New perspective material for building envelopes

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Abstract. Thin-walled fibre-cement elements are widely used in residential and industrial buildings for their appearance and durability. Because they are made of light-weight materials, they are mostly used as cladding elements for façades of multi-storey buildings exposed to hard external conditions. Nevertheless, there are still demands from architects and building companies to decrease their weight for reducing manufacturing, transport and assembly costs. In one part of our research light-weighing possibilities of standard composition were evaluated by means of porous structure creation. In the second part the standard aggregate was substituted with available kinds of light-weight porous aggregates in a certain part or in a whole volume. As the limit criterion there was maximal particle size 1 mm for spraying of fibre-cement mixture by means of special air pressure equipment. From the range of possible fillers with different material properties granulated expanded glass worked the best. This paper brings not only a summary of laboratory experiments but also examples of successful realizations such as balcony panelboards, façade elements, bridge structure cladding elements or bulk flower pots. Even though these are not structural elements, it was necessary to evaluate also strength characteristics and resistance to environment for their durability in certain applications.

1. Introduction

Owing to the use of various kinds of air-entraining agents or light-weight fillers one can reduce the weight also of fibre-cement composites [1]. Mostly used light-weighing material is perlite [2]. The thin-walled elements with a matrix based on the high-value Portland cement with dispersed reinforcement in the form of alkali-resistant glass fibres are used in a range of applications such as large-sized cladding elements, architectural façade elements, the architectural elements of the urban equipment, balcony panelboards or light-weight walls. Thanks to its durability, low basic weight, colouring ability and shape diversity, glass fibre reinforced concrete may properly replace natural materials [3].

The effect of the use of various air-entraining agents or light-weight fillers on the fibre-cement composites was verified by means of the laboratory tests. Their practical applicability was examined in practice in regard of some elements made of the commonly manufactured glass-fibre-reinforced concrete (GFRC) e.g., channels for deposition of high voltage cables in the Prague Underground, manifold architectural element embedded in the urban space, especially various cladding elements.

The aim of our research was to decrease the total weight of the selected building materials and therefore to eliminate the necessity of using heavy machinery during their manufacturing process and further implementation. The light-weight should be achieved by means of lowering the bulk density and preserving the same dimensions of the used products.

Required bulk density corresponds to the decrease in weight amounting to ca. 25%, i.e. to the value of 1,600 kg/m³ compared to the initial bulk density 2,050 kg/m³ of the standard GFRC elements.
2. The possibilities of decreasing the weight of the cement composites

Within a preparation of these fibre-cement composites an exact amount of alkali-resistant glass fibres with length of 12 mm is added into fine-grained matrix consisting of cement, aggregate and admixtures in the last stage of a mixing process and in this way properly dispersed in the whole volume of the mixture. This technology requires the use of highly flowable mixtures free from bleeding and sedimentation of heavier mixture components [4].

By means of various kinds of light-weight aggregates [5] or air-entraining agents it is possible to decrease the weight of the thin-walled fibre-cement composite elements.

In the first part of our research the possibilities of decreasing the weight of the standard composition were evaluated by means of the creation of a porous structure. In the second part, the standard aggregate was substituted – in a certain part or in a whole volume – with the available kinds of light-weight porous fillers. From the range of possible fillers having different material properties, granulated expanded glass turned out to be the most suitable for the proper weight achievement.

Special air pressure equipment was used and maximum particle size 1 mm for spraying of fibre-cement mixture was applied as the limit criterion.

Several compositions were designed by means of the standard mixture modification and substitution of commonly used fine-grained silica sand. Decreasing of the bulk density of the final cement composite was proved, when the filler of distinctive lower density was compared to the standard silica sand.

3. Fibre-cement concrete mixture components

Fibre-cement composite consists of approximately 53% binder, 40% filler, 3% fine filler, 3% fibre reinforcement, 1% plasticizer (in weight percents). Several types of filler in different fractions were used to substitute 50 to 100% vol. of silica sand in the initial matrix according to their bulk density [6]. As an exception to the rule, there were so called microspheres that are very specific in their shape. Even a small addition to the mixture caused the increase of fresh concrete mass up to 2 times of its volume. As suitable amount of these micro-balls was approximately 3–4% of the filler weight.

For decreasing the weight of the fibre-cement the following composites were used:

- Hollow polymer microspheres
- Ceramic aggregate
- Expanded vermiculite
- Air-entraining agent

4. Technologies for GFRC production

The aim of all the laboratory experiments was to design a modified fibre-cement mixture suitable for the production in the premix technology, which is used in a production department of the Research Institute for Building Materials in Brno.

