Development of lightweight structural concrete with the use of aggregates based on foam glass

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Abstract. Lightweight concretes are increasingly being used in the construction industry, either for the overall lightweighting of the structure itself, reducing material consumption for construction and thus CO_2 emissions, or for specific reasons such as improving the thermal insulation properties of the structure or acoustic properties.
Today, lightweight concretes with lightweight expanded aggregates (expanded clay, agloporite) are most commonly used. This paper deals with the production of lightweight concretes lightweighted with foamed glass-based aggregates. Foamed glass is a lightweight material characterised by a very good ratio of thermal insulation and mechanical properties. Foamed glass is made of approximately 90% recycled glass waste (mostly mixed), which cannot be used in any other way, as well as water glass and glycerine. When concrete is lightened with foamed glass, these concretes achieve unique properties while conserving primary aggregate resources, avoiding landfilling of glass waste and efficiently using the waste material to produce lightweight concrete with higher added value. The paper discusses the possibilities of developing lightweight structural concretes using glass foam-based aggregates to achieve higher strength classes while reducing the weight and thermal conductivity of the concrete. As part of the research work, new types of lightweight concrete with a bulk density in the range of 1750–1930 kg/m^3 and a thermal conductivity from 0.699 to 0.950 W/(m·K) were developed.

1. Introduction

Ductile lightweight concretes are most similar to ordinary concrete due to their apparently compact (closed) structure. Weight reduction in these concretes is most often achieved by replacing dense (heavy) aggregates with lightweight ones. All or part of the dense aggregate may be replaced, depending on the final bulk density required. Lightweight aggregates are by definition aggregate with a bulk density of less than 2000 kg/m^3. The most commonly used aggregates for lightweight concrete include aggregates made from sintered clays (expanded clay), sintered fly ash (agloporite), vermiculite, expanded obsidian and others [1].

The use of glass foam-based aggregates for the production of lightweight concrete is not very common in practice. Foamed glass is a relatively long known material that has been used in the construction industry for the last ten years. Foam glass is made from waste glass ground into a fine powder (grain size 40–70 microns). The raw meal is then mixed with foaming and melting additive and placed on a pad, after which the mixture goes into a tunnel kiln. In the furnace, there is a preheating zone (approx. 200°C) in which the material is heated, and unwanted moisture is removed. The mixture passes through a melting zone (approx. 750–850°C) where the volume of the material increases several times, and a regular porous structure is formed. Finally, an intensive cooling process breaks the foam glass into larger pieces moved by a loader to a jaw crusher that crushes the foam glass to the desired

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aggregate fraction. Aggregate made of foam glass is characterized by low bulk density (120–180 kg/m^3), very low thermal conductivity (about 0.06 W/(m·K)), non-flammability (reaction to fire class A1), low water absorption, is not subject to degradation and is recyclable [2–4].

The use of foam glass-based aggregates was investigated as a partial replacement for natural quarried or crushed aggregates in concrete. Foam glass contains large amounts of amorphous SiO_2, has a regular porous structure, a rough surface and can be used in cement-based materials as a partial replacement for natural aggregate. Overall, the use of foamed glass has a minimal effect on workability. Still, over time, due to the higher water adsorption on the aggregate surface resulting from the crushing of larger units of foamed glass, workability is reduced compared to natural aggregates. At higher doses of foamed glass, there is a decrease in compressive strength and modulus of elasticity, which is related to the properties of the foamed glass. The water coefficient also has a major influence on the final properties of lightweight concrete with foamed glass; the excess water that can be adsorbed by the aggregate can be used for internal treatment of the concrete during maturation. From the point of view of durability, it seems optimal to replace 30–40% of the natural aggregate with a coarse fraction of foamed glass (fraction 4–16 mm) and up to 15% of the fine fraction of foamed glass (fraction below 4 mm); at higher doses, negative volume changes occur mainly due to the higher content of very fine fractions contained in the 0–4 mm fraction of foamed glass. Foamed glass aggregate obtained from recycled glass powder can offer many advantages in the design of lightweight concrete. The foam glass-based material is environmentally friendly by reducing landfills and increasing the use of glass recyclate, especially in the conservation of non-renewable natural resources of raw materials [5–7]. The experiment aimed to design the optimum technology for the production of lightweight concrete using glass foam aggregate and to produce lightweight concrete with the highest compressive strength.

