WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2022.141879

ARCHIVES OF CIVIL ENGINEERING

Vol. LXVIII ISSUE 3 2022

pp. 155 –175

Research paper

Assessment of long-term performance of foam glass as an insulating sub-base in varying humidity and temperature conditions

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Abstract: The research focuses on the properties of foam glass, popular insulation material used in various industries and applications, including construction, chemistry and defence, after several years of use under varying load, thermal and humidity conditions. The material used as an insulating sub-base underneath industrial steel tank, which had failed with a threat of leakage of the stored high-temperature medium (200°C), was tested. After macroscopic and material evaluation of the foam glass samples, their compressive strength, water absorption, and behaviour under complex conditions including loading, high temperature, and moisture were examined experimentally. Absorption of water considerably affects reducing the foam glass performance. Investigations show that the foam glass generally does not reach the declared compressive strength. If this surface is additionally heated to high temperature, the foam glass undergoes destruction by chipping or crushing just at stresses several times lower than the limits for this material, and even with no applied load. The test results show that foam glass exposed to simultaneous action of water and high temperature undergoes progressive deterioration, resulting in a decrease in declared parameters and losing its usability. Therefore, effective and durable protection from water is of critical importance to ensure reliability of foam glass exposed to high temperatures.

Keywords: foam glass, long-term behaviour, absorptiveness, high temperature, compressive strength

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1. Introduction

Foam glass is a popular insulation and soundproofing material used in various industries and applications, including construction, chemistry and defence [1]. Its properties allow meeting high environmental criteria relating to the conservation of energy [2]. The most appreciated advantages of foam glass include low thermal conductivity, non-combustibility, water absorption resistance and resistance to moisture, corrosion, micro-organisms, mildew and most chemical agents, and, last but not least, a proven manufacturing process used in its production [3,4]. In addition, it has a high compressive strength with low density, which distinguishes foam glass from other insulating materials. To obtain high compressive and flexural strength without affecting the remaining desirable properties has been the focus of many research projects [5–9].

Recently, particular attention has been paid to materials and processes that would improve the manufacturing process in terms of environmental impact, health hazards and cost, allow recycling of processed and yet enhance the physical and chemical properties of the end product. The specifications of mixtures and information on the production techniques can be found in the literature [3,8,10–14]. The use of alternative raw materials, such as industrial waste and natural materials is also covered in a number of articles [5,8,11, 12,15,16]. A considerable amount of research effort has been devoted to seeking additives or processes that would improve the mechanical properties of foam glass while maintaining the other desirable properties [5,6,17–23]. Some projects dealt with the influence of the size of hollow glass microspheres and chemical composition of foam glass on its energy absorption capacity [24].

Brittleness, susceptibility to dynamic loads, brittle fracture and also compressibility are the obvious disadvantages of foam glass. Nevertheless, the experimental results reported in [7] showed that addition of certain components to the mixture, such as glass fibres, can considerably increase the compressive strength. Also Young's modulus and toughness have increased.

The Standard [25] specifies the requirements for foam glass, including thermal resistance, compressive strength, water absorption resistance. It also gives the recommended test methods for measuring these properties. However, the standard provisions refer to specific, isolated application conditions, not taking into account more complex combined actions.

Nevertheless, the literature review showed only a few recently conducted studies [9, 24, 26, 27] devoted to meeting the essential requirements of the relevant standard [25]. According to the conclusions of [9,26], the value of compressive and flexural strength of foam glass vary strongly, depending on the density of the material and the amount and size of air voids. On the other hand, in [27], compliance with chosen standard requirements was demonstrated, yet only for a specific material produced in the laboratory. Worth noting are the observations reported in [16] that with an increase of temperature the flexural strength and the amount of absorbed water initially decreased considerably (i.e. by ca. 2–3 times) to increase thereafter, yet only up to 0.5 times of the initial values. According to [20,28], the compressive strength of the foam glass depends not only on the density of the material but also on thickness of the struts and the crystalline composition. The authors of [26] found a strong relationship between the compressive strength and the amount and size of

air voids. The effect of porosity on foam glass properties has been discussed, e.g. in [29]. According to other studies [14], a strengthening effect can be obtained by a reduction and self-assembly of nanoglobules in the non-crystalline matrix. However, it is challenging to derive more general conclusions about different temperatures and for the effect of absorbed water on the compressive strength of foam glass.

Considering the increasingly versatile applications of foam glass, it is indispensable to carry out comprehensive laboratory testing before practical application of this material under combined environmental and mechanical loads, especially in applications requiring high reliability. A growing demand for foam glass granules and gravel (loose pieces) [30] that can be used as aggregate for lightweight concrete makes this issue all the more important. That said, the verified chemical and mechanical properties of foam glass are considered most promising and desirable, especially when compared to other commonly used inorganic fibrous materials containing or even emitting potentially hazardous fibres [2].

Information on the durability of foam glass and its long-term performance under the combined effect of various and time-varying external factors can hardly be found in the literature or the manufacturers' guidelines. Also, the combined effect of adverse external factors, such as water and temperature on the otherwise considered virtually unlimited service life of foam glass [31], should be verified. Obviously, porous structure must increase water absorption, and when exposed to high temperatures, this water turns into steam at high pressure, which may destroy the cell walls, resulting in a decreased strength and/or loss of volume. Therefore, it is essential to determine the effect of the above-mentioned factors on the physical properties of foam glass subjected to varying load factors.

