JMEPEG (2012) 21:2380–2388
DOI: 10.1007/s11665-012-0164-9

1059-9495/$19.00

Characterization of New Glass Coated Foam Glass Insulating Tiles by Standard Tests

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

(Submitted June 15, 2011; in revised form December 22, 2011)

This article describes attempts to characterize by standardized tests of tile materials used in the construction area the performance-based properties of foamed glass samples with novel glass coatings. New glass coated foam glass (Foamglas®) insulating tiles have been tested by several standard tests (UNI Iso, ASTM) to define their suitability for energy saving buildings: impact tests, thermal shock resistance, wear resistance, water absorption, frost resistance, resistance to stains. Except for impact tests, glass coated foam glass (Foamglas®) satisfied all the requirements above, resulting to be thermal shock resistant, according to Uni Iso 10545-9 (Al spheres); effective to reduce the pristine Foamglas® surface water absorption, according to Uni En 1609:1999 and 12087:1999; frost resistant, according to Uni Iso 10545-12 and class 5 towards olive oil, according to Uni Iso 10545-14. Wear tests and hot water corrosion behavior tests have been done on the proposed coating and on a commercial soda-lime glass: the glass coated foam glass resulted to be suitable where corrosion and wear resistance are not a concern.

Keywords foams, glass, insulation

1. Introduction

A good thermal insulation of buildings is today more and more requested for energy-saving purposes (Ref 1). Among insulating materials, foam glasses are increasing their importance because of their advantages compared to other insulating materials, in particular, toward inorganic fibrous materials which have main drawbacks such as dust emission and/or the presence of potentially hazardous fibers (Ref 2). Foam glasses are fiber-free inorganic insulation materials with the additional advantage of being made by recycled materials.

Foam glasses are suitable for internal and external insulation of civil buildings and industrial implants, but they need to be coated: currently available coatings have relatively high cost or poor aesthetic appearance (Ref 3).

Glass coated foam glasses can be of potentially high interest for insulating buildings, in particular, Foamglas® thermal conductivity of 0.038-0.040 W/mK, working temperature between −260 and +430 °C and class zero for combustion behavior (Uni Iso 1182), would make a glass coated Foamglas®, a sound insulating material for indoor and outdoor applications, and also for the retro-fitting and weatherizing of buildings, to make them more sustainable from an energy-saving point of view.

In recent works (Ref 4-6), a lead-free glass based on Na_2O-B_2O_3-ZnO has been proposed as a new coating for foam glass, with protective and/or aesthetic functionality, cheap and easy to obtain by slurry deposition followed by heating directly on foam glass, to obtain a sort of "insulating tile" for external and internal building insulation.

The aim of this study is to find some tests, possibly standards, suitable to define the properties of a completely new product: a glass coated Foamglas®.

In general, few papers deal with properties of foam glass (Ref 7) and, to the best of authors' knowledge, properties of glass coated Foamglas® have not been tested before.

Since a glass coated Foamglas® can be considered both as an enameled tile and an insulating tile, a thorough search of standards regarding tiles, enameled products, and insulating materials have been done.

In order to find a group of suitable tests to characterize glass coated Foamglas®, when not differently specified in UNI EN 13167:2009 (thermal insulation products for buildings—factory-made cellular glass (CG) products—specification), some standards have been selected and adapted when necessary.

2. Experimental

The foam glass used in this work is Foamglas® (T4) from Pittsburgh Corning (Pittsburgh, PA, USA): it is a porous heat-insulating glass material, with true porosity up to 90-97%, manufactured from recycled glass (>66%), sand, dolomite, lime, iron oxide, etc. In a further part of the process the glass is ground, mixed with a small amount of carbon, and put in high-grade steel molds. The molds then pass through a furnace in which the glass foam powder is expanded. A material structure emerges with thin cellular glass walls, which are retained in a controlled cooling process. Details about Foamglas® production and properties can be found in Foamglas® Industrial Insulation Handbook (Ref 3). Properties of Foamglas® and of glasses designed as coatings for Foamglas® can be found in Ref 3 and 5, respectively. Coatings are lead-free glasses based

Andrea Ventrella, Federico Smeacetto, Milena Salvo and **Monica Ferraris,** Materials Science and Chemical Engineering Department, Politecnico di Torino, Corso Duca Degli Abruzzi 24, 10129 Torino, Italy. Contact e-mail: milena.salvo@polito.it.

on Na_2O-B_2O_3-ZnO, labeled as in Ref 5 as to G7 (50 B_2O_3, 33 ZnO, 12 Na_2O, 5 Foamglas®, wt.%) and G9 (49 B_2O_3, 32.3 ZnO, 11.8 Na_2O, 2 CuO, 4.9 Foamglas®, wt.%): in G9 copper oxide was added to G7 composition to obtain a colored coating for aesthetic purposes. About 30 Foamglas® samples ($30 \times 30 \times 30$ mm^3) have been coated by slurry technique with G7 or G9 glass powders having grain size lower than 63 μm as described in Ref 5 and Fig. 1. After slurry deposition on the Foamglas® substrate, the samples were submitted to the thermal treatment in a furnace at temperatures between 500 and 650 °C, for 30-60 min in air atmosphere. About 0.29 g glass powder per cm^2 was used to coat Foamglas® samples. Few larger samples ($78.4 \times 78.4 \times 50$ mm^3) have been coated as in Ref 5 and Fig. 2.

Some of the coatings have been reinforced by a glass fiber net, as shown in Fig. 1(g) and described in Ref 5.

Tests have been done on as-received Foamglas®, glass coated Foamglas®, and heat-treated Foamglas®, as specified for each test. Heat-treated Foamglas® has not been coated, but submitted to the same heat treatment used for the coated one, for comparison purposes.

Specific specimens have been prepared just for impact tests (described below): one specimen (Fig. 3a, b) ($200 \times 200 \times 100$ mm^3) and ten specimens (Fig. 3a) ($30 \times 30 \times 30$ mm^3) have been coated with an acrylic latex coating (Pittcote 404) (Ref 8) and reinforced by glass fiber net.

The following tests have been selected and, where needed, adapted to test coated Foamglas® as follows.