2. Production of test specimens

Four trial formulations were produced as part of the development of lightweight concretes with foamed glass aggregate. The different recipes differed in the amount of cement and aggregates used (relation between natural and foam-based aggregate). For the fourth recipe, the amount of foam glass aggregate was significantly reduced, and the plasticizer was exchanged for superplasticizer on the base of polycarboxylate. Prior to the actual production of the test formulations, the foam glass aggregate was soaked in water for a minimum of 24 hours due to the high absorption of water on the surface of the crushed grains. The individual recipes are shown in table 1.

Crushed aggregate from the company Refaglass fraction 4–16 with a bulk density of 160 kg/m^3 and absorbency of 38% was chosen as light aggregate, cement was used CEM I 42.5R from the production Mokrá, plasticizer was used from the company MC Bauchemie based on naphthalene sulfonates, and the superplasticizer was a polycarboxylate additive from Mapei.

Two types of test specimens were produced to determine the required properties. Specifically, these were:

- Cubes 150 × 150 × 150 mm (determination of mechanical and physical-mechanical properties)
- Plate specimens 300 × 300 × 60 mm (determination of mechanical and thermal insulation properties)

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

Entry component		Formula 1 m^3			
		LC 1	LC 2	LC 3	LC 4
Cement CEM I 42.5 R	[kg]	510	390	450	510
Water	[kg]	184	154	161	140
Natural aggregate 0-4	[kg]	730	420	420	800
Foam glass aggregate 4-16	[kg]	140	140	140	100
Natural aggregate 4-8	[kg]	380	0	0	450
Natural aggregate 8-16	[kg]	0	680	680	0
Superplasticizer	[kg]	-	-	-	2.5
Plasticizer	[kg]	3.9	3.9	3.9	-
Water-cement ratio	[-]	0.36*	0.39*	0.36*	0.27*

* the water coefficient is low because the soaked foam glass aggregate contains a considerable amount of extra water

Figure 1. Test specimen after compressive strength test.

Figure 2. Test specimen for determination of thermal conductivity.

3. Methods

Key properties were determined on the manufactured test specimens with a view to subsequent use in construction practice. The following were selected as key properties of lightweight concrete with foamed glass:

- Testing fresh concrete - Part 2: Slump-test (ČSN EN 12350-2) [8],
- The density in a fresh/hardened state (ČSN EN 12350-6, ČSN EN 12390-7) [9, 10],
- The compressive strength of the concrete (ČSN EN 12390-3) [11],
- The thermal insulating properties – coefficient of thermal conductivity (ČSN EN 12667, ISO 8301) [12, 13].

Before mixing began, test moulds were prepared to produce the required test bodies and the individual raw materials in the required quantities to produce of the lightweight concrete analysed. All raw materials were dosed by weight according to the respective recipe and then homogenized in a forced circulation mixer. After mixing, the fresh, lightweight concrete was placed in the prepared moulds. The deposition was carried out in 2 layers, each compacted by vibration for 5 seconds on a vibrating table. After 48 hours of mixing, the test specimens were de-moulded and then placed in water storage. After 28 days, the plate specimens had to be mechanically prepared to build the thermal conductivity coefficient to achieve a flat surface using a polishing grinder.

4. Results and discussion

4.1 Determination of mechanical properties

To observe the rheological properties of fresh concrete, the cone settlement method was selected to determine the consistency of fresh concrete. Furthermore, the fresh concrete was used to determine the fresh and hardened bulk density. The bulk density in the hardened state along with the compressive strength was determined at the age of 7, 28 and 90 days after mixing. The measured values are given in the following table.