In the authors' opinion, it is vital to determine the physical parameters of foam glass that are critical to a specific application. Not taking into account the particular conditions of application and the resulting lack of protection from external factors that may change the physical parameters of foam glass can lead to failures. An example of such failures is the case of the petroleum product storage tank, founded on a layer of foam glass panels, which is analysed in this paper. The primary cause of that failure was very uneven subsidence of the tank walls due to highly varying deformation of the tank base insulation made of foam glass. Brittle crushing of the foam glass occurred after several years of operation, during which the material gradually deteriorated under the combined effect of water and steam penetrating into the insulation, high temperature of the stored product and the imposed mechanical load.

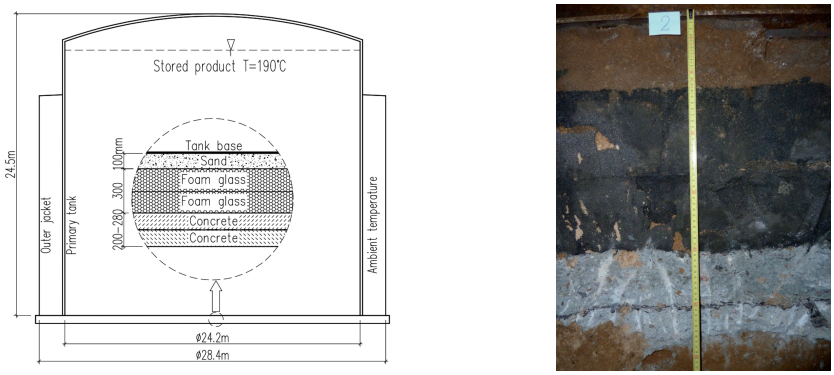
This article presents the experimental research on foam glass working under varying moisture and temperature conditions. The long-term performance, key to its application as tank base insulation.

2. Materials and methodology

2.1. Materials

The material under analysis was foam glass used as a base insulation of a steel tank designed to store products at 200°C. The brand new material, applied in this case, had a closed cell structure and following parameters declared by the producer: bulk density

of 120 kg/m^3, compressive strength 0.70 MPa, vapour-tight, water absorption resistance, thermal resistance to 430°C, resistance to chemical and biological factors. The basic properties of the undamaged/new foam glass were verified experimentally, whereby the thermal resistance was tested up to the temperature required by design (200°C), and some samples did not reach the manufacturer's declared compressive strength of 0.70 MPa. The tank in question was a double-wall, vertically oriented cylindrical structure featuring a single wall bottom – Fig. 1a. Due to the high temperature of the stored substance, thermal insulation was provided both to the inner (primary) tank and to the tank bottom. In the latter case, insulation of appropriate mechanical strength was required due to pressure in the region of 0.25 MPa imposed thereon by the product and by the tank itself. This being so, foam glass was chosen, being a material featuring high mechanical strength and resistance to elevated in-service temperatures. The tank sub-base construction is shown in Fig. 1b. On the 200–280 mm thick concrete bottom slab there are two layers of foam glass, 300 mm nominal thickness, covered by a 100 mm thick layer of sand, with a steel bottom plate resting on the top.



(a) (b)

Fig. 1. Diagram of the tank and sub-base construction: (a) tank, (b) tank sub-base

After a few years of service, the primary tank was found to have settled down considerably, with an almost completely unchanged foundation level in the outer jacket area. The influence of soil and concrete slab subsidence was excluded based on examination of several test pits and various elements that could be blamed for this situation. It turned out that the tank settled down due to damage and, in places, even a complete failure of the foam glass insulation in the area under the primary tank. An example of a tank base including an undamaged foam glass layer is shown in Fig. 1b and a base with damaged foam glass is shown in Fig. 2a, 2b, and 2c. As it can be seen, in some places the insulation layer that was initially 300 mm thick (Fig. 1a and Fig. 1b) turned into 80–90 mm thick damp and compressed lump (Fig. 2a and Fig. 2c).

The picture in Fig. 1b represents the interstitial space of the tank, i.e. the zone beyond the effect of the heat emitted by the stored product. Although damp, the foam glass was

(a) (b) (c)

Fig. 2. Tank base with damaged foam glass, 80–160 mm thick

not damaged there. Figures 2a and 2c show the situation under the tank bottom near its wall, i.e. where the tank base was exposed to both heat and pressure exerted by the stored material, the tank wall and roof. The magnitude of deterioration of the foam glass layer was the greatest there. Figure 2b, in turn, shows the situation under the central part of the tank, where the underlying materials were exposed to the effect of high temperature and also mechanical loading, the latter limited to the weight of the stored product only. This exposure caused deterioration of only one layer of foam glass with the other one remaining in good condition.

Where two separate layers of deteriorated foam glass could be identified in the tank pad (Fig. 2a and 2b), surface undulations of the lower layer were very pronounced (Fig. 3a). On the other hand, where the division into the two layers was hardly distinguishable (Fig. 2c), the deterioration was very severe and the foam glass turned into a wet, compressed lump (Fig. 3b).

