ENVIRONMENTALLY BASED OPTIMIZATION OF RC SLAB FLOOR STRUCTURES


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Summary

Optimization of consumption of structural materials represents one of the basic approaches in the development of new structural concepts, reflecting requirements of sustainable construction. On material level the reduction of consumption of primary non-renewable resources is the key environmental issue. The effective use of all materials including recycled materials is in this context essential.

Within the scope of the previous research several alternatives of RC floor structures were optimized with respect to environmental requirements. Improved environmental quality was achieved by the utilization of elements from recycled municipal waste (RMW) in the form of fillers forming optimized structural shape of lightened cross-section of RC floor slab. This structural concept has been proved not only by theoretical and experimental results, but also by practical applications in construction of buildings. The environmental and economical advantages of these types of structures are evident. Comparisons of environmental profiles of different types of RC floor structures with lightening fillers from RMW are presented.

Keywords: Concrete, recycled waste, environmental assessment, optimization

1 Why environmental assessment and optimization of concrete slabs?

Technical as well as non-technical development still has a significantly extensive character. It is evident that in a short-term perspective, it is impossible to stop the increasing tendency of population growth. In the same way, it will be very difficult to stop the growing tendency of material and energy consumption and increasing volumes of harmful emissions and wastes. Natural resources are, however, limited. This also applies to the essential materials needed for production of basic structural components for concrete construction. The urgent need for changes in the design and technology of concrete construction is obvious.

The **Sustainable Construction** approach represents such a way of construction which respects all basic criterions of sustainable development. Development of construction materials, structures and technologies of construction should be 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. Three significant environmental results of **reduction of material consumption** for construction can be recognised: (i) savings in natural resources, (ii) reduction of embodied environmental impacts (e.g. embodied CO_2, embodied SO_2, etc.) and (iii) reduction of the volume of waste material at the end of the life cycle of the structure. The undisputed influence of these parameters on the **level and quality of environmental impacts** of construction within the entire life cycle is evident.

Structural Safety of construction in all its life-cycle stages, including exceptional situations (like exceptional loads during 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.

The reduction of material consumption (leading to more slender structures) and consequently the increase of structural 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 effort to get a higher level of structural safety is the robust structure (with higher volumes of construction materials).

However, there is a good chance to achieve the required reduction of primary material sources and simultaneously the increase of structural reliability and safety by the **optimised shape of the structure** (which uses the structural material in the cross section in a more efficient way) and/or by the use of new **high performance cementitious composite materials**.

The typical result of the shape optimisation of the RC slab with the objective to reduce material consumption (keeping high level of reliability) is a ribbed or waffle slab. Due to its shape, the **reinforced concrete lightened slab** represents one of the effective types of structures given the relation between the material consumption and structural characteristics. Its structural advantages follow from (i) the ribbed nature of the section, (ii) the two-way behaviour (in the case of waffle slab) and (iii) the lower mass. In contrast to the full RC slab, it is possible to achieve up to approx. 50 % savings of concrete mass and, consequently, reduction of load from the self weight acting on the slab itself, as well as on the supporting structures (lower load → smaller dimensions → material savings).

2 Multi-criteria optimization of RC slabs with lightening fillers

The goal of the optimization of a box RC cross-section in environmental context was to reduce the environmental impact by decreasing (a) the consumption of non-renewable raw materials and energy sources, (b) the amount of embodied energy, (c) the embodied emissions (CO_2, SO_x, etc.), and (d) the amount of waste at the end of a structure lifetime.

In performed study 6 alternatives of lightening fillers were considered: (1) concrete hollow core fillers, (2) fibre cement fillers, (3) ceramic hollow fillers, (4) cellular concrete fillers and (5) fillers from recycled non-sorted plastic.

2.1 Utility function

The optimization criteria considered in this study were environmental criteria (embodied CO_2, embodied SO_x and embodied energy) and economical criteria (cost of acquisition).

These criteria were applied in the first phase in mono-criterion optimization of slab cross-section alternatives. In the following phase these criteria represented particular objective functions in multi-criteria optimization model.

The multicriterion optimization problem was transformed into a single-criterion goal function $F(\{x_j\})$ by the use of weighting method:

$$min\ F(\{x_j\}) \tag{1}$$

where

$$F(\{x_j\}) = w \, . \, f(\{x_j\})\ , \tag{2}$$

$w = \{w_i\} = [w_1, w_2, ... w_m]^T$ is a weighting vector,

$f(\{x_j\}) = [F_{1,\,norm}(\{x_j\}), F_{2,\,norm}(\{x_j\}), ... F_{m,\,norm}(\{x_j\})]^T$ is a vector of normalized goal functions,

$\{x_j\}$ is a vector of optimization variables

i is an index for optimization criteria (embodied CO_2 [kg $CO_{2,equiv}$/kg], embodied SO_x [g $SO_{x,equiv}$/kg] and embodied energy [MJ/kg], cost [CZK/m^3]).

