

The development of ultra-lightweight concrete based on foam glass aggregate.

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Abstract. Foam glass is currently a material produced from waste glass that cannot be used in the glass industry. Therefore, it is currently made from secondary raw materials obtained by recycling unusable waste glass. Due to the large proportion of closed pores in the material structure, the foam glass achieves excellent thermal insulation properties and limited water absorption. The porous structure of the glass is relatively regular, and the pores predominantly have a round character; therefore, the foam glass exhibits very good mechanical properties at a low density. Foam glass in the form of aggregate represents an interesting raw material from which it is possible to produce various types of light composites with a very good ratio of thermal insulation and mechanical properties. The contribution describes the results of research in the field of the development of ultra-lightweight aggregate concretes with subsequent use for producing prefabricated thermal insulating masonry elements for the construction of energy efficient buildings.

1. Introduction

Foam glass is a material that was invented in 1930, but it is currently experiencing its renaissance due to its application on the building materials market gradually growing. At the beginning of its creation, foam glass was produced as a cork replacement for military vessels. The glass began to be used in the construction industry around 1960, but due to its high price, it was applied in very small quantities. In the last few years, a high emphasis on waste-free management, recycling, ecology and the environment has created a unique opportunity for this material to break through into construction practice [1, 2].

Foam glass is used in the construction industry in the form of thermal insulation boards or as aggregate (angular and rounded). The production of both forms of the material is very similar. The waste glass is ground into fine flour up to 50 microns, dried and then homogenised together with blowing agents and other additives (most of them are substances reducing the melting point of glass). The prepared raw material mixture is placed either on a belt or in a mould and passed through a tunnel furnace at a temperature of 800 to 900°C, and then either a gradual controlled cooling – the formation of plate foam glass or rapid intensive cooling – the formation of foam glass aggregate [1, 2].

The contribution deals with the use of foam glass aggregate as a lightweight aggregate for producing ultra-lightweight aggregate composites. The objective of the research work performed was to design concrete with the best possible ratio of thermal insulation and mechanical properties, which could be used for mechanically loaded applications, for example, to produce masonry fittings. The design of the element was based on findings obtained within the previous research work [3, 4].



Based on our experience with light-weight concrete, cement class CEM I 42.5R was chosen as a binder. Six test mixtures were designed and mixed to optimise the production formula. The key thermal insulating, physical and mechanical properties were determined on the specimens produced.

The determination of the thermal conductivity in the dependence on humidity was also performed on the selected formula to predict its real behaviour after incorporation into the structure.

Furthermore, the design of the masonry fitting according to standard shapes used to produce the concrete fittings in construction practice was carried out, and the thermal properties according to ČSN EN 1745 were determined.

The properties of the developed concretes were tested in the prototype production of the masonry fittings, i.e. two productions of the prototype fittings were performed, and in both cases, it was necessary to modify the selected formula (No. 1) to produce test specimens. Due to a slightly different way of producing the test specimens in the laboratory and in the manufacturing plant, a higher amount of cement was designed for the formula.

2. Production of test specimens

As part of the research on the developed material, six formulas of ultra-lightweight aggregate concrete with aggregate based on foam glass were designed. The objective was to create a compact cementitious composite that will be characterised primarily by a unique ratio of mechanical and thermal insulation properties. All the prepared mixtures were made to optimise the subsequently produced formula to produce the thermal insulating masonry fittings. The test formulas varied in the amount of cement (the minimum amount was 60 kg/m^3 , and the maximum was 150 kg/m^3), and the use of cellulose fibres from recycled paper and their effect on the resulting composite was monitored for the last formula. The individual formulas are described in the following table.

Table 1. Test formulas of ultra-lightweight aggregate concrete for 1 m^3 .