(a) (b)

Fig. 3. Surface undulations of the lower foam glass layer (a) and foam glass deterioration (b)

Based on the declared parameters, foam glass should be considered an absorption-resistant material, suitable for thermal insulation applications involving exposure to high

temperatures and high loads, as in the case under analysis. However, in the analysed case, the interaction of the above-mentioned factors has led to deterioration and even failure of this material. In order to identify the causes of such degradation and determine the sensitivity of foam glass to the adverse external factors, such as heat, stress and water and their combinations samples were taken from the pits made in the tank bottom.

2.2. Test method

The choice of the test method was based on the type and history of the material and the purpose of testing, which was to evaluate the foam glass parameters, as specified in the relevant standards and to reflect the actual operating conditions under the tank bottom.

With most of the samples found excessively damp, and considering the declared resistance of foam glass to water absorption, it was decided to determine the moisture content with greater accuracy. To this end, the loss-on-drying technique was used. The samples, after being taken from under the bottom of the tank, were secured in plastic packaging. The moisture content was determined on the specimens representing all the respective test zones of the tank base, differing in size and in the apparent moisture content. The specimens were weighed and then dried to constant weight at 105°C.

Next, the samples taken from under the bottom of the tank were assessed for conformity with the requirements of the material group to which foam glass belongs. After a preliminary macroscopic assessment, which confirmed such conformity, the chemical composition of the samples was determined and compared with that of a brand new material. The chemical composition was determined with atomic emission spectroscopy (AES) using a fibre optic diode array micro-spectrometer.

The essential part of the test program was to assess the compressive strength and determine the failure mechanisms of foam glass under different conditions. The provisions of EN 826 [32] were taken into account, yet subject to the limitations due to available size of samples taken from the tank footprint area. Thus specimens of two sizes were prepared: 200 × 200 mm, as prescribed by the [32] and 100 × 100 mm, to make the most of the sampled material and maximise the number of specimens. Also, while taking into account the standard requirements, the test conditions reflected as much as practicable the actual exposure conditions of foam glass under the tank. Therefore, the following series of specimens and test set-ups were applied:

– specimens of 200×200 mm and 100×100 mm in area, thickness as sampled. Pressure plates, transferring the load without bituminous separators,
– specimens of the same dimensions as above and pressure plates fitted with bituminous separators,
– specimens of 200 × 200 mm and 100 × 100 mm in area – pressure plate without a bituminous separator and specimens resting on a sand base. Considering the temperature of the stored product, the sand on which the specimens were placed was heated up by a hot plate of 200°C surface temperature, i.e. the tank bottom temperature during storage. This arrangement reflected the exposure conditions of the foam glass

installed under the tank which was laid on a concrete base layer and topped with a layer of sand, separating it from the tank bottom plate,

– specimens of the same dimensions as above – pressure plate fitted with a bituminous separator and specimens resting on a sand base. This arrangement approximated the exposure conditions of the upper layer of foam glass insulation under the tank. The same as in the previous arrangement, in most cases the sand layer was heated up by a plate of 200°C surface temperature.

The specimens of the standards size of 200×200 mm allowed comparison of the results with the declared strength parameters and the non-standards specimens of 100 × 100 mm were used to obtain sufficient amount of the test data, taking into account the limited availability of the test material. Thus, the total number of 34 specimens made of foam glass sampled from the area under the tank footprint were tested for compressive strength.

The test set-up included Instron 3382 load frame. The testing speed was adopted according to the [32], i.e. 1/100 sample height per minute.

In addition, the behaviour of the foam glass sampled from the tank footprint area was tested under the load corresponding to the pressure exerted by the filled up tank (inducing a stress of 0.25 MPa) and without such loading, in both cases after heating-up the specimens to the temperature under the tank bottom.

In the first stage, the specimens were placed on a layer of sand, intended to reflect the layer of sand pressing down the foam glass under the tank. The test load was limited to a level corresponding to a stress of 0.25 MPa.

The following test the specimens were exposed to a high temperature with no applied load. Heated specimens came from the tank footprint area, from the cuts made in the area under the interstitial space. They were damp but not exposed to the heat emitted by the tank bottom. Specimens dimensions were as required for testing the compressive strength on the load frame. Two heating methods were used to heat the specimens to 200°C: all-around heating in a laboratory oven and one-sided heating on a hot plate.

The vast majority of the strength test specimens (except 5/*.* – Table 2) were from the interstitial space of the tank, where they were not subjected to high pressure but were exposed to water and steam at high temperatures. Samples for testing were taken from material with relatively well-preserved structure – material with severely damaged structure was not suitable for testing. Samples with varying degrees of saturation were taken for testing, some of which were dried.

3. Results and discussion

3.1. Determination of the saturation level of foam glass

The saturation levels, defined by the percent of liquid contained in the respective specimens are given in Table 1 and an example of the test specimen is shown in Fig. 4. The greatest liquid content was determined on the specimens sampled from the lower layer of foam glass obtained from the test pits under the interstitial space (specimens No. 1/2a,

2/2, 3/2) and in the more damp specimens taken from the pits located in the inner tank (specimens No. 6/1a, 6/1b, 7/1). It means that excessive water absorption occurred both in the area exposed to the heat emitted by the tank bottom (samples 6/1a, 6/1b, 7/1) and in the area without such exposure (samples 1/2a, 2/2, 3/2). In the latter case, the foam glass was exposed only to an elevated temperature of the stored liquid, which after being heated in the central part of the tank, migrated to other part of the tank bottom.

