

# Production of foamed glass-ceramics using furnace bottom ash and glass

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## ABSTRACT

This research has produced foamed glass-ceramics from coal fired power station furnace bottom ash (FBA) and soda-lime-silica glass. The as-received FBA was wet milled with different additions of glass. The resultant slurry was dried and formed into a powder. The powder was pressed and sintered at a range of temperatures with additions of a fluxing agent (sodium tetraborate decahydrate), a bubble stabilising additive (tri-sodium phosphate) and a bloating agent (calcium carbonate) and this produced foamed FBA-glass-ceramics. The effect of glass content and sintering temperature on the properties of the sintered ceramic foams are reported. A range of potential applications including thermal insulation and biological filters for water and wastewater treatment are discussed. The research demonstrates that it is possible to engineer the properties of FBA derived glass-ceramic foams by careful control of the composition and processing conditions in order to transform a problematic waste into commercially interesting materials.

**Keywords:** furnace bottom ash, glass, porous ceramic, ceramic foams, direct foaming, biofilters,

## 1. Introduction

Coal remains an important energy source worldwide, particularly in China, and is currently used to generate ~38% of global electricity [1]. Beneficial reuse of coal combustion residues (CCRs) remains a challenging issue for coal-fired power stations. CCRs include coal fly ash, bottom ash, boiler slag and fluidised bed combustion ash [2].

Fly ash, or pulverised fuel ash (PFA), is recovered from the off-gas stream while furnace bottom ash (FBA) is the high-density non-combustible residue produced from coal combustion. PFA is routinely used in concrete as a supplementary cementitious material, although ~10% of PFA is currently stored or landfilled in the EU [2]. Applications for FBA are more limited and new reuse applications for this material need to be developed.

Kilroot is a coal fired power station in Northern Ireland, located on the north shore of Belfast Lough and it has particular issues with stockpiled CCRs. The plant operates dual oil and coal generators, provides ~520 MW of electricity to the grid and supplies approximately a third of the electricity used in Northern Ireland. Large volumes of FBA are currently stockpiled and a value-added reuse application for this material would be highly advantageous. Previous research has investigated the potential for using Kilroot FBA as a major raw material in the production of sintered ceramics [3] and the addition of glass was found to significantly improve the properties of sintered FBA.

Ceramic foams are lightweight materials containing a network of closed and open porosity. They have low density, high specific area, good thermal and acoustic insulation properties and favourable chemical resistance [4]. Ceramic foams can be used in a wide range of industrial applications. They are used as particulate filters in diesel engines [5], as high-temperature thermal insulators [6] and as biological filters for water and wastewater treatment [7, 8]. The porosity can be open or closed, depending on the composition, processing and the functional properties required. In general, closed pores are preferable for structural components, while open pores are preferable for water absorption and retention materials [8]. The high specific surface area and macroporous structure of the ceramic foam can also provide an ideal habitat for nitrifying bacteria and autotrophic bacteria that are essential for the removal of ammonia and dissolved organic matter (DOM) [9].

The production of ceramic foams from waste glass and industrial wastes such as fly ash [10, 11], slag [12-15] and other mineral wastes [16, 17] using silicon carbide, aluminium nitride and calcium carbonate [15, 17, 18] as foaming agents have been widely reported. Nevertheless, there has been very limited research into the production of ceramic foams from FBA [19].

This research aimed to use FBA and locally available waste glass to produce ceramic foams with low density and high porosity, suitable for use in a range of engineering applications. The processing to produce ceramic foams from FBA at laboratory scale has been optimised and the sintered ceramic foams have been characterised for density, porosity, water absorption and mechanical properties. The effect of glass addition and sintering temperature on the characteristics of sintered products have been investigated and the optimum FBA/glass ratio and sintering temperature determined.

## **2. Materials and characterisation methods**

FBA was obtained from the Kilroot Power Station in Northern Ireland as a 5 kg milled batch with a  $d_{50}$  of 13 $\mu\text{m}$  and a  $d_{90}$  of 108 $\mu\text{m}$ . Recycled post-consumer soda-lime silica glass powder was obtained from Day Group (EcoSand) and this was sieved to give particles in the size range between 45 and 150  $\mu\text{m}$ .

Borax decahydrate ( $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$ ) was used as a fluxing agent to lower the glass softening temperature to allow sintering at low temperatures. Trisodium phosphate ( $\text{Na}_3\text{PO}_4$ ) was also added as an additional fluxing

agent as it is reported to increase the elasticity of liquid films and this helps to stabilise bubbles formed during the production of foamed ceramics [20]. Calcium carbonate ( $\text{CaCO}_3$ ) was used as the foaming agent (99+%, ACS reagent). This decomposes to form  $\text{CO}_2$  and  $\text{CaO}$  during the sintering process. Polyethylene glycol (PEG 6000) was used to bind the particles together prior to heat treatment. Calcium carbonate, trisodium phosphate, borax and PEG 6000 were all supplied by Fisher Scientific.

**Table 1** gives the oxide composition of FBA from Kilroot power station, determined using X-ray fluorescence (XRF) analysis. The major constituents of FBA are  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$  and  $\text{Fe}_2\text{O}_3$  with minor oxide contents of Ca, K, Mg, Na, Ti, P and S. It is classified as a class F ash because the total of  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$  is greater than 70% of the total mass. The compositions of the soda-lime silica glass, borax and trisodium phosphate are also included in **Table 1**.

Extensive initial trial mixes and firings were completed to determine the range of formulations that could be used to form ceramics foams. Three different FBA/glass ratios were selected and these are referred to as G40, G50, and G60, where the number denotes the weight percentage of glass present in the FBA-glass mix. All these mixes contained an additional 5 wt.% of borax, 10 wt.% of trisodium phosphate and 1.5 wt.% of calcium carbonate. Details of the formulations are presented in **Table 2**.

Raw powder batches of 175 g were wet milled with 300 ml of water and 2 wt.% of PEG 6000 for 2 h using a 2L laboratory porcelain ball mill containing 415, 1 cm  $\varnothing$  alumina ceramic balls (milling media). After milling the ceramic slurry was separated from the milling media by sieving and oven-dried at 105°C for 24 h. The hard dried fragments of ceramic powder formed were then ground and sieved through a 180  $\mu\text{m}$  mesh. The sieved powder was then moistened using a few drops of water and formed into granules by rotating the particles formed through a 25-mesh (0.701 mm) sieve. A fixed amount of the granules (11 g) was then placed in a 40 mm  $\varnothing$  steel die and pressed at 12.5 kN (10 MPa) for 2 min using a Nannetti laboratory press to produce a green compacted disc with a thickness of  $\sim 5$  mm. The faces of the die and pressing punch were cleaned between each pressing operation. A few drops of oil was used to lubricate the die wall.

The sieved powder (20mg) was used for thermogravimetric/differential scanning calorimetry (TG-DSC) analysis (Netsch STA 449 Jupiter F5) in  $\text{N}_2$  from 40 to 1000°C using a heating rate of 10K/min to determine the temperatures at which PEG 6000 was removed and sintering occurred.