Table 2. Overview of measured values of consistencies, bulk densities and compressive strengths.

Formula	Settlement of fresh concrete [mm]	Bulk density [kg/m^3]				Compressive strength [MPa]		
		Fresh state	7 days	28 days	90 days	7 days	28 days	90 days
LC 1	100	1840	1780	1750	1780	16.0	17.6	20.9
LC 2	120	1930	1850	1890	1860	20.3	23.5	20.0
LC 3	140	1960	1870	1900	1910	17.1	23.4	25.7
LC 4	180	1990	1950	1930	1950	23.2	29.3	37.5

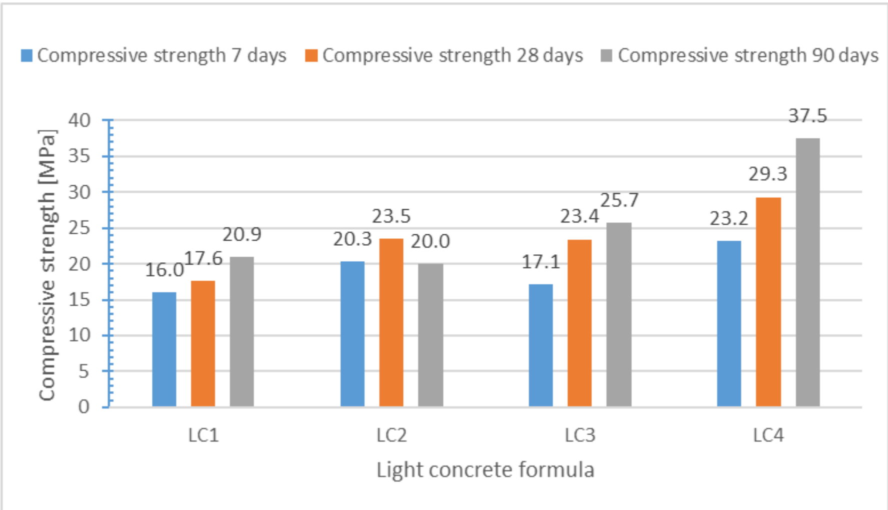

Figure 3. Compressive strengths of individual recipes after 7, 28 and 90 days from mixing.

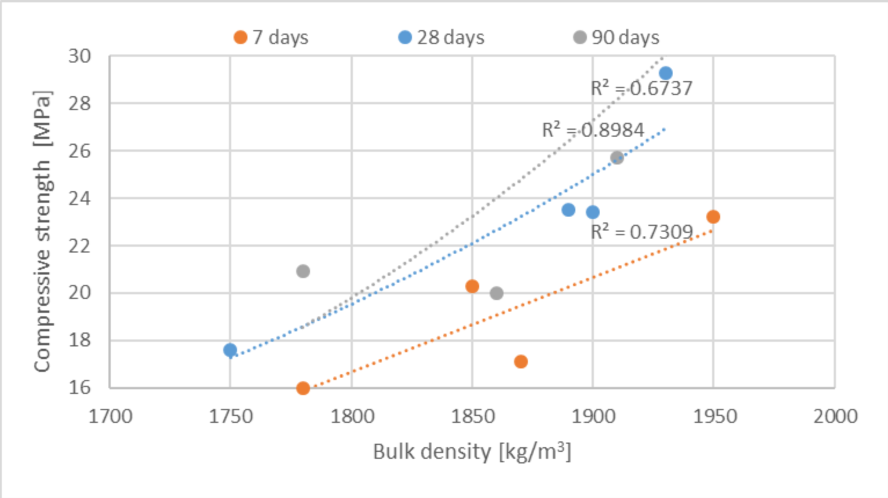

Figure 4. Dependence of compressive strength on bulk density.

