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A New Glass to Join Foam Glass Components

Andrea Ventrella, Federico Smeacetto, Milena Salvo, Monica Ferraris, and Massimiliano Avalle

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This work describes the design and development of a new glass-based joining material, suitable to be applied as slurry between two components of foam glass to be joined. Shear strength tests have been done on as received and on joined samples, measuring a 0.095 and 0.075 MPa, respectively.

Keywords foam glass, joining, slurry, shear tests

1. Introduction

Heating and cooling of buildings account for more than 25% of the total energy demand in Europe; improved energy efficiency and associated greenhouse gas emission reduction are imposed by increasing legislative and environmental pressure, as a consequence, the importance of effective insulation in building also increases (Ref 1).

The European market of insulation materials is dominated by two groups of products: inorganic fibrous and inorganic or organic foamy materials; typically, the insulation materials for applications above 60 °C (i.e., several process plants) are based on rockwool, foam glass, or calcium silicate fibers.

Among insulation materials, foam glasses are increasing their significance because of their effective role in energy saving and for their advantages compared to fiber- or polymer-based insulating materials (Ref 2). Furthermore, foam glass is suitable for internal or external insulation of both civil buildings and technological plants.

The use of foam glass as a structural and highly effective thermal insulation material has raised the question of its joining. Just a few joining materials and joining techniques are available for foam glass (Ref 3): adhesives are generally used to join foam glass insulation to vessels, tanks, chambers, etc., and to join foam glass panels during fabrication (Ref 4).

A simple mechanical joint (rivets, screws, fixing brackets, etc.) is often unsuitable, because foam glass is brittle and a mechanical joint is not tight. There are some hybrid joints resulting from the combination of a mechanical joint with an adhesive, but, to the best of authors' knowledge, none of them use a glass as joining material for foam glass.

The new solution proposed in this article is a glass joining materials for foam glass, cheap, reliable, and easy to obtain by slurry deposition and heating directly on foam glass.

Andrea Ventrella, Federico Smeacetto, Milena Salvo, and **Monica Ferraris**, Materials Science and Chemical Engineering Department, Politecnico di Torino, Corso Duca Degli Abruzzi 24, I-10129 Turin, Italy; and **Massimiliano Avalle**, Mechanical Engineering Department, Politecnico di Torino, Corso Duca Degli Abruzzi 24, I-10129 Turin, Italy. Contact e-mail: monica.ferraris@polito.it.

The main advantage of this new joining material and technique for foam glass is the possibility of obtaining insulation materials in large and complex shapes, while overcoming typical problems (i.e., thermal bridging) occurring with traditional systems (i.e., mechanical joints and/or polymeric adhesives) where the material continuity is interrupted. In this case, a foam glass is joined by a glass, having the same thermomechanical properties.

A lead free glass in the system Na_2O-B_2O_3-ZnO, previously designed and developed as coating material (Ref 5, 6), has been used as joining material for foam glass.

2. Experimental

The composition of the foam glass used in this work (Foamglas®, Pittsburgh Corning, USA) and of the glass (referred to as G7) used to join Foamglas® is shown in Table 1.

Foamglas® is a porous heat-insulating and sound proof material, with true porosity up to 90-97%. The foam glass forms thin porous walls of single cells several micrometers thick and the closed cells are filled with gases. Details about its preparation and properties can be found in (Ref 7).

The glass joining composition was designed by using SciGlass™ and literature data in order to obtain thermomechanical properties matched with those of the Foamglas® parts to be joined (Ref 6).

Details about glass preparation, its characteristic temperatures and thermomechanical properties are reported in (Ref 5, 6).

The as produced glass was ground by milling and sieved to a grain size lower than 60 μm; slurry (solid content 40 wt.%) was prepared by mixing glass powders with ethanol as organic binder.

The slurry has been deposited between the two Foamglas® panels at room temperature, in order to obtain a sandwich-like structure. The optimized joining heat treatment was performed in a laboratory oven at 550 °C for 60 min in air atmosphere with a pressureless process (Ref 6). Reproducible results in terms of thickness homogeneity were obtained.

