The Comparative Study of Lightweight Slab Solutions in Terms of Construction Cost

Renata Bašková, Mária Kozlovská, Alena Tažiková and Zuzana Struková

Institute of Construction Technology and Management, Faculty of Civil Engineering, Technical University of Košice, Vysokoškolská 4, 042 00 Košice, Slovakia.

Orcid: 0000-0002-0950-5668, 0000-0002-8125-4680, 0000-0001-7801-999X, 0000-0003-3468-9697

Abstract

The current construction market offers many construction methods and solutions. Some of the methods take into consideration numerous factors including use of less energy and material, less time and construction cost, resistance against earthquake and wind, more accuracy and so forth. During the past years there have been many developments in lightweight construction. In new methods, an attempt is made to use the precast components so as increasing execution speed and decreasing construction time. The voided slab construction refers to modern technologies with favourable features from economic, architectural and structural point of view. The aim of the study is focused on comparison of several variants of lightweight slab solutions from construction cost point of view. In the comparative case study, the following lightweight slab solutions are compared: the voided slab system Cobiax, the voided slab system U – Boot Beton®, the voided slab system Quad – Deck, the monolithic beam slab and the Spiroll slab. Based on multi-criteria optimization problem, an optimal variant of the slab solution is determined. Moreover, the goal of the study was aimed at confirmation or disproof of the widely presented reduction of construction cost through lightweight slab construction.

Keywords: lightweight construction, lightweight slab, voided slab system, Cobiax, U-Boot Beton®, Quad-Deck

INTRODUCTION

The construction industry is one from permanently advancing and rapidly evolving sectors. Therefore, high demands on construction process in case of new buildings as well as refurbishments are typical for the branch. The refurbishments of buildings are usually limited by characteristics of built-in material. However, in newly built constructions, the use of new modern technologies is more relevant. The modern technologies and the new construction methods offer various benefits, such as reduction of material and hence weight of structure reducing, less environmental impact through reduction of CO2 emissions, reduction of construction time, reduction of construction cost etc. One from possibilities to reach the mentioned benefits consists in application of lightweight construction. The aim of the study presented in the paper rest in exploration of benefits of the modern lightweight constructions that have been long term declared by various producers. It was done through case study of a real construction project in Slovakia. The study focused especially on reduction of construction cost as one from the most emphasized benefits.

In the past, the lightening of the slabs has been realized, for example, by inserting voided elements into slabs. The building of Pantheon in Roma, built in the year 125 AD, belongs to first references of lightweight slab structures. The building is one from the most significant examples in history. The slabs were not reinforced and voided elements were used to lighten the structures. Several research studies presented in literature have focused on lightweight constructions. For example, W.K. Hatt in the U.S. in 1907 performed experiments on one-directionally reinforced lightweight slab structures. Similarly, the American project Ida B. Wells Homes, constructed from 1939 to 1941, is among other things known for lightweight slabs construction [1]. From recent research studies dealing with lightweight construction, the studies of [2, 3] are truly rewarding. They made the analysis of geometric shapes of bodies suitable for slab structures lightening. The numerical simulations through non-linear finite element method were applied to derive the optimal shapes of hollow spheres (Fig. 1).
The invention of the hollow slabs, also known as biaxial voided slabs, was in 1950s [4].

The lightweight construction systems applied in Europe, the U.S.A. and in Japan have acknowledged reduction of slab weight by 25 – 30 %. Mota, M. [1] has indicated the advantages and disadvantages of lightweight slabs through real construction projects. The advantages involve mainly longer spans between columns, increase of clear floor height, less consumption of material, reduction of construction time, improved construction safety. Generally, the buildings with recycled material in lightweight slabs are characterized by lower carbon emissions and have more potential to reach credits in environmental assessment systems, such as for example the Leadership in Energy and Environmental Design (LEED). Several research studies on reinforced concrete slabs have focused on development of hollow plane slabs with properties and benefits comparable to traditional monolithic structures but with significantly reduced weight [4 - 6]. The modern architecture is increasingly known by excessive requirements on enhanced spans and on flat ceilings without any projections. This may be achieved by application of the modern lightweight slab structures.