Based on the TGA-DSC results, the pressed green samples were initially heat-treated at 480°C for 30 min (Carbolite furnace) to remove the binder and then sintered in a furnace (Lenton) preheated to 890, 920, 950, 980 and 1010°C for 20 min. This rapid heating regime (i.e. instantaneous exposure to high temperatures) allowed foamed ceramics to form due to the simultaneous softening of the glass, sintering and decomposition of  $\text{CaCO}_3$ . The samples were fired on a thin layer of alumina powder to prevent the foamed ceramics from

bonding to the supporting refractory board. The sintered samples were then allowed to cool in the furnace.

Figure 1 shows the process used to produce foamed ceramic samples. At least three samples were characterised for each composition and firing temperature and the average and standard error of properties were determined.

The diameter and thickness of the samples were measured before and after firing. This allowed the radial ( $\alpha$ ) and vertical ( $\beta$ ) expansion coefficients to be calculated from the change in radius ( $r$ ) and thickness ( $t$ ), using equations (1) and (2) respectively:

$$\alpha (\%) = \frac{r_{sintered} - r_{original}}{r_{original}} \times 100 \quad (1)$$

$$\beta (\%) = \frac{t_{sintered} - t_{original}}{t_{original}} \times 100 \quad (2)$$

Water absorption was determined using the vacuum saturation method. The foamed samples were immersed in water under vacuum for at least 6 h to ensure that all open pores were filled with water. Water absorption was then calculated from:

$$water\ absorption (\%) = \frac{m_{wet} - m_{dry}}{m_{dry}} \times 100 \quad (3)$$

where  $m_{dry}$  and  $m_{wet}$  are the weight of the sample before and after water saturation respectively. Water-saturated samples were surface-dried using a wet cloth before weighing.

Following water saturation, the envelope volume ( $V_T$ ) of the samples (including all pores and voids) was determined using the water displacement method. Each sample was lowered into a water-filled beaker until fully submerged and the mass change was recorded. Open porosity, which is the void volume accessible to water, was calculated using:

$$open\ porosity (\%) = \frac{m_{wet} - m_{dry}}{V_T} \times 100 \quad (4)$$

where the total weight of water absorbed represents the open pore volume and  $V_T$  represents the total volume or envelope volume, assuming that the density of water is 1 g/cm<sup>3</sup>. The envelope density was then calculated from:

$$envelope\ density = \frac{m_{dry}}{V_T} \quad (5)$$

Closed porosity was obtained by subtracting the open porosity from the total porosity, which was calculated from the density of the initial powder mixture and the envelope density of the formed ceramic foam [4] using equation (6):

$$total\ porosity\ (\%) = \frac{V_T - V_s}{V_T} = \left(1 - \frac{\rho_T}{\rho_s}\right) \times 100 \quad (6)$$

where  $\rho_T$  is the total density of the sintered sample and  $\rho_s$  was the density of the powder mixture obtained using a He pycnometer (AccuPyc II 1340).

Selected samples were then oven-dried at 105°C for 24 h and ground on one flat surface using a 120-grit SiC paper (Struers LaboPol-5) to expose the internal pore structure for scanning electron microscopy observation (Hitachi TM4000plus). Imaging was performed in the backscattered electron mode at 15 kV accelerating voltage and 30 to 50× magnification.

Mechanical properties were also measured for selected samples. Young's and shear moduli were measured by the impulse excitation method (IMCE Resonance Frequency and Damping Analyser (RFDA) Professional). The disc samples were supported on wires at the nodes of the first bending and torsional modes and subjected to a light mechanical impact. The resulting acoustic signal was recorded by a microphone and analysed by the RFDA to calculate the moduli. Four-point bending tests were performed on bars (~ 5 mm × 6 mm × 40 mm) cut from the disc samples (Buehler IsoMet 1000 at 100 rpm) on a Deben Microtest 1 kN rig (6 mm inner span, 24 mm outer span) at a constant loading rate of 0.5 mm/min.

### 3. Results

Representative TGA-DSC data of the FBA-glass powder mix is shown in Figure 2. The two endothermic peaks at 50°C and 100°C in the DSC data are associated with evaporation of water and removal of bound water from borax decahydrate ( $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$ ). A series of exothermic peaks in the temperature range between 900 and 1000°C indicate the formation of new crystalline phases, most likely cristobalite and albite [3] resulting from the interaction of FBA and glass. The TG curve shows a gradual but continuous weight loss with increasing temperature. The two significant reductions at 420°C and 670°C are associated with decomposition of PEG 6000 and  $\text{CaCO}_3$  respectively.

An overview of the sintered ceramics is shown in Figure 3. The colour of the ceramics changed from reddish-brown to brownish-grey as the glass content increases due to dilution of the iron oxide-containing FBA. As the temperature increased, the colour also became lighter with a tint of green, because of the amount of green glass in the glass sample, especially for G50 and G60 samples. The samples 'swelled' with increasing glass

content and sintering temperature as a result of increased foaming effect. The degree of foaming can be classified into three levels i.e. insufficient, moderate and excessive, based on the amount and size of air voids/pores and extent of foaming. G50 and G60 sintered at 980°C and 1010°C were excessively foamed, as indicated by the presence of many large air voids and the uneven sample surface. In comparison, all the G40 samples exhibited insufficient foaming with no visible large air voids and the sample surface remained relatively smooth.

**Figure 4** shows the effect of glass content and sintering temperature on the radial and vertical expansion of FBA-glass-ceramic foams. The radial expansion for all three formulations increased by ~6% as the sintering temperature increased from 890 to 1010°C. For every increment of 10 wt.% of glass content, the radial expansion increased by ~7%. The vertical expansions were significantly larger than the radial expansion, probably due to a higher surface area of the samples exposed to heat in the axial direction. As the temperature increased from 890 to 1010°C, the vertical expansion of G40, G50 and G60 increased by 45%, 130% and 140% respectively. From 890 to 950°C, the increment was generally consistent across all three formulations but as the temperature increased above 980°C, significant vertical expansion was observed for G50 and G60.

The effect of glass content and sintering temperature on the envelope density and total porosity of FBA-glass-ceramic foams is presented in **Figure 5**. The envelope density reduced steadily with increasing temperature until 950°C when a steep drop was observed for G50 and G60 due to a sharp increase in the envelope volume, in line with the expansion results. G50 and G60 samples sintered at 980 and 1010°C exhibited densities of ~0.6 g/cm<sup>3</sup>, which is lower than water, due to excessive foaming. The highest envelope density of ~1.60 g/cm<sup>3</sup> was observed with G40 sintered at 890°C which also exhibited the lowest radial and vertical expansion. The total porosity showed an opposite but complementary trend. As the glass content and sintering temperature increased, the amount of air voids formed also increased. These findings are in line with the expansion results, indicating that the envelope volume increased with foaming. The highest porosity (~74%) was observed with G60 samples sintered at 1010°C.

**Figure 6** shows the effect of sintering temperature on the water absorption, open porosity and closed porosity of the FBA-glass-ceramic foams. As expected, water absorption increased with glass content and sintering temperature especially for G40 and G50. The behaviour of water absorption appears to be broadly in line with the open porosity and the amount of water absorbed reduced with the open porosity, as can be seen in the case of mix G60 samples sintered at 960°C and 1010°C.