The morphological characterization of joined samples was performed by Scanning Electron Microscopy SEM (FEI Inspect, Philips 525 M).

Samples for mechanical testing (modified asymmetrical four-point bending test, adapted from Iosipescu Test) (Ref 8, 9), were accurately machined to the required dimensions (Fig. 1a), from the as-received Foamglas® slab.

Table 1 Composition of Foamglas® and of the glass (G7) used to join Foamglas®

	Chemical composition, wt.%											
Glass ID	B_2O_3	ZnO	Na_2O	CuO	Foamglas®	SiO_2	CaO	Al_2O_3	Fe_2O_3	MnO	K_2O	Others (a)
Foamglas®			13.4		…	66.8	5.8	5.6	3			< 6
G7	50	33	12		5							

(a) MnO, K_2O, SO_3, BaO, TiO_2, SrO, Carbon

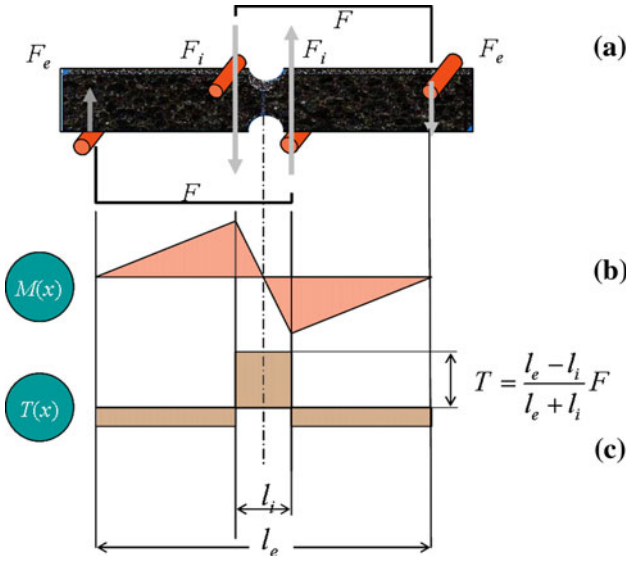

Fig. 1 Modified four point asymmetrical test: (a) schematic of loading and forces applied: F, total external load; F_i, loads acting on the inner supports; F_e, loads acting on the external supports; (b) bending moment $M(x)$ diagram; (c) shear loading $T(x)$ diagram with indication of the shear value within the inner part of the specimen

All tests were performed in a universal material testing machine (Zwick Z100, with a maximum load up to 100 kN, equipped for these tests with a smaller range load cell) using a very low constant cross-head speed (0.15 mm/s). Joined foam glass samples before and after loading are shown in Fig. 2(a) and (b).

Modified asymmetrical four-point bending tests were performed on not joined as received Foamglas® panels and on joined ones. For comparison purposes not joined Foamglas® panels heat treated at 550 °C 60 min (the same thermal treatment of the joined sample), were also tested.

Some FE analysis was carried out by the authors in order to better understand the state of stress in the specimen cross sections (between the notches). These results come from a simple linear elastic FE model of the loaded specimen by using linear solid hexahedron elements. Linear behavior seems a reasonable approximation due to the brittle nature of the considered material.

3. Results and Discussion

Figure 3 shows two Foamglas® specimen joined by the glass G7 (each half-sample has size 30 by 30 by 30 mm).

The choice of the G7 joining glass composition is mainly based on the value of its coefficient of thermal expansion (CTE = $9.19_{(200°\text{-}300\ °C)} \times 10^{-6}\ °C^{-1}$) which matches very well with that of Foamglas® (CTE = $9.24_{(200°\text{-}300\ °C)} \times 10^{-6}\ °C^{-1}$).

SEM cross section of the joined Foamglas® (Fig. 4), shows an average joint thickness of about 500 µm. No cracks in the joining region and at the interface between the glass joining material and Foamglas® are visible. A very good adhesion between the G7 joining glass and the two Foamglas® samples can be observed. As it can be seen in Fig. 4, the samples, joined at 550 °C for 60 min, maintained the pore structure of the original foam glass substrate, thus indicating that neither softening of the glass nor coalescence of pores was observed after joining heat treatment.

