Limit load and failure mechanisms of soda lime glass foam

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ABSTRACT

Foamed glass is widely used in the industry as an insulating material. However, its mechanical properties are not well-investigated yet. Foamed glass is produced from glass waste that causes discrepancy in mechanical properties of the final product. This paper shows a way to increase the limit of the load capacity of foamed glass, which is very fragile and sensitive to mechanical and thermal loading conditions. In this paper, three different methods of load application on cellular glass structure (rough contact, resin and flour interfaces) and their influence on failure mechanisms were investigated in detail. The results of numerical analyses, based on finite elements method and compression strength tests using the digital image correlation method, indicate that the overall strength of the material is limited by boundary effects. A careful adjustment of the interface property is the main factor to draw useful conclusions and to extend load limits of cellular glass in engineering applications.

Introduction

Glass is the material that has had a major impact on the development of civilization through scientific discoveries in the field of microcosm (meaning cell structure of living organisms and infectious agents—microscope) and macrocosm (concerning observations of the planetary system and galactic systems using a telescope). It is also of great importance for the dissemination of hygienic living conditions (glass in windows) and for reading (glasses) [1]. It is obvious that glass is mainly associated with the production of glass, mirrors or containers. However, it has

more not-so-obvious applications. For example, glass is commonly used as an insulating material in the form of glass wool or as fiber for reinforcement in the production of composites, more and more popular these days. Nevertheless, glass can also exist in a completely different form of a cellular solid such as foam, which is a porous material [2]. It means that inside its structure there are voids (free spaces filled with gas). Due to the low conductivity of glass and the presence of numerous pores, foamed glass is a very good insulating material. Its advantages include affordability and good mechanical properties, among others [3].

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Porous materials can exist in two variants: with closed and with open cells. Foamed glass usually has closed cells, and it is made of recycled glass, i.e., waste container glass [4]. Glass containers are usually made from soda-lime glass, also called soda-lime-silica (SLS) glass that represents 90% of total worldwide glass production. A typical composition and a summary of mechanical properties of the SLS glass for containers are shown in Table S1 [5, 6].

A detailed analysis of mechanical strength of glass, described by ATS-129 [6], indicates a large discrepancy in its strength (Table 1). The stresses, at which 0.8% of the samples is damaged, are two times lower than those at which the probability of destruction is 50%. Of course, this affects the uncertainty of the strength of glass foam. Additionally, the data presented in Table 1 were taken from a bending test, in which the strength of glass is limited by its tensile strength. Only fractures originating on the surface of glass are considered. Boundary effects in the scored and cut-glass edge are omitted. Therefore, the presented allowable stresses are optimistic. Consultants and engineers from the NIIR board suggest using 7 MPa as allowable for glass due to imperfections in its structure and its brittle cracking [7].

Despite the material being widely used, there are not many publications about its mechanical properties. Bai et al. [8] studied synthesis and properties of foam glass obtained from waste glass and fly ash. They stated that the material had a closed foam structure with a bulk density of 267.2 kg m^{-3} and a compressive strength of 0.9829 MPa. Guo et al. [9] prepared high strength foam glass ceramics also from waste. They used the sintering method to obtain glass from cathode ray tubes. The mechanical strength analyses of this foam glass resulted in values ranging from 5.61 to 23.73 MPa because of SiC content and the sintering temperature. Finally, they concluded that the precipitation of microcrystals, formed during the sintering process, improves mechanical strength of this material. Soda lime window glass foams were synthesized and studied by Attila et al. [10]. The

authors determined a collapse stress of the foams, ranging from ~ 1 to 4 MPa and the thermal conductivity from 0.048 to $0.079 \text{ W K}^{-1} \text{ m}^{-1}$. Moreover, they stated that an increase in the foam density resulted in the rise of both parameters and that the characteristics of the deformation under the compression are of the open cell brittle foams that are probably a result of the thick cell edges. Foam ceramics of red mud from aluminum industry and fly ash from the thermal power plant with addition of sodium borate and sodium silicate were prepared and studied by Chen et al. [11]. These foams had a porosity of 64.14–74.15%, the compressive strength of 4.04–10.63 MPa, the flexural strength of 2.31–8.52 MPa, bulk density of 0.51 – 0.64 g cm^{-3} , and water absorption of ~ 2.31 – 6.02% . Therefore, these foams were considered good materials for thermal and sound insulation, among others. Other researchers studied failure modes in syntactic foams by experimental methods [12–14], but there has not been found any report on both theoretical and experimental studies yet.