2.1 Impact Resistance

2.1.1 Uni En 13497:2003 (Thermal Insulation Products for Building Applications—Determination of Resistance to Impact of External Thermal Insulation Composite Systems (ETICS) Impact Test for Insulating Materials). A steel sphere of 500 g must be dropped from 408 mm on a sample of at least $200 \times 200 \times 60$ mm^3. The sample after test is then qualitatively evaluated by visual inspection. Since the size of our coated samples is $30 \times 30 \times 30$ mm^3, the sphere weight has been reduced for coated samples to 20 g, by keeping constant the ratio sphere-diameter/coated surface. The scaling factor (sphere diameter/coated area) substantially changed the original nature of the test, but it is here proposed as a way to test impact resistance of porous brittle insulating products.

2.1.2 Uni Iso 10545-5:2000 (Determination of Impact Resistance by Measurement of Coefficient of Restitution for Ceramic Tiles). A steel sphere of 19 ± 0.05 mm diameter must be dropped from 1 m height on the sample surface

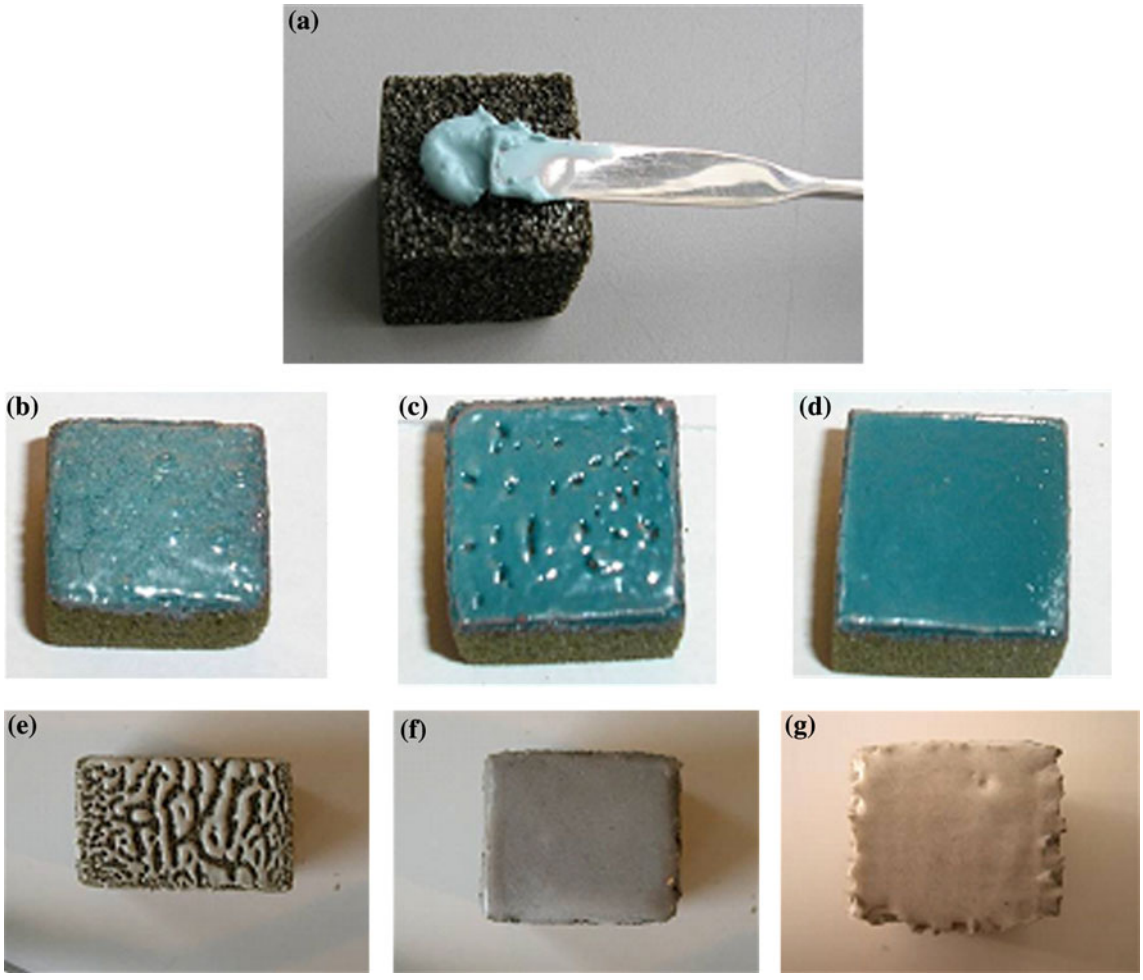

Fig. 1 Glass coating process on Foamglas®, done by slurry (a): some coated samples with imperfections due to a not optimized coating or heating process [G9 (b, c) and G7 (e)]; the optimized coatings G9 (d) and G7 (f) on Foamglas®, as described in Ref 2. Some of the G7 (g) coatings have been reinforced by a glass fiber net supplied by Arrigoni, Como, Italy. Size of the samples: $30 \times 30 \times$ mm^3

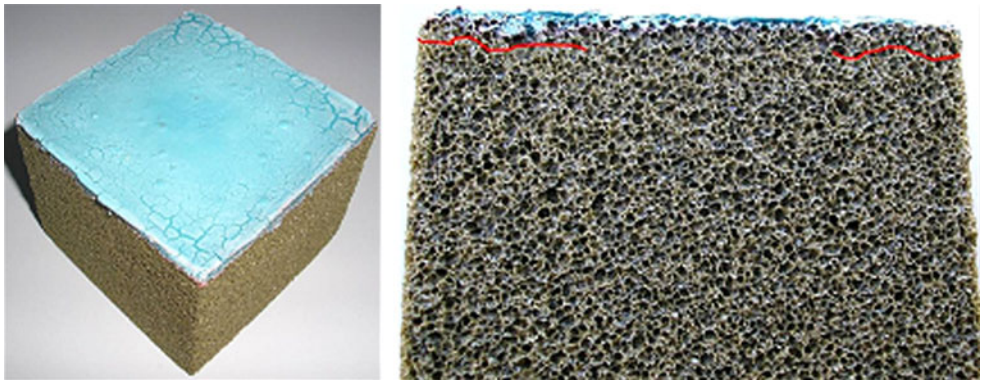

Fig. 2 Top and lateral view of a G9 coated Foamglas® (78.4 × 78.4 × 50 mm^3): cracks due to the thermal treatment are underlined