Entry component		Formula					
		1	2	3	4	5	6
		1 m³					
Cement CEM I 42.5 R	[kg]	150	130	100	80	60	130
Aggregate 4 - 16 mm REFAGLASS	[l]	1000	1000	1000	1000	1000	
Water	[l]	57	52	48	44	40	88
Plasticizing admixture MURAPLAST FK 19	0.8 % from m_c [kg]	1.2	1	0.8	0.64	0.48	1
Fiber recycled paper	7.5 % from m_c [kg]	-	-	-	-	-	9.75
Water-cement ratio	[-]	0.40	0.40	0.48	0.55	0.67	0.68

Two types of test specimens were made from the lightweight aggregate concrete to determine the key properties.

- Cubes 150 x 150 x 150 mm (determination of mechanical and physical-mechanical properties)
- Square specimens 200 x 200 x 35 mm (determination of mechanical and thermal-insulation properties)



Figure 1. Made test samples of ultra-light concrete.



Figure 2. Detail of lightweight concrete surface.

3. Methodology

Several measurements were performed on the specimens produced to determine the required key properties. The measured properties were chosen regarding the subsequent use in practice. Specifically, it was the determination of:

1. The density in a fresh/hardened state (ČSN EN 12350-6, ČSN EN 12390-7) [5, 6],
2. The compressive strength of the concrete (ČSN EN 12390-3) [7],
3. The thermal insulating properties – coefficient of thermal conductivity (ČSN EN 12667, ISO 8301) [8, 9].

3.1. Preparation of the test specimens

To produce the test specimens, moulds provided with a release agent and the necessary raw materials had to be prepared first. Since foam glass is a lightweight aggregate, it is necessary to dose it by volume, i.e. the other raw materials (cement, water and plasticiser) were dosed by weight. The mixture was homogenised in a forced circulation mixer and subsequently placed by means of the vibro-press method into test moulds to produce the test specimens.

4. Results and discussion

4.1 Determination of mechanical properties

A consistency test was carried out on the designed formulas using a cone slump test, and the density in the fresh and hardened state was determined. Finally, the compressive strength was determined 28 days after mixing. The results are summarised in the following table.

Table 2. Overview of values of consistency and mechanical properties, graph of compressive strength.

Formula	Settlement of fresh concrete [mm]	D _{FC} [kg/m ³]	D _{HC} [kg/m ³] (28 days)	Compressive strength f _{c,28} [N/mm ²]
1	0	580	550	1.54
2	0	530	500	1.42
3	0	510	460	1.25
4	0	440	410	1.11
5	0	440	390	0.88
6	0	630	560	1.52

It is apparent from the measured density values that the increase in values occurred with the use of cellulose fibres, and the fibre-free formulas, on the other hand, have lower density values. The lowest value has a formula No. 4 (390 kg/m³), which has only 60 kg of cement and is not fibre reinforced. The difference between the density values in the fresh and hardened state is caused by the loss of mixing water.

Regarding the compressive strength evaluation, the dependence on the density and the amount of cement used is visible. As the amount of cement decreases, the compressive strength decreases relatively linearly. When comparing the formulas with the same amount of cement (Formulas 2 and 6), it can be seen that after the addition of the fibres, the concrete strength slightly increased. This was approximately a 6% strength increase.

4.2 Determination of thermal insulation properties

The characteristic of the lightweight aggregate concrete being developed for use on thermal insulating fittings is the thermal conductivity coefficient. The thermal conductivity was determined by the stationary plate method using a FOX 200 instrument at a temperature gradient of 10 K with a mean temperature of 10°C. The thermal conductivity coefficient λ was determined on specimens of 200 x 200 x 35 mm. The measured values can be seen in the following table.

Table 3. Overview of values of coefficient of thermal conductivity in dried state.