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The designed composition for premix is as follows:

- Portland cement CEM I 52.5 40–60%
- Fine-grained aggregate 30–50%
- Fine admixtures 0–10%
- Super-plasticizer 0–5%
- Alkali-resistant glass fibres 1–5%
- Water/cement ratio (–) 0.3–0.5

Due to the cooperation with the company DAKO Brno, Ltd. it was necessary to prepare the compositions for the spraying technology. It means that a continual glass fibre roving is chopped
into individual fibres having 35 mm length and incorporated into a sprayed cement-sand wet mixture. The key parameter for passing through a nozzle of the spraying equipment is maximal particle size only 1 mm, therefore only suitable fillers with fractions lower than the limit could be used.

The standard composition consists of these materials:

- Portland cement CEM I 52.5 40–60%
- Fine-grained aggregate 40–60%
- Plasticizer 0–5%
- Alkali-resistant glass fibres 1–10%
- Water/cement ratio (–) 0.3–0.5

5. Evaluation of the technological properties of the fibre-cement composites

Basic physical-mechanical properties of the fibre-cement composites were evaluated on test standard specimens (250 × 50 × 10 mm) prepared with the premix technology after 28 days of curing in water. Firstly, bulk density, followed with absorbptivity, flexural strength and impact resistance were evaluated for various compositions (see Table 1).

Bulk density and strength of the composites were determined in relation to each other. The better is the first one the poorer is the second one and vice versa. It is evident with flexural strength values, which are influenced by not only low strength of individual particles of the light-weight component, but also by higher level of water/cement ratio in the range of 0.32 to 0.56, which is needed for highly flowable and workable mixtures.

| Composition          | Bulk density (kg/m³) | Flexural strength (MPa) | Absorptivity (%) | Impact resistance (kJ/m²) |
|----------------------|----------------------|-------------------------|------------------|--------------------------|
| Standard             | 2,050                | 11.0                    | < 10.0           | 7.0                      |
| Microspheres         | 1,430                | 7.5                     | 15.0             | 7.0                      |
| Ceramic aggregate    | 1,650                | 10.5                    | 13.0             | 5.0                      |
| Vermiculite 75       | 1,620                | 10.0                    | 14.0             | 5.0                      |
| Vermiculite 100      | 1,500                | 11.0                    | 17.0             | 6.0                      |
| Air-entraining agent | 1,760                | 9.0                     | 13.0             | 7.5                      |

6. Evaluation in production conditions

The next step was a verification of the parameters from laboratory in real production conditions. It was conducted in cooperation with the company DAKO Brno, Ltd. as three-stage gradual process of the production of the standard GFRC elements [7], [8].

6.1. First stage

For the first stage two compositions of light-weighed fibre-cement composite were selected for the evaluation in the real production conditions. The first composition was designed with the addition of the hollow polymer microspheres and the second one with the air-entraining agent. Three thin-walled balcony panelboards were casted whose dimensions were 1000 × 900 × 20 mm. For impact resistance improvement two balcony panelboards were reinforced with PVA mesh put in the most exposed part; the last panelboard was reinforced with glass fabric. Impact resistance of the completed balcony panelboards, was examined in the Technical and Test Institute for Construction in Prague, Branch Brno, according to the legal standards applicable in the Czech Republic.
Table 2. Properties of light-weight compositions – first stage.

| Composition          | Bulk density (kg/m³) | Flexural strength (MPa) | Absorptivity (%) | Impact resistance (kJ/m²) |
|----------------------|----------------------|-------------------------|------------------|--------------------------|
| Standard             | 2,050                | 11.0                    | < 10.0           | 7.0                      |
| Microspheres         | 1,460                | 6.0                     | 15.0             | 4.5                      |
| Air-entraining agent | 1,620                | 11.0                    | 11.0             | 4.5                      |

After the conducted tests it could be concluded that all the light-weight balcony panelboards assembled into a metal peripheral frame, corresponding to a real balcony construction, fulfilled the required lack of failure and/or any visible cracks on the panel board surfaces at the impact energy of 150 J.

6.2. Second stage

In the next stage the compositions with the addition of ceramic aggregate, expanded vermiculite and again with the air-entraining agent were evaluated in the production of the fibre-cement composites. For the evaluation of the both technologies, i.e. premix and spraying, several planar balcony panelboards reinforced with meshes, façade cladding elements and shaped bridge structure cladding elements were prepared for the comparison. The comparison was done for each variant of the weight-decreasing procedure/composition and regarded its advantages and disadvantages during the production and in the real-world application.