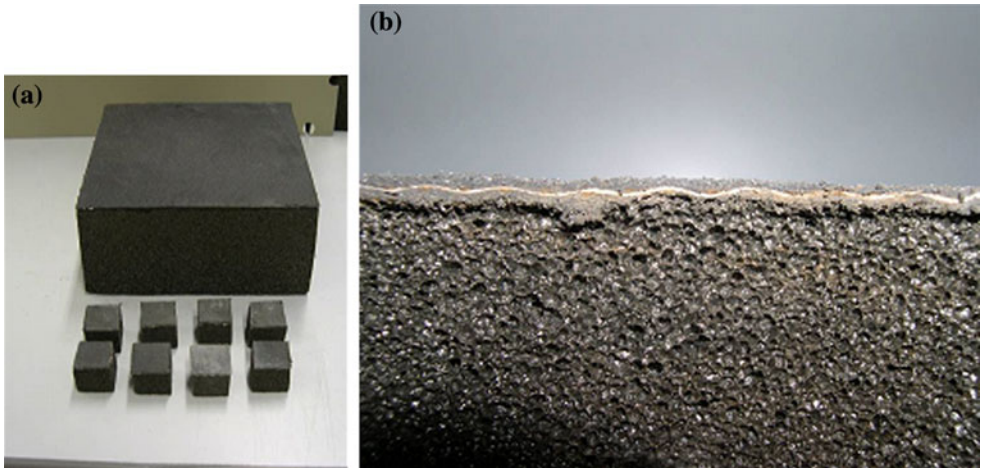

Fig. 3 Top and lateral view of Foamglas® (200 × 200 × 100 mm^3) coated with Pittcote 404 and reinforced by a glass fiber net

(suggested size 75 × 75 mm^2, but smaller is accepted) and let it bounce twice; the time between the two bounces and their height must be measured and used to define the impact resistance accordingly to this test.

2.2 Wear Resistance

2.2.1 ASTM G99-05(2010) (Standard Test Method for Wear Testing with a Pin-On-Disk (POD) Apparatus). The coefficient of friction and wear behavior of coated specimens were determined by using a POD test without lubrication according to ASTM G99-2005. Commercial 7 wt.% cobalt-bonded tungsten carbide (WC) hemispherical-tipped pins with a diameter of 3 mm were employed as counterparts. The specimens are square plates (20 × 20 mm^2, thickness 10 mm) bonded on the rotating steel disc.

A rotational speed of 100 rpm was applied. The diameter of the circle rotation was 12 mm in each case. The tribological investigations were performed at a constant load of F = 10 N (testing time of 1 h 6 min), sliding distance of 150 m. The tests were carried out at room temperature.

In order to compare wear and abrasion results of coated foam glass, the same tests have been done on two commercial tiles both supplied by Iris Ceramica (Bologna, Italy): "IRIS TXT white" and "COSMOS ACQUA" (Ref 9), referred in this article as "Iris" and "Cosmos," respectively.

Profilometry of each wear track was measured by KLA-Tencor P-15 profilometer.

For numerical comparison, the mean friction coefficient (μ) was calculated during the last minute of the 3 h test (Table 1).

2.2.2 Uni En Iso 10545-7:2000 (Determination of Resistance to Surface Abrasion for Glazed Tiles). This has been adapted for our specimens as follows: The standard test requires an abrasive mixture made of steel spheres (spheres diameter ranging between 1 and 5 mm) together with alumina powder and water. Steel spheres were not used for our samples, because of their weight, able to destroy the glass coating by impact: only alumina powder and water were thus used here.

The equipment for wear testing is a tumbling machine (Turbula T60). This machine shakes a 2 L container in a 3D movement. The container contains the parts to be tested, 375 mL of Al_2O_3 (< 75 μm), 250 mL of water with 10% volume soap (Ref 10).

The G7 and G9 coated foam glasses were polished to 6 μm (G9a and G7a) and to 1 μm (G9b) to obtain a surface roughness (R_a, average roughness, and R_z, average of the maximum peaks and valleys) comparable to the commercial tiles (Table 1): G9a and G7a where successfully polished to roughness comparable to Cosmos tile. On the contrary, even after careful polishing, G9b roughness is not comparable to that of Iris (results left in Table 1 for completeness).

Table 1 Roughness parameters (R_a and R_z) measured by a Hommel Tester T1000; friction coefficient (μ) measured by POD

	G9a	G9b	G7a	Iris txt	Cosmos
t_0					
R_a, μm	1.07 ± 0.07	0.20 ± 0.02	1.07 ± 0.74	0.03	1.25 ± 0.15
R_z, μm	13.86 ± 0.40	5.12 ± 0.44	10.36 ± 7.41	0.22 ± 0.04	8.39 ± 0.98
After 3 h					
R_a, μm	1.70 ± 0.32	0.58 ± 0.11	0.98 ± 0.23	0.05 ± 0.02	1.50 ± 0.16
R_z, μm	18.08 ± 2.02	8.51 ± 1.36	9.52 ± 3.61	0.34 ± 0.16	10.56 ± 1.47
Friction coefficient, μ	…		1.051 ± 0.10	0.627 ± 0.03	0.964 ± 0.054

All the specimens have been tested 3 h and the surface roughness has been measured before and after tests by a Hommel Tester T1000.

2.3 Water Absorption

2.3.1 Uni En 1609:2008 (Thermal Insulating Products for Building Applications—Determination of Short-Term Water Absorption by Partial Immersion For Insulation Materials for Buildings). Samples of 200×200 mm^2 (unspecified thickness in the standard) are partially (10 ± 2 mm) immersed in water, 24 h (Uni En1609:2008) or 28 days (Uni En 12087) at 23 ± 5 °C, then weighted after water removal (10 min draining on a 45° grid), to obtain the water absorption (kg) versus the sample surface (m^2). In our case, samples of 30×30 mm^2 have been tested: as-received Foamglas®, glass coated Foamglas®, and heat-treated Foamglas®.