2.2 Multi-criteria optimization

The optimization of the profile of box RC cross-section was executed by utilization of an optimization algorithm developed by authors. This algorithm was created in Microsoft Excel and is based on a combination of discrete optimization and mathematical optimization (non-linear optimization code GRG2 – Generalized Reduced Gradient). The individual cross-sections have been optimized according to four optimization criterions – embodied emission CO_2, embodied emission SO_x, embodied energy and cost. The associated weighting vector containing weights for each optimization criterion has been set up by an expert panel method: $\{w_i\} = [0.24, 0.24, 0.12, 0.4]^T$

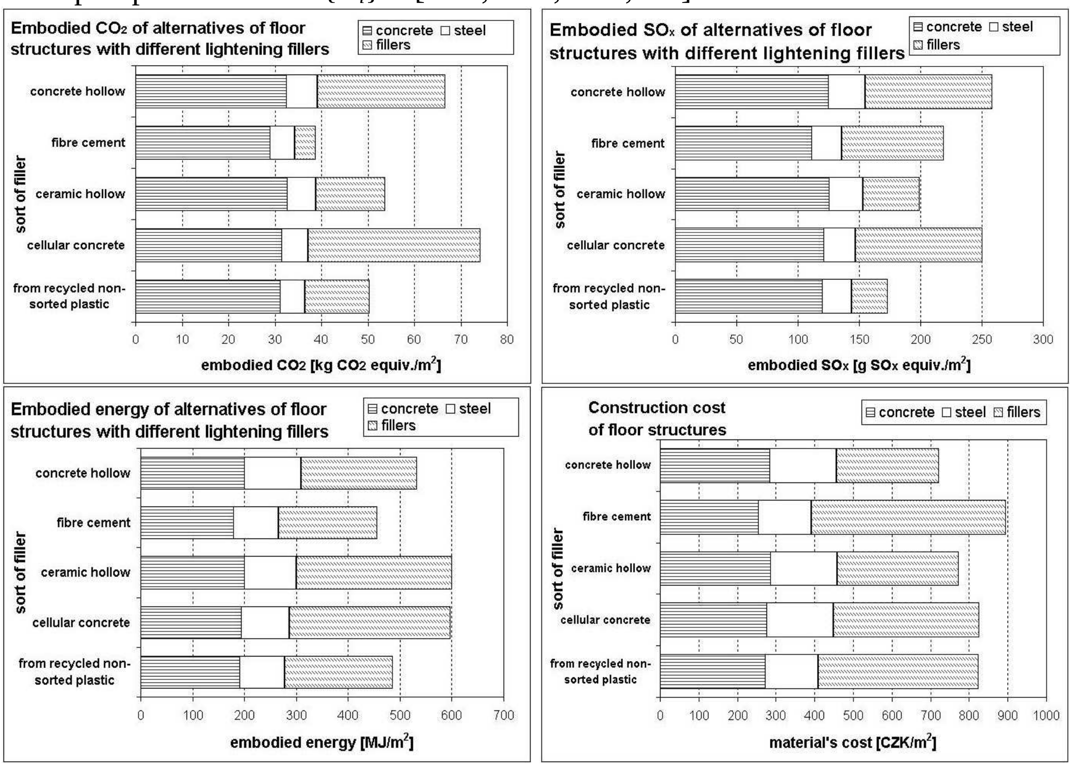

Fig. 1 Results of environmental assessment of optimised alternatives of floor slabs with different types of lightening fillers

Five cross-sections of RC floor slab structures with different types of lightening fillers have been optimized using above described multi-criterion optimization procedure. The graphs on **Fig. 1** show comparisons of slab alternatives considering particular assessment criterions – one after each other. It is evident that in different criterions are different winners. The next graph on **Fig. 2** shows the order of alternatives applying the same set of weights (as used in particular optimizations of slab alternatives). Full RC slab has been used in normalization process as a reference level. It is clear that the final order is influenced by the determination of weights. On the other hand it shows much better the overall multi-criterion quality of evaluated alternatives. The application of sensitivity analysis can help to clarify the reliability of the results.