SEM images of the internal structure of FBA-glass-ceramic foams sintered at 950 °C are shown in **Figure 7**. These indicate that the pore size increased with the glass content. Pores in G40 samples were generally ≤400 μm whereas those in G50 and G60 samples were ≤800 μm and ≤1.5 mm respectively. **Figure 8** shows the pore

structure of G60 samples sintered at different temperatures. The pore size increased with increasing sintering temperature as the proportion of smaller pores and pore connectivity reduced. Overall, the homogeneity of the pore structure reduced with increasing glass content and sintering temperature. Evidently, a glass content of  $\leq 50$  wt.% and a sintering temperature of  $\leq 950^\circ\text{C}$  are optimal for homogenous foaming.

Table 3 presents that the mechanical properties of the FBA-glass-ceramic foams. As expected, all measured properties reduced with increasing glass content and sintering temperature, due to increased total porosity and pore sizes as shown in Figure 5b, 7 and 8 respectively. The Ashby plots [21] in Fig. 9 show that the specific flexural strength and Young's modulus of the foamed ceramics are higher than those of most foams and non-technical ceramics including brick, concrete and natural stones. This indicates the potential of FBA-glass ceramic foams for use in both structural and functional applications (see Discussion).

#### 4. Discussion

This study has demonstrated the potential for reusing FBA and waste glass to produce foamed ceramics. FBA is a aluminosilicate material with a relatively high sintering temperature. The addition of glass and fluxing agents reduces the sintering temperature so that foaming using  $\text{CO}_2$  from the decomposition of  $\text{CaCO}_3$  becomes effective. It is worth noting that  $\text{Fe}_2\text{O}_3$  in FBA may also reduce to  $\text{FeO}$  due to the uptake of oxygen by carbon and form into  $\text{CO}_2$ . This is typically observed with clay-based ceramics and happens only when oxygen is in short supply [22].

Results show that insufficient foaming occurs if the glass content is below 50 wt.% and/or the sintering temperature is below  $950^\circ\text{C}$ . Excessive foaming occurs when the glass content is above 40% and the sintering temperature is above  $950^\circ\text{C}$ . The optimum sample produced in this study contained 40:60 FBA-glass (G60) and was sintered at  $950^\circ\text{C}$ . This exhibited a very low density of  $0.81\text{ g/cm}^3$  and had a high total porosity of 64%. These properties are comparable to those of ceramic foams produced from other waste materials. For example, fly ash-glass ceramic foams exhibit density and porosity in the range of  $0.45$  to  $0.75\text{ g/cm}^3$  and 64 to 80 % respectively [6].

Optimising the processing is critical to produce foamed ceramics with desirable properties. Wet milling provides an efficient way of producing a homogeneous FBA-glass powder mix. Dry pressing the powder at a low pressure of 10 MPa for  $\sim 2$  min was found to improve the strength of the green samples. The temperature of  $480^\circ\text{C}$  was found to be sufficient for removing the binder and providing stability for subsequent sintering. The decomposition of  $\text{CaCO}_3$  occurs at  $\sim 670^\circ\text{C}$  and therefore rapid sintering is required to prevent loss of  $\text{CO}_2$  before the softening of the FBA-glass mixture and ensure an effective foaming process occurs.

The production of foamed ceramics is associated with bloating of the softened ceramic body. As the sintering temperature increases, the viscosity of the glass in samples reduces and this allows an increased level of

bloating. However, a glass content in excess of ~50 wt.% causes bubble coalescence at high sintering temperatures and excessive foaming.

The open and closed porosities determined are corroborated by the pore structure images obtained by SEM. In general, open porosity increases with sintering temperature and glass content. However, once the gas pressure exceeds the viscosity of the softened system, coalescence of pores dominates and this produces a high degree of closed porosity and a reduction in water absorption. Pores can become trapped at the sample surface on cooling and this results in reduced open porosity and reduced water absorption.

There are many potential applications of FBA-glass foamed ceramics. For example, they can be used as thermal insulation to save energy [23], and their water absorption and retention properties mean they can have a role in mitigating heat island effects in urban cities [24]. Foamed ceramics are also used in sustainable urban drainage systems for attenuating and retaining rainwater runoff and as biofilters for aquarium conditioning [25], water purification [26] and wastewater treatment [8]. A key finding from this work is that FBA-glass foamed ceramics can be engineered to have a pore structure appropriate for a particular specific application. Further characterisation of other properties including thermal conductivity, water retention capability and the removal efficiency of dissolved organic matter are necessary to confirm the feasibility of FBA-glass foamed ceramics for the above mentioned applications. The pore structure needs to be further characterised using X-ray micro-tomography to better understand how the pore characteristics are linked to processing and various properties. In addition, a detailed study of the crystalline phases formed in FBA glass-ceramic foams with X-ray diffraction (XRD) is required to indicate how the glass content and sintering temperature control the structure of these ceramic foams. Further research is also needed to optimise the  $\text{CaCO}_3$  content and define the processing required to produce large foamed ceramic tiles with high porosity and a uniform pore size distribution. A comparison with commercially available and other competing materials is also warranted.

## **5. Conclusions**

Foamed ceramics can be produced from FBA and waste glass by incorporating  $\text{CaCO}_3$  and rapid sintering at a range of temperatures. The degree of foaming increases with glass content and sintering temperature. The samples produced exhibited densities ranging from 0.6 to 1.6  $\text{cm}^3/\text{g}$ , porosities ranging from 36 to 74% and flexural strength ranging from 5.87 to 25.2 MPa, indicating high flexibility of FBA-glass-ceramic foams for various applications. Additional work is necessary to optimise and up-scale the processing method in order to fully exploit the properties of FBA-glass-ceramic foams.

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**Table 1**

Chemical composition of FBA from Kilroot power station, soda-lime glass, borax and trisodium phosphate.

| Oxide (wt.%)                    | SiO <sub>2</sub> | Al <sub>2</sub> O <sub>3</sub> | Fe <sub>2</sub> O <sub>3</sub> | CaO  | MgO  | Na <sub>2</sub> O | K <sub>2</sub> O | TiO <sub>2</sub> | P <sub>2</sub> O <sub>5</sub> | B <sub>2</sub> O <sub>3</sub> |
|---------------------------------|------------------|--------------------------------|--------------------------------|------|------|-------------------|------------------|------------------|-------------------------------|-------------------------------|
| FBA <sup>a</sup>                | 53.3             | 20.1                           | 8.24                           | 4.53 | 1.92 | 0.99              | 2.02             | 0.83             | 0.38                          | -                             |
| Glass                           | 74.4             | 1.28                           | -                              | 10.5 | 0.20 | 13.3              | 0.29             | 0.008            | -                             | -                             |
| Borax                           | -                | -                              | -                              | -    | -    | 16.3              | -                | -                | -                             | 36.5                          |
| Na <sub>3</sub> PO <sub>4</sub> | -                | -                              | -                              | -    | -    | 56.7              | -                | -                | 43.3                          | -                             |

<sup>a</sup> Glymond *et al.*, 2018

**Table 2**

Formulations used in this study with different FBA/glass ratios.

| Formulation | Main component materials (100 wt.%) |              | Additives (wt.% of main component materials) |                                 |                   |
|-------------|-------------------------------------|--------------|----------------------------------------------|---------------------------------|-------------------|
|             | FBA (wt.%)                          | Glass (wt.%) | Borax                                        | Na <sub>3</sub> PO <sub>4</sub> | CaCO <sub>3</sub> |
| G40         | 60                                  | 40           | 5                                            | 10                              | 1.5               |
| G50         | 50                                  | 50           | 5                                            | 10                              | 1.5               |
| G60         | 40                                  | 60           | 5                                            | 10                              | 1.5               |

