Light autoclaved foam concrete with foam glass-based aggregate

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Abstract. The presented research aims to develop new optimized composition of novel lightweight concrete with a very low bulk density. Low bulk density of developed lightweight concrete is achieved by using a combination of non-traditional lightweight artificial fillers, dispersed fibre reinforcement and pre-generated technical foam. The methodology of lightweight concrete test specimen production, based on technologies commonly applied for the production of lightweight concrete, foam concrete or autoclaved aerated concrete was also designed and verified. Not only the physical and mechanical parameters, but also the thermal insulation properties were verified on the produced test specimens of the developed lightweight concrete.

1. Introduction
Low bulk density is a characteristic feature of lightweight building materials. Lightweight building materials have good thermal insulation, ie. low thermal conductivity. On the other hand, these materials also have an unfavorably low heat accumulation. If we consider other conflicting properties such as strength and porosity, basis weight and soundproofing, sorption and sound absorption, we see that the problem of matching the low bulk density of these building materials with their other properties can be complicated [1].

Low bulk densities of lightweight concrete can be achieved in three ways:
a) Using aggregate voids
b) Using aggregate porosity
c) By creating pores in fine-grained cement, lime or lime-cement mortar
These methods can be combined with each other [1].

Lightweight concretes marked LC are lightened by cavities and pores in the concrete texture. They are used in structural-insulating, insulating structures and sometimes also for structural purposes, if the actual weight of the structure represents a decisive load. In other words, lightweight concrete is used for structural purposes only in the case of the minimum expected total load on the structure. Furthermore, lightweight concretes can be divided into dense lightweight concretes made of porous aggregate, interstitial concretes, aerated concretes and foam concretes. As light concretes, we commonly refer to a group of concretes with a bulk density of less than 2,000 kg/m³, while it is currently possible to achieve values of significantly lower than 600 kg/m³ by various production methods. In order to achieve such a low values of bulk densities of these lightweight concretes, it is necessary to replace all or a certain part of the natural aggregates with another input raw material. Artificial aggregates such as expanded perlite, polystyrene and various types of ceramic aggregates are currently used as the most common fillers for the production of lightweight concrete, due to the very limited possibilities...
of availability of natural lightweight aggregates. However, a lightweight concrete structure can also be achieved with the help of special foam additives, in this case we speak of so-called foam concrete, which is produced by implementation of a special foam or foam additive and related air pores into the cement matrix of concrete [2].

The term foam concrete is misleading in itself, as the majority of foam concrete does not contain any major aggregates, only fine sands in combination with cement, water and foam, so the final product should rather be referred to as foam mortar. In general, foam concrete is described as a material with an air content of more than 25%, which distinguishes it from other highly aerated materials. In its basic form, foam concrete is a mixture of sand, cement, water and a foaming agent or a pre-prepared synthetic or protein-based foam. The addition of pre-prepared foam to the base concrete mix reduces its bulk density, the more foam we add to the base mix, the lighter the final product will be. Depending on the application of foam concrete, part of the cement can be replaced or supplemented with other admixtures in the form of granulated blast furnace slag or fly ash. The filler in the form of sand can then be partially supplemented or replaced with ground limestone or crushed concrete. The foam that is added to the base mix is equally important and must be able to remain stable and not degrade during pumping, application and treatment of the concrete mix. This factor is especially important if the foam becomes the dominant component (more than 50% of the composition) of the foam concrete. This situation occurs especially with foam concrete with a bulk density of about 1,100 kg/m³. Foam concretes with a lower bulk density must then be handled very carefully [3].

Lightweight concretes can be divided into structural or infill according to their strength characteristics. Marking of lightweight concretes is performed according to the ČSN EN 206-1 standard with an additional parameter D, which indicates their bulk density. The advantages of lightweight concrete are especially excellent thermal insulation capacity, low weight and frost resistance. The disadvantages may be lower resistance to mechanical stress and lower load-bearing capacity compared to conventional and structural concretes [2].

The aim of the presented research is the development and optimization of the composition of lightweight concrete using a combination of production technologies for lightweight concrete, foam concrete and autoclaved aerated concrete. Low bulk densities of developed concrete were achieved by a combination of lightweight aggregate based on foam glass and technical foam for the production of foam concrete. Sufficient mechanical parameters of the developed lightweight concrete were then supported by hydrothermal technology of curing in an autoclave and by the addition of dispersed fiber reinforcement. Fiber reinforcement is commonly used to provide enhanced toughness and ductility to brittle cementitious matrix [4]. Lightweight environmental concretes with physical-mechanical characteristics comparable to commonly introduced lightweight concretes were achieved. The intended use of this lightweight concrete is for infill non-load-bearing structures of buildings, floors and light monolithic partitions. The developed concrete mixture can also be used for the production of building elements in the form of blocks, insulating "sandwich" structures or composite building materials.

