Keywords: material efficiency, environmental performance, high performance concrete, recycled materials, optimization

Summary
Development of progressive materials, structures and technologies for sustainable buildings is based on the struggle for the reduction of primary non-renewable material and energy resources, while keeping safety and durability of the structure on the required high level. Material effective structures for buildings can be based on several structural principles and their combinations: optimization of structural form, use of recycled waste materials, use of natural and renewable materials, use of composite and high performance materials. New composite high performance silicate materials can be used for thin "shell" elements enabling design with significantly reduced use of materials and leading to reduction of environmental impacts. Several preliminary research results followed by applications in construction practice showed already possibilities of the reuse of waste materials (preferably from municipal waste) for lightening fillers used in optimized concrete structures. Experimental investigation and case studies performed by authors in the frame of long term research, focused to environmental optimization of building structures, support the expectation that it will be possible to reach factor 3 or even more while keeping structural reliability on the needed high level. Developed structural concepts have been proved not only by theoretical and experimental results, but also by practical application in construction of several buildings.

1. Background
During the twenty years from 1974 to 1994 the world population increased by 40%. Cement and steel production and municipal waste generation are increasing even faster (Hajek 2006) (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 (CIB 1999). 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 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.

Performance quality and 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 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 performance quality, reliability, durability and safety can be at first sight considered as being in contradiction. 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 materials it is possible to design more slender structures, while performance quality, structural reliability and safety is kept at the required high level.

2. **Optimization of material consumption in building structures**

The problem of sustainability of structures is very complex and includes a large number of parameters and criteria from different areas of technical as well as non-technical sciences. One of the most important criteria in the optimization of load bearing structures is consumption of non-renewable materials and associated consequences during the whole life cycle of the structure (transport and manipulation with material during construction, demolition, recycle ability etc.).

Material effective structures (with reduced amount of structural material) can be based in general on several structural principles and their combinations:

- optimization of structural form and shape of structural elements,
- use of high performance silicate materials,
- use of recycled waste materials (including municipal waste),
- use of renewable materials.

The reduction of primary non-renewable resources and consequent reduction of waste amounts can also be achieved by the use of waste from construction, as well as other industries as a secondary material for production. Some secondary materials (such as fly-ash, silica fume, slag, etc.) can be used in production of new concrete. The initial optimization steps, covering the use of the ribbed or waffle shape and use of recycled materials, result in the reduction of embodied values (CO₂, SO₂, energy). The cut in consumption of natural (non-renewable) sources (limestone, granite, oil, etc.) is evident, and can be very significant.

2.1 **Optimization of structural form and shape of structural elements**

The typical outcome of the shape optimization of the concrete structure with the objective to reduce structural material consumption (while high level of reliability is kept) is the ribbed or waffle structure. The basic structural advantages of waffle and ribbed elements are demonstrated in the layout of the structural material in a cross-section. The “T” shape of RC ribs allows a convenient distribution of the structural material, saving material in the tension part of the section. In comparison with the full RC slab, the basic shape of waffle or ribbed slab structures reduces concrete use by 40-55%, and also the corresponding steel use. Consequently, the reduction of the total self-weight acting on vertical bearing structures and foundations can decrease their sizes.
Due to their shape, the reinforced concrete waffle and ribbed structures represent the effective types of structures given by the relation between the material consumption and structural characteristics. This principle is traditionally applied in construction of floors (e.g. ribbed and waffle RC slabs) and walls (e.g. timber framed structure) and could be thus used in sustainable optimized design.

2.2 Use of high-performance silicate materials

The process of optimization of structures from silicate materials (different types of concrete, ceramics, geopolymers) is generally based on the following principles:

- optimization of production technologies of components,
- optimization of concrete mix composition,
- optimization of the shape and reinforcement of structural elements,
- life cycle optimization of the whole structure

There is a good chance to achieve the required reduction of primary material sources and simultaneously the increase of structural reliability and safety (mainly in the case of exceptional load cases) by the use of new high performance fiber concrete (with optimized mechanical properties) in an optimized shape of the structure (which uses less structural material in a cross section in a more efficient way).

