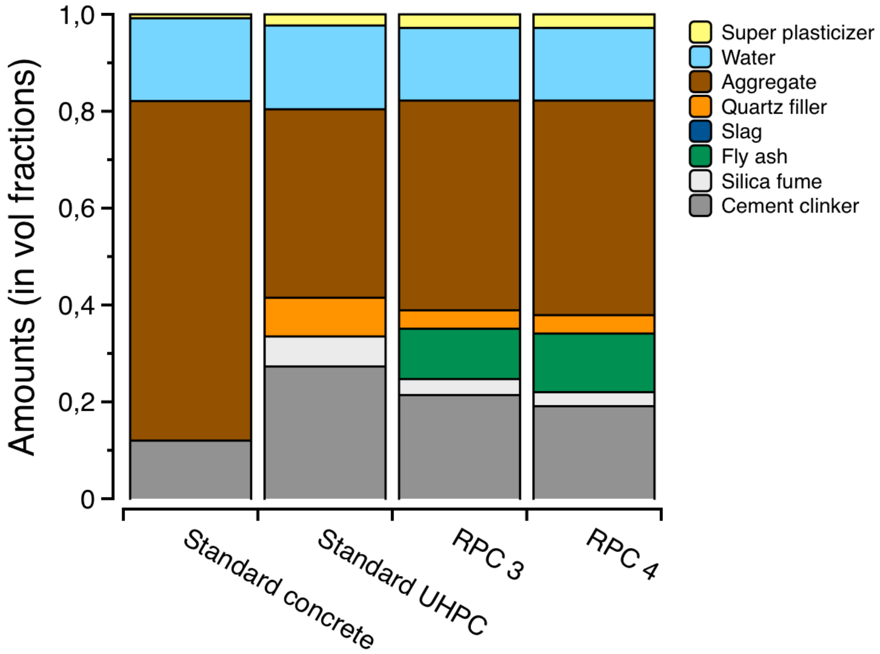

Fig. 5. Mix design of concrete façade panels in volume fractions.

The RPC and UHPC are used to make thin façade panels with a thickness of 20 mm whereas the standard concrete has a minimum thickness of 80 mm due to steel reinforcement. The thin panels consist of two layers of carbon fiber grid per panel while the standard concrete panel is strengthened with steel bar reinforcement with 8 mm diameter and a longitudinal spacing of 0.15 m (Table 2) calculated according to Eurocode 2. Carbon fibers are highly energy demanding to produce where the embodied energy varies between 150 MJ/kg and 700 MJ/kg, depending on the precursor, manufacturing processes and energy source [24].

Table 2. Dimensions and reinforcement properties of concrete panels with the different mix designs.

	Concrete panels			
Properties	RPC-3	RPC-4	UHPC	Standard concrete
Panel thickness [mm]	20	20	20	80
Reinforcement type	Carbon grid	Carbon grid	Carbon grid	Steel bars
Reinforcement dimensions	2 x 2D grid	2 x 2D grid	2 x 2D grid	#8150

Sandwich Elements. As previously mentioned, the façade panels are also evaluated in the context of a sandwich element. The thin RPC and UHPC panels are 20 mm each and connected with glass fiber ties. The amount of ties have been calculated and tested within the SESBE project. The standard concrete panels are 80 mm each and connected with stainless steel ties according to a steel connector producer [28]. The sandwich elements are non-loadbearing. Expanded polystyrene (EPS) insulation is chosen as reference insulation for the sandwich elements but since there is a big variation in thermal performance and environmental impact not only between different types of insulating materials but also within the same material, different insulation materials are compared as well. The thermal resistance, R-value, for the insulations is set at 6 m^{2}·K/W which would result in a heat transfer coefficient of approximately 0.15 W/(m^{2}·K). Typical densities based on inventory data and EPDs are applied. Table 3 shows the properties of the insulating materials.

Table 3. Properties of different thermal insulation materials for façade application.

	EPS	**Glass wool**	**Rock wool**	**XPS**	**PU**
Density [kg/m^3]	30	40	60	31	40
Thickness [mm]	220	220	220	200	170
Thermal conductivity [W/(m·K)]	0.037	0.037	0.037	0.033	0.028
Thermal resistance [m^2·K/W]	6	6	6	6	6
Market	Global	Global	Global	Northern Europe	Europe

Environmental Impact

Façade Panels. The GWP and PE, expressed in kg CO_2-eq and MJ, per cubic meter of the different concrete mixes for façade application is shown in Fig. 6. As seen in the figures, the standard concrete has the lowest impact at 350 kg CO_2-eq and 1700 MJ. The RPC-3 and RPC-4 show a relatively high impact between the results of UHPC and standard concrete. However, when applied as façade panels, the RPC show a significantly lower impact than the standard concrete (Fig. 7). The lowest impact was reached by the RPC-4 panel which has a 33 % lower GWP than the standard concrete panel. The carbon fiber grid requires a large amount of energy when produced which can be seen in the primary energy and also on the GWP. The GWP and PE of the façade panels are, as predicted, not so sensitive to the transport to factory and production energy.