**Table 3**

Mechanical properties of FBA-glass-ceramic foams produced with different FBA/glass ratios at different sintering temperatures (mean ± standard error).

| Sample ID | Flexural strength (MPa) <sup>a</sup> |                |                |               | Young's modulus (GPa) |                |                |               | Shear Modulus (GPa) |                |                |                |
|-----------|--------------------------------------|----------------|----------------|---------------|-----------------------|----------------|----------------|---------------|---------------------|----------------|----------------|----------------|
|           | 890°C                                | 920°C          | 950°C          | 1010°C        | 890°C                 | 920°C          | 950°C          | 1010°C        | 890°C               | 920°C          | 950°C          | 1010°C         |
| G40       | 25.2                                 | 19.6           | 16.5           | 11.8<br>± 0.8 | 23.1                  | 23.4           | 20.5           | 15.5<br>± 1.7 | 9.51                | 9.72           | 8.51           | 5.64<br>± 0.77 |
| G50       | 10.4<br>± 0.8                        | 10.8<br>± 1.3  | 8.34<br>± 0.45 | -             | 14.0<br>± 0.5         | 13.0<br>± 0.2  | 12.4<br>± 0.1  | -             | 5.77<br>± 0.18      | 5.37<br>± 0.09 | 5.14<br>± 0.04 | -              |
| G60       | 7.89<br>± 0.27                       | 7.34<br>± 0.01 | 5.87<br>± 0.74 | -             | 9.67<br>± 1.38        | 9.42<br>± 0.36 | 8.95<br>± 0.63 | -             | 3.98<br>± 0.57      | 3.91<br>± 0.17 | 3.72<br>± 0.26 | -              |