The consistency of the concretes in the fresh state ranged from 100 to 180 mm cone settlement. The lowest value of cone settlement was found in the LC1 formulation (100 mm) due to the large amount of fines in the concrete compared to the other formulations. In contrast, the highest value of cone settlement was measured in the LC4 concrete (180 mm) when a more effective superplasticizer was used. The bulk density ranged from 1750 to 1950 kg/m^3 depending on the concrete formulation. Lightweight concrete LC4 (1950 kg/m^3) showed the highest bulk density due to the lower amount of glass foam aggregate in the concrete.

The compressive strengths corresponded to the bulk density of the individual concrete, ranging from 17.6 to 29.3 MPa after 28 days. The amount of foamed glass aggregate used had a significant effect on the compressive strengths, where the strength increased significantly as the amount of foamed glass in the concrete decreased, at the same time as the bulk density of the hardened concrete increased. Another factor influencing the strength of LC4 lightweight concrete was using a more effective superplasticizer, which allowed for a higher reduction of the water content. In the case of LC2, the strength decreased after 90 days. Still, this decrease was due to the variability of service samples, when in the set used to determine the compressive strength after 90 days, there were samples with a lower bulk density than in the previous sets.

4.2 Determination of thermal insulation properties

Determination of thermal insulation properties, specifically the thermal conductivity coefficient, was carried out to determine the effect of foamed glass in lightweight concrete on this physical characteristic. The thermal conductivity was determined by the stationary plate method using a Lambda 2300, Holometrix Micromet at a temperature gradient of 10 K with a mean temperature of 10°C. The thermal conductivity coefficient λ was determined on specimens of 300 × 300 × 60 mm. The fabricated plate test specimens had to be prepared using a stationary horizontal grinder with a diamond wheel. The surfaces were perfectly flat and no air gaps were created between the measuring plate and the specimen itself - figure 5. The measured values can be seen in the following table.

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

Formula	Weight [g]	Dimensions [mm]			Bulk density [kg/m³]	Average bulk density [kg/m³]	Thermal conductivity [W/(m·K)]			Average thermal conductivity [W/(m·K)]
		width	length	height						
LC 1	8920.1	303	300	57.9	1700	**1680**	0.660	0.658	0.657	**0.699**
	8943.1	302	301	59.3	1660		0.732	0.742	0.748	
LC 2	9765.4	304	301	58.3	1830	**1820**	0.768	0.770	0.784	**0.757**
	9568.4	300	301	59.0	1800		0.750	0.739	0.730	
LC 3	9748.1	300	300	58.6	1850	**1840**	0.799	0.802	0.806	**0.818**
	9718.8	300	301	58.7	1830		0.838	0.839	0.824	
LC 4	10194.1	301	300	58.5	1930	**1880**	1.073	1.064	1.062	**0.950**
	9327.4	300	304	55.8	1830		0.833	0.838	0.831	

Figure 5. Modification of plate samples for perfect placement in the measuring device.

The correlation between the thermal conductivity coefficient and the bulk density is evident from the measured thermal conductivity values. These bulk masses were determined by weighing and measuring test plate samples dried at 105°C to constant weight. The lowest bulk density for LC 1 (1680 kg/m^3) corresponds to a thermal conductivity coefficient of 0.699 W/(m·K). On the other hand, the highest bulk density for LC 4 (1880 kg/m^3) corresponds to the thermal conductivity (0.950 W/(m·K)). It can be seen that in all cases, the thermal conductivity is significantly lower than the typical values for structural concretes of classical volumetric masses according to ČSN 720540 [14].