Table 3. Properties of light-weight compositions – second stage.

| Composition          | Bulk density (kg/m³) | Flexural strength (MPa) | Absorptivity (%) | Impact resistance (kJ/m²) |
|----------------------|----------------------|-------------------------|------------------|--------------------------|
| Standard             | 2,050                | 11.0                    | < 10.0           | 7.0                      |
| Ceramic aggregate    | 1,290                | 6.5                     | 15.0             | 5.0                      |
| Vermiculite 100      | 1,550                | 10.5                    | 17.5             | 7.5                      |
| Air-entraining agent | 1,570                | 8.0                     | 9.0              | 6.5                      |
| Vermiculite 75 – spraying | 1,630            | 17.5                    | 19.5             | 18.0                     |
| Air-entraining agent – spraying | 1,850      | 18.5                    | 13.5             | 19.0                     |

Selected balcony panelboards were evaluated for the resistance to impact loading in the Technical and Test Institute for Construction in Prague, Branch Brno (TTIC) in the same way as the previous variants. The casted bridge structure cladding elements made of air-void fibre-cement composite were examined in the laboratory at the Brno University of Technology (BUT) for their resistance to wind loading. Façade panels made of both compositions by means of the spraying technology were subjected to durability examinations in a specially designed equipment simulating real weather conditions during a longer period of time (whole year), which included repeated exposition to water sprinkling, sun radiation and frost and defrost. The device was built in the testing laboratories of the Research Institute for Building Materials (RIBM). The results of the examination were positive.

6.3. Third stage

In the third stage of evaluation we carried out the optimization of the composition with vermiculite for better workability achievement, and, on the other hand, the optimization of the composition with the air-entraining agent – in that case to achieve lower bulk density.
Again, both technologies were used for the production of balcony panelboards, façade cladding elements, bridge cladding elements and a bulk flower pot as well. Despite the fact that the variant using the air-entraining agent was not successful because of the aerating effect was lost during the process of spraying, the weight of the elements with vermiculite was approximately 20% lower in comparison to the standard fibre-cement elements.

### Table 4. Properties of light-weight compositions – third stage.

| Composition                  | Bulk density (kg/m³) | Flexural strength (MPa) | Absorptivity (%) | Impact resistance (kJ/m²) |
|------------------------------|----------------------|-------------------------|------------------|--------------------------|
| Standard                     | 2,050                | 11.0                    | < 10.0           | 7.0                      |
| Vermiculite                  | 1,485                | 10.2                    | 16.2             | 5.6                      |
| Air-entraining agent         | 1,722                | 8.4                     | 11.9             | 5.6                      |
| Vermiculite – spraying       | 1,566                | 11.8                    | 17.3             | 14.8                     |
| Air-entraining agent – spraying | 1,886               | 12.7                    | 12.1             | 12.9                     |

At this stage of production several products were chosen for the further experiments. The casted balcony panelboard with vermiculite was examined in TTIC for the impact resistance. The very promising bridge cladding element with vermiculite was examined in the laboratory at BUT for wind resistance. The bulk flower pot served as a prototype for the production in the company DAKO Brno, Ltd. as well as for a small-scale production in RIBM.

Subsequently, the static evaluation of the planar façade panel and the shaped bridge cladding element made of light-weight composition with vermiculite was carried out. All the variants fulfilled the requirements according to the I. as well as the II. ultimate state.

### 7. Granulated expanded glass

Granulated expanded glass is a new perspective material for achieving distinctive lower weight for a range of applications, e.g. [9]. In the Research Institute for Building Materials it was, among others, used as a material suitable for absorbing blast energy [10], [11].

In the next stage of our research we assessed the possibilities of decreasing the weight of the materials by means of substitution of 50–100% vol. of silica sand with the granulated expanded glass [12], in different fractions (0.25–0.5 mm, 0.5–1 mm and 1–2 mm). Glass fibre reinforcement was used in amounts 2.0, 2.5 or 3.0% wt. of total dry mixture.

According to our expectations, the decrease in bulk density corresponded to the amount of the used filler. With 50% silica sand substitution we were able to reach only 1,800 kg/m³ bulk density value, but 75% substitution caused substantial weight decrease to the level of 1,600 kg/m³. The substitution of 100% of silica sand with the granulated expanded glass enabled us for the decrease in bulk density even to 1,500 kg/m³.

Achieved flexural strength was in the interval 9–14 MPa. The higher amount of the expanded glass and the lower amount of glass fibres were applied, the lower values of the flexural strength were observed. The range of results varied between 4.5 and 6.5 kJ/m² for the impact resistance and between 10 and 15% for the absorptivity.

