Zurich, June 15-17 2016
Sustainable Built Environment (SBE) Regional Conference

Expanding Boundaries:
Systems Thinking for the Built Environment

ENVIRONMENTAL ASSESSMENT OF RADICAL INNOVATION IN CONCRETE STRUCTURES

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Abstract

In the building sector, the contribution of concrete structure to the overall emissions of greenhouse gases is significant. Switzerland is engaged in a 2050 energy strategy where the reduction of the embodied energy of buildings is a key aspect. In this study, we assess the environmental impact of different low energy concrete solutions. The study focuses on technologies that use cement with very high substitution rate (up to 65%) and tensile resistant materials other than steel in order to keep high durability targets. Hybrid wood-concrete structure, low carbon high performance concrete prestressed with carbon fibre reinforced polymer, and ultra-high performance fibre reinforced concrete with synthetic fibre reinforcement are among the studied options. The environmental assessment is done through life cycle analysis using the Ecoinvent database for Switzerland and the SimaPro software. Results of an initial environmental assessment of production of the new technologies, present huge energy and emission savings potential for the energy turnaround.

Keywords:

Low energy concrete; hybrid wood-concrete structure; high performance concrete prestressed with carbon fibre reinforced polymer; ultra-high performance concrete with synthetic fibre reinforcement

1 INTRODUCTION

After the Fukushima incident in 2011, the Swiss Federal Council has decided to gradually phase-out nuclear energy [1]. Nuclear energy has the biggest share at 37.9% in the Swiss electricity mix and comprises about a quarter of the total energy use in Switzerland in 2014 [2]. To cover the shortfall in energy due to the decision to withdraw from nuclear power, the Swiss Federal Council has redefined its energy policy to ensure long-term energy supply and outlined the “Energy Strategy 2050” [3]. A coordinated research has been set-up through the National Research Program (NRP) 70 and 71 funded by the Swiss National Science Foundation to support the implementation of the Energy Strategy 2050.

1.1 Low energy concrete solutions project

The building sector consumes around 40% of the global energy use [4]. In a building life cycle, the operation phase represents the largest share in the energy consumption; about a quarter is consumed in the production of building materials [4]. Continuous improvements in operation through construction of energy-efficient buildings highlights the increasing contribution from materials. Among the most representative building materials, concrete still dominates in the share of the total embodied energy of buildings [5]. A joint research project "Concrete Solutions" under NRP 70 has been set up to look into low energy constructive systems to support the overall target of the energy strategy for the Swiss energy turnaround. The project aims to develop *innovative* concrete structures with low energy concrete and reduced steel content. Concrete protects the steel in a structure from corrosion. The substitution of steel, a high energy building material, eliminates the risk of corrosion in a structure and therefore allows further reduction of concrete.

This paper presents the results of the initial environmental assessment of the production of new technologies targeted in the joint research project.

2 MATERIALS AND METHODS

The environmental assessment is done through life cycle assessment (LCA) according to the ISO standard [6] using the Ecoinvent 3 database for Switzerland [7] and SimaPro 8.0.5 LCA software [8]. The Ecoinvent database is selected as it is currently the most reliable database for Swiss unit processes.

2.1 Impact assessment methods

LCA methods used in this study are harmonized with the methods employed in the KBOB list, a well-established LCA data of buildings and constructions in Switzerland [9]. These methods are: the IPCC 2013 100a method for the calculation of the Global Warming Potential (GWP) or greenhouse gas emissions (also termed as carbon emission in this paper) [10]; the Cumulative Energy Demand (CED) for the calculation of primary energy demand [10]; and the Ecological Scarcity Method 2013 for the calculation of total environmental impacts (UBP) or eco-points [11]. UBP integrates different environmental factors into one indicator. It is an indicator particularly applicable for Switzerland as the method employs eco-factors based on Swiss environmental targets and legislation.