<sup>a</sup> Measured from bars cut from disc samples

Note: only one sample was tested for G40 sintered at 890°C, 920°C, 950°C

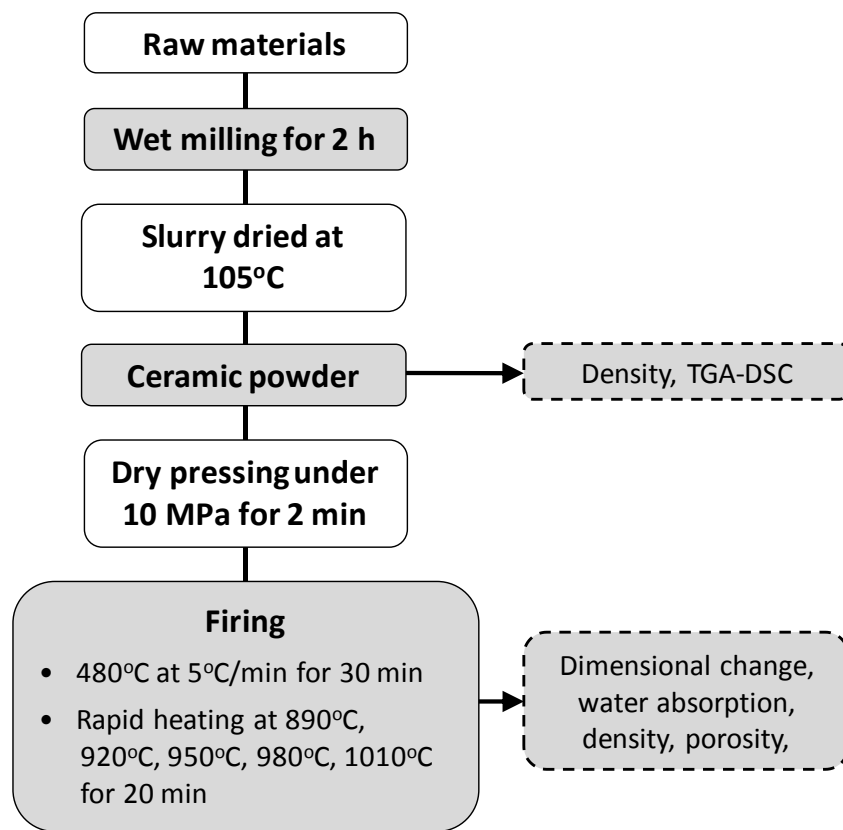


**Fig. 1.** Schematic diagram showing an overview of the process used to produce FBA-glass-ceramic foams.

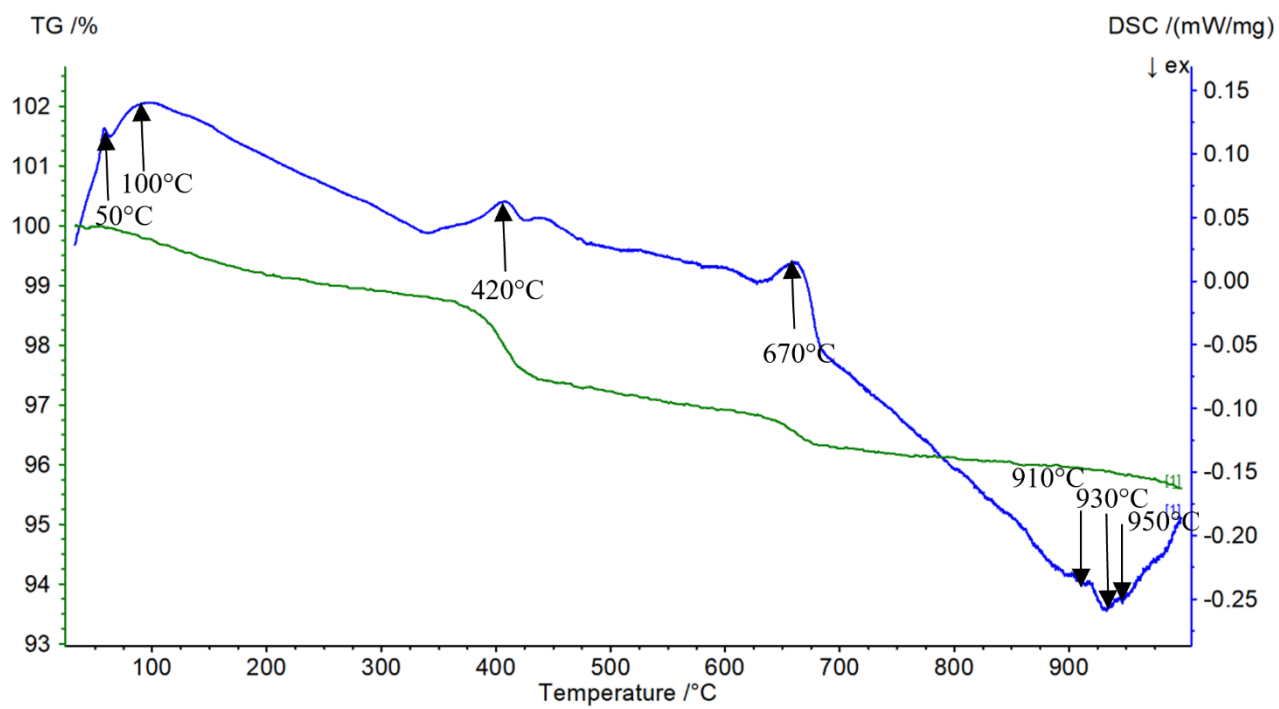


**Fig. 2.** A typical TGA-DSC plot of a FBA-glass powder mixture (G50) with additives.

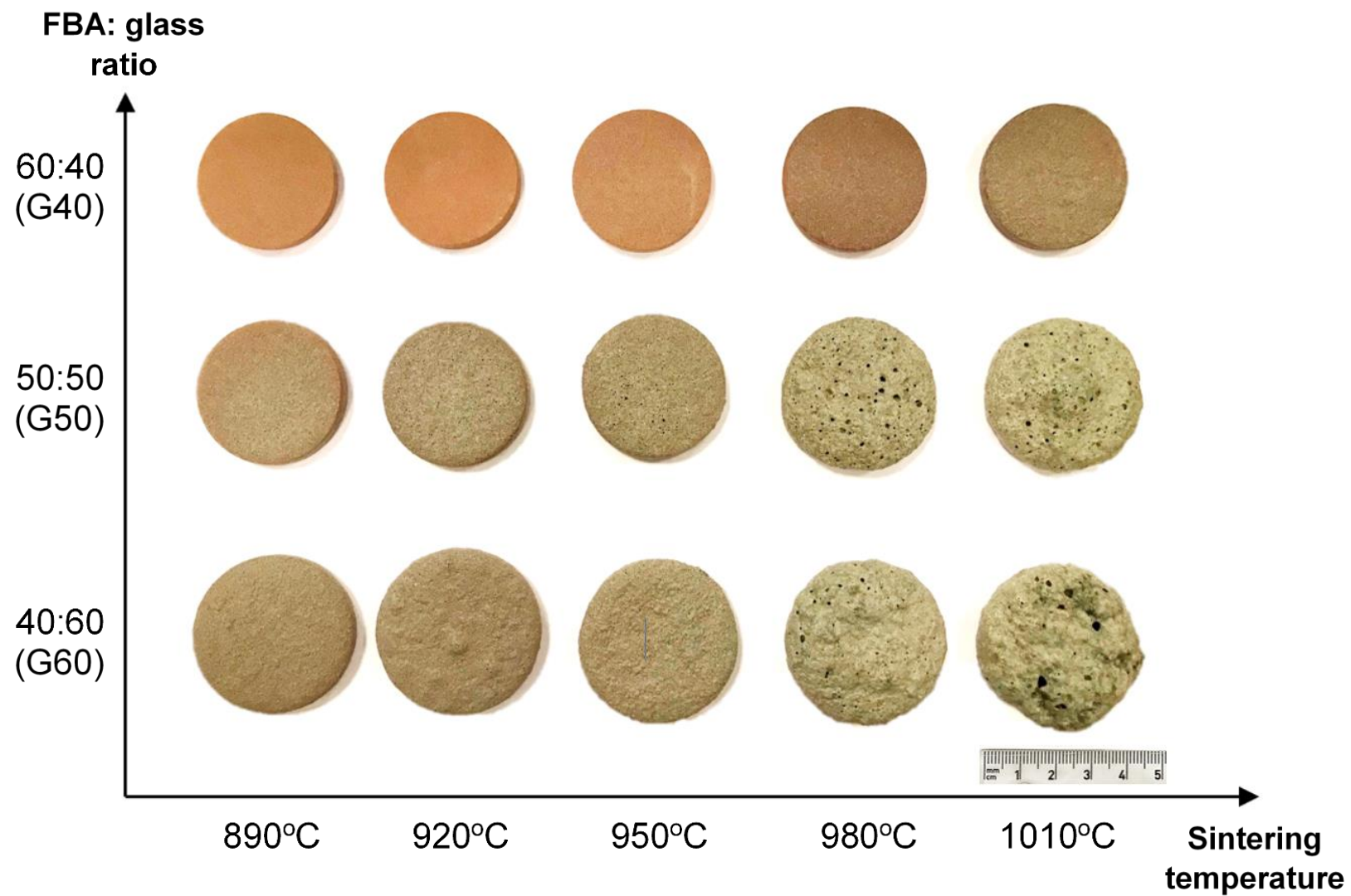


**Fig. 3.** Overview of the sintered FBA-glass ceramic foams showing the effect of sintering temperature and FBA/glass ratio.

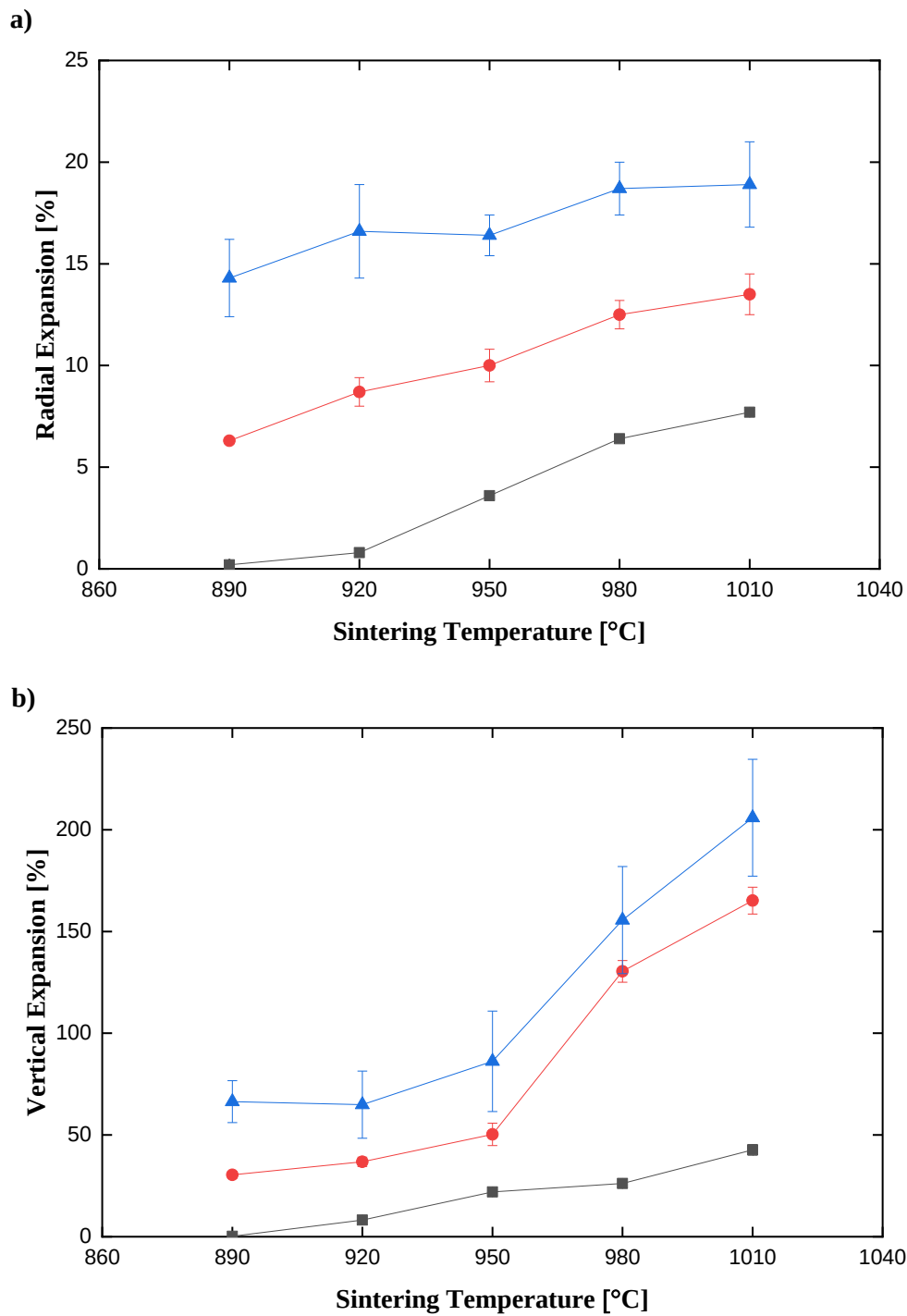


**Fig. 4.** Effect of sintering temperature and glass content on a) radial expansion and b) vertical expansion of FBA-glass-ceramic foams.