2. Experimental works
The proposed composition of the lightweight foam concrete was optimized to ensure the immediate stability of the fresh foam concrete mixture and to avoid a decrease in the mixture deposited in the molds due to the degradation of the pores in the foam concrete structure. For this reason, new input raw materials were successfully tested in the proposed recipes, especially light artificial fillers in the form of crushed waste foam glass of various fractions.

2.1. Mixture composition
The composition of the final mixture for the production of functional samples of lightweight concrete is shown in table 1. This is the mixture for which the best ratio of high strength and low bulk density was achieved.
Table 1. Composition of developed lightweight concrete mixture.

| Composition                  | Quantity for 1 m³ |
|------------------------------|-------------------|
| Cement CEM I 52.5 R          | 315 kg            |
| Alumina Cement               | 56 kg             |
| Mikrosilika                  | 37 kg             |
| Foam glass aggregate 8-16 mm | 222 kg            |
| Lithium Carbonate            | 0.4 kg            |
| Tartaric Acid                | 0.4 kg            |
| Water                        | 222 kg            |
| Technical Foam               | 370 l             |
| Glass Fibres                 | 0.8 kg            |

This mixture was used for research works aimed at verifying the laboratory and pilot production technology of developed lightweight concrete using hydrothermal curing of test specimens in an autoclave.

2.2. Production of test specimens, testing methods

Production of test specimens was carried out according to the requirements and statutes of the standard ČSN EN 12390-1 (731302) Testing of hardened concrete - Part 1: Shape, dimensions and other requirements for test specimens and molds. Lightweight concrete test specimens were produced - beams measuring 400 × 100 × 100 mm.

The weighed dry components - cement, microsilica, sand, light aggregate were placed in a homogenizer, mixed and homogenized for three minutes. The required amount of mixing water was weighed and the homogenized dry components were mixed thoroughly with water using a hand mixer for three to five minutes, depending on the appearance of the fresh mixture. The addition of fibres in a volume of 1% of the total dry mixture was added to the mixture at the end of the mixing, and stirring was continued for another two minutes to allow sufficient distribution of the fibres in the whole volume of the fresh mixture.

The laboratory foam generator was used for the production of technical foam. The laboratory foam generator is connected to a mobile air compressor, a liquid foaming additive is metered into the tank and then the required amount of technical foam is produced by means of a regulated air pressure. Prepared technical foam was further mixed with the fresh cement mixture at low speed, so that the foam structure and individual closed pores did not collapse. The volume of foam dosed into the fresh mixture was on average 1 l of foam per 5 kg of dry mixture.

The produced fresh mixture was placed in molds for the production of test specimens 400 × 100 × 100 mm. The test specimens were demolded and transferred to an autoclave.

The physical-mechanical parameters were tested and the influence of the autoclaving process on the resulting strength and bulk density of the test specimens was evaluated after 7 and 28 days of wet storage of the test specimens. Specimens were tested for physical-mechanical parameters according to the standards listed below.

- EN 12390-7. Testing hardened concrete - Part 7: Density of hardened concrete
- EN 12390-5. Testing hardened concrete - Part 5: Flexural strength of test specimens
- EN 12390-3. Testing hardened concrete - Part 3: Compressive strength of test specimens
The technology of lightweight concrete production was modified by a new technological step in the form of hydrothermal hardening of lightweight concrete test specimens in an autoclave and subsequently the influence of temperature and pressure on the resulting physical and mechanical properties of autoclaved foamed concrete was observed and then pilot plant production of lightweight foam concrete test beams was carried out.

2.3. Pilot production of the developed lightweight concrete
Verification of the possibility of pilot production of lightweight foam concrete with artificial aggregates based on foam glass was performed as part of research work. The aim was to verify the production of lightweight foam concrete for future products of larger formats. Test specimens of lightweight foam concrete measuring 400 × 100 × 100 mm were made for this purpose. Test specimens were cured by a hydrothermal process in a large autoclave during the pilot production process. Conditions for hydrothermal curing in the form of temperature, pressure and time of storage of manufactured specimens in the autoclave were as follows. The temperature of 190°C, the pressure of 1.3 MPa and the storage time of the test specimens in the autoclave was 24 hours. After hydrothermal curing in autoclave, the lightweight foam concrete test specimens were stored in a laboratory humid environment for another 26 days, after which time the beams were tested for physical and mechanical properties - flexural strength, compressive strength and bulk density.

