Environmentally optimized floor slabs using UHPC - contribution to sustainable building

Summary
Optimization of material consumption is one of the basic approaches applied in the development process of new types of structures, respecting requirements of sustainable construction. New composite high performance silicate materials could be used for construction of more strong, more durable and at the same time slender structures. The optimized lightened shape of structural elements demands less material and consequently it can lead to improved environmental parameters of the entire structure. The application of HPC and UHPC is more frequent in engineering structures, such as bridges. However, in building structures there is also a good chance to reduce environmental impacts and simultaneously to increase structural reliability and safety by the use of new types of high performance concretes.

Keywords: environmental impact, optimization, RC floor structure, HPC, fibre concrete

1 Background
During the twenty years from 1974 to 1994 the world population increased by 40%. Cement and steel production, municipal waste generation are increasing even faster [1] (Fig. 1).

Figure 1: Tendencies of cement production and generation of municipal waste (OECD data) are compared with the population growth and its expected development up to the year 2020
The need for material saving was clearly specified in general Rio Agenda 21 (Changing Consumption Patterns) published in 1992: "To promote efficiency in production processes and reduce wasteful consumption in the process of economic growth".

Buildings in EU and other developed countries are responsible for more than 40% of the total energy consumption, and the construction sector generates approx. 40% of all man-made wastes [2]. The extraction of raw materials for construction of buildings, manufacturing of building products and waste landfill or incineration are associated with corresponding environmental impacts, including greenhouse gas emissions. Buildings are thus consequently responsible for more than 30% of released CO₂ emissions.

Development of new materials, structures and construction technologies for construction of buildings should be thus based on the struggle for the reduction of primary non-renewable material and energy resources, while keeping performance quality, safety and durability on a high performance level.

Structural safety of construction in all its life cycle stages, including exceptional situations (natural disasters, explosions, fires, etc.) comes to prominence in the hierarchy of the design criterion importance. This is also due to the increasing risk level resulting from the rise of exceptional load situations caused by global climatic changes, as well as terrorist attacks.

Both, the requirements, (i) the reduction of material consumption (leading to more slender structures) and (ii) the increase of structural reliability, durability and safety can be at first sight considered as being in contradiction – the search for the optimum assuming one criterion often causes decreasing of the other criterion value. Using traditional construction materials and technologies, the typical result of the effort to ensure a higher level of structural reliability and safety is the robust structure (which needs more construction materials). However, using high performance concrete it is possible to design more slender structures, while structural reliability and safety is kept at the required high level.

2 Application of UHPC in building construction

The most significant feature of UHPC is high compressive strength which allows the design of more slender structural elements. Such filigree structures could be at the same time more strong and durable. It is due to the very dense material structure and increased resistance to corrosion. Thus, UHPC offers new solutions for innovative construction in more exposed situations like aggressive environment or exceptional loads (earthquakes, floods, strong winds, blasts etc.). Moreover, environmental parameters of filigree structures can be due to primary material savings improved.

The application of UHPC is currently more frequent in engineering structures like roads and bridges [3]. However, there is a big potential for the use of UHPC also in building structures. The advantages of application of HPC and UHPC in building construction are as follows:
- higher compressive strength enables construction of slender and lighter structural members with reduced use of primary material,
- UHPC can be used for larger spans and heavier loads,
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- due to higher density the material is more durable (it requires less maintenance and repairs); it can be used also in aggressive environment,
- lower load from lighter structural members on supporting members (walls, columns, foundations),
- structural members from UHPC are more strong and can be more ductile (e.g. if fibres are used) – the structure is more resistant in case of earthquakes or other exceptional load cases – like natural disasters, terrorist attacks etc.,
- slender structures will produce less demolition waste and corresponding transport load,
- lighter structure = less material consumption = less demands on transportation = lower environmental impacts.

Several examples from abroad show that new composite fibre silicate materials and corresponding technologies can be used for thin "shell" elements with the thickness less than 30 mm (e.g. Ductal® – France). For more than two decades, high strength concretes with compressive strength 50 – 130 MPa have been used in construction of tall buildings. Due to higher compressive strength of HPC in vertical load bearing structures, it is possible to design smaller cross sections with a reduced amount of material. The first known use of UHPC (with more than 150 MPa) in building construction dates to 2001, when in Joppa (USA Illinois) a clinker silo was built with the roof from Ductal® concrete with compressive strength up to 220 MPa and flexural strength 50 MPa. The ultra light, thin precast panels were designed without any conventional reinforcement by steel bars.