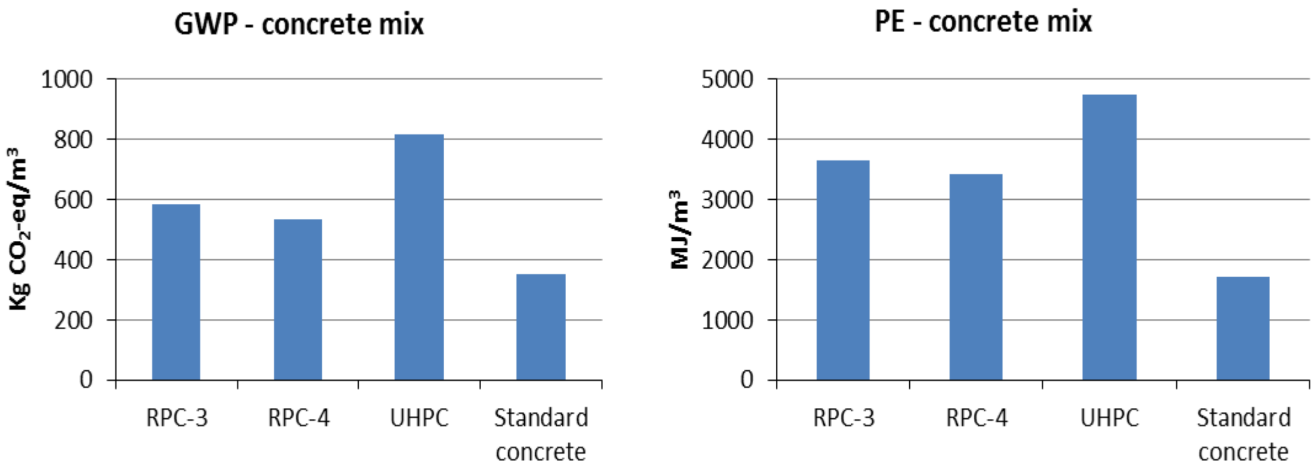

Fig. 6. GWP and PE of concrete mix designs measured per cubic meter.

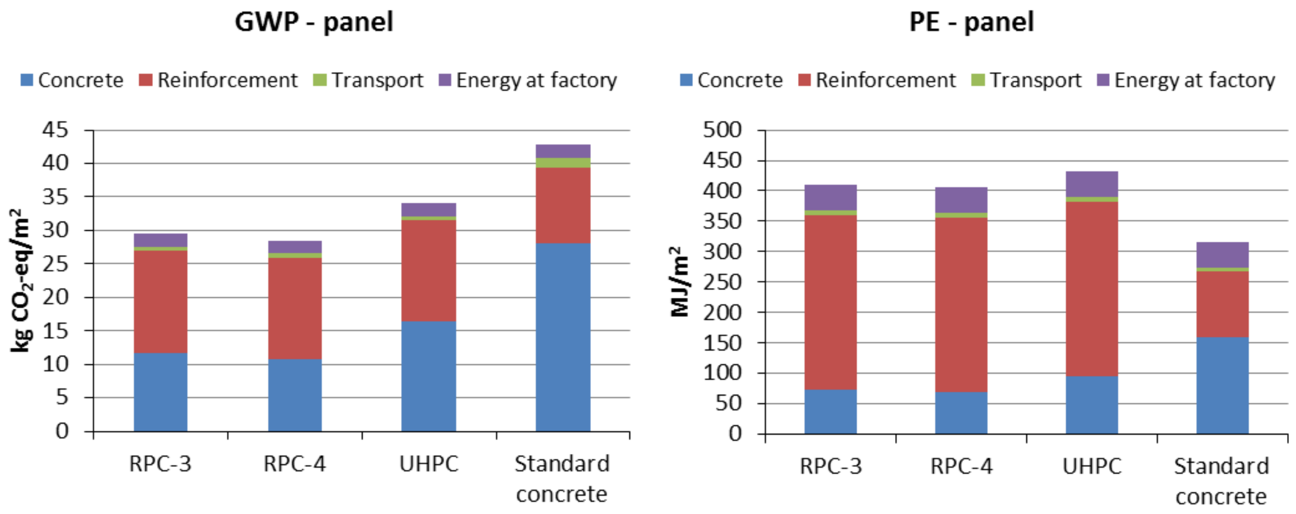

Fig. 7. GWP and PE per square meter of one panel.