The best known lightweight slab systems include Cobiax biaxial voided slab system and BubbleDeck slab. The several research studies [7 - 11], were aimed at advantages and disadvantages of the system BubbleDeck. Compared to traditional monolithic concrete slabs, the BubbleDeck slab system declares 40% larger area of slab structure and 15% reduction of construction cost while using the same amount of steel and concrete. Moreover, the BubbleDeck system indicates 33% less concrete usage and 30% reduction of construction cost for the same area of roof structure. The research studies focused on lightweight construction system BubbleDeck concluded that hollow elements of slabs do not make any strength reduction of slab structures. Moreover, based on the results of the studies, the shear strength is higher compared to expectations. This comes from positive shape of ball elements, applied to reduce the weight of slab structures. In practice, the ball shape of weight-reducing elements affects positively the concreting process as the effect is similar to application of plasticizing admixtures. Many test, statements and practical experiences have confirmed the BubbleDeck lightweight slab structure works as a traditional monolithic concrete slab and is therefore governed by the same rules [12]. Its application points to significant savings in labour, material and cost.

**MATERIALS AND METHODS**

The aim of the presented study is focused on comparison of selected lightweight slab systems most widely used in Slovakia. The comparison is made in terms of demands on construction cost, material resources and labour force. These construction systems were examined: Cobiax, U – Boot, Quad – Deck, a beam-based monolithic slab and a slab made of prestressed Spiroll panels. The mentioned lightweight slab systems were compared on the basis of a case study of construction project “Wastewater Treatment Plant in Trebišov – SO 102 – Building of Mechanical Pre-cleaning”. The construction cost is determined on the basis of special budget indicators provided by Cenkros Plus – software for construction costing. Moreover, based on two-criteria optimisation analysis, an optimal variant of the lightweight slab structure is selected. The weighted point evaluation method is applied. The demands on construction cost reduction and reduction of slab structure weight are considered as the most important. The results are presented in graphical and tabular way.

**The characteristic of the construction project “Wastewater Treatment Plant in Trebišov”**

The different variants of lightweight slab structures were compared through the case study of the construction project “Wastewater Treatment Plant in Trebišov – SO 102 – Building of Mechanical Pre-cleaning”. Pre-cleaning of inflowing wastewater and its pumping into following process is made in the building. A floor plan of the building is presented in Fig. 2. The orange-coloured part of the slab represents the base for comparison of different variants of lightweight slab structures.

<table>
<thead>
<tr>
<th>Shape</th>
<th>Solid</th>
<th>Sphere</th>
<th>Mushroom</th>
<th>Ellipse</th>
<th>Rect Donuts (D=50mm)</th>
<th>Rect Donuts (D=30mm)</th>
<th>Round Rect (R=70mm)</th>
<th>Round Rect (R=50mm)</th>
<th>Square</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume (cm³)</td>
<td>1436</td>
<td>5625</td>
<td>6300</td>
<td>7380</td>
<td>1355</td>
<td>1055</td>
<td>8910</td>
<td>10125</td>
<td></td>
</tr>
<tr>
<td>Diameter (cm)</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Height (cm)</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Weight reduction (%)</td>
<td>0%</td>
<td>20%</td>
<td>25%</td>
<td>28%</td>
<td>32.8%</td>
<td>34%</td>
<td>34.6%</td>
<td>39.6%</td>
<td>45%</td>
</tr>
</tbody>
</table>

*Figure 1: The properties of hollow spheres [2]*
The characteristic of the variants of lightweight slabs in terms of design and technology

When designing any concrete slab structures that may be monolithic, prefabricated or semi-prefabricated, one-way, two-dimensionally and multi-directionally reinforced or prestressed, the advantages and disadvantages of different variants are usually considered. The shape variability and biaxial rigidity belong to benefits of monolithic slab structures. On the other hand, the prefabricated slab structures make it possible to reduce labour intensity and thus construction time, eliminate wet processes with technological breaks and minimize or exclude the use of formwork. The concrete monolithic, semi-prefabricated and prefabricated slab structures may be designed in a variety of form and technology designs. In the case study, the following variants of the concrete slab structures were compared:

1. the voided slab system Cobiax
2. the voided slab system Quad – Deck
3. the voided slab system U – Boot Beton®
4. the monolithic concrete beam slab
5. the Spiroll slab

The voided slab system Cobiax consists in realization of special hollows in a slab to reduce the amount of concrete that is not inevitable in terms of statics. The hollows are achieved by the hollow ball components Cobiax, placed between top and bottom concrete slab. The weight of the slab is reduced by 35% through application of the components. The voided slab system Cobiax is suitable for slabs of larger dimensions and slabs with emphasized esthetical requirements on surfaces in terms of architecture [13]. There are two main methods to realize the Cobiax slab; as a monolithic concrete structure or as a prefabricated concrete slab. In case of the monolithic concrete slab, the Cobiax components are placed on lower reinforcement elements and upper reinforcement elements are putted directly on the ball components. Thus, the distance between upper and lower reinforcement of the slab is limited by dimensions of the Cobiax components. To ensure the stable positions of the ball Cobiax components, the concreting is recommended in two layers. In case of one layer concreting, the position of the components must be ensured by a special arrangement. In case of prefabricated slab, the Cobiax components are integrated into prefabricated slab panels manufactured in a factory or are placed on prefabricated slab components directly at the site to realize a semi-prefabricated concrete slab. To ensure the stable...
position of the Cobiax components, the upper reinforcement is connected with the lower one through special S-hooks. The top monolithic concrete coat may be performed in an only layer.

The depth of the monolithic concrete slab is designed under the empirical formula: 1/35 Lx, Ly, considering the slab span and it is 500 mm. Thus, the height of the Cobiax elements is 360 mm (height of the elements together with prefabricated reinforcement is 366 mm).

The voided slab system Quad-Deck rests in weight reduction through Plastbau technology. The technology enables creation of high-insulating and energy effective slab structures. The voided slab system is based on the expanded polystyrene panels that are supported and reinforced with two integral steel beams moulded into the product from end to end [14]. The result is a self-supporting joist and deck forming system that provides the maximum strength of a reinforced concrete deck with a minimum of materials and labour. The Quad-Deck panels are available in several thicknesses to allow varying spans and loads of the one-way concrete slabs. Each panel is reinforced with two continuous, galvanized steel, Z-shaped furring strips.

Reinforced concrete joists are spaced at 610 mm on centre and poured monolithically with the slab to form a T-Beam reinforced concrete structure. Because of the support provided by the reinforced concrete joists every 610 mm, a much thinner slab section is required. This results in around 40% concrete savings and therefore eliminates around 40% of the mass of the floor or roof.

The depth of the voided slab structure is 445 mm while the depth of upper concrete slab is 127 mm in the presented case study.

The voided slab system U – Boot Beton® is based on recycled polypropylene formwork elements that were designed to create two-way voided slabs and rafts. The U-Boot Beton® formworks are positioned using the lateral spacer joints to place them at the desired centre distance that will determine the beam width. The construction method is used to create slabs with large span or that are able to support large loads without beams [15]. The dimensions of U-Boot Beton® elements are 520 x 520 mm and are produced with different heights from 100 to 280 mm (single elements) and from 200 to 560 mm (double element). The most significant economic, practical and operational advantages provided with U-Boot Beton® for the entire structure include less use of reinforcement in slabs, columns and foundation up to a total of 15%, less concrete usage, reduced building weight, the architectural freedom of the structure and possibility of slimmer columns and foundations and thus lower cost related to excavation for foundations.

In the presented comparative case study, the depth of the monolithic concrete slab is 500 mm and based on this the height of double formworks is 360 mm with 70 mm high foots.

The monolithic concrete beam slab consists of beams framing into columns and supporting slabs spanning between the beams. It is a very traditional system. The relatively deep beams provide a stiff floor capable of long spans and able to resist lateral loads. However, the complications of beam formwork, co-ordination of services, and overall depth of floor have led to a decrease in the popularity of this type of floor [16].