3 Environmental impact of concrete and concrete structures

Considering the volume of produced concrete and number of concrete structures, the problem of their environmental impact forms a significant part of the whole global problem of sustainable development. The specific amount of harmful impacts embodied in a concrete unit is, in comparison with other building materials, relatively small. However, due to the high production of concrete (Fig. 1), the total negative impact of concrete structures is significant. Every improvement of concrete design principles, production, construction and demolition technologies, methodologies of assessment and management of operation of concrete structures thus provides a very significant contribution on the way towards sustainable development.

3.1 Potential for reduction of environmental impact by the use of UHPC

Using UHPC it is possible to design slender shell structures with reduced use of materials. This leads to reduction of environmental impacts connected with the use of primary natural sources and reduction of deposition of waste from demolished structures.

Potential reductions of environmental loads are:
- savings in natural resources (especially non-renewable ones),
- savings in transport environmental loads (less material, lighter structural elements, less demolition waste),
- savings in maintenance and repair demands due to higher durability,
- reduction of the volume of waste material at the end of the life cycle of the structure.
3.2 Use of recycled waste materials

The reduction of primary non-renewable resources and consequent reduction of waste amounts can also be supported by the use of secondary recycled materials originating from the waste from construction, as well as other industries. Some secondary materials (such as fly-ash, silica fume, slag, etc.) are already used in production of new types of concrete.

The main concern should be paid to those waste materials which are produced in large amounts and are not recycled or just a small amount is recycled. Such waste materials are e.g. non-sorted plastics and laminated carton drink boxes from municipal waste.

Several alternatives of RC floor structures lightened by fillers from recycled municipal waste have been developed, optimised and experimentally tested within the previous research at CTU in Prague.

Two types of lightening fillers from recycled waste plastic and one type from structural boards from recycled laminated cartons were developed [4]. The shapes of fillers were determined as a result of integrated environmental design and optimization considering environmental criterions, as well as structural parameters of the resulting composite RC structure.

3.3 Environmental parameters of concrete

Evaluation of environmental impact of any structure is highly determined by the quality of available data. There is no standard data set of unit embodied values for all components used in concrete mix. One of the often used data source is Ökologisher Bauteilkatalog [5] in which the data are based on UCPTE electricity mix. These data were used in the following study for evaluation of embodied energy and embodied CO$_2$ of plain concrete, steel reinforcement and thin-coat plaster. Unit embodied values for recycled non-sorted plastic were calculated using energy and production statistical data provided by producer – recycling company Transform Lazne Bohdanec. The data used for UHPC were taken from [3] (Teichmann and Schmidt). Composition of both types of concretes (C30/37 and UHPC) used in the study is presented in Table 1, environmental parameters are in the Table 2.

<table>
<thead>
<tr>
<th>Type of concrete</th>
<th>C30/37</th>
<th>UHPC</th>
</tr>
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<tbody>
<tr>
<td>cement kg/m$^3$</td>
<td>370</td>
<td>733</td>
</tr>
<tr>
<td>quartz powder kg/m$^3$</td>
<td>-</td>
<td>183</td>
</tr>
<tr>
<td>quartz sand/gravel kg/m$^3$</td>
<td>1800</td>
<td>1008</td>
</tr>
<tr>
<td>water kg/m$^3$</td>
<td>170</td>
<td>161</td>
</tr>
<tr>
<td>silica fume kg/m$^3$</td>
<td>-</td>
<td>230</td>
</tr>
<tr>
<td>steel fibres kg/m$^3$</td>
<td>-</td>
<td>75</td>
</tr>
</tbody>
</table>

It is evident that UHPC have unit embodied values higher in comparison with plain concrete. This is due to the fact that steel and plastic fibres have higher values of embodied environmental parameters than plain concrete itself. An inclusion of fibres in the concrete mix
represents an additional increase of embodied parameters. However, UHPC can be used for more slender structures with significantly less concrete content and without conventional reinforcement in thin parts of element cross sections.