Table 1. The content of liquid in percent

No.	Specimen No.	Weight of wet foam glass [g]	Weight of dry foam glass [g]	Liquid content [g]	Liquid content [%]
1	1/1	727.2	492.2	235.0	47.7
2	1/2	1461.3	1083.9	377.4	34.8
3	1/2a	888.6	357.5	531.1	148.6
4	2/2	1349.3	585.4	763.9	130.5
5	3/1	729.6	509.0	220.6	43.3
6	3/2	3645.7	1720.7	1925.0	111.9
7	4	417.1	227.2	189.9	83.6
8	5/1a	204.7	150.3	54.4	36.2
9	5/1b	126.0	86.8	39.2	45.2
10	5/2a	414.0	274.9	139.1	50.6
11	5/2b	279.5	169.9	109.6	64.5
12	6/1a	171.3	80.3	91.0	113.3
13	6/1b	120.0	48.9	71.1	145.4
14	6/2	676.8	369.1	307.7	83.4
15	7	471.5	268.1	203.4	75.9
16	7/1	184.3	65.9	118.4	179.7
17	8	641.7	335.2	306.5	91.4

In all the specimens, the liquid content was greater than 4 kg/m^2, i.e. many times the limit of 0.5 kg/m^2 for long-term partial immersion of foam glass, as prescribed by [25].

A significant degree of saturation of the foam glass results in a deterioration of its thermal insulating capacity. Taking into account the thermal conductivity coefficients of foam glass and water at a temperature of 200°C amounting to 0.076 W/(m·K) and about 0.66 W/(m·K) respectively, without detailed research and analysis, it can be concluded that such a high saturation of foam glass will result in a several-fold decrease in its thermal insulating capacity. This property was further deteriorated by a 2–3 times reduction of the layer thickness. Investigations into the degree of saturation of the foam glass also indicate that the closed cell structure of the material has been significantly damaged. The

Fig. 4. Cross-section through an saturated foam glass specimen

simultaneous interaction of water and high temperature, and consequently water vapour, led to damage of the pore walls and a change in the structure to an open porous one, susceptible to saturation. The tested material was already saturated, so the pore structure was damaged, and therefore it was not possible to study the structure degradation process. Evaluation of this phenomenon will be carried out on a new undamaged foam glass.

3.2. Determination of the chemical composition of foam glass

The chemical analysis, determined with atomic emission spectroscopy (AES) using a fibre optic diode array micro-spectrometer, revealed the presence of silicon, calcium, magnesium, aluminium, sodium, potassium and iron in the specimens sampled in the tank footprint area. More deteriorated specimens contained more iron and also more calcium, aluminium and potassium.

In addition, the most deteriorated specimens had pH = 10, higher than the other ones. However, the chemical composition was largely the same among all the analysed specimens, meaning that the pH had no effect in this respect.

The same applied to the specimens made of the brand new material, i.e. they had a very similar composition irrespective of the prior treatments. Moreover, their composition was very close to the composition of the material sampled from the tank footprint area. Potassium was not found and the amounts of calcium and aluminium were higher and lower respectively, as compared to the control. However, such differences in the chemical composition should be considered insignificant for foam glass.

The same elements were found in the tested sample of liquid. The pH of the liquid was about 10, which corresponds to the pH of the most deteriorated specimen and of the water solution formed during heating of the concrete sampled from the tank footprint area in contact with water. Considering the amount of calcium hydroxides present in the concrete and possible leaching of these hydroxides by soft rainwater, this mechanism was considered the most probable cause of the basicity of the liquid contained in the foam glass.

The analyses showed that in all cases we deal with the same type of construction material, namely foam glass, and the differences in the chemical composition should be considered insignificant.

3.3. Destructive tests of foam glass

A number of conclusions can be derived from the compressive test results. Some of them are common to all four groups of tested elements, and some are divergent, due to the specific circumstances of a specific test. The results are summarised in Table 2.

Table 2. Strength and failure mode of tested specimens

Specimen No.	Dimensions $a \times b \times h$ [mm]	Failure load [kN]	Stress [MPa]	Strength > 0.7 MPa	Dominant failure mode
Series 1					
1/2.1	200×200×150	16.6	0.415	no	Sudden horizontal fracture at half the height
1/2.2	200×200×150	21.4	0.535	no	Gradual crushing in the pressure zone
1/2.3	200×200×150	30.0	0.750	yes	Gradual crushing in the pressure zone
1/1.1	100×100×150	5.1	0.510	no	Sudden horizontal fracture at half the height
1/1.2	100×100×150	6.7	0.670	no	Gradual crushing in the pressure zone
1/1.3	100×100×120	5.0	0.500	no	Gradual crushing in the pressure zone
1/1.5	200×200×150	23.8	0.595	no	Vertical fracture, splitting and crushing
3/2.1	100 × 100 × 90	9.4	0.940	yes	Cracking and separation in the oblique and vertical planes in the lower part of the specimen and crushing
3/2.2	100 × 100 × 90	8.2	0.820	yes	Gradual crushing in the pressure zone
3/2.3	200×200×150	20.0 (25.4)*	0.500 (0.635)*	no	Horizontal fracture in the lower part, gradual crushing in the pressure zone
3/2.4	200×200×150	27.4	0.685	no	Gradual crushing in the pressure zone

Continued on next page

Table 2 [cont.]