Formula	m [g]	Dimensions [mm]			D [kg/m ³]	σ D [kg/m ³]	λ [W/(m.K)]			$\sigma \lambda$ [W/(m.K)]
		b	l	h						
1	2780.2	299	299	63.37	490.7	500	0.1226	0.1201	0.1193	0.1223
	2848.3	300	300	63.13	501.4		0.1254	0.1237	0.1227	
2	667.3	200	199	35.97	466.1	460	0.1208	0.1207	0.1207	0.1144
	644.2	200	200	35.99	447.6		0.1082	0.1081	0.108	
3	575.2	198	200	36.42	398.9	410	0.1006	0.1004	0.1002	0.1032
	601.9	200	200	36.45	412.9		0.1061	0.1060	0.106	
4	558.6	200	200	36.86	378.9	370	0.1022	0.1020	0.102	0.0994
	528.5	199	199	36.00	370.7		0.0969	0.0967	0.0965	
5	523.9	200	199	35.75	368.2	360	0.0961	0.0959	0.0958	0.0934
	497.9	200	200	36.09	344.9		0.0911	0.0909	0.0908	
6	730.1	200	200	36.42	501.2	510	0.1131	0.1130	0.1130	0.1170
	741.8	200	200	36.10	513.7		0.121	0.1209	0.1209	

In order to simulate the real conditions during the incorporation of the developed material into the structure, the change of the thermal insulation properties were monitored in dependence on various humidity exposures. More specifically, it was a dried state (i.e. 0% moisture), 30% moisture, 50% moisture and 80% moisture. The dependence of the thermal conductivity coefficient on the humidity of the environment was demonstrated on the board specimens of formula No. 6, which was chosen for the best ratio of the thermal insulation and mechanical properties.

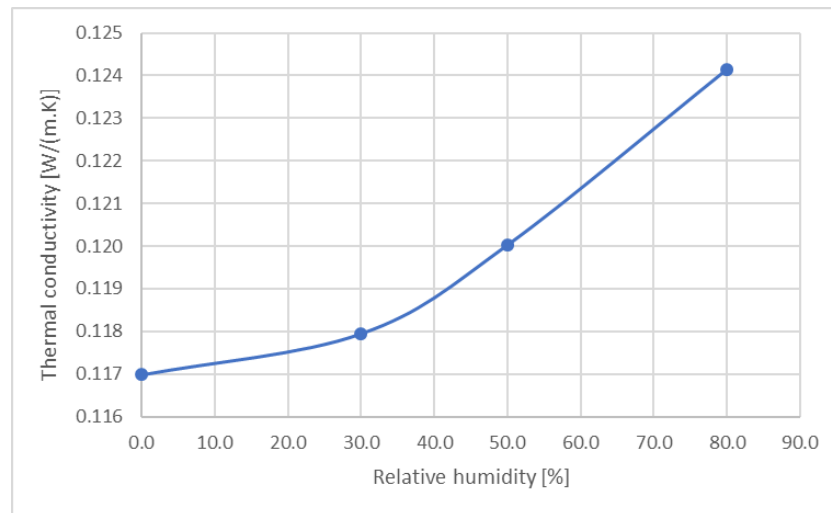


Figure 3. Dependence of the thermal conductivity coefficient on moisture of lightweight aggregate concrete, formula No. 6.

The graphical evaluation shows a noticeable increasing tendency of thermal conductivity with increasing environmental humidity. However, the sorption ability of the material being developed is minimal. For the thermal conductivity of the specimen obtained in an environment with 80% humidity, the thermal conductivity coefficient increased only by 6% compared to the values in the dried state. From the measured results, it is evident that the material is only slightly sensitive to humidity change and still retains very good thermal insulation properties. Use in exterior construction applications seems to be appropriate.

5. Design of masonry blocks

Based on the measured results and the possibility of cooperation with the producer of concrete goods, the design of the masonry fitting was made according to the shapes used to produce the concrete fittings (dense concrete). The design of the masonry fittings was based on formula 1 mixed in the laboratory.

Experimental production of masonry fittings made of lightweight aggregate concrete for masonry thickness of 200 mm was carried out. The production formula had to be optimized for production (and fibers were finally omitted), but it was based on experience and knowledge from previous research results.

Table 4. Optimized production formulas of lightweight concrete for the production of masonry fittings.

