Savings in Primary Material Use through Optimized RC or FRC Structures in Building Construction

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ABSTRACT: Optimization of material consumption is one of the basic approaches applied in the development process of new types of structures and structural elements, respecting requirements of sustainable construction. New composite high performance silicate materials (HPC, FRC, HPFRC, etc.) could be used for design of more slender structural elements. Using recycled materials it is possible to replace primary material resources by already utilized materials (waste). The optimized lightened shape of structural elements demands less material. All these approaches lead to savings in primary material use and to improvement of environmental parameters of the entire building. Using FRC structural safety parameters could be improved. Within the scope of the previous research several new types of RC floor structures were optimized. The possibility of the use of recycled municipal waste has been proved by theoretical, as well as experimental and in situ results. The application of environmentally optimized RC composite slabs is presented and discussed. The LCA analysis and comparison with other standard types of RC floor structures have shown that using FRC, recycled 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 embodied CO₂, embodied SO₂ and embodied energy.

Keywords: sustainable construction, RC floor slab, fibre concrete, optimization, environmental impact, municipal waste, recycling

1. BACKGROUND

During the twenty years from 1974 to 1994 the world population increased by 40%, the world consumption of cement increased by 77% and that of plastics even by 200% (UNEP, 2004). Cement production, steel production, municipal waste generation are increasing even faster than population growth [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 2050

A minority of rich, developed countries comprising about 22% of the world population is responsible for consumption of more than 60% of the industrial raw material sources. It is evident that in a short-term perspective, it is impossible to stop the increasing tendency of population growth. Consequently the increasing need for new constructions of buildings (requiring more structural material) should be expected. Natural resources are, however, limited. While the reduction of total consumption of materials is limited by the legitimate higher needs of increasing population in the world, the increased use of recycled waste - is becoming more and more important.

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". Among basic actions towards sustainability specified in the Agenda 21 are:

- minimization of non-renewable resources use,
- minimization of total waste production,
- maximization of environmentally sound waste reuse and recycling.

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 (GHG) emissions. Buildings are thus consequently responsible for more than 30% of released CO₂ emissions.

From the above mentioned state of affairs follows the undisputed need for significant reduction of consumption of primary non-renewable materials – one of the basic principles of Sustainable Construction.

Development of construction materials, structures and construction technologies 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 of the structure on the required high level.

Structural Safety of construction in all its life cycle stages, including exceptional situations (like 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 of 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 and safety could be at first sight considered as being in contradiction – the search for the optimum assuming one criterion often causes decreasing of the value of the other criterion. The typical result of the current effort to ensure a higher level of structural reliability and safety is the robust structure (which needs higher volumes of construction materials). This is true especially if common design approaches and traditional construction materials and technologies are used.

The urgent need for changes in the design and technology of concrete construction is obvious. Using new types of high performance fibre concretes it is possible to design more slender structures, while structural reliability and safety is kept on a high level.

2. OPTIMIZATION OF MATERIAL CONSUMPTION IN RC FLOOR 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, recycleability, etc.).

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

- optimization of the structural form and shape of structural elements,
- use of high performance materials (HPC, UHPC, FRC, HPFRC),
- use of recycled waste materials (including municipal waste),
- use of renewable materials.

The process of optimization of concrete structures is generally based on the following principles:

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

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 Shape (Cross-section) of RC Floor Slab

The typical outcome of the shape optimization of the concrete slab structure with the objective to reduce structural material consumption (while a high level of reliability is kept) is the ribbed or waffle structure. The basic structural advantages of waffle and ribbed slabs 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 slabs represent the effective types of structures given by the relation between the material consumption and structural characteristics.

Several types of the hidden formwork are used in constructions to form the ribbed or waffle shape of the RC slabs. One, in some European countries common, alternative comprises the use of ceramic fillers (hollow bricks). On the other hand, ceramic material has a very high embodied energy and is produced from natural non-renewable resources. Here, optimization was taken to replace these commonly used elements by the ones from recycled materials from municipal waste.

2.2 Use of High Performance Silicate Materials

There is a good chance to achieve the required reduction of primary material sources and simultaneously the increase of structural reliability and safety (mainly for exceptional load cases) by the use of new high performance fibre 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 attained 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 fibre silicate materials and corresponding technologies can be employed in the erection 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 applies 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 [4]. This approach permits to keep primary materials in the material cycle longer (considering usually longer service life of the building compared to the service life of the primary product). 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 are not recycled or 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).

Most 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.

The possibility of the use of structural components from recycled municipal solid waste (MSW) has been proved by theoretical, as well as experimental and in situ results of the long term research performed at the Czech Technical University in Prague [5]. Several potential environmental results of reduction of the material used in the structure can be recognized: savings in natural resources (especially non-renewable ones), savings in transport and maintenance due to reduction of the total amount (volume and weight) of construction materials, reduction of the volume of waste material at the end of the life cycle of the structure, and others.