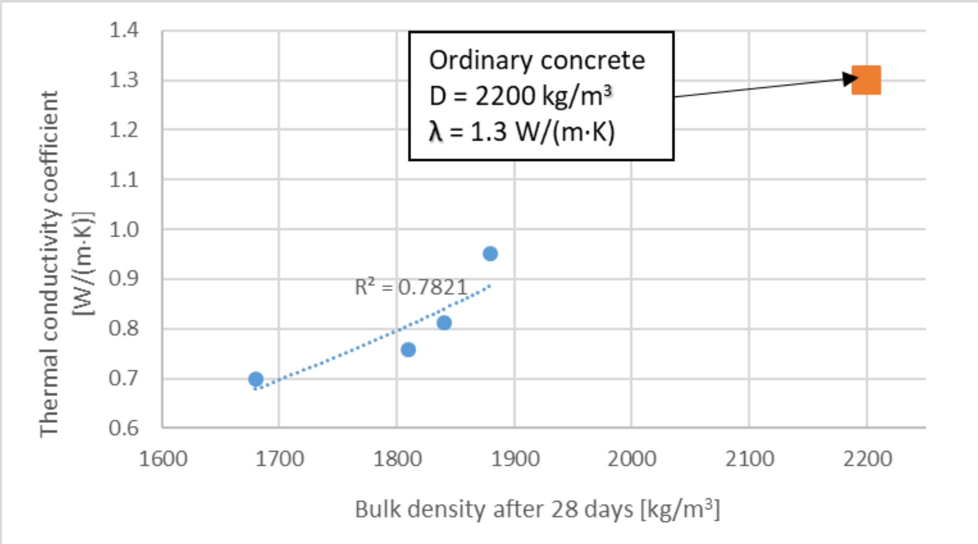

Figure 6. Dependence of the thermal conductivity on the density of lightweight concrete.

The graphical evaluation (figure 6) shows a significant relationship between the bulk density and the thermal conductivity coefficient. For comparison, the values of the bulk density and thermal conductivity of the traditional compacted unballasted concrete (bulk density 2200 kg/m^3 and thermal conductivity 1.3 W/(m·K)) are also added to the graph [14]. The graph shows that the resulting dependence for manufactured lightweight concrete with foamed glass corresponds to the value generally reported for traditional dense concrete.

As part of the research work, four test formulations of lightweight compacted concrete with aggregates based on foamed glass fraction 4–16 mm were experimentally produced in the laboratory. The foam glass aggregate is present in the concrete in quantities of 7 and 11% of the total weight of aggregate. When working with foam glass in concrete, the aggregate must first be placed in water for a minimum of 24 hours before mixing. This is to avoid any negative effects on the consistency of the fresh concrete, mainly due to the adsorption of water during the deposition of the fresh concrete on the surface of the crushed foam glass grains. It was found that a higher amount of foam glass in the formulation (11%) had a negative effect on the consistency of fresh concrete and the compressive strength of concrete. Conversely, a higher dose of foam glass significantly reduced the thermal conductivity coefficient. The compressive strength of the lightweight concrete after 28 days ranged from 17 to 29 MPa and was significantly affected by the bulk density of the concrete. The compressive strength increased with the increasing bulk density of the lightweight concrete, see figure 6. The developed lightweight concretes have very good thermal insulation properties. The thermal conductivity coefficient varied from 0.699 to 0.950 W/(m·K) depending on the bulk density. The values obtained correspond to the tabulated values of other similar types of lightweight concrete (e.g. slag/cinder concrete) and are lower than the typical thermal conductivities for some kinds of conventional lightweight aggregate concrete used, such as ceramsite concrete, which has characteristic thermal conductivity values at 1700 kg/m^3 is 1.25 W/(m·K) [14].

5. Conclusions

The use of lightweight concretes with foamed glass in building structures seems to be an interesting option that is environmentally friendly and at the same time meets the high demands on mechanical and other required properties. The developed concretes are suitable for producing prefabricated elements (wall and ceiling panels, lintels and spans) while reducing the overall load on the structure due to its weight. Due to the higher porosity of the used aggregate, the ideal use appears to be the main use in constructing buildings in structures not directly stressed by weather conditions. It is not necessary to directly address the issue of alkali-silica reaction (ASR) for this aggregate. However, common types of concrete from the ASR point of view, the glasses are also suitable for outdoor use. When comparing the developed concretes with similar concretes based on the classic light rounded (packed) clay or foam glass-based aggregate, the developed concretes show higher mechanical properties in the case of recipes with a higher bulk density [15].