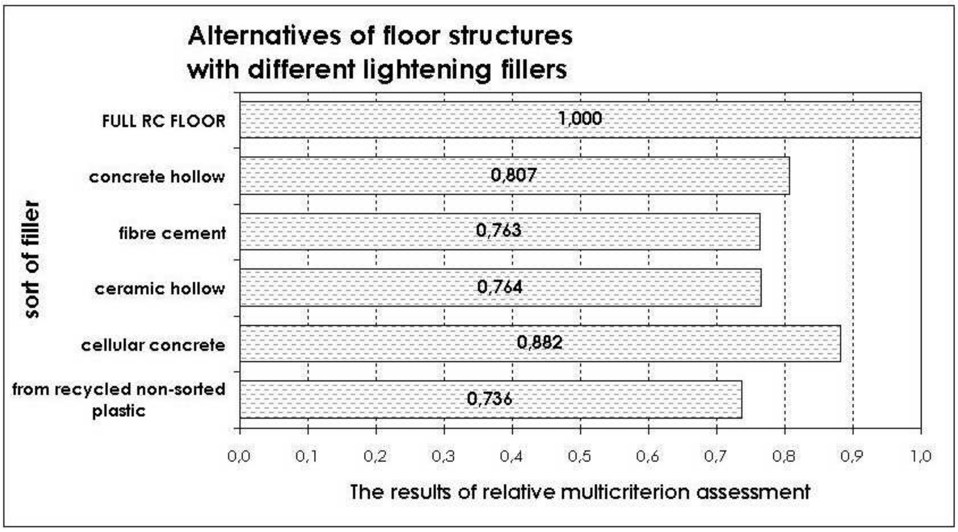

Fig. 2 The results of relative multicriterion assessment. 1,0 = reference level – Full RC slab

3 Application of floors with fillers from recycled waste in construction practice

3.1 Senior Centre in Moravany

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 RC floor structure was changed to a composite RC slab with shell installation fillers from recycled waste plastics from municipal waste (RMWP). This resulted in reduction of concrete consumption up to 0.08 m^3 per m^2, i.e. 34 %. The self weight of the floor structure was reduced by 2.0 kN/m^2. The installation space inside the floor structure was used for the wiring and for the heating system. This brought additional cost savings compared to the originally assumed installation system to be placed in the upper layers – inside the flooring (**Fig. 3**).

3.2 Reconstruction of the two storeys Skoda factory hall

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/m^2. 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, unfavorable. In principle this alternative would represent almost complete demolition of the existing structure. The optimization analysis showed that construction of a new load bearing floor structure dimensioned to the required load and covering the old openings would be a more favorable solution.

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.

The new RC waffle floor slab was placed directly on the existing floor structure (**Fig. 4**). RMWP 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 m^2 of RMWP fillers. The construction was erected between December 2003 and January 2004 without any technological problems.

Fig. 3 Composite RC floor slab with installation fillers from RMWP

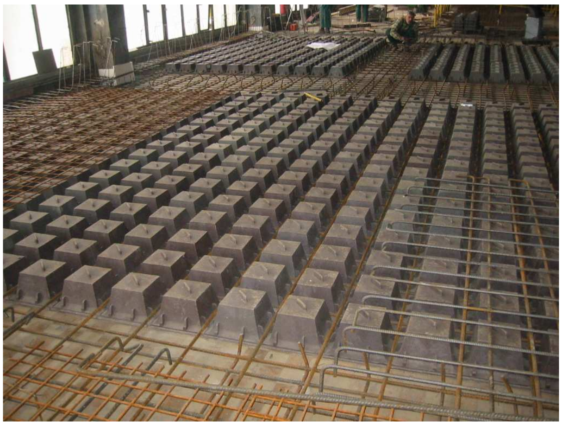

Fig. 4 Reconstruction of Skoda factory hall in Mlada Boleslav – composition of waffle fillers from RMWP on existing floor structure

3.3 Precast floor panels lightened by installation fillers from recycled waste plastic

A new type of an RC precast floor panel with installation fillers from recycled plastic from municipal waste (RMWP) 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, CZ. 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. 5**). The top covering RC slab is 50 mm thick. The panel has two border ribs and three internal ribs 80 mm wide. The internal installation space can be accessed from the top of the panel through installation holes in axial distances 600×580 mm.

In comparison to a full RC slab, the reduction 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.

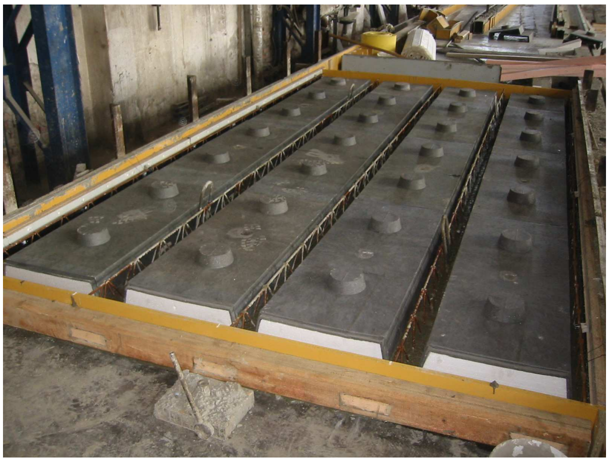

Fig. 5 Precast filigran panel with installation shell elements – during experimental manufacturing

4 Environmental assessment

Some previously performed LCA analyses showed that using recycled materials and the optimized shape of the floor structure it was possible to reduce environmental impacts, such as consumption of non-renewable silicate materials, the resulting level of embodied CO_2, embodied SO_x and embodied energy. Some results of previous LCA analyses have already been presented by Hajek and Wasserbauer (2002) and by Fiala and Hajek (2006).