2.4 Thermal Shock Resistance

2.4.1 Uni Iso 10545-9:2000 (Thermal Shock Resistance for Tiles and Enameled Products). According to the method without immersion (for the determination of thermal shock resistance of the ceramic tiles with water absorption higher than 10%), the samples were submitted to ten thermal shock cycles from $T = 15 \pm 5$ °C, 15 min, to 145 °C in an oven, 15 min and then observed. This test uses a water bath covered with a 50 mm aluminum sheet and layer of aluminum grains (0.3-0.6 mm diameter) kept at 15 ± 5 °C by water.

2.5 Frost Resistance

2.5.1 Uni Iso 10545-12 (Frost Resistance for Tiles). Tiles (unspecified size in the standard) are cooled at −5 °C in a refrigerator and kept at this temperature 15 min, then immersed in water or sprayed with water up to +5 °C on the sample for 15 min, this cycle repeated 100 times. Tiles are weighted at the end of test then dried in an oven at 110 °C, 40 min and weighted again before and after soaking in water, to obtain the water absorption percentage after test. Glass coated Foamglas® samples of $30 \times 30 \times 30$ mm^3 have been tested.

2.6 Stain Resistance

2.6.1 Uni Iso 10545-14:2000 (Stain Resistance for Tiles). 3-4 olive oil droplets are kept 24 h on the surface to be tested, then the surface is cleaned with running warm water and dried by a cloth, then in an oven at 110 ± 5 °C. If no stains are present on the surface, the coating is defined class 5, the highest one. If stains are present, glasses are defined as of lower class.

2.7 Chemical Durability

In order to investigate the chemical durability, the dissolution rate (Ref 11) of G7 and G9 glasses used as coatings, bulk samples of G7 and G9 glasses, were prepared as described in Ref 5. Samples were cut with a diamond blade then polished to 1000 SiC grit, a surface of approximately 300-400 mm^2 was used for testing. Some commercial soda-lime glasses have been measured in the same way for comparison purposes.

Three specimens of each glass have been measured. Samples were cleaned in acetone and soaked in distilled water at 90 °C, then removed every 1, 2, 4, 8, and 12 days, then dried and weighed. Average dissolution rates were calculated on 12 days.

3. Results and Discussion

A recurrent problem in materials science and technology is the industrial transfer of a new product developed and produced in a laboratory scale. The new product is requested to fulfill standard test requirements, but very often standard tests are not suitable for the new product itself.

The aim of this work was to find out if standardized tests of tile materials used in the construction area might be suitable for testing the properties of a new glass coated foam glass, proposed as a building insulation material.

Some of standards were found not suitable for samples of $30 \times 30 \times 30$ mm^3, which is the maximum reproducible size obtainable by our laboratory equipment. Figure 1(a) shows the coating process done by slurry, some coated samples (b, c, e) with imperfections due to a not optimized coating or heating process, and the optimized (d) G9, (f) G7, and (g) fiber reinforced G7 coated Foamglas®, as described in Ref 5.

It must be highlighted that the whole sample is heated in a laboratory oven to obtain the coated Foamglas®: This can be a drawback when the sample size is increased from $30 \times 30 \times 30$ mm^3 to $78.4 \times 78.4 \times 50$ mm^3, as shown in Fig. 2, where cracks due to the thermal treatment are evidenced.

For this reason, it was decided to continue the experimental activity on $30 \times 30 \times 30$ mm^3 samples (Fig. 1d) and to adapt the standards, when possible, to this size.

For an industrial up-scaling of the coating process for Foamglas®, a more suitable coating method should be investigated, possibly using a localized surface heating and not the heating of the whole sample.

In order to compare a polymeric commercial coating currently used to coat Foamglas® with the new glassy coating proposed here, specific specimens have been prepared just for impact tests (described below): One specimen (Fig. 3a, b) ($200 \times 200 \times 100$ mm^3) and ten specimens (Fig. 3a) ($30 \times 30 \times 30$ mm^3) have been coated with an acrylic latex coating (Pittcote 404) (Ref 8) and reinforced by glass fiber net (provided by Arrigoni, Como, Italy).

3.1 Impact Resistance

3.1.1 Uni En 13497:2003 (Impact Test for Insulating Materials). This has been previously tested on as received Foamglas® of $200 \times 200 \times 100$ mm^3, with a steel sphere of 500 g dropped from 408 mm on the sample, as shown in Fig. 4(a). This test is not suitable to determine the impact resistance of a glass coated Foamglas® (Fig. 4b), even if the steel sphere weight has been adapted to the reduced size of the available samples (20 g instead of 500 g, Fig. 4c).

The intrinsically brittle nature of the glass coating and of the porous glass substrate does not allow the correct use of this test on glass coated Foamglas®.

However, also tests on glass fiber reinforced polymer (Pittcote 404) coated Foamglas® (Fig. 3b) showed a complete spallation of the polymeric coating (Fig. 4e, f) from the Foamglas® substrate, (steel sphere 500 g and reduced size specimens of $30 \times 30 \times 30$ mm^3) and a partial spallation of the coating is shown with high load (500 g) on larger specimen ($200 \times 200 \times 100$ mm^3), thus suggesting the unsuitability of this standard for coated foam glass.

Unfortunately, it was impossible to obtain a measurable value of impact resistance for glass coated Foamglas® also with