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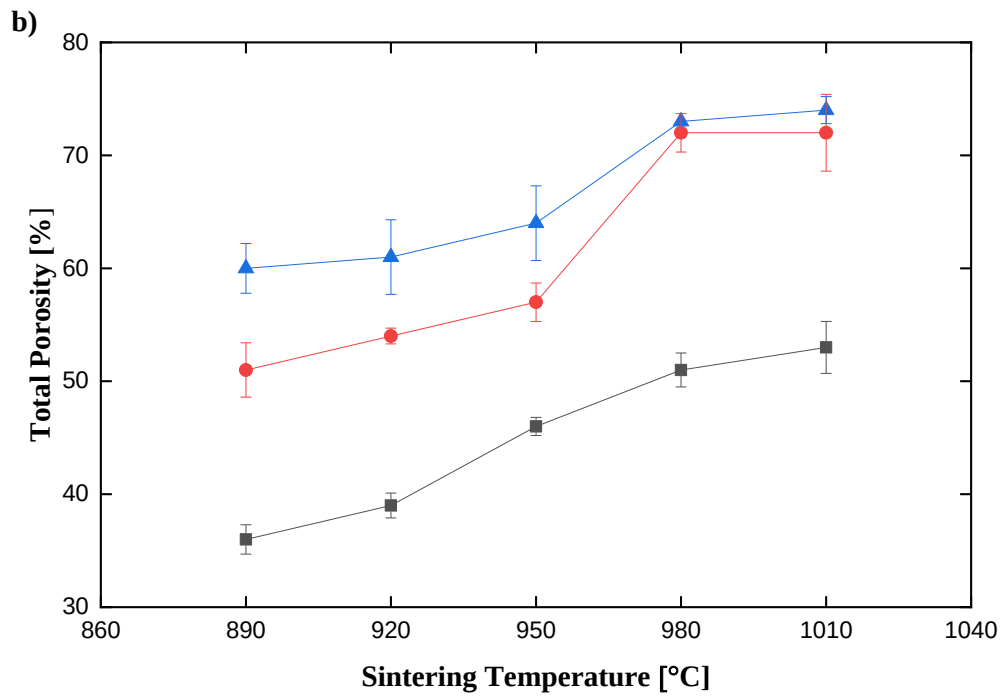
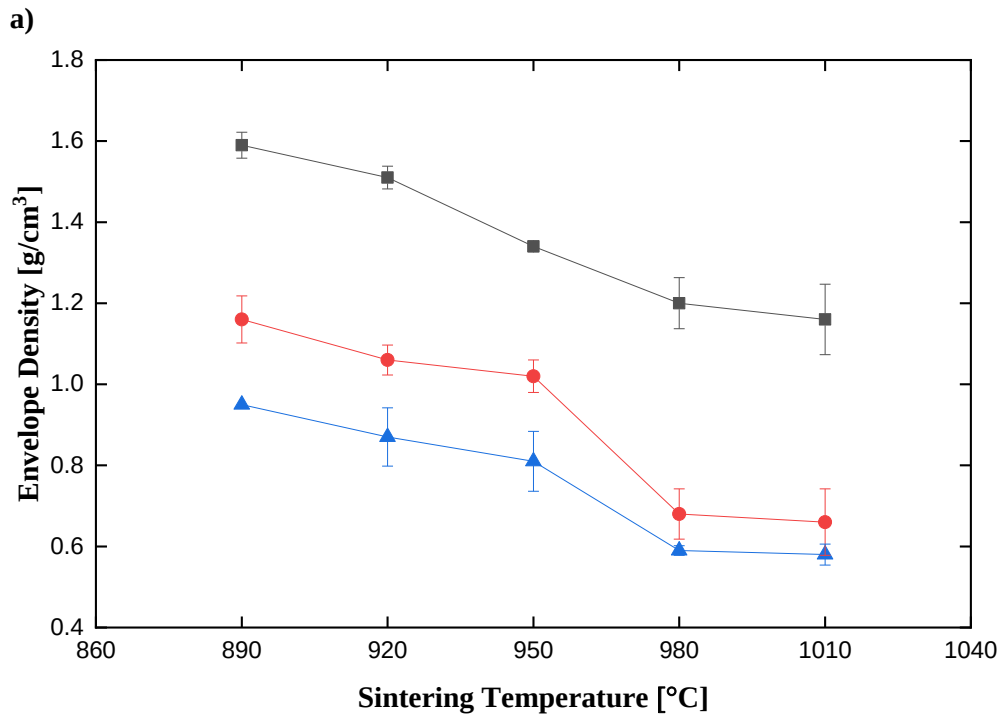
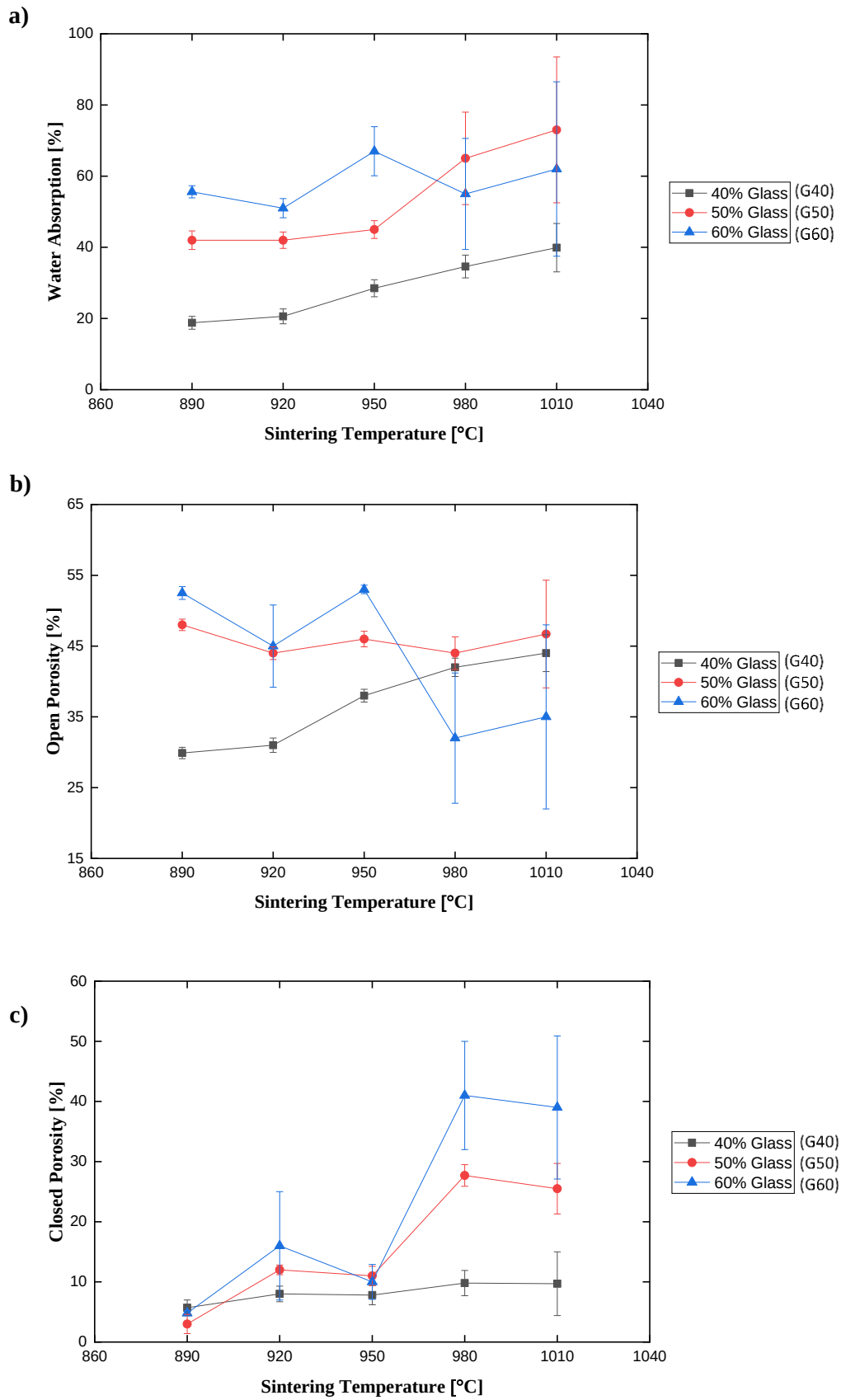