The designed distance between beams is 3,000 mm in the presented case study. The width of each beam is 350 mm and the depth of the slab is 900 mm (depth of the slab between beams is 150 mm).

The Spiroll slab is based on lightweight voided concrete sections that are designed to meet the span-load requirements while providing extremely efficient sections with concrete material and weight savings reaching up to 45% [17]. It is also known as pre-stressed hollow-core slabs. The Spiroll hollow-core slabs are up to 30% lighter than equivalent in-situ floor. The thickness of the Spiroll slabs may be from 160 mm to 400 mm and the width of each hollow-core slab is 1,200 mm. The thickness of the prefabricated slabs designed in the presented case study is 250 mm.

The mentioned variants of slabs were designed according to standard STN EN 1992-1-1 (73 1201) Eurocode 2: Design of concrete structures. An identical span and an identical load were considered in all the variants. The concrete C20/25 is designed in the variant of Spiroll slab and the concrete C 30/37 is intended in other four variants. The labour crew consists of six workers for installation of temporary supporting structures including formwork, six workers for execution of reinforcement, installation of hollow elements and concrete casting and four workers for formwork removing. To compare the construction time of all the variants, the number of workers is the same in all of them. The economical profit is determined at the level of 15% from total cost of wages, cost of construction machines, taxes and overheads. The factory overhead is 47% and the administrative overhead expenses are 13% from total cost of taxes and wages. The demands on base material, machines, workers and costs were determined in the study.

RESULTS AND DISCUSSION

The labour cost, cost of machines and cost of machines operation are involved in particular construction processes included in execution of the different slab variants. The budget cost that are structured and determined on the basis of construction cost equation established in Slovakia are presented in Table 1. The cost of the base material represents the highest entry in all the slab variants.
Table 1: The budget cost of the slab construction – the variants

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobiax</td>
<td>16,952</td>
<td>13,294</td>
<td>1,379</td>
<td>485</td>
<td>199</td>
<td>1,118</td>
<td>477</td>
</tr>
<tr>
<td>Quad-Deck</td>
<td>18,163</td>
<td>13,354</td>
<td>1,636</td>
<td>576</td>
<td>643</td>
<td>1,327</td>
<td>627</td>
</tr>
<tr>
<td>U-Boot Beton®</td>
<td>14,943</td>
<td>10,992</td>
<td>1,469</td>
<td>517</td>
<td>259</td>
<td>1,191</td>
<td>515</td>
</tr>
<tr>
<td>The beam slab</td>
<td>11,745</td>
<td>5,534</td>
<td>2,368</td>
<td>833</td>
<td>279</td>
<td>1,921</td>
<td>810</td>
</tr>
<tr>
<td>Spiroll slab</td>
<td>5,783</td>
<td>5,452</td>
<td>71</td>
<td>23</td>
<td>136</td>
<td>58</td>
<td>43</td>
</tr>
</tbody>
</table>

The graphical expression of the total construction cost of different variants of lightweight slab construction (Fig. 3).

![Graph of slab constructions costs](image)

**Figure 3:** The total construction cost

As it was mentioned, the cost of material represents the largest part of the total construction cost. It is presented in Fig. 4. When comparing the variants of voided lightweight slab construction, a markedly expensive construction material is evident in Cobiax, Quad-deck and U-boot Beton®. This is reflected in total construction cost of slab construction.

![Graph of material costs](image)

**Figure 4:** The cost of material
Because of the biggest labour demands of the beam slab (variant iv), the variant is characterized by the highest cost of wages (Table 1 & Fig. 5). Based on the results of the study, it can be concluded that the construction cost of the Spiroll slab is by far the lowest compared to other variants of lightweight voided slab constructions.

For each of the variant, the economical profit is determined at the level of 15% from total cost of wages, cost of construction machines, taxes and overheads. The factory overhead is 47% and the administrative overhead expenses are 13% from total cost of taxes and wages. The total construction cost is influenced mainly by the span of the slab – 16,000 x 11,100 mm – and involves the cost of material, machines, wages, taxes, overhead and profit (Fig. 5).