2.2 Functional unit and system boundary

Different functional units were used for different assessments. On the material scale, a functional unit of one cubic meter of concrete was used (Section 3.1 and 3.4); on structural scale, one square meter of wood-concrete floor slab (Section 3.2) and one linear meter of prestressed concrete beam (Section 3.3) were used. The functional units were designed on the assumption that the targeted technologies fulfil the same performance and service life as the reference. A cradle-to-gate approach was employed focusing on processes from material up to structural element production.

2.3 Data collection

Data of all processes and materials relevant in the development of technological solutions in the joint project were gathered. Processes that are not available in the Ecoinvent database, e.g. laminated veneer lumber (LVL), carbon fibre reinforced polymer (CFRP) and basalt fibre, were modelled using available data from literature. The modelled data is preliminary. LCA modelling will be improved in parallel with the technological development from the joint project.

2.4 Statistical analysis

For the analysis of environmental impact, *"Environmental savings potential (ESP)"* was calculated using percentage relative difference (Equation 1) adapted from Zea Escamilla and Wallbaum (2011) [12]:

$$ESP = \frac{Impact_{ref} - Impact_x}{Impact_{ref}} \times 100 \quad (1)$$

where $Impact_x$ is the environmental impact (UBP, CED or GWP) of the specific technological solution; and $Impact_{ref}$ is the environmental impact (UBP, CED or GWP) of the reference.

Positive ESP indicates a lesser environmental impact of the technology being assessed compared to the reference; *negative* ESP indicates a higher environmental impact.

3 RESULTS AND DISCUSSION

Results of the environmental assessment done at concrete and at structural scale are discussed in this chapter. Three structures are presented: hybrid wood-concrete structure *(Section 3.2)*, low energy high performance concrete prestressed with carbon fibre reinforced polymer structure *(Section 3.3)*, and ultra-high performance fibre reinforced concrete with synthetic fibre reinforcement structure *(Section 3.4)*.

3.1 Low energy concrete

Motivation for the development of low energy concrete was underpinned by the introduction of new guidelines from the Swiss Society of Engineers and Architects, the SIA Merkblatt 2049, allowing production of a new generation of Portland cements with clinker substitution level up to 65% [13]. European standard EN 197-1 currently allows up to 35% clinker substitution for Portland composite cements [14].

The study focuses on the optimisation of ternary blend cement with burnt oil shale (BOS) and limestone (CEM II/B-M(T-LL)) which, as of 2015, has the highest share in the total cement supplied in the Swiss market [15]. Compatible *polycarboxylate ether* (PCE) superplasticizers will be developed to address the issues on low strength development at early ages and the uncertainty on long-term properties associated with high clinker substitution.

For the interim assessment, a low energy concrete with 40% clinker content in the cement has been modelled. Polynaphthalene sulfonate (PNS)

G. Habert, A. Schlueter (eds.): Expanding Boundaries © 2016 vdf Hochschulverlag AG an der ETH Zürich
DOI 10.3218/3774-6_110, ISBN 978-3-7281-3774-6, http://vdf.ch/expanding-boundaries.html

plasticizer in the Ecoinvent dataset for concrete was replaced with PCE superplasticizer modelled from Häner, et al (2005) [16]. Due to an unavailability of BOS data in Ecoinvent, whose impact allocation was assumed as negligible based on the available LCA of oil shale industry [17], a binary cement with limestone was used in the model.

The production of the modelled low energy concrete presents more than 40% savings on primary energy and around 50% savings on emission compared to the reference concrete with ordinary Portland cement (OPC / CEM I). Savings on concrete come almost entirely from low clinker cement. The substitution of clinker with limestone presents a reduction directly proportional to the substitution rate because limestone, a locally available resource in Switzerland, has almost a negligible environmental burden compared to clinker.

It is noted however that a higher clinker substitution does not necessarily mean better savings as presented in the study of Pushkar and Verbitsky (2016) [18]. The choice of supplementary cementitious material (SCM) is critical to optimizing the concrete mix. Depending on the environmental burden allocation of secondary material used as SCM, e.g. fly ash, slag or BOS, the resulting concrete mix could have a lower or a higher environmental impact [18]. LCA modelling of low energy concrete will be improved to consider the allocation impact from secondary material particularly BOS, in parallel with the optimization of concrete.