![Figure 1](image-url) Figure 1. Test specimens of light foam concrete after completion of hydrothermal curing in an autoclave for 24 hours.

Figure 1 shows test specimens of lightweight foam concrete with artificial aggregate placed in a large autoclave before the start of the pilot phase of hydrothermal curing at a temperature of 190°C, a pressure of 1.3 MPa for 24 hours. Figure 1 shows the test specimens after the completion of the hydrothermal curing process. As can be seen in the figure, the integrity and appearance of the test specimens were not disturbed due to the effect of increased temperature and pressure.

3. Results and Discussion

3.1. Thermal insulation parameters of developed lightweight concrete
The produced test specimens of lightweight concrete with artificial aggregate showed relatively high porosity and low bulk densities of test specimens in the range of 600–800 kg / m³. Therefore,
the measurement of thermal insulation properties was performed on the samples. The measurement was performed with an ISOMET instrument using an attached probe with a measurement range of 0.04 – 0.3 $W\cdot m^{-1}\cdot K^{-1}$. The probe was always placed in the centre of the sample. The measurement was performed on 3 samples of foam concrete, first in the direction of compaction and then in the perpendicular direction. The measurement with the ISOMET 2114 instrument is based on the analysis of the temperature response of the analyzed material to heat flow pulses. The heat flux is excited by the electric heating of a resistance heater inserted in the probe, which is in direct thermal contact with the test sample. The evaluation of thermal conductivity and volume heat capacity is based on the results of temperature records of regularly repeated measurements.

The following tables show the measured values of thermal insulation properties of developed lightweight concrete with artificial aggregate.

**Table 2.** Thermal insulation parameters of developed lightweight concrete.

| Thermal insulation parameter | Value          | Average values of all measurements |
|-----------------------------|----------------|------------------------------------|
| Thermal conductivity coefficient $\lambda$ | $W\cdot m^{-1}\cdot K^{-1}$ | 0.1014 |
| Volumetric heat capacity $c\rho$ | $10^6\cdot J\cdot m^{-3}\cdot K^{-1}$ | 0.4435 |
| Thermal conductivity coefficient $a$ | $10^4\cdot m^2\cdot s^{-1}$ | 0.2335 |

As can be seen from table 2, the coefficient of thermal conductivity $\lambda$ of the developed lightweight concrete is equal to the average value of 0.1014 $W\cdot m^{-1}\cdot K^{-1}$. If we compare this value with the coefficients of thermal conductivity $\lambda$ of other light building materials [5], then we can state that the thermal insulation properties of developed lightweight concrete appear to be very satisfactory, with a better value of coefficient $\lambda$ than other light building materials and concretes such as aerated concrete or lightweight concrete with expanded clay aggregate. A comparison of the values of the thermal conductivity coefficient $\lambda$ for different materials, including the developed lightweight concrete, is shown in table 3.

**Table 3.** Thermal conductivity coefficient $\lambda$ ($W\cdot m^{-1}\cdot K^{-1}$) for different materials.

| Material                        | Thermal conductivity coefficient $\lambda$ ($W\cdot m^{-1}\cdot K^{-1}$) |
|--------------------------------|--------------------------------------------------------------------------|
| Developed lightweight concrete | 0.10–0.12                                                                |
| Fly ash based aerated concrete  | 0.18–0.20*                                                              |
| Lightweight concrete with slag pumice | 0.55–0.84*                                                           |
| Lightweight concrete with expanded clay | 0.28–1.3*                                                        |
| Lightweight concrete with Perlite aggregate | 0.10–0.16*                                                        |
| Lightweight concrete with slag | 0.52–1.00*                                                              |

*Values of thermal conductivity coefficient of the other lightweight construction materials. [5]

The coefficient of thermal conductivity $\lambda$ of the developed lightweight foam concrete with artificial aggregate made of foam glass reaches better values than the values $\lambda$ of the other lightweight concretes mentioned. [5] Only light concretes with light artificial aggregate Perlite reach comparable values.

3.2. Physical-mechanical parameters of developed lightweight concrete

The achieved values of autoclaved test specimens were compared with reference test specimens for which hydrothermal curing in an autoclave was not used and subsequently the influence of the autoclaving process on the resulting parameters was evaluated.
The resulting values of physical-mechanical parameters of lightweight concrete test specimens, hardened in an autoclave are shown in table 5, values of physical-mechanical parameters of non-autoclaved reference test specimens are shown in table 4.