The benefit of replacing part of the natural aggregate with foamed glass aggregate is not only the conservation of natural non-renewable resources, but also an increase in the performance of the elements in the structure or the whole structure. When used in wall or ceiling panels, these structures can achieve much higher thermal insulation properties than traditional concretes. It is possible to reduce the need for thermal insulation materials for these structures, which are necessary in the case of traditional concretes to meet the energy requirements for buildings.

In practice, the production of these concretes will mean the careful use of primary natural resources (aggregates, clay), a reduction in the amount of all input raw materials (less CO_2 in cement production), the use of glass recyclate and a new perspective on the production of lightweight concretes in terms of ecology and the environment.

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References

[1] ČSN EN 206+A2: 2021 Beton – Specifikace, vlastnosti, výroba a shoda (Rue de Stassart 36, B-1050 Brusel) p 106 (73 2403)

[2] Arulrajah, Arul, Mahdi M. Disfani, Farshid Maghoolpilehrood, Suksun Horpibulsuk, Artit Udonchai, Monzur Imteaz and Yan-Jun DU 2015 Engineering and environmental properties of foamed recycled glass as a lightweight engineering material *Journal of Cleaner Production* **94** pp 369–375 ISSN 09596526. 10.1016/j.jclepro.2015.01.080

[3] Yassaman Y, Schneider A, Baaj H, Tighe S and Youssefi A 2016 Foam glass lightweight aggregate: The new approach p 8

[4] Bubeník J and Zach J 2019 The use of foam glass based aggregates for the production of ultra-lightweight porous concrete for the production of noise barrier wall panels *Transportation Research Procedia* **40** pp 639–646 ISSN 23521465

[5] Sedlmajer M, Zach J and Bubeník J 2019 Using secondary raw materials in lightweight open-structure concrete with good utility properties *Acta Polytechnica CTU Proceedings* **22** pp 94–98 ISSN 2336-5382 10.14311/APP.2019.22.0094

[6] Zach J, Sedlmajer M, Bubenik J and Drdlova M 2019 Development of lightweight composites based on foam glass aggregate *IOP Conference Series: Materials Science and Engineering* pp 583 ISSN 1757-899X. 10.1088/1757-899X/583/1/012016

[7] Limbachiya, Mukesh, Mohammed Seddik Meddah and Soumela Fotiadou 2012 Performance of granulated foam glass concrete *Construction and Building Materials* 28(1) pp 759–768 ISSN 09500618. 10.1016/j.conbuildmat.2011.10.052

[8] ČSN EN 12350-2: 2020 Testing fresh concrete — Part 2: Slump-test (Rue de Stassart 36, B-1050 Brusel) p 12 (731301)

[9] ČSN EN 12350-6: 2019 Testing fresh concrete – Part 6: Density (Rue de Stassart 36, B-1050 Brusel) p 16 (731301)

[10] ČSN EN 12390-7: 2019 Testing hardened concrete - Part 7: Density of hardened concrete (Rue de Stassart 36, B-1050 Brusel) p 16 (731302)

[11] ČSN EN 12390-3: 2019 Testing hardened concrete - Part 3: Compressive strength of test specimens (Rue de Stassart 36, B-1050 Brusel) p 24 (73 1302)

[12] ČSN EN 12667: 2001 Thermal performance of building materials and products - Determination

of thermal resistance by means of guarded hot plate and heat flow meter methods - Products of high and medium thermal resistance (Rue de Stassart 36, B-1050 Brusel) p 60 (73 0569)
[13] ISO 8301: 1991 Thermal insulation — Determination of steady-state thermal resistance and related properties — Heat flow meter apparatus (Rue de Stassart 36, B-1050 Brusel) p 30
[14] ČSN 73 0540-3: 2005 Thermal protection of buildings - Design values of quantities (Prague: Czech Standards Institute) p 89
[15] Adhikary, Suman Kumar, Deepankar Kumar Ashish and Žymantas Rudžionis 2021 Expanded glass as light-weight aggregate in concrete – A review *Journal of Cleaner Production* 313 ISSN 09596526. 10.1016/j.jclepro.2021.127848