In this contribution, we show two different methods (theoretical and experimental) of the load application on a cellular glass structure and its influence on failure mechanisms. We performed numerical analyses based on the finite elements method and strength tests, with the usage of digital image correlation method (DIC) that allows us to draw useful conclusions for engineering applications of foamed glass.

Materials and methods

We performed the theoretical analysis by using the finite element (FE) model. The detailed procedure is described in “[Model of the structure](#).”

We conducted the experimental analysis on blocks of foamed glass (FOAMGLAS[®] manufactured by Pittsburgh Corning; Fig. S1a, Fig. 5a) cut out as cylinders of 30 mm height and 33 mm diameter. We

Table 1 A typical modulus of rupture for 50 and 0.8% probability of breakage in bending test Adapted from [6]

Type of glass	Modulus of rupture with probability of breakage (MPa)	
	Probability 50%	Probability 0.8%
Annealed	41	19
Heat-strengthened	83	93
Toughened	165	77

prepared seven samples of each of three types. The first type was a cylinder of pure foam, the second type was a similar cylinder, but it had the external pores (top and bottom) filled by resin (EPIDIAN 53 with TFF as a curing agent; KRISKO, Poland), and the third one was filled with the ground flour type 450 (GoodMills Polska Ltd.; Poland).

We measured the force in quasi-static conditions with the displacement of 0.05 mm s^{-1} using INSTRON 8516, as shown in Fig. S1b [15].

The DIC method was used to analyze deformations of the samples. For the purpose of this analysis, we marked samples with acrylic paint. We performed this analysis by using the same method and software as described elsewhere [16–18].

The samples were numbered from 1 to 7; the letter S was assigned to the samples of pure glass, R to resin and F to sample with flour.

The results and discussion

Model of the structure

Modeling a porous structure of glass foam is important to understand its mechanical properties. There are many ways to describe and model the structure of foam. One of them refers to the microstructure observation and understanding its manufacturing process. During the production of low-density foam, isolated spherical bubbles of gas tend to expand, so the adjacent ones start sticking, while further bubbles grow in polyhedral morphology. Depending on the achieved density and surface tension of the material, the foam is formed with closed or open cells.

Common observation shows that the structure of real foams is neither regular nor periodic, even though it is created by topologically similar cells (dispersion in cell size). Nevertheless, to simplify the problem of theoretical prediction of macroscopic foam behavior we shall focus our attention on idealized periodic microgeometries, created by the repetition of fundamental piece called the unit cell. Study of the physical aspects of foam manufacturing gives us guidelines for unit cell selection.

The latest solution of the minimization problem of unit cell surface energy, where unit cells have planar faces (the bubbles are in contact), was presented by Gabbrielli [19]. Apart from that, and aiming to analyze the foam behavior theoretically, many other

idealized structural models were proposed. One of the very first polyhedron, described by Lord Kelvin [20] in 1887, was tetrakaidecahedron, which best describes the structure of a single cell. This model has been used in calculation. Figure 1a presents single tetrakaidecahedron, and Fig. 1c shows a model of foam with open cells modes of polyhedrons from Fig. 1a. As it has already been mentioned, the main advantage of tetrakaidecahedron is that it is periodically repetitive. From the structure presented in Fig. 1c, it is possible to cut out other periodical element different from the one presented in Fig. 1a. It is shown in Fig. 1b, and it is made of 6 square frames. Based on this model and frame theory, an equivalent Young's modulus for the foam can be determined by Eq. 1.

$$\frac{E^*}{E_s} = \frac{8}{a^2\sqrt{2}} \left[\frac{a^2}{96I_y} + \frac{1 + 2\psi(1 + \nu)}{A} \right]^{-1} \quad (1)$$

where E^* is Young's modulus for the foam, E_s is Young's modulus for the solid material, a is length of the edge of rectangular frame from Fig. 1b, A is an area of beam cross section, I_y is the second moments of cross section area of beam, ψ is form factor, and ν is Poisson's ratio.