3.2 Hybrid wood concrete structure

One of the innovative concrete structures to be developed in the project is the hybrid wood-concrete structure without steel. This is a targeted improvement to the wood-concrete technology used in the construction of ETH House of Natural Resources (HoNR), a two-storey building located in ETH Zurich Campus. HoNR is an innovation in timber construction, where laminated veneer lumber (LVL) was used as formwork and reinforcement to substitute steel [19]. To comply with fire safety standards, steel was not totally replaced [20]. A connection system without steel fasteners will be developed by looking into material lay-up and potential glue that could effectively bind wood and concrete. The research will also look into LVL with improved fire retardancy to totally eliminate dependency on steel. Low energy concrete will be used to optimize the wood-concrete structure.

Figure 1 presents the results of the environmental assessment of the floor slab structure using the targeted low energy wood-concrete solution of the project *(wood concrete optima)* relative to the reference conventional reinforced concrete and compared to wood-concrete technology used in HoNR *(wood concrete HoNR)*. Design specifications are presented in *Table 1*. The production of *wood concrete optima* presents around 50% potential savings in energy and 70% in emission compared to the conventional reinforced concrete due to an improvement in concrete and a total elimination of steel. A total elimination of steel however is an optimistic assumption. The task of the research is to look into the right balance of steel substitution that would ensure structure durability and fire safety.

	Conventional reinforced concrete[a]	Wood concrete HoNR[b]	Wood concrete optima[c]
Cement per cubic meter, kg/m^3	300	375	375
Concrete thickness, mm	280	160	160
LVL thickness, mm	0	40	40
Steel fraction, %	1.12	1.07	0

[a, b] Modelled from actual application of wood-concrete technology (using CEM I) in HoNR floor slabs [21].
[c] *Wood concrete optima* is modelled using cement with 40% clinker and no steel.

Table 1: Design of one square meter wood-concrete floor slab. Based on Tai Ly (2014) [21].

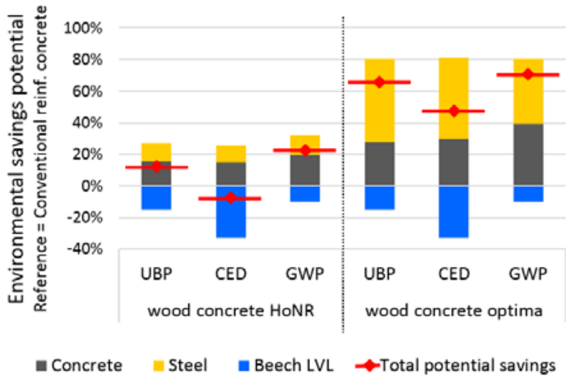

Fig. 1: Environmental impact assessment of 1 m^2 of wood concrete floor slab structure. Reference is conventional reinforced concrete. Design is based on Table 1.

LVL in this study is modelled from *beech* wood, which is a locally available resource in Switzerland and the production process is modelled based on Zimmer and Kairi (2011) [22]. The environmental assessment done on beech LVL shows that more than 50% of the embodied energy comes from adhesives. Phenolic resin is the adhesive used based on the production process of Pollmeier, the LVL supplier in Germany [23]. Phenolic resin has a higher environmental impact than other adhesives like melamine urea formaldehyde (MUF) and polyurethane (PUR), but is attractive because of its high strength and high adhesion to wood [24]. It has also a lesser impact on health compared to MUF as less formaldehyde is released [24]. One limitation of the phenolic resin data in Ecoinvent, as noted by Messmer (2015), is that it is not based on a real production situation but rather on rough estimates [24]. The beech LVL model will be improved to consider primary data from industry.