Tab. 1 Embodied values of 3 alternatives of floor structures with fillers from recycled waste materials, and of 2 reference RC floor slabs

Alternative of floor structure	**Self weight** kg/m^2	**Thickness** m	**Embodied energy** MJ/m^2	**Embodied** $CO_{2,equiv.}$ kg/m^2	**Embodied** $SO_{x,euiv.}$ kg/m^2
two-way floor slab 6 x 6 m					
Waffle RC slab with fillers from recycled waste plastic and gypsum board lower ceiling on timbre frame	341	0,28	481	51	0,22
Reference structure: RC two-way full slab	534	0,22	561	78	0,29
one-way floor slab 4.5 m span					
Composite RC slab with installation fillers from recycled waste plastic	325	0,20	419	50	0,20
Ribbed RC slab with permanent formwork made from boards from recycled laminated drink cartons	244	0,24	380	40	0,17
Reference structure: RC one-way full slab	508	0,21	515	73	0,28

The goal of the current analysis was to show how the use of recycled materials from municipal waste for the formwork of an optimized shape of an RC floor slab can contribute to reduction of environmental impacts. The analysis was performed for structural alternatives of floor structures with fillers from recycled waste described in Chapter 3 and for RC floor structure with fillers from boards from recycled laminated cartons. There were considered two structural cases which differ by the vertical support (one- or two-way slab). The two-way slabs were considered for spans 6×6 m, one-way alternatives were designed for a span 4.5 m. All alternatives were designed for the use in living areas of buildings with an identical live load and a final flat ceiling finish. The overview of all the analyzed alternatives, i.e. three alternatives of RC slabs with lightening fillers from recycled waste materials and two reference structures (RC full slabs), is presented in **Tab. 1**. The same table shows associated values of embodied CO_2, embodied SO_x and embodied energy calculated using a data set based on UCPTE electricity mix (SIA 1995 and Waltjen 1999). The graph in **Fig. 6** shows the resulting relative comparison of the 3 analyzed alternatives of RC slabs with fillers from recycled municipal waste with the reference level represented by a corresponding RC full slab (100 %). The reduction of embodied CO_2 is 32-45 %, the reduction of embodied SO_x 24-40 %, the reduction of embodied energy 15-24 %. The factor of reduction of corresponding environmental impacts varies in the range 1.2-1.8 x.

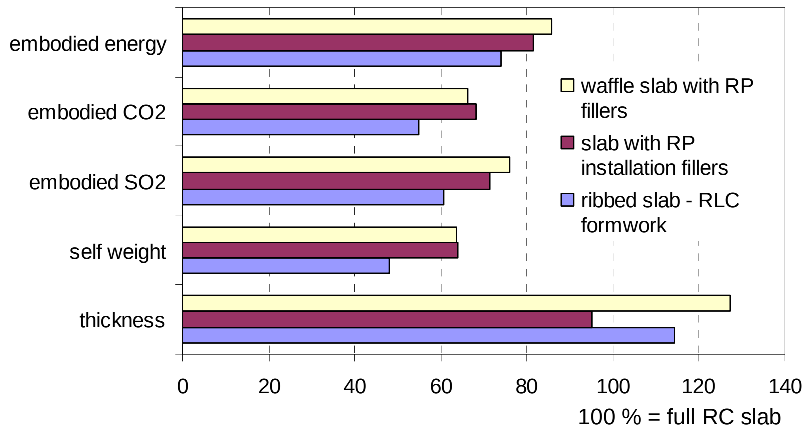

Fig. 6 Relative comparison of embodied values of 3 alternatives of RC floor structures with lightening fillers from recycled MSW (RP = recycled plastic; RLC = recycled boards from laminated carton) with reference level RC full slabs (100 %)

5 Conclusions

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

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 CO_2, embodied SO_2, 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 considered that these impact reductions are associated with material savings in a load bearing system where the main criterion is structural reliability and reduction of the use of structural materials is thus limited by safety reasons.

Nevertheless, there is a big potential for the use of high performance silicate materials (UHPC, HPFRC etc.) to form ultra thin shell (ribbed, waffle, etc.) structures with higher 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. Preliminary studies made by 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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