A similar approach can be used for the foam with close cells, but it is necessary to use the model of plate and beam instead of just the frame theory. Gibson and Ashby [21] give the formula of Young's modulus for the foam with a closed cell in Eq. 2.

$$\frac{E^*}{E_s} = C_1 \phi^2 \left(\frac{\rho^*}{\rho_s} \right)^2 + C'_1 (1 - \phi) \frac{\rho^*}{\rho_s} \quad (2)$$

where $\frac{\rho^*}{\rho_s}$ is the relative density of the foam, ϕ is a fraction of solid contained in beam elements, a mass of cell is split between plane and beam regions, and C_1 and C'_1 are constants of proportionality.

In the case of a bigger structure, the usage of the plate model causes a significant impediment. Therefore, the finite element (FE) model is used for the analysis of foams with closed cells [22]. Figure 1d shows the FE model of a unitary cell used in this analysis. The model could be prepared basing on solid and shell elements, where the walls of cells are very thin when compared to the rest of their sizes; therefore, for simplification reasons, shell elements are used in Fig. 1d. Typically, the cell wall in the center is thinner than the ones on the line of walls connection. This is caused by the process of foam production, during which the walls of glass bubbles

Figure 1 Unit cell model and structure of foam with open cells made of tetrakaidecahedrons (a, b and c), and the model of a unitary cell and structure of the foam with closed cells built basing on a unitary cell (d and e).

become thinner and thinner when size increases. The density of the glass foam was of 130 kg m^{-3} , so we determined the thickness of walls using these data and the density of the solid glass (Table S1).

During the calculation process, we idealized the foam material. We assumed that it had isotropic and linear elastic properties up to the brittle fracture, which determines the limit load of the material. We also assumed that the structure of the foam consists of periodically repetitive cells; therefore, one unitary cell should be enough. This would be true if the boundary on the interface between the foamed glass and the foundation were not considered in the analysis. In that case, the continuity of the structure could be ensured by constraints equations. Those equations relate the movement of free edges of a unitary cell. Based on that model, it is possible to determine stress and strain field far from the boundary of foam specimen and equivalent Young modulus and Poisson ratio for the foam structure. Using those assumption and the FE model, we determined constants from Eq. 1. The FE model is made of shell elements only; therefore, ϕ is equal to 1 and C'_1 could be omitted. Consequently, for the considered structure, constant C_1 is 5.77.

Strength properties of foamed glass

Damage of the glass foam usually starts at the boundary, so the boundary effects must be analyzed first. The analysis requires a use of a larger FE model, consisting of multiple cells. An example of the boundary issue is the effect of the type of load application method on the strength of the structure. Figure 1e presents the used FE model of foam. It was cut out from a bigger structure. Therefore, it was necessary to apply the appropriate boundary conditions. The obtained structure was not purely symmetrical. Nevertheless, for the purpose of this analysis, symmetries were used. On the walls, along

which the cuts were made (back, left, and bottom), displacements in the normal directions were fixed.

First, we analyzed the effect of the pressure of gas enclosed within the foam structure. This gas is a residue from the foam production process. There are many different methods of foam production. However, for the industrial purposes the most popular method is foaming glass granules with the addition of a foaming agent [2, 8]. To obtain the product with the best possible physical properties, it is necessary to maximally disperse the gas phase inside the glass. This allows to produce the foam with closed cells of a uniform size. During the production of foamed glass, finely ground glass granules are mixed with a suitable amount of the foaming agent. Then, the whole substance is heated evenly and maintained at a constant temperature [4]. Over 600°C , the melting glass surrounds and closes the particles of the foam substance. Under these conditions, they undergo decomposition and a gas phase arises. During the process, the glass mass should be plastic. The increase in the pressure causes the growth of gas bubbles. After the structure is completely cured, the gas used for the production remains inside the structure (bubbles). In each closed cell, the pressure acts on the walls in a normal direction from all sides (Fig. 2a) or from the outer cell (located near the verge; Fig. 2b). However, the pressure does not work on all its walls, so in the calculations it was assumed that the pressure in each cell was the same. This assumption is correct due to the equilibrium established during the foaming process. Therefore, the situations in Fig. 2a, b can be simplified by Fig. 2c, d. It was assumed that the pressure of gas closed in a cell is equal to 0.3 bar. This pressure was applied on the external surfaces of AlSi10 closed cell foams during the analysis using the 3D FE model of tetrakaidecahedron [22].