3.3 Low energy high performance concrete prestressed with carbon fibre reinforced polymer

Another concrete structure targeted in the project is the low energy high performance concrete (HPC) using carbon fibre reinforced polymer (CFRP) as pre-stressing. Special prestressed structural elements with lightweight and durable properties are targeted by replacing steel with CFRP, a strong and more corrosive-resistant material [25]. Although CFRP is more energy intensive than steel [26], the benefit from the substitution is the reduction of volume of concrete in the structural design. A concrete cover is needed to protect the structure from corrosion due to steel.

One linear meter of beam with design parameters presented in *Table 2* is the functional unit used for the environmental assessment of the HPC beam prestressed with CFRP (HPC-CFRP) compared to the conventional reinforced concrete beam and HPC beam prestressed with steel (HPC-steel).

	Conventional reinforced concrete[a]	HPC-steel[b]	HPC-CFRP[c]
Tensile load, kN	270	270	270
Concrete strength, MPa	30	90	90
Cross-section, cm^2	900	429[d]	189
Volume, m^3	0.09	0.043	0.019

[a] 1.12% vol. steel; [b] 0.85% vol. steel; [c] 0.84% vol. CFRP
[d] Additional *concrete cover* for steel protection is included.

Table 2: Design of one linear meter beam structure. Based on e-mail communication with T. Lämmlein (EMPA) dated 04.03.2016.

The environmental assessment of HPC-CFRP presented in *Figure 2* gives a savings potential in energy of around 60% and 70% in emission relative to the reference conventional reinforced concrete. This huge savings potential is consequent to almost a fivefold reduction in volume of the beam *(Table 2)*. Analysis relative to HPC-steel, which is more reasonable in terms of lightweight and durable applications, presents around 10% savings in energy and more than 20% in emission *(Figure 2)*. Note that further optimization of HPC-CFRP using cement with 40% clinker instead of OPC (see *HPC-CFRP optima* in Figure 2) presents an additional 5% to 8% environmental savings potential.

LCA of CFRP shows a high impact contribution from carbon fibre. The life cycle inventory of CFRP is not readily available in the Ecoinvent database. Processes were modelled from Griffing and Overcash (2010) [27] for the carbon fibre production, Suzuki and Takahashi (2005) [28] for the Pultrusion process, and Terrasi (2008) [29] for the carbon fibre and epoxy mix. The high embodied energy of carbon fibre is due to the carbon fibre production, specifically the production of a precursor [30], which is a good target for energy optimization. According to Suzuki and Takahashi (2005), the production scale of carbon fibre is not yet high enough to result in high efficiency as the industry is relatively young [28]. Efficiency in the carbon fibre production is largely dependent on technology and facility [26].

A further reduction of the environmental impact of HPC-CFRP is expected during the construction phase. Savings from structural designs due to a potential reduction in concrete volume for foundations and columns, as well as from transportation and machine usage due to lightweight and durable HPC-CFRP elements, will be assessed. The issue on carbon fibre recyclability will also be looked at in the next steps of this study.

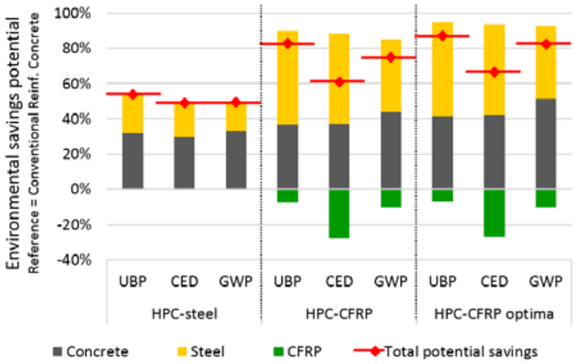

Fig. 2: Environmental impact assessment of 1 linear meter HPC-CFRP beam structure. Reference is conventional reinforced concrete. HPC and reference are modelled using OPC while HPC optima is modelled using cement with 40% clinker. Beam design is based on Table 2.