Specimen No.	Dimensions $a \times b \times h$ [mm]	Failure load [kN]	Stress [MPa]	Strength > 0.7 MPa	Dominant failure mode
3/1.4	100 × 100 × 90	4.8	0.480	no	Gradual crushing in the pressure zone
3/1.5	100 × 100 × 90	4.0	0.400	no	Gradual crushing in the pressure zone
5/1.1	100 × 100 × 55	5.2	0.520	no	Fracture and splitting in oblique and vertical planes
5/1.2	100 × 100 × 60	4.6	0.460	no	Fracture and splitting in the oblique and vertical planes
Series 2					
1/1.6	100 × 100 × 70	9.2	0.920	yes	Sudden vertical fracture
3/1.6	100×100×100	13.0	1.30	yes	Sudden horizontal fracture and splitting
Series 3					
1/1.6	200×200×150	12.5	0.313	no	Sudden horizontal fracture at half the height
2/1.1	200×200×150	10.0 (13.3)*	0.250 (0.333)*	no	Fracture and splitting in the oblique and vertical planes
2/1.3	100×100×130	3.8	0.380	no	Vertical fracture and splitting in the lower part
2/1.4	100×100×130	4.0 (4.2)*	0.400 (0.420)*	no	Fracture and splitting in the oblique plane in the lower part
3/1.1	200×200×150	15.8 (16.4)*	0.395 (0.410)*	no	Sudden horizontal fracture at half the height
3/1.2	200×200×150	15.7 (17.7)*	0.393 (0.443)*	no	Fracture and splitting in the oblique and vertical planes in the lower part
3/1.3	100×100×130	5.5 (5.8)*	0.55 (0.58)*	no	Fracture and splitting in the oblique and vertical planes in the lower part
Series 4					
2/1.5	100×100×125	4.0	0.400	no	Fracture and splitting in the oblique and vertical planes in the lower part
2/1.6	100×100×125	3.3	0.330	no	Sudden oblique fracture

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Table 2 [cont.]

Specimen No.	Dimensions $a \times b \times h$ [mm]	Failure load [kN]	Stress [MPa]	Strength > 0.7 MPa	Dominant failure mode
2/1.7	200×200×145	15.0	0.375	no	Sudden horizontal and vertical fracture
3/2.5	100×100×150	3.9	0.390	no	Sudden fracture in the upper part
3/2.6	100×100×150	5.0	0.500	no	Fracture and splitting
3/2.7	100×100×135	4.6	0.460	no	Fracture and splitting in the oblique plane in the lower part
3/2.8	100×100×150	4.3	0.430	no	Sudden horizontal fracture at half the height
3/2.9	100×100×125	3.5 (4.6)*	0.350 (0.460)*	no	Fracture and splitting in the oblique plane in the lower part
3/2.10	200×200×135	7.0 (11.8)*	0.175 (0.295)*	no	Sudden horizontal fracture in the lower part
3/2.11	100×100×140	–	0.25**		Fracture and splitting in the oblique plane in the lower part

* – maximum load/stress in the phase following fracture, ** – constant load.

In the test series No. 1 (pressure plates without bituminous separators) most specimens did not reach the declared compressive strength of 0.7 MPa and three main failure modes have been identified:

- sudden fracture at half the height of the specimen, accompanied by a cracking sound and shock (Fig. 5a and 6a),
- gradual crushing of the sample at the interface with the hard plate, in some cases preceded by a sudden fracture of the specimen (Fig. 5b and Fig. 6b),
- fracture and splitting in the vertical and oblique planes (sometimes accompanied by crushing in the pressure zone (Fig. 6c and 6d).

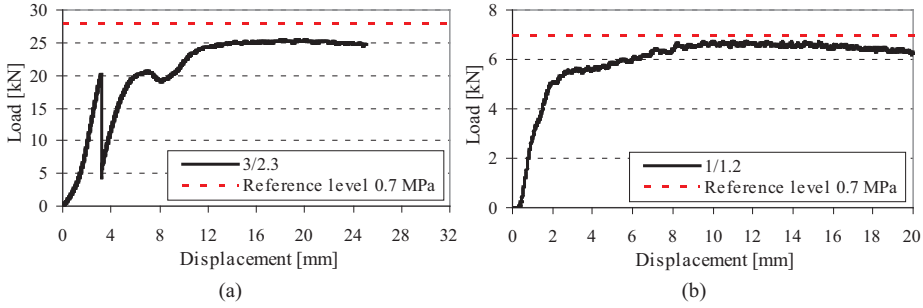


Fig. 5. Load-displacement diagram: (a) specimen 3/2.3 200 × 200 mm – horizontal fracture mode, (b) specimen 1/1.2 100 × 100 mm – gradual crushing mode