Using new types of composite materials with programmed mechanical properties, it is possible to achieve significant improvements in environmental parameters of the structure. This can be achieved mainly by the design of more slender shell structural forms saving primary resources and by the reduction of environmental impacts from depositing and recycling the structure at the end of its life cycle.

Several examples from abroad show, that new composite fiber silicate materials and corresponding technologies can be used for realization of thin "shell" elements with the thickness less than 30 mm (e.g. Ductal – France).

2.3 Use of recycled waste materials

Building construction typically uses large amounts of materials in relatively less demanding techniques. Therefore, there is a high potential for the use of secondary materials obtained from recycling of waste generated by other industrial processes and from municipal waste (Hajek 2006). This approach permits to keep materials in the material cycle longer (considering usually longer service life of the building compared to the service life of the primary product disposed in municipal waste). This results in reduction of consumption of primary material sources and reduction of waste generation and emissions including GHG emissions. Using recycled materials including recycled municipal waste it is possible to keep once used primary material in a many times longer life cycle, and therefore considerably support saving of natural resources.

The main concern should be paid to those waste materials which are produced in large amounts and just a small amount is recycled. Such waste materials are e.g. non-sorted plastics (yellow collecting containers) and laminated carton drink boxes from municipal waste.

The technical value of recycled material is often lower than that of the material when first used in the primary product (down-cycling). Preference should be given to the high-value reuse of recycled materials replacing high-quality primary non-renewable raw materials. In some specific cases, new products from recycled waste can have a higher performance value in comparison with the primary product (up-cycling).

The most of plastic waste and drink boxes from laminated paper are still as a part of mixed municipal waste incinerated with all consequential negative environmental impacts. However, separated salvage of municipal waste particles (plastic, glass, paper, laminated carton) is becoming common in developed countries.

Further recyclability of the newly developed construction with recycled waste materials represents an important aspect that has to be considered. A feasible, effective and environmentally-sound recycling technique should be available for the specific case to avoid the necessity and uncertainty of development of a special recycling procedure. Preferably, the technology process should not limit the number of recycling cycles. An example in Figure 2 shows the potential of use of recycled plastic from throwaway plastic drink bottles for production of plastic shell elements to be used as a permanent formwork in construction of ribbed or waffle RC floor slabs. The utility period of primary raw material could be thus prolonged several thousand times in comparison with waste disposal (incineration) of used plastic bottles in non-sorted municipal solid waste.
Another material that utilizes waste products is geopolymer concrete. Geopolymer concrete is formed by the alkali activated polymerization of aluminosilicates. Fly ash or granulated blast furnace slag (GBFS) are used as cementitious materials instead of Portland cement. There are two motives for replacement of Portland cement in concrete. Firstly, its production consumes large amount of energy (3.7MJ per kg) and secondly, there is a need for utilization of waste materials that are recently being dumped in landfills. Geopolymer concrete gives significant carbon dioxide emissions reduction while having some excellent properties such as high strength, durability and acid resistance. The disadvantage of this material is that efflorescence can appear on its surface as a result of leaching alkalis reacting with atmospheric carbon dioxide and forming carbonates.

2.4 Use of renewable materials

There is a wide range of possible applications in building construction for renewable materials. The use of wood, wooden based materials, clay unburned bricks and or non-traditional natural materials like palm tree fronds, bamboo etc. leads to reduction of environmental impacts, including savings of natural non-renewable natural materials. Especially wood is due to its properties and availability the most challenging material. However, the utilization of wood and wooden based materials is limited by fire safety, strength and durability and thus large multistory buildings, buildings for heavy industry or transport will be still dominantly built from more strong and more fire resistant materials like concrete or steel.

3. Comparison of environmental profiles of building structure alternatives

Two presented case studies – one comparing alternatives of RC floor slabs, the second comparing alternatives of external walls - show the potential for reduction of environmental impacts by optimization of material concept of basic structural components. The alternatives have been designed for the same performance quality (spans, imposed load, flat surface etc.). The results show differences associated just with the structural alternatives themselves. However, several additional savings can be expected in supporting structural elements (columns, walls, foundations) due to lower self weight of optimized lightened structures. Further savings in the case of lightened alternatives is in construction and demolition phase due to lower transport demands.