A SEM cross section of the interface between the G7 glass and Foamglas® is reported in Fig. 5; a continuous interface can be observed with a closed porosity in both G7 and Foamglas®, no cracks or voids are present at the interface thus indicating that this glass provides a hermetic joint. EDS measurements in two different areas revealed no diffusion of elements from the Foamglas® into the G7 and vice versa.

Modified asymmetrical four-point bending tests were performed on joined and not joined Foamglas®. The four-point asymmetrical bending test is a straightforward solution to get a pure shear loading in a specimen's section. With this type of loading the bending moment $M(x)$ drops to zero in the central section (Fig. 1b), exactly in the middle position between the supports, whereas the shear loading $T(x)$ is constant between the supports (Fig. 1c). The middle section is thus only subjected to pure shear stress. However, bending moment steeply increases from zero when shifting from the middle section along the specimen axis. To avoid failure due to combined bending and shearing away from the middle section it is necessary to reduce its strength there. A couple of symmetrical U-notches had to be machined in the specimen's middle section, as in Fig. 1(a).

This ensures to have a pure shear loading in the middle section but cannot avoid the occurrence of a nonuniform stress distribution. As is well known as the Jourawski approximation, the shear stress distribution is nearly parabolic. Figure 6 shows the results of a finite element analysis of the specimen during the test. The shear stress distribution, obtained by a simulation with hexahedral solid elements and shown for the middle section only, follows approximately the parabolic distribution predicted by the Jourawski theory, but a variation along the thickness is found.

Therefore, to estimate the (local) material strength, the usual average stress calculation is not sufficient to give an accurate evaluation. The maximum stress within the transverse section, which is the cause for the onset of failure, is in fact higher than the average: according to the Jourawski approximation the maximum stress value is 3/2 times the average (T/A) stress.

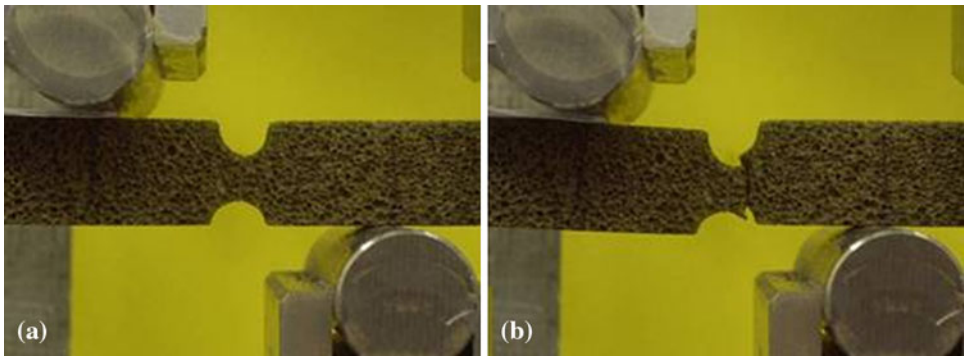

Fig. 2 Modified four-point asymmetrical test on joined Foamglas®, before (a), and after failure (b)

Fig. 3 Foamglas® specimen joined by glass G7 (half-sample size 30 by 30 by 30 mm)