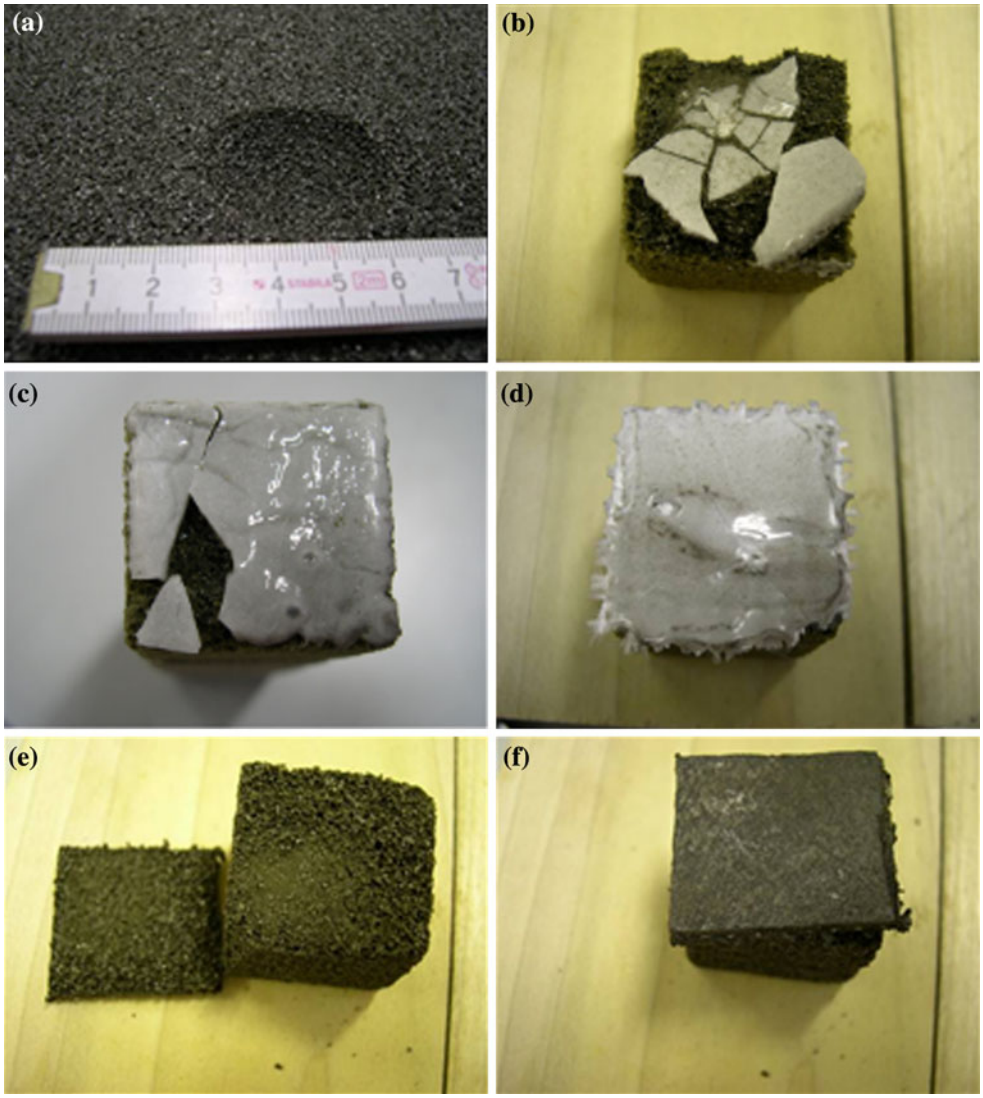

Fig. 4 Impact test (Uni En 13497): (a) as-received Foamglas® ($200 \times 200 \times 100$ mm, a steel sphere of 500 g dropped from 408 mm on the sample); (b) G7 glass coated Foamglas® ($30 \times 30 \times 30$ mm^3, steel sphere of 500 g dropped from 408 mm on the sample; (c) G7 glass coated Foamglas® ($30 \times 30 \times 30$ mm^3, steel sphere of 20 g dropped from 408 mm on the sample); (d) glass fiber reinforced G7 glass coated Foamglas® ($30 \times 30 \times 30$ mm^3, steel sphere of 20 g dropped from 408 mm on the sample); (e) and (f) glass fiber reinforced Pittcote 404 coated Foamglas® ($30 \times 30 \times 30$ mm^3, steel sphere of 500 g dropped from 408 mm on the sample)

Uni Iso 10545-5 (impact test for tiles and enameled products). The steel sphere did not bounce on the $30 \times 30 \times 30$ mm^3 coated samples, but breaks the glass coating at the first impact. This standard is not suitable for glass coated foam glasses.

It appears quite clear that the impact resistance of the foam glass itself is quite low. Even coating it with another glass composition does not significantly improve the impact resistance. However, an attempt to establish an impact test procedure for these products should be done, to find out if coated foam glass can be used in applications where they would be subject to moderate impact.

In this respect, an improvement can be observed with a glass fiber reinforced glass coated Foamglas® (Fig. 4d), suggesting a potential use of this kind of reinforcement for glass coated Foamglas®, for applications in which the impact resistance is relevant.

3.2 Wear Resistance

The coefficient of friction (μ) of the G7a coated Foamglas® (Table 1) and of two commercial tiles have been tested for comparison purposes by POD test.

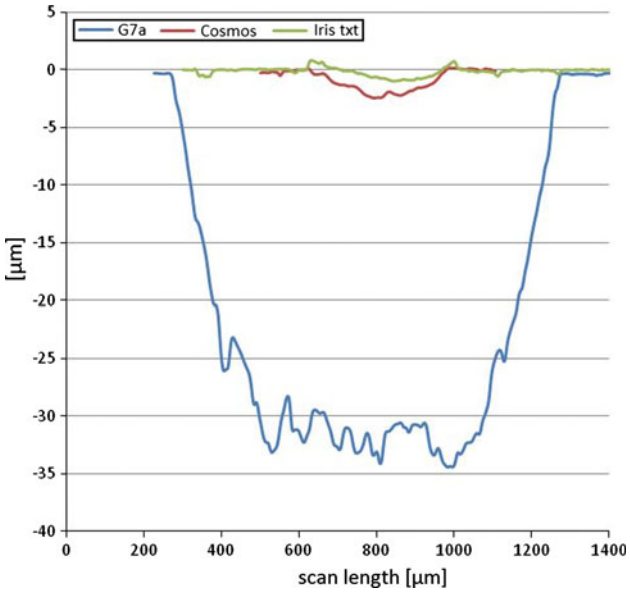

Fig. 5 Wear track profiles of the two commercial tiles (Iris txt and Cosmos) compared to the G7a coated Foamglas®

G7a specimen gave an average friction coefficient higher than that of the "Iris txt" tile, but comparable to that of "Cosmos" tile, having almost the same roughness parameters (Table 1).

The wear track profiles (Fig. 5) measured by KLA-Tencor P-15 profilometer showed important differences. It is possible to determine the wear rate from the residual wear track by measuring the worn area of the surface profile (Ref 12, 13, 14). Wear rate of the materials studied are, respectively, $K = 7.79 \times 10^{-4}$ (mm^3/N·m) for G7a coated Foamglas®; $K = 2.31 \times 10^{-5}$ (mm^3/N·m) for Cosmos tile, and $K = 9.20 \times 10^{-6}$ (mm^3/N·m) for Iris.