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 construction. In the both analyses was used data set updated according to currently published Passivhaus-Bauteilkatalog by Waltjen (2008). These data were used in the following studies for evaluation of embodied energy, embodied CO$_2$ and embodied SO$_2$. Unit embodied values for recycled non-sorted plastic were calculated using energy and production statistical data provided by recycling company Transform a.s. The data used for UHPC (Ultra High Performance Concrete) were taken from Schmidt (2007).
3.1 Case study 1: Environmental assessment of selected alternatives of RC floor structures

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 by Hajek (2006 and 2007). The goal of the current analysis is to show how the use of different material base and optimized shape of an RC floor slab can contribute to the reduction of environmental impacts.

In total, six 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, same thickness 200 mm and final flat ceiling finish. The overview of all the analyzed alternatives is presented in Table 1.

Table 1 Floor slab alternatives used in the environmental analysis

<table>
<thead>
<tr>
<th>Floor slab alternative</th>
<th>Self-weight Kg/m²</th>
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<tbody>
<tr>
<td>A</td>
<td>composite / monolithic full RC slab from ordinary concrete 478</td>
</tr>
<tr>
<td>B</td>
<td>precast RC panel with lightening shell elements from recycled non-sorted plastic 302</td>
</tr>
<tr>
<td>C</td>
<td>precast UHPC panel with lightening shell elements from recycled non-sorted plastic 212</td>
</tr>
<tr>
<td>D</td>
<td>composite floor slab with filligran panels and lightening fillers from polystyrene 305</td>
</tr>
<tr>
<td>E</td>
<td>RC ribbed floor slab with ceramic hollow core fillers 311</td>
</tr>
<tr>
<td>F</td>
<td>RC ribbed floor slab with lightening fillers from recycled laminated carton boards 213</td>
</tr>
</tbody>
</table>

Figure 3 Comparison of environmental parameters of RC floor slab alternatives. Reference level 100% is represented by a full RC floor slab – alt. A
Fig. 3 and 4 present graphs showing potential savings of environmental impacts. The reduction can be in some cases more than 50%. These results cover just the floor structure itself. More savings are associated with the reduced use of material (savings in transport) and lower load from lighter structure acting on supporting structures (columns, walls, foundations). From this point of view major savings will be for alternatives C and F.

3.2 Case study 2: Environmental assessment of selected alternatives of external walls

The basic idea of this case study was a complex comparison of different external wall structures that are more or less typical for family and residential houses. All designed structures have the thermal performance set to recommended U values according to the Czech national standard ČSN 73 0540-2, Thermal protection of buildings - Part 2: Requirements. This means that the structures with area weight over 100 kg/m² have the U value set to 0.25 W/m²K, the structures with area weight less than 100 kg/m² have the U value set to 0.20 W/m²K.

All the structures are designed with ETICS (External Thermal Insulating Composite System) which consists of mineral wool thermal insulation and a thin silicate glass-fiber reinforced plaster (except alternative 8 which uses porous wood fiberboard as an insulation). The decision to use mineral wool as the thermal insulation have several reasons. Namely the perfect fire resistance enabling universal use, better water vapor permeability, and finally a good sound proofing. Concerning the load bearing part of the structure, there are several types of massive structures i.e. reinforced concrete wall (1), concrete hollow block wall (2), aerated concrete block wall (3), calcium silicate block wall (4), and honeycomb brick (5) wall and also lightweight structures i.e. load-bearing laminated wood panel (6), timber frame panel with mineral wool insulation (7), and another timber frame panel with cellulose fiber insulation (8).

Table 2 Exterior wall alternatives used in the environmental analysis

<table>
<thead>
<tr>
<th>Exterior wall alternative</th>
<th>Thickness mm</th>
<th>Area weight kg/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Reinforced concrete wall with ETICS *</td>
<td>334</td>
<td>403</td>
</tr>
<tr>
<td>2 Concrete hollow block wall with ETICS *</td>
<td>410</td>
<td>346</td>
</tr>
<tr>
<td>3 Aerated concrete block wall with ETICS *</td>
<td>390</td>
<td>207</td>
</tr>
<tr>
<td>4 Calcium silicate block wall with ETICS *</td>
<td>430</td>
<td>483</td>
</tr>
<tr>
<td>5 Honeycomb brick wall with ETICS *</td>
<td>424</td>
<td>258</td>
</tr>
<tr>
<td>6 Laminated wood panel with ETICS *</td>
<td>270</td>
<td>128</td>
</tr>
<tr>
<td>7 Timber frame panel with ETICS <em>/</em>*</td>
<td>260</td>
<td>64</td>
</tr>
<tr>
<td>8 Timber frame panel with ETICS (wood-fiber board) <em>/</em>*</td>
<td>278</td>
<td>85</td>
</tr>
</tbody>
</table>