Figure 2 Scheme of internal pressure in the foam structure. The pressure acts from all sides (a), from the outer cell (b), no pressure at all (c) and pressure to the cell center (d).

Since the overall strength of the foamed glass is limited by the boundary effect (related both to the internal pressure and to the way how external loads are applied to the structure), three types of interface specimen—foundation—were investigated in detail: pure foam, foam with external pores filled with resin and the one in which pores on the verge of the foam were filled with coarse grain flour. The main analyzed problem was the differences in the results caused by different methods of loads application into the structure. To understand the problem better, it is convenient to introduce the concept of stress concentration factor (k) defined by Eq. 3.

$$k = \frac{\sigma_{eq}}{p} \quad (3)$$

where p is the external equivalent compressive stress applied to glass foam and σ_{eq} is the maximal stress obtained inside the structure. The concentration factor depends on many components such as density or the type of foam structure, among others [3]. At this point, it is important to distinguish between the area on the verge of the foam and inside the structure, which can be done by using the relation in Eq. 4.

$$\sigma_{eq_{internal}} \leq \sigma_{eq_{external}} \quad (4)$$

Consequently, the separate stress concentration factor (k) for internal and external cells can be defined. The maximum stress in the area far from the edge (hereinafter referred to as ‘the interior area’) is proportional to the average pressure applied on the external area and does not depend on the way the load is applied to the shore (based on Saint–Venant’s principle; Eq. 5).

$$\sigma_{eq_{internal}} = pk_{internal} \quad (5)$$

In the case of areas located near the boundary layers, the maximum stress mainly depends on the method of distribution of average pressure p on the surface of the foam. Preliminary foam damage tests

indicate that the part of the load applied on the surface of the foam is directly transferred by the edge of the plates as a continuous linear load q_1 [N m^{-1}], and the pressure p_s is transferred by the surfaces of the cell. The resulting load is the sum of these components, as in Eq. 6.

$$p = p_1 + p_s \quad (6)$$

where p_1 is the resultant pressure from q_1 .

Using the FE model, we considered three types of load applying methods. In the first case (pure foam case), the compression load was transferred to the foam structure only by the free edges of cut cell. In the FE calculation, we modeled it by applying vertical displacement on nodes located on the top edge of the structure (nodes marked by the red frame in Fig. 3). In the second case (pores filled with resin), the same load was applied on the surfaces and the edges of open cells. The resin provided additional stiffness and constrained relative movement in a perpendicular direction to the loading direction. In the analysis,

Figure 3 Scheme of load application on nodes from the structure.

nodes from the violet (Fig. 3) frame were offset down simultaneously with a blocked translation in other directions. In effect, the resultant force acted only in the vertical direction. The last case was the foam with the flour. The flour behaves similarly to fluid, it pushes on all surfaces, but it does not provide stiffness in the perpendicular direction. It causes that external pressure acts on slanted walls, thus elbowing the structure of foam. Therefore, the nodes from the violet frame in Fig. 3 were just moved down without any constraining movements in the remaining directions. The value of the node offsets was set to obtain the equivalent compression load of 0.7 MPa (equivalent to 0.6 kN of compression force applied during the test). This load was calculated, as forces distributed of the equivalent area were separated by the foam structure 5×5 cells. The size of unit cell was assumed as 1 mm.

Using these assumptions, we obtained the stress plots shown in Fig. 4. The ultimate strength of glass is limited by allowable tension; therefore, the maximum stress is shown in principal directions. In the case of pure foam (load applied on the cut edge of the structure), the stress level is the highest (as compared to the rest of the results). Based on the stress plot, we noticed that due to the differences in stress levels in the structure (the stress is lower inside than in the outer area) during loading, the destruction of the structure is initiated at the edge and moves deeper into the structure until the final collapse. In this case, the method of load application causes the bending of free, i.e., cut, edges of foam, which manifests in high stress (Fig. 4a). The maximum principal stress of external region was equal to 7.75 MPa and of the internal region was 4.56 MPa. The distribution of the load was smoother for the foam set on resin (Fig. 4c) and flour (Fig. 4b) interfaces that have maximum stress, for the external regions, of 6.65 and 6.78 MPa, respectively, and for the internal regions it was 4.17 and 4.17 MPa for the resin and flour, respectively.

