Laminar foam glass as a lightweight concrete aggregate

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Abstract. In this study, 100% recycled glass foam granules obtained from waste glass were tested as a lightweight concrete aggregate (LWA). The characteristics of the raw materials used, grain-size distribution, bulk density, self-strength, frost resistance, chemical composition and the morphology of foam glass were examined. Subsequently, a series of concrete mixes were proportioned with water-to-cement ratios (w/c) of 0.4 with 0-30 wt%. Foam glass granules and probe cubes were formed. The mechanical and physical properties of concrete samples, such as compressive strength, density, water absorption, and thermal conductivity were tested. In addition, compressive strength values were compared with lightweight concrete specimens containing the same amount of Liapor aggregates. The results showed that foam glass increased concrete’s thermal insulation and density, and also decreased its water absorption. However, it significantly decreased its strength properties.

1. Introduction
Nowadays concrete is one of the most widely used construction materials in the world. As a result of population growth and infrastructural and societal development, the production of concrete, along with a great demand for raw materials, is constantly increasing [1, 2]. In parallel with the growing demand for extractable primary raw materials, the concrete industry may be one of the most suitable target areas for the use of recycled materials and industrial by-products [3, 4]. Concrete with highly heterogeneous properties is an essential material and its properties are significantly influenced by its components [5]. In addition to traditional Portland cement, numerous types of concrete, such as self-compacting [6, 7], heavy [8], and lightweight concrete [5, 9], have been developed for special purposes. Lightweight concrete is characterized by good thermal insulation, energy savings, durability, low cost, and good fire resistance [10]. It can be made with primary aggregates like expanded clay (also known as Liapor or Leca) [11, 12], fly ash [13], rhyolite tuff [14], perlite [15], polystyrene [16], or by using industrial by-products, such as glass foam, wood chips [17], rice husks [18], or with a foaming agent [19]. Among the above listed by-products, glass foam is of great importance because of the accumulation of waste glass, as this aggregate provides an excellent opportunity to recycle it. The use of waste glass in concrete also has an economic aspect: it results in energy and raw material savings and it can reduce the number of landfills [20]. Foam glass as a lightweight concrete aggregate has been the subject of much research, but it has been usually applied in a spherical [21, 22, 23] or granulated form [24, 25]. However, there are few studies which have analysed laminar-shaped glass foam granules. The aim of this research is to determine how this peculiarly shaped foam aggregate affects the properties of concrete.
2. Materials and methods

2.1. Foam glass granules
Foam glass is a widely used, multifunctional, low-density material that exceeds the mechanical strength, thermal conductivity and water absorption of alternative materials (e.g. polystyrene, ceramic-perlite, ceramic fibers) [26]. The principle of glass foam production is based on the mixing, washing and crushing of glass. Foam activator is also added to a prepared glass mixture to form a foam structure. During heat treatment at 800-900 °C, glass is in a viscoelastic state, activator decomposes, and gas is released, blowing up the melted mixture [27].

During the manufacturing process of foam glass granulates, a tow chain carries the raw materials into a furnace. Foamed glass in a softened state may adhere to a segment of the tow chain and at the end of the process a chain-link extracts the adhered piece from a larger foam table. This particle usually has anisotropic geometry of nearly the same shape and size. Although the waste is recyclable, because of its high energy and milling requirements, it is not economical to recycle it. Such unique laminar-shaped glass foam granules were used in our tests (Fig 1-2) [28].

Figures 1-2. The glass foam granules used in this study

For comparison purposes, experiments were carried out using Liapor (Fig 3-4), one of the most commonly used lightweight aggregates in Hungary. During Liapor production, dried clay is heated and then fired in a furnace at 1100-1300 °C, whereby the gases released produce a porous structure [29].

Figures 3-4. Liapor lightweight concrete aggregate

The physical properties, such as grain-size, grain-size distribution, average particle size, bulk density, self-strength and frost resistance, of the glass foam aggregate which we used were determined in laboratory tests (Table 1). In addition, SEM and EDX tests were performed. Characterization of the shape of the granules was
determined according to the guidelines of the standard MSZ 18288-3, in h/s and v/s axis ratios [30]. 51% of the granules were laminar and oblong and 41% of them were oblong (Fig. 5). Frost resistance was performed according to the MSZ EN 1367-1 [33]. The granules that were subjected to 20 freeze-thaw cycles lost 1.99 m/m% of weight by averaging the values obtained (Table 1). Standard screening and screening equipment are required to examine grain-size and grain-size distribution. The average particle size was between 0.03 and 12 mm. The granules in the largest fraction had an average particle size of 6 mm (73.95%) (Fig. 6).