**Fig. 5.** Effect of sintering temperature and glass content on a) envelope density and b) total porosity of FBA-glass-ceramic foams.

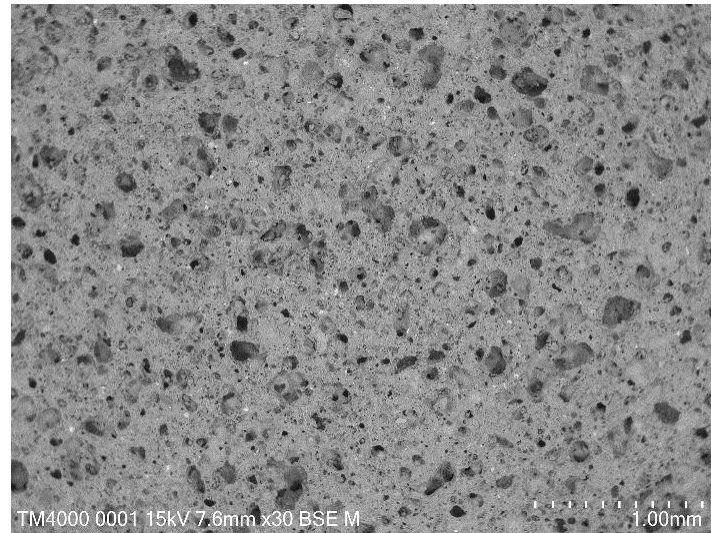
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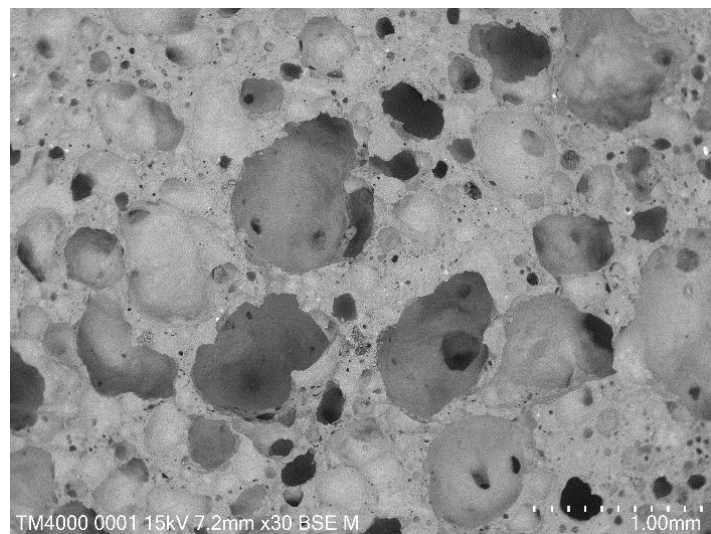


1 **Fig. 6.** Effect of sintering temperature and glass content on a) water absorption, b) open porosity and c)  
2 closed porosity of FBA-glass-ceramic foams.

a)



b)



c)

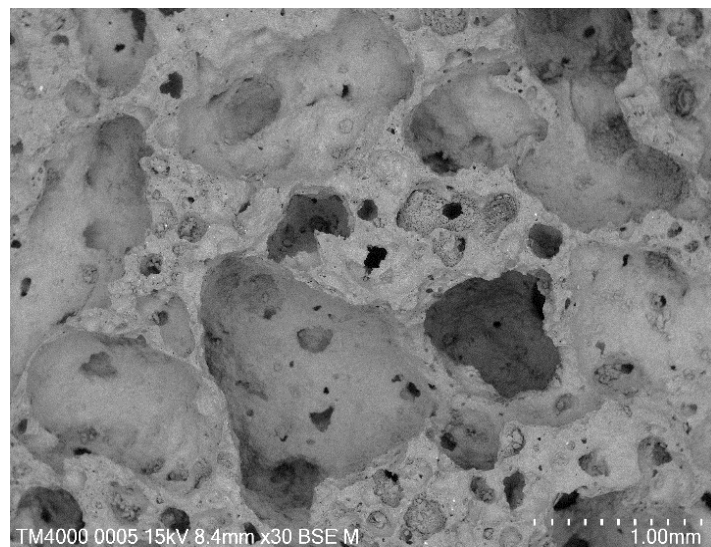


**Fig. 7.** SEM images of FBA-glass-ceramic foams produced with a) 40 wt.% (G40), b) 50 wt.% (G50) and c) 60 wt.% (G60) of glass content sintered at 950°C.