3. RC FLOOR SLABS LIGHTENED BY FILLERS FROM RECYCLED MUNICIPAL WASTE

Several alternatives of RC floor structures lightened by fillers from recycled municipal waste have been developed, optimized 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. 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).

3.1 Lightening Fillers from Recycled Municipal Waste

The shape of shell fillers was optimized for the use as a formwork of ribbed or waffle RC floor slabs.
The results of the research proved the acceptability of replacement of silicate fillers by fillers from recycled waste materials. Three selected alternatives of fillers for waffle and ribbed slabs were experimentally produced and tested [4]:

- waffle fillers from recycled non-sorted plastic from municipal waste (Fig. 3),
- shell installation fillers from recycled non-sorted plastic from municipal waste (Fig. 4),
- waffle fillers from structural boards from recycled laminated cartons from municipal waste (Fig. 5).

**Figure 3:** Waffle fillers from recycled non-sorted plastic from municipal waste

**Figure 4:** Shell installation fillers from recycled non-sorted plastic from municipal waste

In the case of plastic fillers there are two basic alternatives, (1) a removable formwork and (2) a permanent formwork that remains in the floor structure. The second alternative requires application of fire protection of plastic filler elements by a suspended lower ceiling.

### 3.2 Floor Structure in Senior Centre in Moravany

Installation shell plastic fillers (Fig. 4) were employed in the construction of the two-storey building of the 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 the 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. 6).

**Figure 6:** Construction of Senior Centre Moravany – composite “filigran” RC slab lightened by installation fillers from recycled non-sorted plastic from municipal waste, 2000

### 3.3 Reconstruction of the Factory Hall, Skoda, Mlada Boleslav, CZ

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. 7). 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.

Figure 7: Reconstruction of floor slab in Skoda factory hall. Slab is lightened by waffle fillers from recycled non-sorted plastic, 2003-2004

3.4 Precast Floor Panels Lightened by Installation Fillers from Recycled Plastic

A new type of an RC precast floor panel with installation fillers from recycled plastic from municipal waste has been developed. The installation fillers are of the same type as those used in the construction of Senior Centre. The test production of panels started in March 2006 in the Company ZPSV Uhersky Ostroh – prefab plant Borohradek, Czech Republic. The width of the panels is 2.4 m, length 4.5 m and the total thickness 200 mm. The lower part of the panel with thickness 50 mm is reinforced by "filligran" space reinforcement girders. Installation fillers from recycled plastic are placed between "filligran" reinforcements (Fig. 8). The top covering RC slab is 50 mm thick. The internal installation space can be accessed from the top of the panel through installation holes in distances 600 x 580 mm. In comparison to a full RC slab, the decrease of the self weight is 38% and the reduction of concrete consumption is 43%. This type of precast panels will be used in the construction of Old Age Pensioners Home near Brno, CZ.

Figure 8: Precast filligran panel with installation shell elements – during experimental manufacturing, 2006

4. ENVIRONMENTAL ASSESSMENT OF ALTERNATIVES OF RC FLOOR STRUCTURES

4.1 Environmental Parameters of Fibre Concrete

Steel and plastic fibres have significantly higher values of embodied environmental parameters than plain concrete itself. Thus an inclusion of fibres in the concrete mix represents an additional increase of embodied parameters of resulting fibre concrete. The associated values of embodied CO₂, SOₓ and energy for different types of fibre concrete (FC) were calculated using a data set based on UCPTE electricity mix [7] and [8] (Table 1).

Table 1: Embodied environmental parameters of plain concrete and different types of FC; SFRC – steel fibre reinforced concrete, SSFC – structural synthetic fibre concrete, GFRC – glass fibre concrete

<table>
<thead>
<tr>
<th>Type of concrete</th>
<th>Fibre content</th>
<th>Embodied energy</th>
<th>Embodied CO₂</th>
<th>Embodied SOₓ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% vol</td>
<td>MJ/kg</td>
<td>kg CO₂/kg</td>
<td>kg SOₓ/kg</td>
</tr>
<tr>
<td>concrete</td>
<td>0.0</td>
<td>0.80</td>
<td>0.13</td>
<td>0.50</td>
</tr>
<tr>
<td>SFRC 0.5</td>
<td>0.5</td>
<td>1.38</td>
<td>0.17</td>
<td>0.67</td>
</tr>
<tr>
<td>SFRC 1.0</td>
<td>1.0</td>
<td>1.97</td>
<td>0.21</td>
<td>0.85</td>
</tr>
<tr>
<td>SSFC 0.5</td>
<td>0.5</td>
<td>1.03</td>
<td>0.14</td>
<td>0.55</td>
</tr>
<tr>
<td>SSFC 1.0</td>
<td>1.0</td>
<td>1.26</td>
<td>0.14</td>
<td>0.59</td>
</tr>
<tr>
<td>GFRC 1.0</td>
<td>1.0</td>
<td>1.04</td>
<td>0.14</td>
<td>0.54</td>
</tr>
</tbody>
</table>

It is evident that fibre concrete itself has unit embodied values higher in comparison to the plain concrete. However, the material properties of fibre concrete permit the application in more slender structural elements with a significantly lower concrete content and without conventional reinforcement in thin short span slabs between ribs.