**Table 4. Values of physical and mechanical properties of reference test specimens.**

| Sample | Bulk density (kg/m³) | Flexural strength (MPa) | Compressive strength (MPa) |
|--------|----------------------|-------------------------|---------------------------|
| 1      | 715                  | 0.62                    | 2.77                      | 2.82 |
| 2      | 718                  | 0.65                    | 2.60                      | 2.90 |
| Ø      | 717                  | 0.63                    | 2.77                      |      |

**Table 5. Values of physical and mechanical properties of autoclaved test specimens.**

| Sample | Bulk density (kg/m³) | Flexural strength (MPa) | Compressive strength (MPa) |
|--------|----------------------|-------------------------|---------------------------|
| 1      | 660                  | 0.67                    | 2.66                      | 2.86 |
| 2      | 687                  | 0.80                    | 3.27                      | 2.99 |
| Ø      | 647                  | 0.74                    | 2.95                      |      |

Table 5 shows the results of autoclaved test specimens produced by a hydrothermal curing process during the verification pilot plant production phase. The test specimens were cured in an autoclave at a temperature of 190°C, a pressure of 1.3 MPa and for 24 hours. If we compare the individual average values of physical and mechanical parameters of autoclaved and non-autoclaved test specimens, given in table 4 and 5, then it can be stated, that due to hydrothermal hardening of test specimens in the autoclave there was a slight decrease in the values of bulk densities of autoclaved test specimens with a simultaneous slight increase in strength characteristics. The positive influence of the hydrothermal process in the autoclave on the resulting physically mechanical and probably also thermal insulation parameters of the test specimens was verified.

Table 6 shows a comparison of the achieved parameters of the developed concretes with the typical properties of common foam concretes depending on the required bulk density [3].
Table 6. Comparison of the achieved parameters of the developed light concrete with the typical properties of common foam concretes.

| Material            | Bulk density (kg/m$^3$) | Compressive strength (MPa) | Thermal conductivity (W·m$^{-1}$·K$^{-1}$) |
|---------------------|-------------------------|----------------------------|-----------------------------------------------|
| Developed concrete  | 647                     | 2.95                       | 0.1–0.12                                       |
| Foamed concrete 400 | 400*                    | 0.5–1.0*                   | 0.1*                                          |
| Foamed concrete 600 | 600*                    | 1.0–1.5*                   | 0.11*                                         |
| Foamed concrete 800 | 800*                    | 1.5–2.0*                   | 0.17–0.23*                                    |
| Foamed concrete 1000| 1,000*                  | 2.5–3.0*                   | 0.23–0.30*                                    |

*Typical properties of foamed concrete [3].

Based on the findings above, it can be stated, that the developed lightweight concrete with the bulk density value of about 650 kg/m$^3$, reached values of compressive strength comparable to compressive strength values typical for foamed concretes with a bulk density of about 1,000 kg/m$^3$. The lower bulk density of the developed lightweight concrete had a positive effect on the values of thermal conductivity. As can be seen from table 6, conventional foam concretes with comparable values of compressive strengths reach bulk densities of about 1,000 kg/m$^3$. At this bulk density, the typical value of foam concrete thermal conductivity coefficient $\lambda$ is equal to the range 0.23–0.30 W·m$^{-1}$·K$^{-1}$. The value of the thermal conductivity coefficient $\lambda$ of developed lightweight concrete was equal to the range 0.1–0.12 W·m$^{-1}$·K$^{-1}$ and the value of bulk density was around 650 kg/m$^3$. The achieved results proved that the test beams of developed lightweight concrete had significantly lower bulk density, higher strength and better thermal conductivity, compared to conventional foam concrete.

4. Conclusion

Implemented research work has shown that it is possible to realize the production of lightweight foam concrete with artificial waste aggregates based on foam glass and fibre reinforcement, even in the case of pilot production of composite elements of larger dimensions. It has been shown that the use of the hydrothermal curing process of the designed lightweight foam concrete in an autoclave leads to increased values of strength characteristics of specimens. However, the use of hydrothermal hardening of the developed foam concrete in practice will depend mainly on the economic aspect in the form of energy prices necessary for the implementation of this proposed production process.

The thermal insulation properties of the developed foam concretes, with very satisfactory results, were achieved. In particular, the achieved values of the coefficient of thermal conductivity $\lambda$ have shown that the developed lightweight foam concrete achieves better thermal insulation parameters than in the case of compared lightweight concretes with artificial aggregates or typical foam concretes. It is thus possible to assume the successful application of lightweight foam concrete, e.g. in the form of lightweight insulating fillings for ceilings, thermal insulation partitions and panels, or lightweight insulating composite prefabricates.

During the described research, a proven technology for the production of lightweight concrete with artificial aggregates and fibre reinforcement was developed. This result was fulfilled in the form of a Technological Regulation describing a proven technology for the production of lightweight concrete with artificial aggregates and fibre reinforcement.

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