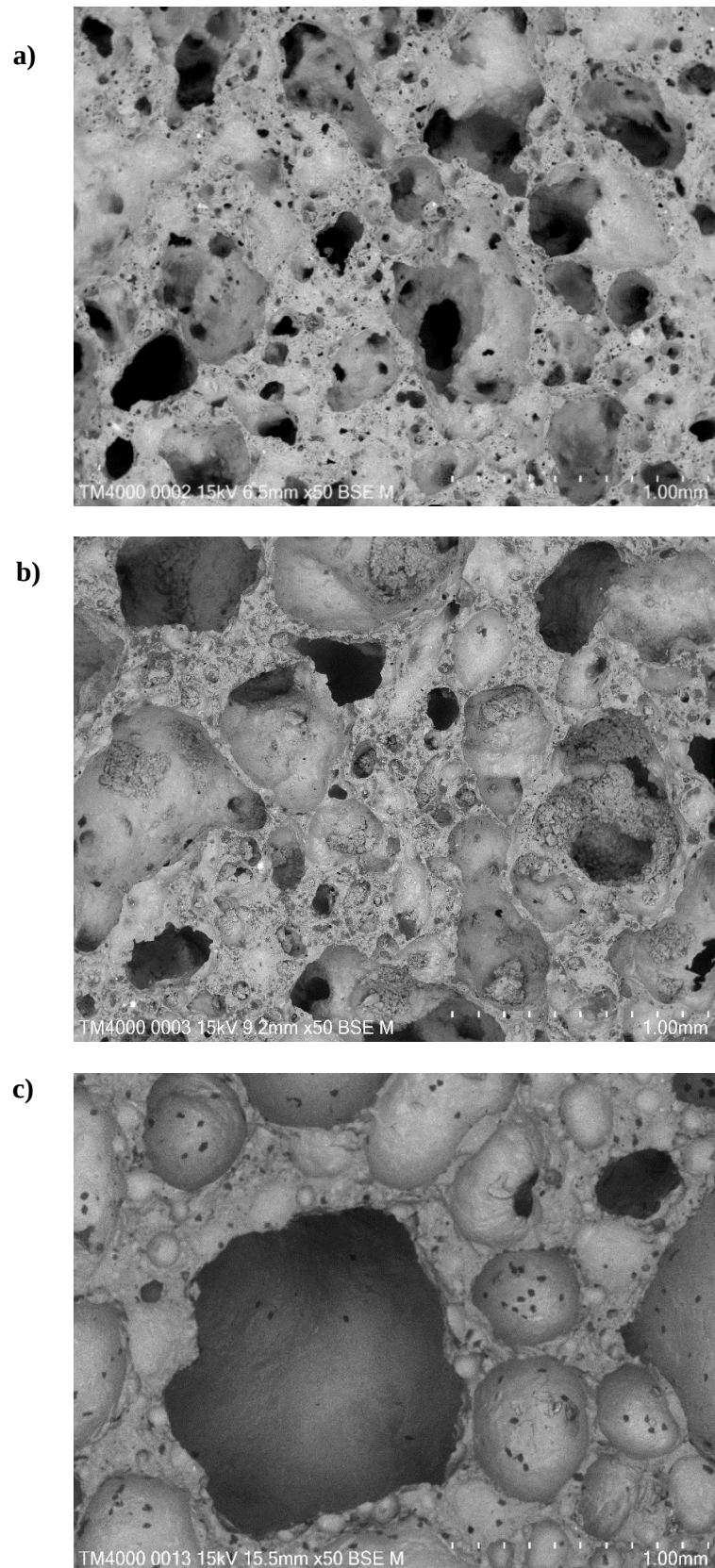


**Fig. 8.** SEM images of FBA-glass-ceramic foams produced with 60 wt.% of glass (G60) sintered at a) 920°C, b) 950°C and c) 980°C.

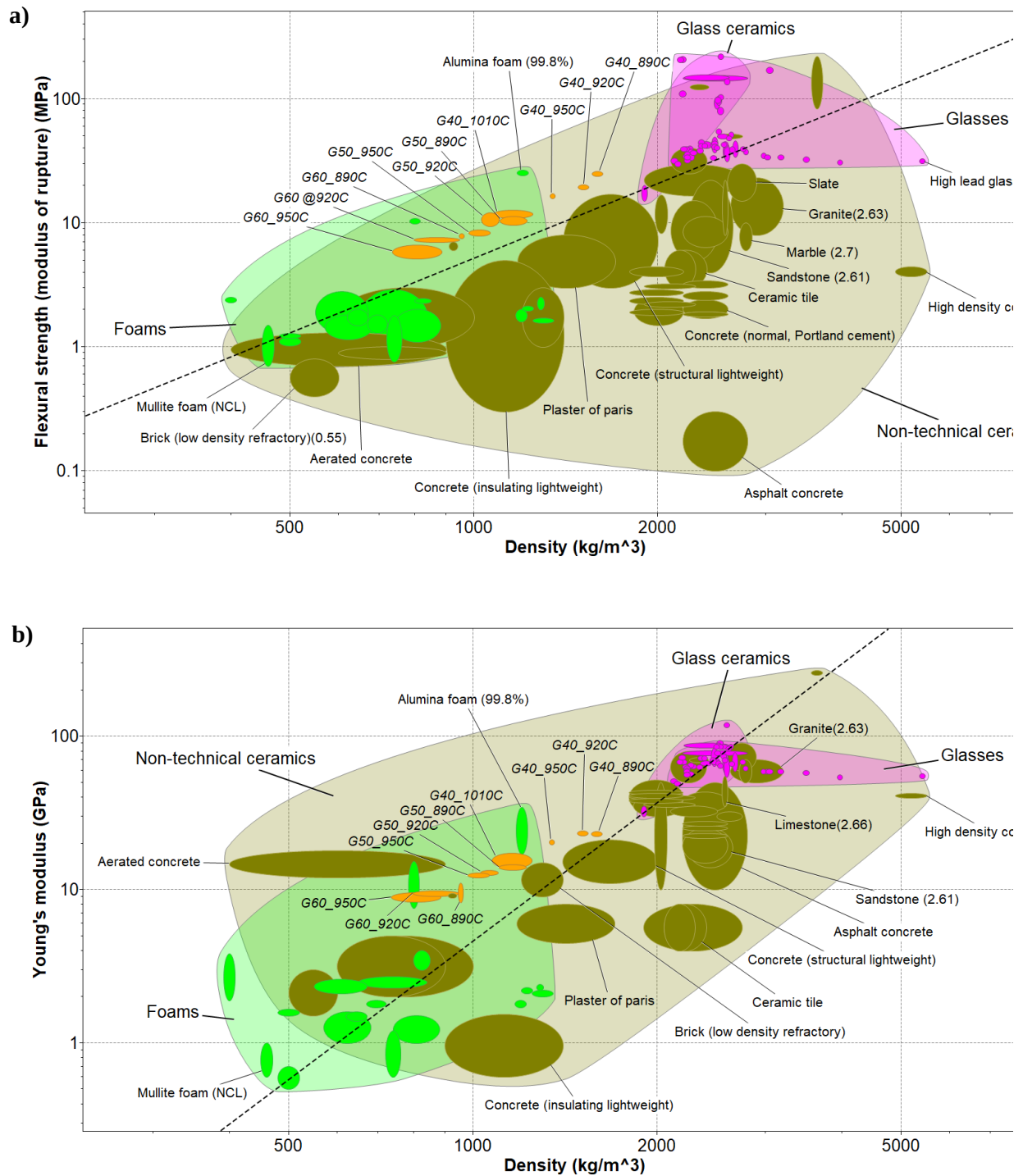


**Fig. 9.** Ashby plots comparing the specific flexural strength (a) and Young's modulus (b) of FBA-glass-ceramic foams (orange bubbles) with various other materials. The slopes represent the guidelines for minimum weight design [21].

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