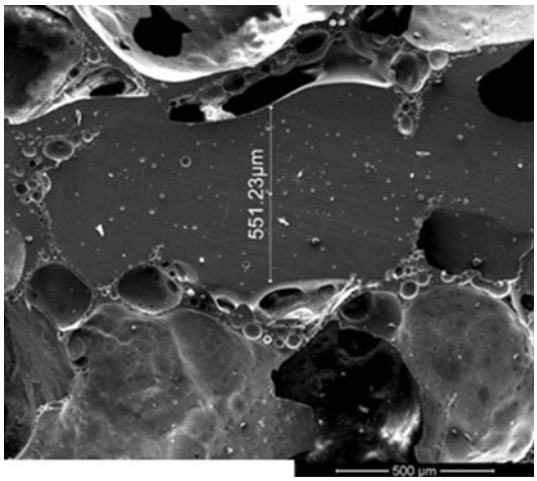

Fig. 4 Scanning electron microscopy cross section of glass joined Foamglas®

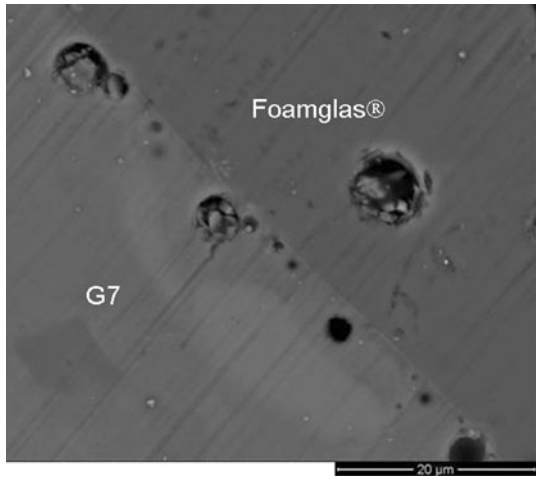

Fig. 5 Scanning electron microscopy of the interface between the G7 and Foamglas®

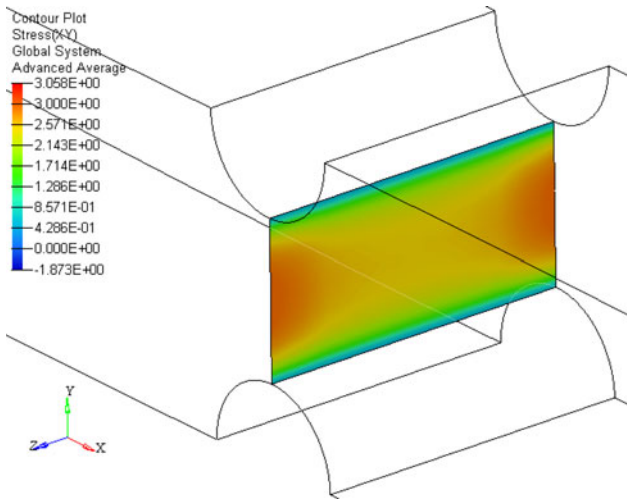

Fig. 6 Results of a finite element analysis of the specimen during the test

Compared with other test methods, such as the thin-walled tube test and the solid rod torsion test (ASTM E2207-08 and ASTM F734-95), the Iosipescu shear test uses a parallelepiped shaped specimen that is easier to obtain. Consequently, more reliable results can be obtained, and the test has become well accepted among researchers in the field (Ref 8) even if some authors (Ref 10) advice against testing high porous and brittle material (e.g., carbon foam) with the Iosipescu test. Roy et al. (Ref 10) always found premature failures in the specimens due to overstress under the loading pins. In contrast, in our experimental activity this problem has never been detected: the failure always occurred in the gauge section both for not joined and joined samples.

Table 2 Shear strength results (MPa)

Samples	Shear strength, MPa									
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	Average	SD
Joined Foamglas®	0.103	0.032	0.023	0.067	0.098	0.076	0.130	0.070	0.075	0.036
Not-joined Foamglas® samples after thermal treatment	0.039	0.112	0.118	0.078	0.030	…	…	…	0.075	0.040
As received not joined Foamglas®	0.140	0.071	0.058	0.048	0.119	0.140	…	…	0.095	0.042

In order to understand if the thermal treatment used to join the Foamglas® has an effect on its mechanical properties, tests on the three following sets have been carried out: a first set of as received not joined Foamglas®, a second group of not joined Foamglas® heated at 560 °C for 30 min for comparison purposes with the third group of Foamglas® joined by slurry at 560 °C for 30 min; Table 2 summarizes the shear strength results.

For all the joined specimens the failure occurred in the Foamglas® substrate (Fig. 2b) and never through the joined area. For the not joined foam glass specimens the failure did not occur at the center of the U-notches, as expected, but at intermediate positions.