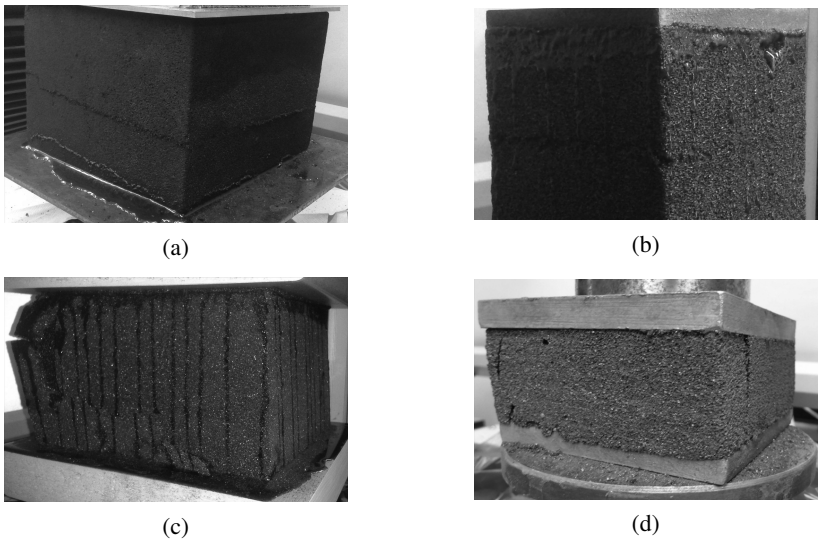


Fig. 6. Example of samples during the tests: (a) horizontal fracture, (b) crushing in the pressure zone and horizontal fracture, (c) crushing in the pressure zone and splitting, (d) fracture in different planes

The liquid contained in the specimens was intensively squeezed during load application.

A vast majority of the specimens of series No. 1 did not reach the declared compressive strength of 0.7 MPa, yet all had sufficient capacity to withstand the maximum stress under the tank bottom, i.e. 0.25 MPa. Different failure models resulted from varies degrees of saturation and deterioration of the material. Crushing of the material at the interface with the hard plate was the prevalent failure mode. In other cases, material cracking was observed in different planes and of different intensity.

In series No. 2, where the pressure elements were fitted with bituminous spacers, the specimens reached a strength of 0.7 MPa (Table 2) and two failure modes were identified: vertical fracture (Fig. 7 and Fig. 8a) and horizontal fracture (Fig. 8b).

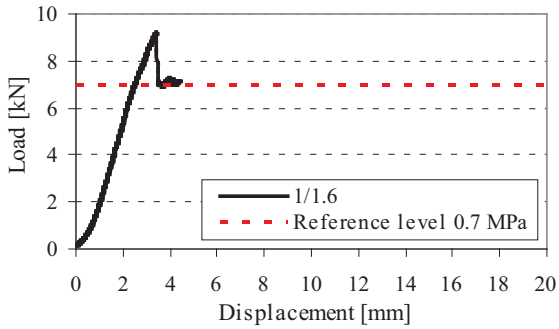


Fig. 7. Load-displacement diagram for vertical fracture mode – specimen 1/1.6 100 × 100 mm

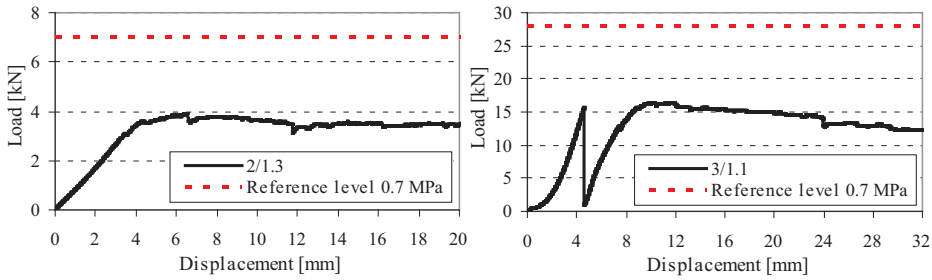
(a) (b)

Fig. 8. Example of samples during the tests: (a) vertical fracture, (b) horizontal fracture

The series No. 2 specimens achieved the declared compressive strength of 0.7 MPa. Bituminous spacers eliminated the prevalent failure mode, namely crushing of the foam glass at the interface with hard surfaces, in this way increasing the obtained compressive strength.

In series No. 3, the specimens were placed on the sand base and pressed by the load plate without a bituminous spacer. None of the samples reached the strength of 0.7 MPa (Table 2). Two failure modes were identified in this series:

– fracture in an oblique and/or vertical plane, initiated at the bottom of the specimen, where the specimen rested on the hot sand base (Fig. 9a and Fig. 10a), which was sudden in the case of damper specimens,
– sudden horizontal fracture at half the height of the specimen (Fig. 9b and Fig. 10b). This failure mode was noted only for 200 × 200 mm specimens.



(a) (b)

Fig. 9. Load-displacement diagram: (a) specimen 2/1.3 100 × 100 mm – vertical fracture mode, (b) specimen 3/1.1 200 × 200 mm – sudden horizontal fracture mode

None of the series No. 3 specimens reached the declared compressive strength of 0.7 MPa yet all had sufficient capacity to withstand the maximum stress under the tank bottom, i.e. 0.25 MPa. The maximum achieved loads did not induce stresses that would initiate crushing of the specimen material in the pressure zone, how it occurred in series

(a) (b)

Fig. 10. Example of samples during the tests: (a) vertical fracture, (b) horizontal fracture

No. 1, even though the load was applied directly by hard plates. Thus the specimens failed by fracture initiated at the bottom due to limited stability of the sand base or fractured at other locations, especially in the case of larger samples for which the stability of base was of lesser importance. In the latter case, the fracture was not initiated near the sand base.