Thus, these surfaces make the foam glass structure much more durable. The lower value of maximum stress for the foam with the resin was due to its additional stiffness in the direction perpendicular to the direction of loading. It counteracts the spreading of the structure, and this is especially visible in results obtained from the experimental tests. In all the cases, the maximum stress level was about 7 MPa, recommended by NIIR [7]. This means that in all the cases the structure was destroyed. Thus, $p = 0.7$ MPa is the upper bound of the elastic limit load for the glass foam based of the FE model. This value is to be verified by an experimental test.

Experimental tests

To confirm the results obtained by a theoretical analysis, we performed a series of practical tests.

Figure 5 presents the consecutive stages of the destruction of foam structure S1 before the test (Fig. 5a) and after the destruction of 1/3 (Fig. 5b) and 2/3 (Fig. 5c). These images confirm theoretical calculations (Item 1.1) that the process of destruction begins on the edge and proceeds layer by layer deeper into the structure. The central part of the sample does not seem to be deformed and remains a rigid block. This is evidenced by DIC images presented in Fig. 6 that even shows the deformation of the structure. These images show a vertical displacement of the sample S1 after 1/3 (1st stage; Fig. 61a) and 2/3 (2nd stage; Fig. 62a) of its destruction, deformation in the vertical direction in microstrains (Fig. 61b, 2b) and microshear strain (Fig. 61c, 2c). The process occurs uniformly in the whole extension, and the glass foam layers are destroyed successively one-by-one.

The compression force in the function of displacement and averaged curves with a standard deviation were plotted for all samples (S1–S7), and the results are shown in Fig. 7a. The results reveal a constant

Figure 4 Maximum stress of a glass foam set on a hard surface (a), flour (b) and resin (c).

Figure 5 Pictures of the sample S1 before (a) and during the first (b) and the second (c) stage of the destruction test.

Figure 6 Vertical displacement (in mm) (a), deformation in the vertical direction in microstrains (b) and microshear strains (c) of sample S1. 1a, 1b and 1c in the first and 2a, 2b and 2c in the second stage of sample S1 destruction.

increase in a compression force as a function of the displacement up to maximum, at about 10 mm, and after that, a decrease. The visible fluctuation on the curves corresponds to the gradual collapse of the structure of the samples, which occurred layer by layer. The maximum average compression force after 10 mm of the displacement is about 0.8 kN (Fig. 7b).

The same experiments were made for the foam with pores located on the verge and filled with the resin (R samples) that was applied in a way to ensure the flatness of both surfaces of the contact. The pictures of sample R6 before and during the destruction process are shown in Fig. S2. Figure S2 a presents successive stages of the test for the sample R6 before

Figure 7 Compression force in the function of the displacement of pure foam samples S1–S7 (a) and the average result with a standard deviation $\pm S$ (b).

the test, after the detachment of the upper layer of resin (Fig. S2 b) and after the detachment of the lower layer of resin (Fig. S2 c). Comparing this figure with Fig. 6, we can observe that the sample with the resin is more resistant than the one without the resin because there are changes in the first stage of the destruction process (Fig. S2 b). However, in the 2nd stage of the destruction (Fig. S2 c) 1/5 of the sample, R6 is destroyed, while in the same condition only 1/3 of sample S1 (Fig. 6c) remained.