3.4 Ultra-high performance fibre reinforced concrete with synthetic fibre reinforcement

The replacement of steel reinforcements with synthetic fibres for ultra-high performance fibre reinforced concrete (UHPFRC) is another low energy concrete structure to be developed in the project. UHPFRC has a very high durability compared to conventional concrete due to its extremely low permeability and is attractive to use for applications such as bridge construction and rehabilitation [31]. Two potential synthetic fibres are targeted in the project – polyethylene (PE) and basalt. The use of basalt fibre in construction is gaining attention in research due to its promising mechanical properties [32]. PE fibre is also considered due to its high tensile strength, relatively high modulus of elasticity, and much lower density compared to steel [33]. Dataset for basalt fibre production is not readily available in Ecoinvent and is modelled from production data provided by De Fazio (2011) [34].

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DOI 10.3218/3774-6_110, ISBN 978-3-7281-3774-6, http://vdf.ch/expanding-boundaries.html

in kg	Conventional UHPFRC	UHPFRC with PE	UHPFRC with basalt
Cement	650	657	657
Limestone filler	559	565	565
Silica fume	137	138	138
Quartz sand	573.5	580	580
Water	180	182	182
Superplasticizer	42.5	42.8	42.8
Steel fibre	314	0	0
PE fibre	0	19.6	0
Basalt fibre	0	0	54

Table 3. Preliminary mixes of 1 m^3 UHPFRC with different fibre reinforcements. Based on email communication with E. Denarie and A. Hajiesmaeili (EPFL) dated 01.12.2015.

Interim mix designs for the environmental assessment of one cubic meter of UHPFRC with different fibre reinforcements are presented in *Table 3*. The environmental assessment of mixes with synthetic fibres and low clinker cement presents more than a 50% environmental savings potential compared to conventional UHPFRC as shown in *Figure 3,* mainly because of the substitution of steel with PE and basalt fibres.

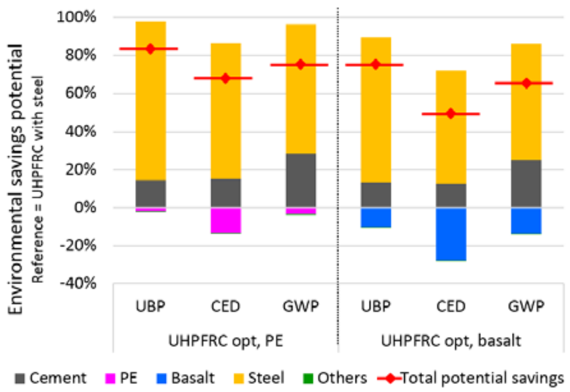

Figure 3: Environmental assessment of 1 m^3 of UHPFRC with synthetic fibre substitutes. Reference is conventional UHPFRC with steel and OPC. UHPFRC with PE and basalt are modelled using cement with 40% clinker. Design is based on Table 3.

This study is focused on the environmental assessment of UHPFRC on the material level to see the substitution potential from selected synthetic fibres. Next steps will look into the structural level and will consider the whole life cycle analysis to assess also savings from maintenance. According to Habert, et al (2013), the use of UHPFRC could provide a considerable impact reduction within the whole life cycle compared to conventional concrete solutions due to savings from service life maintenance [31].

4 CONCLUSIONS

The initial environmental assessment of production of the targeted technologies in the project presents a huge energy and emission savings potential for the energy turnaround. Low energy concrete could reduce energy by more than 40% and cut carbon emission by half compared to conventional concrete. Interim analysis done on structural elements using low energy concrete and a substitution of steel with other tensile-resistant materials gives promising results in terms of the energy and emission savings potential, as well as eco-points.

The next step of this study is the assessment on a structural level from cradle-to-grave, including savings from structural design, transportation and end-of-life. LCA modelling will be improved in parallel with the development of low energy concrete technologies in the project.

5 ACKNOWLEDGMENTS

The authors would like to thank Swiss National Science Foundation for funding “Concrete Solutions Joint Research Project” under NRP 70 Energy Turnaround. We acknowledge the whole team working in the joint research project from EMPA, EPFL and ETHZ for their respective works developing the technological solutions where this environmental assessment is anchored on.

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DOI 10.3218/3774-6_110, ISBN 978-3-7281-3774-6, http://vdf.ch/expanding-boundaries.html