**Table 1. Physical properties of glass foam**

| Properties             | Value     |
|------------------------|-----------|
| Average grain-size [mm]| 0.03-12   |
| Bulk density [kg/m³]   | 168.55    |
| Self-strength [MPa]    | 0.62      |
| Freezing resistance [-] | F₂       |

Lightweight concrete aggregates are usually characterized by their self-strength. The disadvantage of these tests is that an aggregate by itself has a different strength property than when it is used in concrete. Traditional methods, such as the Los Angeles, Deval, Micro-Deval, or dynamic tests are not used for lightweight aggregates. For these reasons, the test that we performed was done using mortar for the Hummel test and a piston. The fracture resistance, i.e. the self-strength of the aggregate, had a value of 20% compression according to MSZ-EN 13055-1 [31, 32].

**Figure 5.** Characterization the shape of the glass

**Figure 6.** The grain-size distribution

For comparison, the self-strength of several lightweight aggregates was tested (Liapor, perlite, rhyolite tuff and glass foam), and the values are summarized in Table 2. Based on the results, we found that glass foam has the lowest self-strength (0.62 MPa) among the aggregates.

**Table 2. Self-strength of the lightweight concrete aggregates**

| Aggregate    | Self-strength [MPa] |
|--------------|---------------------|
| Foam glass   | 0.62                |
| Liapor       | 4.87                |
| Perlite      | 0.64                |
| Rhyolite tuff| 9.87                |

The morphology of the granulates was examined by an AMRAY 1830I scanning electron microscope (SEM), and prepared glass foam particles were analysed at 20x (Fig 7) and 250x (Fig 8) magnifications. The particle size of the test grain was 1.564 mm and the pore wall was 165x10⁻³ mm. The pores were separated by a thin pore wall which made the granule structure fragile.
Figures 7-8. SEM image of glass foam at 20x and 250x magnifications

To determine the chemical composition, three points were examined with an EDAX DX4 microscope. Spectrum 1.1. shows the average composition, while spectrum 2.1. shows the pore wall, and 2.2. spectrum was recorded on the pore surface. The results of the EDX analysis are shown in Table 3, which corresponds to a typical flat glass composition. The porous wall of the glass foam contains higher amounts of O, Na, Mg, and K, but the pores have a higher Si and Ca content.

Table 3. EDX analysis of glass foam granules

| Spectrum       | O     | Na    | Mg    | Al    | Si    | K     | Ca    | Ba    | Fe    | Total |
|----------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Spectrum 1.1   | 28.2  | 8.08  | 1.49  | 1.76  | 49.08 | 0.71  | 9.85  | 0.83  | -     | 100   |
| Spectrum 2.1   | 32.05 | 10.99 | 1.88  | 1.44  | 45.02 | 0.93  | 6.96  | -     | 0.72  | 100   |
| Spectrum 2.2   | 22.88 | 6.64  | 1.14  | 1.39  | 53.05 | 0.98  | 13.92 | -     | -     | 100   |

2.2. Sample preparation

Seven mixtures were prepared in which the glass foam granules ranged from 0 to 30 w/w% (Table 4). The mixes were prepared with cement (type: CRH 42.5 N), with 0.4 water-to-cement ratios (w/c). The concrete was produced by a conventional method with a vertical axis mixer. 70 x 70 x 70 mm concrete cubes were prepared for the compressive strength, density, and water absorption test, while 300 x 300 x 50 mm samples for the measurement of thermal conductivity. The concrete cubes were aged under water for 7 days, and then in the open air for 28 days.

Table 4. Prepared mixtures

| Mixes | w/c ratio | Foam glass [g] | Cement [g] | Water [g] |
|-------|-----------|----------------|------------|-----------|
| 0%    | 0.4       | -              | 3750       | 1500      |
| 5%    | 0.4       | 175            | 3500       | 1400      |
| 10%   | 0.4       | 325            | 3250       | 1300      |
| 15%   | 0.4       | 450            | 3000       | 1200      |
| 20%   | 0.4       | 550            | 2750       | 1100      |
| 25%   | 0.4       | 625            | 2500       | 1000      |
| 30%   | 0.4       | 675            | 2250       | 900       |