These samples were also analyzed by DIC images. Figure S3 1a presents displacements in the vertical direction in first stage, shown in Fig. S2 b. The deformation in the vertical direction in microstrains and microshear strains is shown in Figs. S3 b and c, respectively. The nature of the destruction is similar to S-type samples (Fig. 6), where the degradation occurs layer by layer and the middle part of the foam remains stiff. The differences between these two samples destruction tests are seen in force versus displacement curves (Fig. 8). In the initial stage of loading, the sample shows a high resistance (Fig. 8a). The force increases to a large value of about 0.52 kN, and then, it decreases to 0.05 kN, which is caused by the difference in the stiffness of two materials: glass and resin. The layer with the resin is detached from the structure. At a later stage, the force increases again to 0.6 kN for displacement of 10 mm (Fig. 8b). The maximum average force of 0.8 kN is the same for S and R samples (Figs. 7b and 8b). However, at the beginning, samples with the resin have greater strength, while the subsequent layers of S-type samples are quickly destroyed without any resistance. At

some point, after the destruction of several layers, the increase in the resistance in cells destruction is seen. This is caused by the process of filling the cellular voids with the material formed by crushing the edge of the cells. Owing to this, some force is transferred by plate surfaces as an evenly distributed pressure.

Finally, we analyzed samples with flour (F) and collected pictures of sample F3 before (Fig. S4 a) and during the two stages of the destruction test (Figs. S4 b and c). These images are quite different from previous, because they show cracks of the glass foam structure. A beginning of the crack is almost invisible in Fig. S4 b, but it is clearly visible in Fig. S4 c, and it extends from top to bottom. We confirmed these observations by DIC images, shown in Fig. S5, and plots in Fig. 9. The vertical displacements DIC images confirm the start of the crack (Fig. S5 1a) and its propagation in Fig. S5 2a. The same is observed in the deformation in the vertical direction (Fig. S5 1b and 2b) and microshear strains (Fig. S5 1c and 2c).

In Fig. 9a, we present the force displacement curves for seven samples of the foam with flour and averaged curves with standard deviation in Fig. 9b. From these figures, we can observe that in the initial stage of load application, the behavior of F-type samples is somewhere between S and R types. Sample F is stiffer than S but less stiff than R, because it resists more. When the level of the load is higher, i.e., when it reaches the first stage of the destruction, the flour begins to elbow the structure and tears it apart, which is clearly visible in Fig. 9b and Figs. S5 1a, 1b and 1c, when the sample displacement reached about 4 mm. The maximum of an average compression

Figure 8 Compression force in the function of displacement for samples of R1–R7 (a) and the average results with a standard deviation (b).

Figure 9 Compression force in the function of the displacement for samples of F1–F7 (a) and the average result with a standard deviation (b).

force for this sample was almost 0.6 kN, and the average displacement is 5 mm (Fig. 9b). After that, a propagation of structure shrinkage and decrease in sample's thickness occurred.

A comparative analysis of all the obtained data is shown in Fig. 10. The glass foam sample and the glass foam covered with the resin sample showed similar results except of the beginning of the force application (Fig. 10a). The sample with the resin was more resistant in the initial stage of force application (elastic deformation until delamination point, Fig. 10b), while the glass foam sample suffered a destruction from the beginning. This is due to the irregularity of surface. An unevenly distributed load shatters the protruding elements. It causes that there is no pure linear range, since some local preliminary structure degradation is present. The maximum force

of compression for both samples was about 0.8 kN for the displacement of ~ 10 mm. On the other hand, the sample, covered with flour, due to the lateral expansion of its structure, caused by the very flour, achieved a lower maximal force of 0.6 kN for the displacement of ~ 5 mm. But in the case of flour, the loading could be split into two linear ranges. In the first case, the flour subsides and penetrates the structure. The second case is about the elastic range of foam deformation. The slope of the line for the resin is two times greater than for the flour. (It means that resin is also two times stiffer than flour.) From the numerical results, it can be seen that the average maximum force in S and R specimens was equal to 0.846 kN with a standard deviation of 0.054 kN. Considering the area of the circular sample (diameter 33 mm), the critical stress was of 0.989 MPa, which is

Figure 10 Comparison of the average compression force in the function of the displacement during the whole experiment (a) and in its initial step (b) for the pure foam (—AVG-S) with resin (—AVG-R) and with flour (—AVG-F).

similar to the results published by Guo et al. [9] and Attila et al. [10]. Our experimental results also show that the elastic limit load for the resin reinforced foam is 0.68 MPa (0.58 kN), the flour distributed load 0.61 MPa (0.52 kN), and 0.55 MPa (0.47 kN) for the rough material. Our results are also consistent with the properties provided by the manufacturer of foamed glass (Table 2 [23]), while the results of our theoretical model point to a higher material capacity.