To assess the selected characteristics of the studied lightweight slab constructions (weight and cost) the cardinal scale was defined: the weight and the cost are estimated per 1m² of the slab area without floor layers and ceiling construction (weight in t/m² and cost in EUR/m²). The selection of an optimal variant of the lightweight slab was made based on one from multi-criteria optimisation method – weighted point evaluation method. The optimization weights of the studied parameters are the following: the construction cost – 68 % and the weight of the structure – 32%. The construction costs and the structure weights of lightweight construction variants determined in the case study, where the span of the slab is 16,000 x 11,100 mm, are presented in Table 2.

The preference ranking of the variants of lightweight slab construction based on the weight and the construction cost determined through two-criterion optimization problem:

1. The Spiroll slab
2. The monolithic concrete beam slab
3. The voided slab system U-Boot Beton®
4. The voided slab system Quad-Deck
5. The voided slab system Cobiax

<table>
<thead>
<tr>
<th>The slab construction</th>
<th>Construction Cost (68%)</th>
<th>Structural weight (32%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Preference order</td>
<td>EUR/m²</td>
</tr>
<tr>
<td>Cobiax</td>
<td>4</td>
<td>95.46</td>
</tr>
<tr>
<td>Quad – Deck</td>
<td>5</td>
<td>102.27</td>
</tr>
<tr>
<td>U – Boot Beton®</td>
<td>3</td>
<td>83.26</td>
</tr>
<tr>
<td>The beam slab</td>
<td>2</td>
<td>66.15</td>
</tr>
<tr>
<td>The Spiroll slab</td>
<td>1</td>
<td>32.44</td>
</tr>
</tbody>
</table>

The graphical presentation of the results of comparative study in terms of the construction cost and the structural weight determined for 1 m² of the slab area is in the Fig. 6. The left vertical axis represents the construction cost in EUR/m² while the right vertical axis represents the construction cost in t/m².
The top horizontal axis represents the scale for the standard importance weight of assessment criterion “minimal structural weight of the slab” and the lower axis represents the scale for the standard importance weight of assessment criterion “minimal construction cost of slab”.

Based on the two-criterion optimisation problem, the optimisation of the problem solution on change in optimising criteria weights is evident. The rank order of the studied variants varies with the change in criteria weights. For example, if the weight of “construction cost” criterion is 70% and the weight of “structural weight” criterion is 30%, the preference ranking of the variants is different compared to opposite weights arrangement. Even if, in the presented case study, the Spiroll slab from both sides - construction cost and structural weight. But for example, the voided slab system Quad-Deck would be an optimal solution if the weight of “structural weight” criterion was more than 85%.

CONCLUSION

The purpose of the broad case study, the partial results of which are presented in the paper, is focused on modelling and comparison of the variants of lightweight slab construction in terms of structural weight, cost of material and labour resources as well as in term of the total construction cost. The study results related to comparison of construction cost of innovative lightweight slab systems versus traditional lightweight slabs as the beam slab and Spiroll slab are much useful in construction practice. It can be concluded that the modern voided slab systems are suitable mainly for specific cases of construction projects where construction cost is not decisive or traditional solution may not be used. The modern lightweight slab solutions use recycled material and are characterized by less CO2 emissions mainly due to less concrete usage. This can guarantee better assessment of a building in environmental assessment procedures. The analysis from construction cost and structural weight point of view could be performed in each of intended construction projects. Based on the analysis, the real construction cost of lightweight slab solutions could be determined. As the cost of material inevitable to construct the modern voided slab system is in Slovakia relatively high, the widely presented benefit of lightweight slab solutions related to construction cost reducing cannot be entirely confirmed.

ACKNOWLEDGEMENTS

The article presents a partial research result of the project KEGA - 031TUKE-4/2015 "Use of interdisciplinary knowledge for new programs aimed at improving the investment activities in transport infrastructure projects".

REFERENCES