Lightweight Sandwich Elements made of RPC. When applied in sandwich elements, the RPC panels with carbon grid reinforcement show a lower GWP than the alternatives and although the PE is still higher, the gap has been reduced (Fig. 8). RPC-4 shows a 27 % reduction compared to standard concrete. The input materials have an equally big influence on the GWP. However, concerning PE the sandwich element with standard concrete shows a significant contribution from the concrete itself while in the RPC and UHPC elements focus has been switched to mainly EPS insulation and reinforcement.

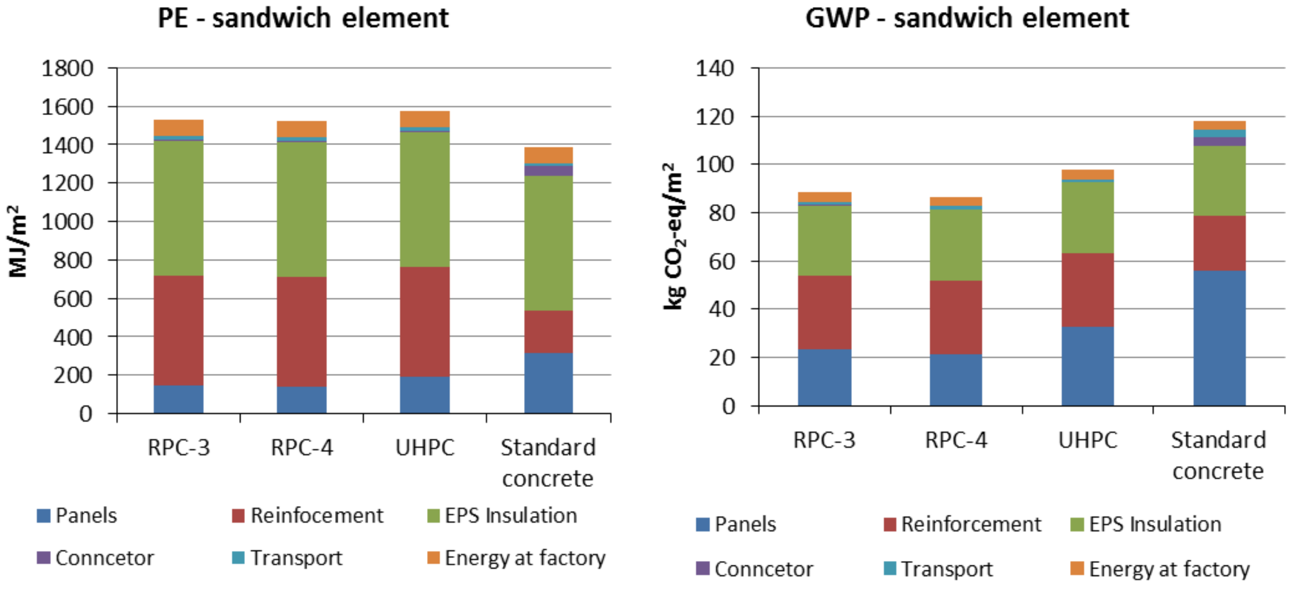

Fig. 8. PE and GWP of one square meter of concrete sandwich element.

Sensitivity Analysis. The sensitivity analysis in Fig. 9 shows that the carbon fiber grid has the highest GWP and PE per square meter of panel of all reinforcements in this study. The steel reinforcement is approximately 74 % of the GWP of the carbon fiber grid and 38 % of the PE. The AR-glass reinforcement shows the lowest environmental impact.