The two commercial tiles (Iris txt and Cosmos) showed smooth wear surfaces as compared to the G7a coated Foamglas®, which exhibited much wider and deeper wear profiles implying material loss during the wear test.

The micrograph of G7a coated Foamglas® sample after POD test (Fig. 6) shows the worn surface, but no cracks are present on the G7a glass surface close to the wear track.

As described in experimental section, a second technique (Turbula T60) was used for the determination of resistance to surface abrasion. Table 1 summarizes profile roughness parameters measured by Hommel Tester T1000 (R_a and R_z, μm). A comparison of Ra and R_z made at t_0 and after 3 h on the glass coating specimens and commercial tiles shows that the trend is quite similar, in particular for G7a and Cosmos. The increase of the surface roughness is slightly more evident for G7 and G9 samples respect to the commercial tiles. The surface roughness before and after these tests is shown in Fig. 7(a) to (d): SEM and roughness measurements show only a slight erosion of the coating after tests. Furthermore, even if the erosion of the Foamglas® substrate after 6 h is clearly visible in Fig. 8, the coating is still intact, the adhesion between the coating and the substrate is still sound and that and no cracks were detected in the coating despite the stresses induced by Turbula test.

3.3 Water Absorption

3.3.1 Uni En 1609:2008 (Thermal Insulating Products for Building Applications—Determination of Short-Term Water Absorption by Partial Immersion). The results of water absorption after 24 h are given as follows:

$$W_p = (m_{24} - m_0)/A_p \quad (\text{kg/m}^2)$$

where m_{24} is the specimen weight after soaking for 24 h (kg), m_0 is the dry weight of the specimen (kg), A_p is the soaked surface (m^2) (test has been performed at $T = 23 \pm 5$ °C in accordance with the standard).

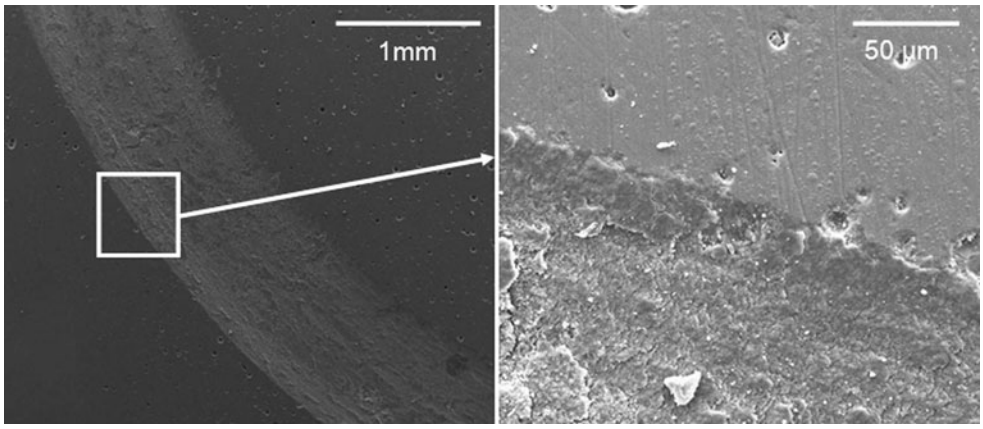

Fig. 6 Wear track profile obtained after POD wear tests on G7a coated Foamglas®

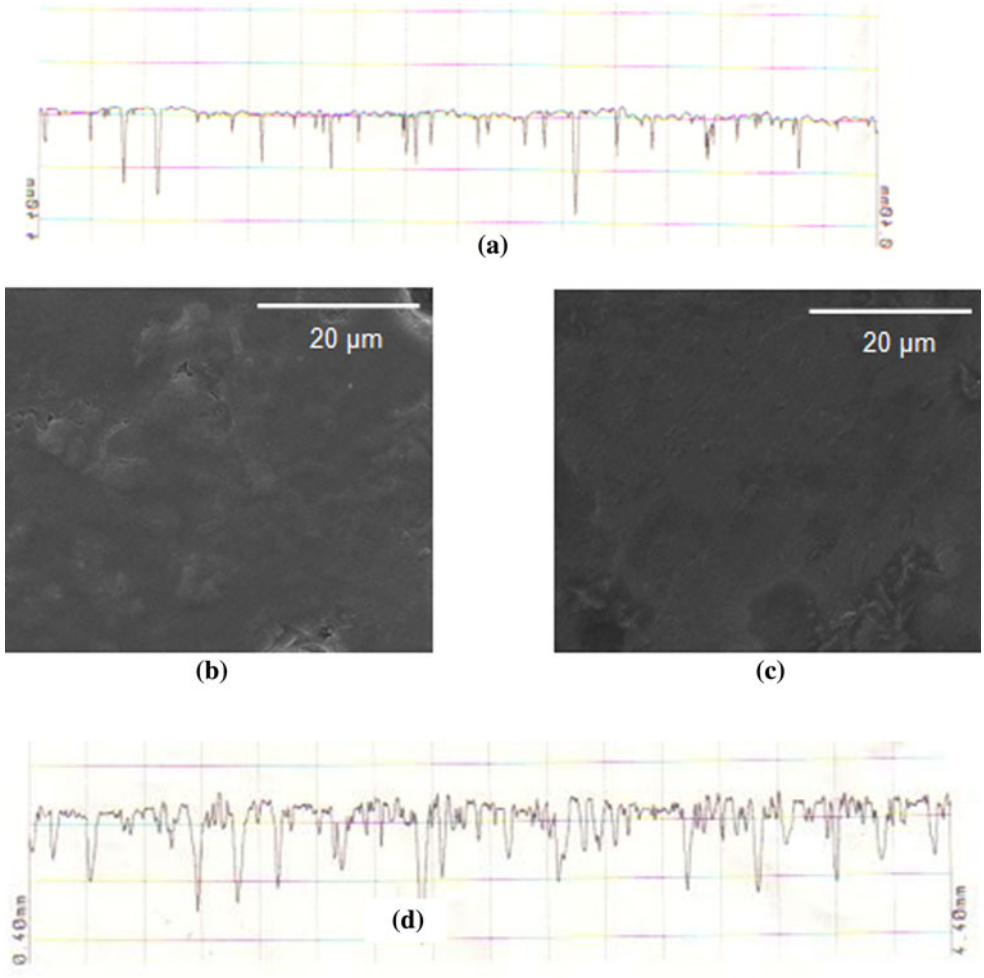

Fig. 7 SEM (b, c) and the roughness measurements (a, d) of G9 glass coated Foamglas® before (a, b) and after (c, d) 6 h of erosion test, modification of Uni En Iso 10545-7