The analysis of the presented data allows to single out two significant problems that can be encountered while studying the structure of foamed glass: firstly, the big discrepancy of the material properties and, secondly, the difficulties with modeling the foam structure. In the calculation presented in this article, we used the model with identical and periodical cells. Although there are no two identical cells in the nature, from the macroscopic point of view, this assumption is correct, and it makes it possible to study the boundary effects. The method of load application can change the distribution of stress inside the foam structure. In the case of pure foam (samples S), the cut edges of the open cell do not have any support. The load applied causes in plates tension stress that comes from bending, so the foam does not resist and crashes with force close to zero. The following destruction of several layers of cells produces a dust that fills up the subsequent open cells.

The load transferred by the structure is relocated from edges to surfaces of the cells and the foam begins to resist, so the transferred load increases. At some point the equilibrium is set, but then the structure is being destroyed at a constant force. Dynamic and abrupt collapses of subsequent layers of structure cause its degradation. The force transferred by the structure is reduced to zero. In the second case, the free edges of cut cells are supported by resin (samples R), which provides additional stiffness. The foam with the minimal squeeze of structure puts up a significant resistance, which means that the resin protects the structure. It allows a transfer of a bigger load without (or with minimized) the destruction process. As the force grows up, the layer of the resin is detached. The force decreases, and then, it starts to increase again. Then, the process of the destruction of the structure proceeds similarly to the case of pure foam, layer by layer. The samples with the flour (samples F) can be placed somewhere in between the resin and the pure foam. The flour provides a redistribution of the loads and allows the transfer of force through surfaces. Unfortunately, the flour behaves like liquid; it pushes on the structure in all directions. In the initial phase, it helps to transfer the load (a higher low is allowed), but afterward it elbows the structure. The flour becomes the initiator of the crack and bursts the structure. We determined

Table 2 Properties of FOAMGLAS® floor board S3 Adapted from [23]

Thickness (mm)	Density (kg m^{-3})	Compressive strength (kPa) (EN 826-A)
40–180	$130 \pm 10\%$	≥ 900

the stress concentration factors and the maximum principal stress for the internal and external regions of the foam by using FE analysis. There is a correlation between the results obtained from the numerical analysis and the experiment. From FE, we observed that the stress in internal regions is lower than for external surfaces and that the maximum stress is higher than the allowed stress for glass. However, our experimental data revealed much lower maximum stress values. Therefore, besides checking the impact of changing the type of resin and relative density on the overall capacity of the structure, it is planned in the future work that other more flexible materials should be investigated as top and bottom coatings of soda lime glass foam. Finally, the effect of the change in the internal pressure should also be examined.

Conclusions

This study presents theoretical and experimental results of the failure mechanism of glass foam obtained from glass waste, which can cause discrepancy in mechanical properties of the final product. The numerical analysis was based on the finite elements method and an experimental one by compression strength tests coupled with digital image correlation method (DIC). The obtained results indicated that the overall strength of the material is limited by boundary effects. To prove that, these tests were conducted on glass foam as it is (a rough material) and with interfacial coatings of resin and flour. Actually, the failure of the foam structure starts at the loaded boundary and then it proceeds sequentially, layer by layer, deep into the sample interior. The glass foam sample and the glass foam covered with the resin sample showed similar results except for the beginning of the force application. The average maximum force for both types of samples was equal to 0.846 kN for the displacement of ~ 10 mm, and the critical stress was of 0.989 MPa. The sample, covered with flour, due to the lateral expansion of its structure caused by flour, achieved the lower maximal force of 0.6 kN for the displacement of ~ 5 mm.

In summary, the experimental results proved to be consistent with our theoretical model and properties provided by the manufacturer of the foamed glass. The detailed stress analysis carried out on finite element model shows that the local stress concentration

on the specimen boundary is more than 60–70% higher than inside the structure. Comparing the results from the FE analysis and the test, it could be assumed that there is still additional margin. This indicates quite a wide range for possible glass foam strength improvement, which should be done by careful distribution of loads using flexible interface layers or boundary coatings.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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