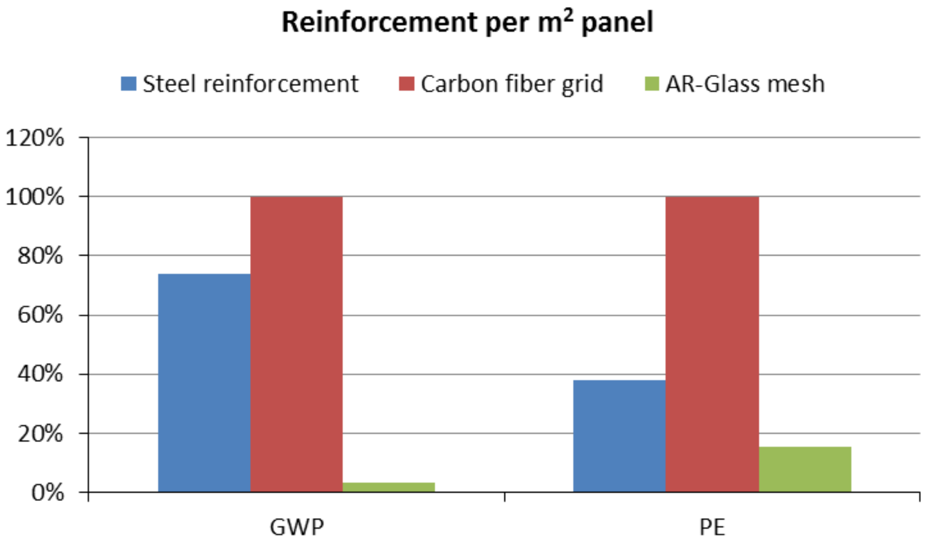

Fig. 9. Sensitivity analysis of steel reinforcement, carbon fiber grid and AR-glass mesh per square meter of panel.

Fig. 10 shows the global warming potential of the chosen insulating materials. The EPS has the highest environmental impact for a constant R-value while the rock wool has the lowest. However, since the insulating materials have a high variation in thermal and physical properties the GWP is also expressed per kg of material. The overall result does not vary per kg and the EPS still has the highest contribution.

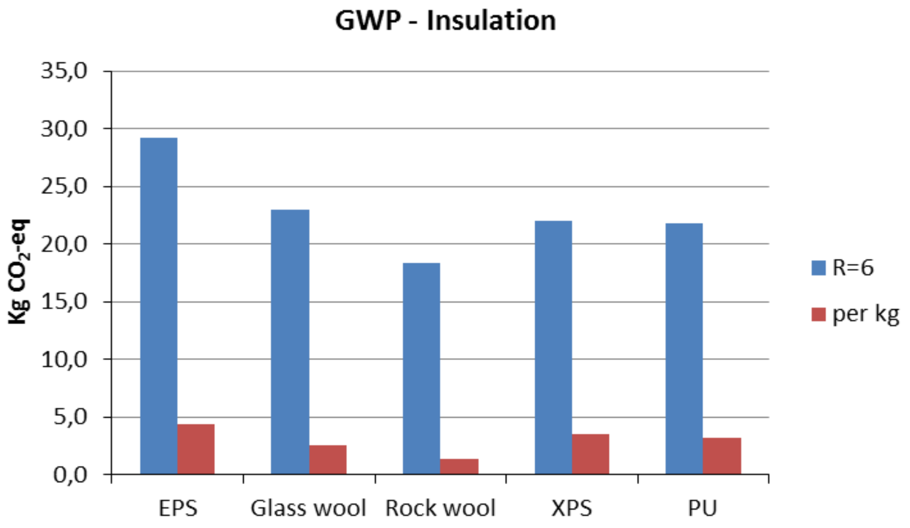

Fig. 10. GWP of different insulating materials for façade application measured per R=6 and kg.

Conclusion

Even though the reactive powder concrete contains a large amount of cement and has a high global warming potential and primary energy per cubic meter, applying it in a 20 mm thin textile reinforced panel will reduce the environmental impact. By using a durable high performance concrete a reduction of 33 % in GWP could be made. The results also showed that there is a possibility to reduce the environmental impact of UHPC and yet obtain a high compressive strength with the use of SCMs.

The carbon fiber grid was shown to have an environmental impact which is as high as or higher than the concrete in the thin façade panels. This could be reduced by using an alternative reinforcement such as an AR-glass mesh or by trying to minimize the weight of the carbon fiber grid. The results are somewhat general and further detailed studies are therefore needed on carbon fiber grids which should also include a coating.

This study shows that there is a potential to reduce the GWP by 27 % by using thin RPC panels and EPS insulation. However this value is highly dependent on the insulation material. The sensitivity analysis shows that the lowest global warming potential could be made with rock wool. Nevertheless, the energy recovery and recycling potential should also be considered when choosing insulation.

The high durability of the RPC and the corrosion free carbon reinforcement suggests that the façade element could have a longer service life than a standard concrete façade. Therefore further research needs to be made to include the service life in the LCA. A longer service life would result in a lower environmental impact per year.

Acknowledgements

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