Fig. 8 G9 glass coated Foamglas® after 6 h of erosion test (modification of Uni En Iso 10545-7, measured by Turbula T60). Original sample size: 30 × 30 × 30 mm^3

The results are shown in Table 2; the absorbed water by the G9 glass coated Foamglas® was, as expected, lower than those for the heat-treated (Ref 5) Foamglas® and close to the as-received Foamglas®. In particular, the average value for heat-treated Foamglas® was higher than for the as-received one, suggesting a slight detrimental effect (i.e., formation of microcracks in the cell walls) of the thermal treatment used to coat Foamglas®. If confirmed, this drawback can be avoided with a more suitable coating process, able to heat only the slurry and not the whole Foamglas® tile.

3.4 Thermal Shock Resistance

3.4.1 Uni Iso 10545-9:2000 (Ceramic Tiles—Determination of Resistance to Thermal Shock for Ceramic Tiles with Water Absorption Higher Than 10%). The glass coated Foamglas® before and after test is the same at visual inspection and no cracks have been found in the Foamglas® substrate after 10 cycles. The G9 coated Foamglas® is thus thermal shock resistant.

3.5 Frost Resistance

Glass coated Foamglas® samples of 30 × 30 × 30 mm^3 have been tested for frost resistance according to Uni Iso 10545-12.

Table 2 Absorbed water amount in 24 h versus surface (W_p) for as-received, heat-treated, and G9 coated foam glass, according to Uni En 1609 :2008 (thermal insulating products for building applications—determination of short-term water absorption by partial immersion)

	As-received Foamglas®		Heat-treated Foamglas®		G9 coated Foamglas®	
	Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
Surface, cm^2	9.18	8.76	8.44	9.09	8.49	9.03
m_0, g	3.13	3.06	2.72	3.28	5	4.84
m_{24}, g	3.44	3.41	4.52	4.92	5.71	5.78
W_p, kg/m^2	0.34	0.40	2.13	1.80	0.84	1.04
Mass increase, %	9.9	11.4	66.2	50.0	14.2	19.4
Average mass increase, %	10.7		58.1		16.8	

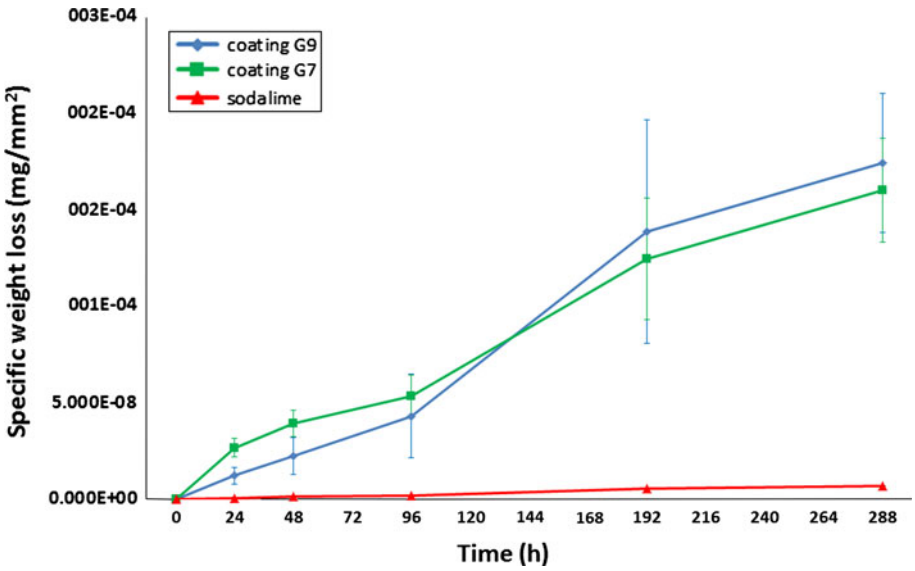

Fig. 9 Specific weight loss of G7, G9, and soda-lime glasses soaked in hot water (90 °C), 12 days. Soda-lime values as comparison

All coated samples did not show any morphological alteration in the coating or in the Foamglas® substrate after the tests. The glass coated Foamglas® can be defined as frost resistant.

3.6 Stain Resistance

Glass coated Foamglas® and the commercial tiles resulted in the same class 5, the highest towards olive oil, according to Uni Iso 10545-14.

Promising results obtained on thermal shock, frost, and stain resistance for the glass coated Foamglas® may open the way to new application of this material for building insulation.

3.7 Chemical Durability

In order to investigate the chemical durability and the dissolution rate of G7 and G9 glasses used as coatings, bulk samples of G7 and G9 glasses were prepared and the weight loss results when immersed in hot water are shown in Fig. 9 (the curves represent an average on three samples). The highest weight loss was obtained for G7 and G9 glass whereas, as expected, the lowest one was found for soda-lime glasses.

The addition of 2 wt.% of CuO in the system Na_2O-B_2O_3-ZnO does not significantly affect the dissolution rate in water at 90 °C, as shown in Table 3, the dissolution rates of G7 and G9 glasses are similar.

Table 3 Dissolution rate of G7 and G9 glasses soaked in hot water (90 °C), 12 days

	Average dissolution rate, $g/(cm^2\ min)$
G9	$2.22\ E^{-09}$
G7	$1.23\ E^{-09}$
Soda-lime	$3.49\ E^{-11}$

Poor chemical durability of borate-based glasses, due to dissolution controlled by reaction kinetics, remains one of their main disadvantages (Ref 15-18). As expected, the average dissolution rate ($1.19\ E^{-9}$) of G7 and G9 was found to be comparable with other borate glasses.

A white reaction layer (pictures not reported here) was formed on the surfaces of G7 and G9 glasses after 4 days of exposure to water at 90 °C, whereas no layer was observed in the soda-lime glasses used as comparison.