Table 2: Embodied environmental parameters of different types of materials, using data from [3] and [5]

<table>
<thead>
<tr>
<th>Type of material</th>
<th>embodied energy MJ/kg</th>
<th>embodied emissions CO₂ kg CO₂,equiv./kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>ordinary concrete C30/37</td>
<td>0.80</td>
<td>0.130</td>
</tr>
<tr>
<td>ultra high performance concrete - UHPC [3]</td>
<td>1.44</td>
<td>0.239</td>
</tr>
<tr>
<td>reinforcement (steel)</td>
<td>13.00</td>
<td>0.800</td>
</tr>
<tr>
<td>recycled non-sorted plastic</td>
<td>7.36</td>
<td>0.492</td>
</tr>
<tr>
<td>thin-coat plaster</td>
<td>1.40</td>
<td>0.140</td>
</tr>
</tbody>
</table>

4 Environmental assessment of selected alternatives of RC floor structures – case study

Several previously performed LCA (Life Cycle Assessment) analyses of RC floor structures showed that using the optimized shape and recycled materials it was possible to reduce environmental impacts, such as consumption of non-renewable silicate materials, the resulting level of embodied CO₂, embodied SOₓ and embodied energy. Some results of previous LCA analyses have already been presented in [1] and [4]. The goal of the current analysis is to show how the use of UHPC in an optimized shape of an RC floor slab can contribute to the reduction of environmental impacts.

In total, three alternatives of RC floor structures have been analyzed. All alternatives were designed for the same performance – live load 2.0 kN/m², span 4.5 m and final flat ceiling finish. The overview of all the analyzed alternatives is presented in Table 3.

Table 3: Floor slab alternatives used in the environmental analysis

<table>
<thead>
<tr>
<th>Floor slab alternative</th>
<th>Thickness mm</th>
<th>Self-weight kg/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>A full RC slab from ordinary concrete C35/45</td>
<td>200</td>
<td>491</td>
</tr>
<tr>
<td>B precast RC panel with lightening shell elements from recycled non-sorted plastic</td>
<td>200</td>
<td>310</td>
</tr>
<tr>
<td>C precast UHPC panel with lightening shell elements from recycled non-sorted plastic</td>
<td>200</td>
<td>223</td>
</tr>
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</table>
The shape of the two composite concrete floor panels alt. B and C is based on previous optimization with the goal to reduce the amount of used concrete. Both types of panels are lightened by shell installation fillers from recycled non-sorted plastics.

Alternative B (Fig. 2): The lower ceiling and top slab are 50 mm thick. In ribs (axial distance 600 mm) is inbuilt lattice reinforcement. Sides of the ribs are formed by installation fillers from recycled non-sorted plastic. Ordinary concrete C30/37 has been used for casting.

![Figure 2: Precast filligran panel with installation shell elements – during experimental manufacturing in ŽPSV Company, 2006](image)

Alternative C: The lower ceiling and top slab are 30 mm thick from UHPC without conventional reinforcement. In ribs (axial distance 450 mm) is inbuilt lattice reinforcement. Sides of the ribs are formed by installation fillers from recycled non-sorted plastic.

The resulting relative comparison of environmental profiles of analyzed alternatives of RC floor structures is in Figure 3. The reference level is represented by the RC full slab from concrete C16/20. The graph shows that embodied energy in UHPC alternative (Alt. C) is higher in comparison with reference RC full slab (Alt. A). This is due to very high unit embodied values of UHPC (see Tab 2). However, very important is reduction of the primary material use (for UHPC 62%) and self weight (for UHPC 56%) due to optimized slender hollow core cross section. This has a positive effect on a level of environmental impacts associated with transport of materials and with the deposition/recycling of waste materials at the end of the life cycle. Consequently lighter floor structures load less supporting columns, walls and foundations – this can lead to reduction of its dimensions and additional material and environmental savings. Figure 4 show comparisons of input material flows (construction phase) and output material flows (demolition phase).
5 Conclusion

The need for more efficient ways of the use of material resources (especially primary materials) is becoming more and more important.

The study has shown significant reduction of primary material use while using optimized hollow core cross section of RC floor slab. Using UHPC it was possible to design more slender sections with higher reduction of material consumption. On the other hand the comparison of environmental profiles show higher embodied energy (although less material was used). This is due to content of fibres and other admixtures in UHPC. This increases significantly unit embodied values. Maybe, this result could lead to negative conclusion that
UHPC is not suitable for sustainable construction of buildings. However, more complex assessment of the entire building considering whole life cycle (including demolition, recycling) and entire structure (including supporting structures) would show other associated environmental benefits. Moreover, high performance material properties (fire safety, water tightness, frost resistance, etc.) make structures more durable and more resistant against climatic effects and also safer in case of exceptional loads (like climatic disasters or terrorist attacks). This all creates the potential for wider application of UHPC for construction of sustainable buildings in the future.

6 Acknowledgements
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7 References