* ETICS - External Thermal Insulating Composite System
** U = 0.20 W/m²K; in other cases U = 0.25 W/m²K
There are significant differences between massive and lightweight structures. The lightweight structures benefit from the low area weight, small thickness, and its renewable nature that result in the superb values in all the evaluated criteria. Concerning the massive structures, good results show the alternative with concrete hollow blocks (2) even though having a pretty high area weight. On the contrary, the alternative with calcium silicate blocks show relatively bad results namely due to its high area weight.

3. Application in construction practice

Two types of lightening fillers from recycled waste plastic and one type from structural boards from recycled laminated cartons were developed. 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. The initial optimization steps, covering the use of the ribbed or waffle shape and use of recycled materials, resulted in the reduction of embodied values (CO₂, SO₂, energy).

Three selected alternatives of fillers for waffle and ribbed slabs were experimentally produced and tested:
- shell installation fillers from recycled non-sorted plastic from municipal waste,
- waffle fillers from recycled non-sorted plastic from municipal waste,
- waffle fillers from structural boards from recycled laminated cartons from municipal waste.

Installation shell plastic fillers were used in the construction of the two storey building of Senior Centre in Moravany near Pardubice in the Czech Republic. The original design of the floor structure – a composite RC slab was changed to a composite RC slab with shell installation fillers. This resulted in reduction of concrete consumption up to 0.08 m³ per m², i.e. 34%. The self weight of the floor structure was reduced by 2.0 kN/m². The installation space inside the floor structure was used for the wiring and for the heating system in plastic tubes. This brought additional cost savings compared to the originally assumed installation system to be placed in the upper layers - inside the flooring (Fig. 7a).
The reconstruction of the two storey RC factory hall into a storage hall required an increase of the load bearing capacity of the intermediate floor structure so that the new structure would facilitate a new function with a higher live load of 5 kN/m². The existing cast-in-place RC slab with a thickness of 120 mm did not meet such requirements; moreover, there were a lot of openings unsuitable for the new way of use. The removal of the inconvenient RC floor slab was, due to the time limits, technological demands and total costs, unfavourable.

With respect to the limited load bearing capacity of the existing vertical load bearing RC structure, the originally expected alternative (solid full RC slab) would require strengthening of RC columns and footings. Thus, a specific solution was requested to lighten the floor slab compared to a solid one.

The new RC waffle floor slab was placed directly on the existing floor structure (Fig. 7b). Plastic fillers were placed on the floor so that the existing RC floor structure provides sufficient fire safety. Plastic formwork fillers were made in the Transform Lazne Bohdanec Company in a total amount of 650 m² of the fillers.

4. Conclusions

The theoretical analysis, optimization and performed case studies have supported preliminary assumptions about the undisputed significance of the selection of materials, including recycled materials and optimization of the shape of the structure. The performed case studies have showed that using recycled waste materials and the optimized shape of the floor structure, it is possible to reduce environmental impacts, such as consumption of non-renewable silicate materials, the resulting level of emissions (embodied CO₂, embodied SO₂) and embodied primary energy. The evaluated factor of environmental impact reduction in the range 1.2 – 1.8 can be considered insufficient, compared with the range of the needed improvements (factor 4 and more). However, these impact reductions are associated just with material savings in a structure itself and do not cover other related impact reductions in supports and transport.

Nevertheless, there is a big potential for the use of high performance silicate materials to form thin shell (ribbed, waffle, etc.) structures with reduction of the use of primary raw materials, and correspondent reduction of associated environmental impacts. Consequently, there are other possibilities how to reuse waste materials, preferably from municipal waste.

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References