As widely reported in the literature for borate glasses of several compositions (Ref 15-18), and confirmed also for G7 and G9 glasses proposed here, corrosion has been observed after exposure to water at 90 °C, thus suggesting the use of these glasses where corrosion is not a concern.

The dissolution rates of the borate glasses are several orders of magnitude higher than that of the sodium silicate samples. Moreover, borate glass surfaces are attacked and dissolved by water and their poor chemical durability severely limits their possible use. The dissolution rate in a borate glass can be decreased by substituting lithium for sodium because lithium is a smaller ion and is therefore more tightly bound to the glass network.

Future work will be addressed to study new glass coating compositions also suitable for external building insulation panels (Ref 19).

4. Conclusions

The glass coated foam glasses may have broad application in the thermal insulation of buildings, provided that they fulfill standardized tests of tile materials used in the construction area.

The aim of this work was to find out if standardized tests of tile materials used in the construction area might be suitable for testing the properties of a new glass coated foam glass.

Glass coated foam glass (Foamglas®) insulating tiles have been successfully characterized by several standard tests, some of them have been adapted to the reduced size ($30 \times 30 \times 30$ mm^3) of the available samples.

The glass coated Foamglas® resulted to be:

- thermal shock resistant, according to Uni Iso 10545-9 (Al spheres);
- effective to reduce the Foamglas ®surface water absorption, according to Uni En 1609:1999 and 12087:1999;
- frost resistant, according to Uni Iso 10545-12;
- class 5 towards olive oil according to Uni Iso 10545-14.

The glass coated Foamglas® can be then considered suitable for applications requiring these properties.

The impact tests (Uni En 13497 and Uni Iso 10545-5) were found to be unsuitable for glass coated Foamglas® of reduced size, but an improved behavior of coatings reinforced by a glass fiber net was found.

Durability and wear resistance results suggest the use of these glasses as coatings for foam glass only where corrosion and wear are not a concern.

Finally, it must be pointed out that the samples were prepared in a laboratory facility and reproducibility of samples was not comparable to that of an industrial production. Therefore, it must be emphasized that these results can only give general direction, not quantitative conclusions. Experimental activity to scale up the coating process from few square centimeters to square meters is on-going; mechanical tests will be done also on larger samples to validate the results discussed in this article.

Acknowledgments

The contributions to the experimental work of S. Pronsati, D. Calone and F. Orsina, graduate students in Civil Engineering at Politecnico di Torino are kindly acknowledged.

References

1. YuA Spiridonov and L.A. Orlova, Problems of Foam Glass Production, *Glass Ceram.*, 2003, **60**, p 313–314
2. A.M. Papadopoulos, State of the Art in Thermal Insulation Materials and Aims for Future Developments, *Energy Build.*, 2005, **37**, p 77–86
3. Pittsburgh Corning Europe N.V., *Foamglas Industrial Insulation Handbook*, Pittsburgh Corning Europe N.V, Brussels, 1992
4. M. Ferraris, C. Saponaro, M. Salvo, F. Smeacetto, and A. Ventrella, A Method of Preparing Coated Foam Glass Articles and Articles thereby Obtained, EU Patent WO2006059306, 2006
5. A. Ventrella, F. Smeacetto, M. Salvo, and M. Ferraris, A New Glass Coating for Foam Glass, *Int. J. Appl. Ceram. Technol.*, 2011, **8**, p 187–193
6. A. Ventrella, F. Smeacetto, M. Salvo, M. Ferraris, and M. Avalle, A New Glass to Join Foam Glass Components, *J. Mater. Eng. Perform.*, 2010, **4**, p 1244–1247
7. Y. Méar and R. Viennois, Mechanical Behaviour and Thermal and Electrical Properties of Foam Glass, *Ceram. Int.*, 2007, **33**, p 543–559
8. Pittcote®404, Coating Product Data Sheet. http://www.foamglas.com
9. www.irisceramica.com
10. M.H. Bouix and C.P. Dumortier, Colour Trends in PVD, *43rd SVC Technical Conference Proceedings*, Denver, Colorado, USA, April 15–20, 2000
11. M. Bengisu, R.K. Brow, E. Yilmaz, A. Moguš-Milanković, and S.T. Reis, Aluminoborate and Aluminoborosilicate Glasses with High Chemical Durability and the Effect of P_2O_5 Additions on the Properties, *J. Non-Cryst. Solids*, 2006, **352**, p 3668–3676
12. E.A. Almond and M.G. Gee, Effects of Test Variables in Wear Testing of Ceramics, *Mater. Sci. Technol.*, 1988, **4**, p 877–884
13. J. Park, G. Pekkan, and A. Ozturk, Wear of MgO-CaO-SiO_2-P_2O_5-F-Based Glass Ceramics Compared to Selected Dental Ceramics, Res. Lett. Mater. Sci., 2007, **2007**, Article ID 69897, 5 pp
14. B.K. Tay, D. Sheeja, Y.S. Choong, S.P. Lau, and X. Shi, Pin-on-Disk Characterization of Amorphous Carbon Films Prepared by Filtered Cathodic Vacuum Arc Technique, *Diam. Relat. Mater.*, 2000, **9**, p 819–824
15. M. Bengisu, E. Yilmaz, H. Farzad, and S.T. Reis, Borate, Lithium Borate, and Borophosphate Powders by Sol-Gel Precipitation, *J. Sol-Gel. Sci. Technol.*, 2008, **45**, p 237–243
16. M.H. Velz, H.L. Tuller, and D.R. Uhlmann, Chemical Durability of Lithium Borate Glasses, *J. Non-Cryst. Solids*, 1982, **49**, p 351–362
17. N.A. El-Alaily, F.M. Ezz-Eldin, and H.A. El-Batal, Durability of Some Gamma-Irradiated Alkali Borate Glasses, *Radiat. Phys. chem.*, 1994, **44**, p 45–51
18. Z. Zhang, K. Hirao, and N. Soga, Water Corrosion Behavior of Densified Glass. II. Borate Glasses, *J. Non-Cryst. Solids*, 1991, **135**, p 62–66
19. F. Smeacetto, M. Salvo, A. Ventrella, S. Rizzo, and M. Ferraris, Durable Glass-Ceramic Coatings for Foam Glass, Int. J. Appl. Glass Sci. doi:10.1111/j.2041-1294.2011.00071.x