3. Results and evaluation

3.1. Compressive strength and water absorption

For the measurement, CONTROLS 65-L 1301 was used at a breaking speed of 0.2 MPa*s (Fig 9). The values have a high standard deviation, which is probably due to the laminar and elongated structure of the glass foam granulates. The glass foam granulates reduced the appearance of the initial cracks and also drastically reduced
their load capacity. For comparison purposes, lightweight concrete cubes were also made with Liapor aggregate. From the values shown in Table 5, we see that when using Liapor, the compressive strength values in the amounts from 5-15 w/w% are almost identical to those of the glass foam aggregate specimens, but at 20-30 w/w% the compressive strength is less. Due to the fragile structure of glass foam, it is easily broken, as its bulk density and self-strength are nearly eight times lower than Liapor. Thus, particle size distribution moves on a wider scale. Mixtures prepared with Liapor additive resulted in lower compressive strength due to the lack of fractions below 4 mm, despite the high bulk density and self-strength of the aggregate.

For analysing the water absorption, mass measurements were conducted after thirty minutes, one hour, one day, and in a water-saturated state. The results are illustrated in Fig 10. The mixture without aggregate consumed a total of 22.47% water, while the mixture containing 30 wt% glass foam granules only 18.83%. Based on the results, it can be concluded that increasing the amount of the glass foam granules caused a decrease in the water uptake of the lightweight concrete specimens.

Table 5. Compressive strength test values

| Mixes | Foam glass aggregate | Liapor aggregate |
|-------|-----------------------|------------------|
|       | 7 days | 14 days | 28 days | 7 days | 14 days | 28 days | 7 days | 14 days | 28 days | 7 days | 14 days | 28 days |
|       | Rm [MPa] | σ [-] | Rm [MPa] | σ [-] | Rm [MPa] | σ [-] | Rm [MPa] | σ [-] | Rm [MPa] | σ [-] | Rm [MPa] | σ [-] |
| 0%    | 26.76 | 4.21 | 25.28 | 4.88 | 39.56 | 14.59 | - | - | - | - | - |
| 5%    | 18.72 | 2.43 | 25.04 | 4.39 | 24.2 | 4.75 | 20.98 | - | - | - | - | - |
| 10%   | 15.82 | 1.58 | 17.49 | 0.83 | 15.24 | 7.37 | 17.12 | - | - | - | - | - |
| 15%   | 15.48 | 1.87 | 18.05 | 2.22 | 18.33 | 4.17 | 16.04 | - | - | - | - | - |
| 20%   | 14.94 | 2.53 | 16.61 | 3.11 | 19.83 | 4.41 | 12.61 | - | - | - | - | - |
| 25%   | 17.81 | 1.24 | 16.12 | 3.24 | 16.12 | 4.20 | 9.15 | - | - | - | - | - |
| 30%   | 15.55 | 4.92 | 13.71 | 1.39 | 13.3 | 2.66 | 8.83 | - | - | - | - | - |

3.2. Density and thermal conductivity
The mixture without foam glass granules had a bulk density of 1621.68 kg/m³. Ten percent foam glass granules reduced density by 11.72% and thirty percent by nearly 25% (1218.66 kg/m³). Plotting bulk density values (Fig 11), it can be seen that the density of concrete cubes steadily decreased with the increase of the glass foam aggregate.

The measurement of thermal conductivity was carried out according to the guidelines of MSZ EN 12667:2001 [34]. Dimatech Rapid K was used for the test. Based on the measured values, the foam glass granules reduced thermal conductivity. The thermal conductivity value of the mixture without foam glass granules was 0.45 W/mK, while mixed with thirty percent glass foam granules it was 0.25 W/mK. It can be stated that the aggregate improved the thermal insulation capacity of lightweight concrete by 44%.
4. Conclusion
Based on the results of the experiment, the main conclusions are summarized as follows: Glass foam granules have a mean particle size of 0.03-12 mm, low bulk density and self-strength. The aggregates have high content of Si, Na, and Ca, similar to the composition of flat glass. Considering the mechanical properties, the addition of glass foam granules to the mixture clearly reduced the strength. Based on the high standard deviation of the strength values, it can be concluded that the shape of the granulates as elongated and laminar structures in the cement paste influences the strength of the cement. By contrast, analysis of other physical properties, such as density, and thermal conductivity, shows that foam glass granules can reduce a structure’s overall weight and also increase its thermal insulation. All in all, concrete aggregates from waste have a number of benefits: their use in environmentally friendly lightweight concrete, cost reduction, environmental protection, and the conservation of naturally occurring raw materials.

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