In the series No. 4 the specimens resting on sand base were loaded through bituminous separators. The same as in the previous case, none of the specimens reached the strength of 0.7 MPa (Table 2), and two prevalent failure modes were identified:

– sudden fracture in a horizontal, vertical or oblique plane, not initiated in the lower part of the specimen (Fig. 11 and Fig. 12a),
– fracture in the oblique and vertical planes initiated in the bottom part of the specimen (Fig. 12b). During the failure of wetter specimens, pieces of foam glass fell off at the interface with hot sand base, producing a loud sound.

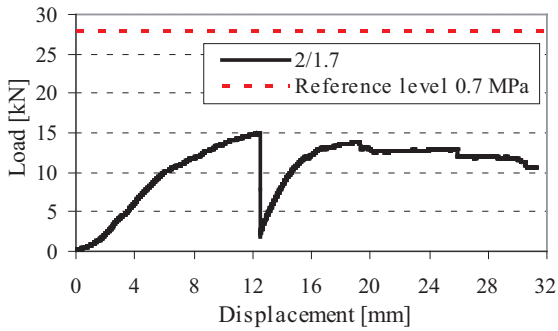


Fig. 11. Load-displacement diagram for the sudden horizontal fracture mode – specimen 2/1.7 200 × 200 mm

None of the series No. 4 specimens reached the declared compressive strength of 0.7 MPa, yet a majority of them had sufficient capacity to withstand the maximum stress under the tank bottom, i.e. 0.25 MPa. As in tests without the bituminous separators, the prevalent failure mode was the fracture initiated at the bottom of the specimen, at the

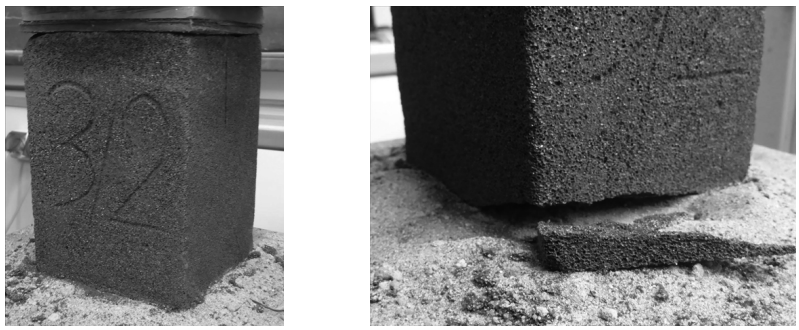
(a) (b)

Fig. 12. Specimens during the tests: (a) horizontal fracture, (b) oblique and vertical fracture

interface with the sand base. Also noted were horizontal and oblique fractures not initiated near the interface with the sand base. The breaking loads were at the same level as in the testing of series No. 3, which means that the bituminous separator did not increase the measured compressive strength of the specimens.

Of the 34 samples tested, only 5 reached the declared compressive strength of 0.7 MPa. In 26 cases, failure consisted of cracking and crushing of the specimens, with horizontal cracks in 9 specimens while vertical and oblique cracks in the remaining specimens. The other 8 specimens were destroyed by crushing in the pressure zone. Thus, the study shows that generally only 15% of the samples achieved the declared compressive strength under complex thermal and moisture conditions.

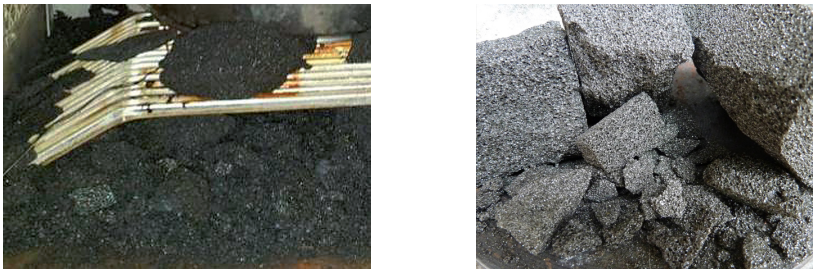
In the next test the foam glass was placed on a layer of sand heated up to the temperature under the tank bottom, and a constant load was applied to induce stress of 0.25 MPa (corresponding to the stress under the most heavily loaded zone of the tank bottom). The observed process of deterioration was very rapid and manifested by fracture and splitting in an oblique plane in the bottom part of the specimen (Fig. 13), accompanied by falling off of various size pieces of glass, producing a loud sound in the process.



(a) (b)

Fig. 13. A sample during the tests: (a) initial phase, (b) chipping in the bottom part of the specimen

The phenomena observed in the material subjected to simultaneous heating and loading called for a subsequent test to assess the behaviour of foam glass exposed to the specified temperature of 200°C without any mechanical loading. During heating in the laboratory oven already at ca. 130–140°C, the foam glass started to crack, producing crackling sounds to get completely destroyed when the temperature reached 200°C (Fig. 14a). Heating of samples from one side only up to the specified temperature of 200°C also caused their failure (Fig. 14b).