4.2 Environmental Analysis of Floor Structures

Five alternatives of RC floor structures have been analyzed. All alternatives were designed for the same performance - use in living area of buildings with the span 4.5 m, an identical live load and an identical final flat ceiling finish. The overview of the analyzed alternatives, i.e. two alternatives of RC slabs from FC, two alternatives with lightening fillers and one reference RC full slab is presented in Table 2 [6].

The shape of the two composite steel fibre reinforced concrete (SFRC) floor slab alternatives is based on previous optimization with the goal to reduce the amount of the used concrete. The lower ceiling slab with ribs in axial distance 450 mm is formed from SFRC. The width of the ribs is 60 mm, the thickness of the lower ceiling slab is only 30 mm (without conventional reinforcement). In the ribs there is inbuilt lattice reinforcement.

The sides of the ribs are formed by U-shaped shell fillers from structural synthetic fibre concrete (SSFC) or from recycled non-sorted plastic. The top
RC slab is 40 mm thick and it is cast in site from common concrete C20/25.

**Table 2:** Floor slab alternatives used in the environmental analysis (RP – recycled plastic, PS – polystyrene)

<table>
<thead>
<tr>
<th>Floor slab alternative</th>
<th>Thickness mm</th>
<th>Self weight kg/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full RC slab</td>
<td>200</td>
<td>491</td>
</tr>
<tr>
<td>Precast panel with installation fillers from RP</td>
<td>200</td>
<td>310</td>
</tr>
<tr>
<td>Composite RC slab with PS fillers</td>
<td>230</td>
<td>325</td>
</tr>
<tr>
<td>Composite SFRC slab with fillers from SSFC</td>
<td>200</td>
<td>280</td>
</tr>
<tr>
<td>Composite SFRC slab with fillers from RP</td>
<td>200</td>
<td>241</td>
</tr>
</tbody>
</table>

**Figure 9:** Environmental profiles of RC floor slab alternatives. Reference level 100% is represented by the full RC slab from concrete C16/20

The graph in Figure 9 shows the resulting relative comparison of environmental profiles of the analyzed alternatives of lightened floor structures. The reduction of embodied CO₂ and embodied SOₓ is for FC alternatives 23 – 27%, the reduction of embodied energy 10 - 15%. The reduction of primary material use is even more significant 43 – 56%.

Very important is also reduction of self weight by 43 – 51%. 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 of the structure. The reduction of environmental impacts of the two last parameters reaches in average factor 2.

Figures 10 and 11 present comparisons of input material flows (during construction) and output material flows (during demolition). It is evident that all the lightened alternatives use less primary material on one hand and more recycled material on the other. However, the amount of primary materials and materials with an expected down-cycling process after demolition is still very high. This is due to the fact that concrete is nowadays mainly produced from primary materials and demolished concrete is usually used just for products with lowered quality/performance. These proportions should be changed in the future with respect to the current fast development of recycling techniques. Tamura et al. [9] show the importance and possibilities of complete recycling of concrete in the future.

**Figure 10:** Input material flows for analyzed RC slabs; see legend in Table 2

**Figure 11:** Expected output material flows after demolition (based on current recycling practice and available techniques – 2007); see legend in Table 2

5. CONCLUSION

The undisputed need for a significant reduction of consumption of primary non-renewable materials is
The use of recycled waste materials in building construction represents an approach leading to the required cut in environmental impacts including the decrease of GHG emissions. Especially the use of those waste materials which are produced in large amounts but only a low percentage is recycled, is very important. Mixed plastic municipal waste collected in yellow collecting containers or waste laminated drink cartons represents such a typical waste material.

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 - LCA analyses and comparisons with other standard types of RC floor structures 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 GHG emissions (embodied CO₂, embodied SOₓ, etc.) 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, it should be noted that these impact reductions are associated with material savings in a load bearing system where the main criterion is structural reliability and the reduction of the use of structural materials is thus limited by safety reasons.

Nevertheless, there is a big potential for the employment of high performance silicate materials (UHPC, HPFRC etc.) to form ultra thin shell (ribbed, waffle, etc.) structures with a higher decrease 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. Preliminary studies made by the authors support the expectation that it will be possible to reach factor 3 or even more while keeping structural reliability on the needed high level.

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