This behavior has been experimentally studied by Borzani Manhani et al. (Ref 11) and by finite element simulation by Roy Xu et al. (Ref 12), which confirmed this mechanism: failure occurs when the maximum principal stress reaches the limit value of the brittle, foam glass. Unfortunately, this condition does not occur in the mid section where the load is pure shear, but in a nearby position, where a combination of shear load and bending moment has been calculated.

This means that this test is not suitable to measure the shear strength, but only to estimate a lower limit, since the shear strength of the joint is certainly higher than the measured value.

Even if not evident after SEM on joined samples (Fig. 4), the thermal treatment chosen to join the samples gave slightly lower shear strength (0.075 ± 0.040 MPa) than the as received Foamglas® (0.095 ± 0.042 MPa, Table 2). This problem will be likely avoided with a more suitable joining process, able to heat only the slurry and not the whole Foamglas® components to be joined.

4. Conclusions

A new glass has been designed to join Foamglas®. Shear strength tests have been performed on joined Foamglas® and on not joined as received and thermally treated samples, measuring a slight decrease in shear strength after joining process. The mechanical strength of the joint is satisfactory since its strength overcomes that of the substrates. Failure always occurred outside the joined region.

The slight decrease in mechanical strength of Foamglas® after the heat treatment could be likely avoided with a more suitable joining process, able to heat only the "joining zone" and not the whole Foamglas® tile.

The glass was found to be effective to join Foamglas®, opening the possibility of obtaining tight complex shapes and large components without using adhesives or mechanical joints.

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References

1. S. Long, A Burning Issue—Changing Perspectives on the Fire Performance of Buildings, *Global Insulation Magaz.*, May, 2008, p 28–33
2. A.M. Papadopoulos, State of the Art in Thermal Insulation Materials and Aims for Future Developments, *En. Build*, 2005, **37**, p 77–86
3. Performance Characteristics of Industrial Insulation; First Quarter 2002; Pittsburgh Corning Corporation Report, FI-PC/TN24 13.5M 4/02, Printed in USA, http://pcfoamglass.com/literature/tn24.pdf
4. C. Saponaro, Pittsburgh Corning, private communication
5. M. Ferraris, C. Saponaro, M. Salvo, F. Smeacetto, and A. Ventrella, A Method of Preparing Coated Foam Glass Articles and Articles Thereby Obtained, 2006, Patent WO2006059306, Politecnico di Torino
6. A. Ventrella, F. Smeacetto, M. Salvo, and M. Ferraris, A New Glass Coating for Foam Glass, *Int. J. Appl. Ceram. Technol.*, in press, doi: 10.1111/j.1744-7402.2009.02426.x
7. *Foamglas® Industrial Insulation Handbook*, Pittsburgh Corning Europe N.V., Brussels, Belgium, 1992
8. N. Iosipescu, New Accurate Procedure for Single Shear Testing of Metals, *J. Mater.*, 1967, **2**(3), p 537–566
9. J. He, M.Y.M. Chiang, W.G. McDonough, and D.L. Hunston, Experimental and Theoretical Evaluations of the Iosipescu Shear Test for Hybrid Fiber Composites, *SAMPE* (Long Beach, CA), 2002, p 154–164
10. A.K. Roy and J.D. Camping, Development of a Shear Test for Low Modulus Foam Materials, *Recent Advances in Experimental Mechanics*, E.E. Gdoutos, Ed., Kluwer Academic Publishers, The Netherlands, 2002, p 43–54
11. L.G. Borzani Manhani, L.C. Pardini, and F.L. Neto, Assessment of Tensile Strength of Graphites by the Iosipescu Coupon Test, *Mater. Res.*, 2007, **10**(3), p 233–239
12. L. Roy Xu, S. Sengupta, and H. Kuai, An Experimental and Numerical Investigation of Adhesive Bonding Strengths of Polymer Materials, *Int. J. Adhesion Adhesives*, 2004, **24**, p 455–460