(a) (b)

Fig. 14. Heating of samples at 200°C: (a) completely destroyed samples after all-around heating in the laboratory oven, (b) cracked foam glass specimens after one-sided heating on a hot plate

4. Conclusions

This paper presents research concerning the application of foam glass as a sub-base material for a industrial building exposed to high temperatures and varying humidity conditions. Foam glass used as an insulating material usually has a closed cell structure and density ranging from about 100 kg/m^3 to 200 kg/m^3. Closed structure of pores has a positive influence on a number of foam glass parameters, such as: mechanical strength, thermal conductivity, resistance to water and steam, as well as chemical compounds. Increasing the proportion of open pores in the material structure deteriorates the above mentioned parameters, while increasing the material density improves the strength parameters, simultaneously decreasing the thermal insulation properties of foam glass. In this case, the particular material used for tank bottom insulation was tested – foam glass with originally closed cell structure and density of 120 kg/m^3.

The research presented here concerns the foam glass applied as thermal insulation under the bottom of a tank, used to store a product at 200°C, which suffered significant deterioration after only a few years of operation, which led to failure and decommissioning of the tank. The magnitude of deterioration varied, depending on the exposures in the different areas of the tank base. Total material destruction occurred in the zone of simultaneous temperature and the maximum load imposed by the tank. Moderate degradation of foam glass occurred in the area of thermal impact at diminished pressures at the bottom of

the tank. The least significant changes, generally limited to dampness, occurred where the material was not exposed to large pressures or direct heating.

Regardless of the thermal and mechanical loading the tested foam glass was highly saturated, all the cases, many times above the limit prescribed by the relevant standard. This means that, in the analysed case, the material was not resistant to damage of the closed cell structure and failed to resist absorption in the long-term run. This is a serious consideration as regarding the practical application of this material where even a small, hardly detectable waterproofing leakage can cause uncontrolled, gradual deterioration of the foam glass insulation. In the present case, the soaking of the foam glass was caused by rainwater penetrating under the bottom of the tank through a leak in the joint between this bottom and the foundation.

Absorption of water considerably affects reducing the foam glass performance. Investigations show that the foam glass generally does not reach the declared compressive strength. Moreover, it becomes more prone to progressive deterioration at an interface with a hard surface, especially if non-uniform and rough, such as a layer of sand. If this surface is additionally heated to high temperature, the foam glass undergoes destruction by chipping or crushing just at stresses several times lower than the limits for this material, and even with no applied load. Prolonged exposure of wet foam glass to high temperatures results in a virtually complete destruction of the material.

The test results presented in this article shows that particularly unfavourable for foam glass is the long-term combined action of water and high temperature, and gravity loads further increase this adverse effect. Therefore, particular care should be taken to protect the foam glass from moisture when used as an insulation in applications involving high temperatures. The applied protection must be effective at all times. In practice, this means that, in addition to durable waterproofing to prevent the possibility of water penetrating into the foam glass, it is necessary to design effective drainage in case a water insulation is damaged. Failing to provide such protection may result in serious and complicated hard-to-recover damages, not only to the foam glass itself, but also to the structure on which it is applied. With this in mind, caution should be exercised when using foam glass in situations subject to high temperatures, where the risk of moisture in the foam glass cannot be excluded and damage to this material has consequences beyond the simple replacement of the foam glass.

In order to obtain a better insight into the above described properties of foam glass the same tests were carried out on a brand new material, not previously exposed to thermal and humidity influences. The results will be presented in a separate publication.

Acknowledgements

The authors would like to thank Prof. Andrzej Garbacz (Department of Building Materials Engineering, Faculty of Civil Engineering, Warsaw University of Technology) for a very valuable discussion and Dr. Stanisław Kuś (Department of Analytical Chemistry, Faculty of Chemistry, Warsaw University of Technology) for performing atomic emission spectroscopy (AES) tests.

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Ocena długoterminowych właściwości użytkowych szkła piankowego jako podłoża izolacyjnego w zróżnicowanych warunkach wilgotnościowych i temperaturowych

Słowa kluczowe: szkło piankowe, właściwości długoterminowe, nasiąkliwość, wysoka temperatura, wytrzymałość na ściskanie

Streszczenie:

W artykule przedstawiono ocenę właściwości szkła piankowego, popularnego materiału izolacyjnego stosowanego w różnych gałęziach przemysłu, m.in. w budownictwie, chemii i obronności,

po kilku latach użytkowania w zmiennych warunkach obciążenia, temperatury i oddziaływania wody. Badaniom poddano materiałzastosowany jako podłoże izolacyjne pod stalowym zbiornikiem przemysłowym, który uległawarii grożącej wyciekiem magazynowanego medium o temperaturze 200°C. Po dokonaniu oceny makroskopowej i materiałowej próbek szkła piankowego, zbadano jego wytrzymałość na ściskanie, absorpcję wody oraz zachowanie się w złożonych warunkach obciążeniowych, termicznych i wilgotnościowych. Wyniki badań wykazały, że szkło piankowe poddane jednoczesnemu działaniu wody i podwyższonej temperatury ulega stopniowej degradacji, co skutkuje obniżeniem deklarowanych parametrów technicznych i utratą przydatności użytkowej. Oznacza to, że zapewnienie niezawodności szkła piankowego eksploatowanego w warunkach wysokich temperatur wymaga bezwzględnie skutecznego i trwałego zabezpieczenia tego materiału przed działaniem wody. Brak takiej ochrony może doprowadzić do poważnych i trudnych do usunięcia uszkodzeń nie tylko samego szkła piankowego, ale również konstrukcji, do izolacji której szkło piankowe zostało zastosowane.

Received: 21.10. 2021, Revised: 24.02. 2022