Entry component		Formula	
		1	2
		1 m ³	
Cement CEM I 42.5 R	[kg]	148	158
Aggregates 4–16 mm REFLAGLASS	[l]	1000	1000
Water	[l]	90	90
Plasticizing admixture REBAMIX 606	0.8 % from m _c [kg]	1.2	1.2
Water-cement ratio	[-]	0.61	0.57

The two above-mentioned formulas were produced in the production plant, and the behaviour of the material in the production line was monitored. Because the aggregate of the maximum fraction of 4–8 mm was used in the plant for the production of the existing products, the line was not perfectly adapted for the light aggregate of 4–16 mm fraction, which caused problems, especially in the filling section. To produce perfect functional products, it would be necessary to slightly adjust the filling part of the line and optimise the size of the moulds, especially the wall thickness of the individual products. At the existing thickness, there was a significant collapse of the fresh material (see figures 4 and 5). In consultation with plant workers, there was a positive response when working with material with a significantly lower weight than the existing assortment.



Figure 4. Ultra-lightweight masonry blocks - fresh state after pressing.



Figure 5. The resulting ultra-lightweight masonry block - after drying.

Test samples were taken from the manufactured fittings (Formula 2) and the following were determined:

- density: 810 kg/m³,
- compressive strength: 3.7 N/mm².

Due to the small sample size, the thermal conductivity of the fitting concrete was calculated on the basis of measured values on laboratory samples (see table 3). The bulk density of the concrete samples taken from the fitting was significantly higher than that of the test specimens, therefore the measured values (table 3) were approximated by the logarithmic function and the thermal conductivity corresponding to a bulk density of 810 kg/m³ equal to 0.147 W/(m.K). The results are

fully comparable with similar masonry elements made of classic lightweight concrete on the construction market [10].

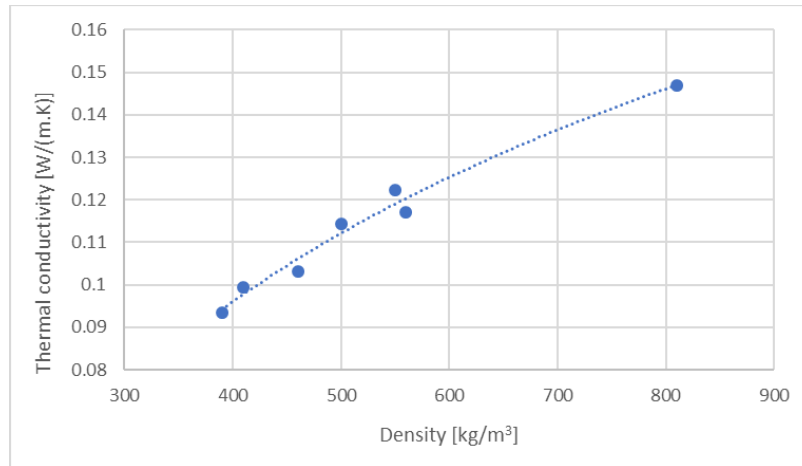


Figure 6. Dependence of thermal conductivity on density.

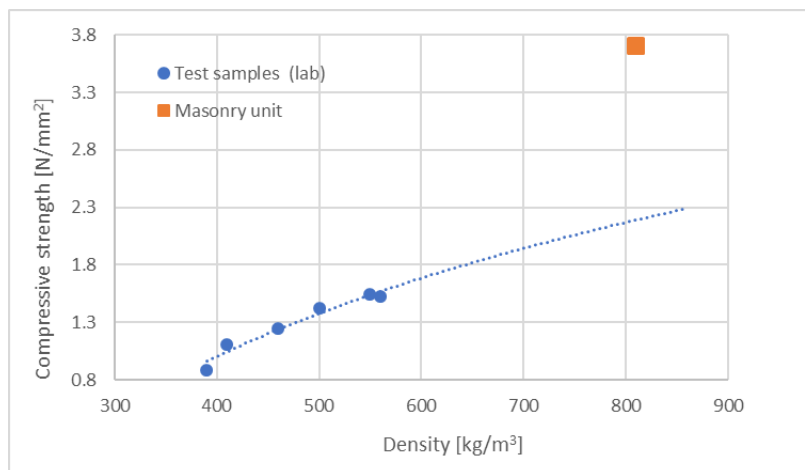


Figure 7. Dependence of mechanical properties on density (test samples and masonry unit).