According to the results presented in table 5 we can conclude that the granulated expanded glass is the most suitable filler for the required bulk density of the GFRC.
### Table 5. Properties of the cement composites with the weight-decreasing fillers.

| Filler (vol. %)                          | Bulk density (kg/m³) | Flexural strength (MPa) | Absorptivity (%) | Impact resistance (kJ/m²) |
|-----------------------------------------|----------------------|-------------------------|------------------|---------------------------|
| Expanded polymer microspheres 15–25 μm (3.5 a) | 1,434                | 7.57                    | 15.13            | 7.32                      |
| Expanded volcanic glass 0–1 mm (100)   | 1,726                | 13.95                   | 14.65            | 7.43                      |
| Granulated expanded clay 0–2 mm (75)   | 1,650                | 10.75                   | 12.92            | 5.09                      |
| Granulated expanded silica sand 0.6–2.5 mm (100) | 1,694                | 6.42                    | 15.73            | 5.97                      |
| Exfoliated vermiculite 0.25–0.71 mm (100) | 1,501                | 11.12                   | 16.98            | 6.00                      |
| Granulated expanded glass 0.25–0.5 mm (85) | 1,545                | 10.31                   | 13.76            | 5.68                      |

a This filler was added in the amount of 3.5% wt. from the total sand weight without its substitution.

### 7.1. Durability testing of the bridge cladding elements exposed to wind loading

For this evaluation a mixture consisting of 3 fractions of granulated expanded glass (GEG) was used. The final fraction was counted as a weight ratio 33:33:33 of fractions 0.25–0.5, 0.5–1 and 1–2 mm.

Two compositions were designed with different sand substitutions and glass fibre additions. The first mixture marked as GEG I consisted of granulated expanded glass (75% substitution) and of 3.5% fibre content. The second mixture marked as GEG II consisted of granulated expanded glass (80% substitution) and the fibre content was decreased to 2.5% for better workability and fluidity of the fresh mixture [6].

For the sake of homogenization, a mixer with rotating central paddle was used in the same way as in the standard production of the glass-fibre reinforced concrete elements with silica sand.

The same mixtures with the expanded glass filler were adapted for a spraying technology and several cladding elements were made for further testing.

This technology has been successfully verified in the production of the company DAKO Brno, Ltd.

The promising bridge cladding elements were examined in the laboratory at BUT concerning their resistance to wind loading [13].

Tested elements were fixed in the same way as the standard cladding elements to simulate real conditions. One part of each element was fixed to steel profiles whereas the other part was not supported. In real construction the second part serves for covering of installation cables and pipelines. This part works as an overhanging end or rather a cantilever under uniform loading.

The effect of uniform loading caused by wind is simulated by the means of vacuum creation. Each element was fixed in a solid box and covered with transparent plastic foil. Air was sucked out of this space and induced atmospheric pressure had the same effect on the tested element as real uniform loading caused by wind. The setting of the durability test for each of the tested cladding elements is shown in Figure 1.
Figure 1. Setting of durability tests within wind loading.

Two cladding elements lightened with the expanded glass filler were compared to standard cladding elements with silica sand. After the conducted tests it could be concluded that the variant GEG II brought positive results, which is stated in the Table 6.

Table 6. Maximal loading and strain in cross section of individual elements.

| Element No. | Composition | Weight (kg) | Maximal loading $p_u$ (kN/m²) | Maximal strain $\sigma_u$ (MPa) |
|-------------|-------------|-------------|---------------------------------|---------------------------------|
| T1          | Standard    | 58.9        | 10.45                           | 11.48                           |
| T2          | GEG I       | 41.3        | 7.55                            | 10.20                           |
| T3          | GEG II      | 40.7        | 13.45                           | 17.19                           |

8. Conclusions

Both production technologies may allow the manufacturing of the assortment from the glass fibre reinforced concrete: balcony panelboards, cladding elements for façades or bridges and various architectural elements with lower weight.

By the means of using air-entraining agents, and various kinds of light-weight fillers – especially granulated expanded glass – it is possible to decrease bulk density of the fibre-cement composites up to 25%.

The fibre-cement composite with bulk density 1,600 kg/m³ can be therefore obtained, as it was confirmed in the real production conditions. Subsequently, the reduction of transport costs was calculated at ca. 18%, reduction of assembly costs was calculated at ca. 25% and the reduction of material costs for a distinctive lighter superstructure was calculated at ca. 15%.
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