Subsequently, the thermal properties of the proposed fitting under given boundary conditions were determined (see figure 8).

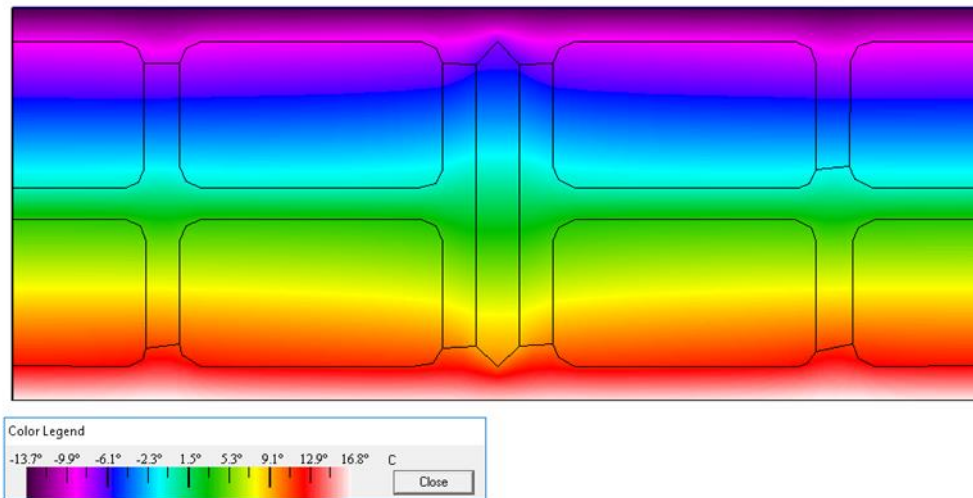


Figure 8. Computational distribution of temperature field (IR image) in masonry elements of lightweight aggregate concrete at boundary conditions: $\theta_1 = \theta_i = +21^\circ\text{C}$, $\theta_2 = \theta_e = -15^\circ\text{C}$.

The heat transfer coefficient of the fitting was calculated to be $U_{unit} = 1.03 \text{ W}/(\text{m}^2.\text{K})$ (at a wall thickness of 200 mm).

6. Conclusions

Six formulas of ultra-lightweight concrete based on foam glass were designed in laboratory. Developed concretes have a relatively high ratio of mechanical and thermal insulation properties, making this material suitable for many other applications in construction practice. Subsequently, the design and manufacture of the masonry unit was made from a modified laboratory formula of ultra-lightweight concrete. The concrete of the resulting fitting exhibited a higher bulk density (due to the different deposition method compared to the laboratory conditions). However, a significantly higher compressive strength was also achieved, which was $3.7 \text{ N}/\text{mm}^2$, which at a density of $810 \text{ kg}/\text{m}^3$ is a very high value, which significantly exceeds the values measured for laboratory samples.

Due to the very good ratio of bulk density, compressive strength and thermal conductivity, the masonry unit exhibits a relatively low heat transfer coefficient at 200 mm thickness and could be used, for example, in internal partition structures between rooms with a temperature difference of up to 10°C . Choosing a suitable internal arrangement of the masonry unit would allow a very low heat transfer coefficient to be achieved at higher masonry thicknesses and it can be argued that the developed lightweight concrete made from foamed glass aggregate has very high potential for wider application especially in civil constructions. Equivalent value of thermal conductivity of masonry block was calculated of $\lambda_{equ} = 0.25 \text{ W}/(\text{m}.\text{K})$. The results are fully comparable with similar masonry elements made of classic lightweight concrete on the construction market. A further improvement could be achieved by changing the geometry of the masonry blocks using air cavities with a smaller thickness perpendicular to the direction of heat flow. When using ultralight concrete for the production of masonry blocks, it would be appropriate to design elements with greater wall thickness of individual elements. Achieving an increase in the thickness of the walls of the blocks would eliminate problems in the production line, increase the load-bearing capacity of the masonry and increase the weight of individual masonry elements.

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