STUDYING THE PRODUCTION OF FOAM GLASS FROM WASTE GLASS AND BLAST FURNACE SLAG

NGHIÊN CỨU CHẾ TẠO THUỶ TINH BỌT TỪ THUỶ TINH PHẾ THẢI VÀ XỈ LÒ CAO

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Abstract - Foam glass is a lightweight material with many advantages such as heat insulation, fire resistance, insect resistance, water and steam resistance. This research is on manufacturing foam glass from waste glass and ground blast furnace slag. The results showed that foam glass can be manufactured by two forming methods: pouring and compressing, the foaming agent is dolomite or a mixture of glycerol and liquid glass, the firing temperature varies in the range of 800-900^{o}C. The manufactured foam glass has bulk density from 0.29 to 1.63 g/cm^3 and porosity from 85.51 to 11.87%, suitable for different usage needs. The study also examines two important factors affecting the technical properties of foam glass: firing temperature and slag content. Foam glass with simple production technology will contribute to diversifying the choice of lightweight materials on the market today.

Key words - Foam glass; waste glass; blast furnace slag; glycerol; dolomite.

Tóm tắt - Thuỷ tinh bọt là loại vật liệu nhẹ với nhiều ưu điểm như cách nhiệt, chống cháy, chống được côn trùng, chịu được tác dụng của nước và hơi nước. Bài báo nghiên cứu chế tạo thuỷ tinh bọt từ thuỷ tinh phế thải và xỉ lò cao nghiền mịn. Kết quả cho thấy thuỷ tinh bọt có thể được chế tạo với hai phương pháp tạo hình là đổ rót và nén ép, chất tạo bọt là đôlômit hoặc hỗn hợp glycerol và thuỷ tinh lỏng, nhiệt độ nung thay đổi trong khoảng 800-900^{o}C. Thuỷ tinh bọt chế tạo được có khối lượng thể tích từ 0,29 đến 1,63 g/cm^3 và độ xốp thực từ 85,51 đến 11,87%, phù hợp với các nhu cầu sử dụng khác nhau. Bài báo cũng nghiên cứu hai yếu tố quan trọng ảnh hưởng đến tính chất kỹ thuật của thuỷ tinh bọt là nhiệt độ nung và hàm lượng xỉ. Thuỷ tinh bọt với công nghệ sản xuất đơn giản sẽ góp phần đa dạng hoá sự lựa chọn vật liệu nhẹ trên thị trường hiện nay.

Từ khóa - Thuỷ tinh bọt; thuỷ tinh phế thải; xỉ lò cao; glycerol; đôlômit.

1. Introduction

Glass is a traditional material, yet its demand continues to increase in the modern world. Consequently, alongside the growing consumption, there is a corresponding need to manage post-consumer glass, which is typically addressed in three ways: recycling (remelting into other glass products), destruction, or landfill disposal [1].

Glass recycling has become relatively common, especially in developed countries. This practice not only reduces the amount of waste glass released into the environment but also helps protect water quality and human health. Furthermore, recycling lowers the production costs of new glass and reduces the consumption of natural resources (both raw materials and fuels). Therefore, glass recycling is highly significant from both economic and environmental perspectives.

However, glass recycling still faces several challenges, even in developed countries. In 2014, EU countries produced 18.5 million tons of glass, of which 25% was not recycled [1]. In 2015, the United States produced 11.5 million tons of glass and recycled only 26.4% [2]. The main obstacles stem from the need for fine grinding and impurity removal during the recycling process. For container glass, variations in color among glass cullet complicate recycling, especially for glass products with high aesthetic requirements. Recycling is even more difficult for special types of glass, such as LCD glass, medical glass, and glass fibers [1].

To provide a more diverse and feasible approach to glass recycling, we investigate the production of foam glass from waste container glass and industrial by-products using a process that does not require excessively high temperatures [3, 4]. The industrial by-product used in this study is finely ground blast furnace slag, a by-product of steel production. When the slag content in the mixture is below 20 wt %, it does not affect the properties of the foam glass; however, if the content exceeds 60 wt %, it becomes difficult to form the foamed structure [5].

Additionally, a variety of foaming agents can be used to create the porous structure of foam glass, such as a mixture of glycerol and liquid glass, a mixture of NaF and $Na_2B_4O_7$ [5, 6], SiC [2, 4], dolomite [2, 7], among others. In terms of shaping, samples can be formed by pressing or pouring methods.

Foam glass is commonly used as an insulating material in civil and industrial construction. It possesses many desirable properties, including low density, excellent thermal insulation, outstanding fire resistance, chemical inertness, non-toxicity, resistance to insects and rodents, and durability against water and steam without the degradation seen in other materials. Additional advantages include ease of transportation, low transport costs, and the

material's suitability for machining, cutting, drilling, and integration with mortar or cement concrete [2]. All these characteristics make foam glass a promising material for building applications.

This study is significant in terms of environmental protection, promoting recycling processes, and fostering the circular economy to utilize and conserve valuable natural resources.

2. Experimental

2.1. Materials and chemicals

2.1.1. Waste glass

The raw material used was colorless waste container glass, classified as sodium calcium silicate glass. The glass was cleaned, dried, crushed, and finely ground using a wheel mill to a particle size passing through a 0.2 mm sieve.

The chemical composition of the container glass is shown in Table 1.

Table 1. *Chemical composition of container glass (wt %)*

SiO_2	Al_2O_3	CaO	MgO	Na_2O	K_2O	Fe_2O_3
71.86	0.08	9.22	5.64	13.13	0.02	0.04

2.1.2. Blast furnace slag

The slag used was granulated blast furnace slag from Hoa Phat Steel Company, Quang Ngai Province. During pig iron production, molten blast furnace slag is rapidly cooled with high-pressure water to form granulated slag, which is then finely ground into an active mineral admixture commonly used as an additive for concrete [8] (see Figure 1).

Figure 1. *S95 ground granulated blast furnace slag and granulated blast furnace slag*

The chemical composition of the ground S95 granulated blast furnace slag is presented in Table 2 [9].

Table 2. *Chemical composition of S95 Hoà Phát ground granulated blast furnace slag (wt %)*

SiO_2	Al_2O_3	CaO	MgO	SO_3	Cl^-
35.53	12.89	40.77	7.49	0.17	0.001

X-ray diffraction (XRD) analysis performed on a SmartLab X-Ray Diffractometer (Rikagu, Japan) using Cu-Kα radiation, with a scanning range of $2\theta = 5^o \div 80^o$ (see Figure 2), shows that the slag consists mainly of an amorphous glassy phase, with a very low content of crystalline phases.

The slag has a moisture content of 0.33%, a density of 2.89 g/cm^3, a fineness of 5281 cm^2/g, a ratio of flow value of 108.31%, and a 28-day strength activity index of 116.53% [9], meeting the requirements of TCVN 11586:2016 [10].

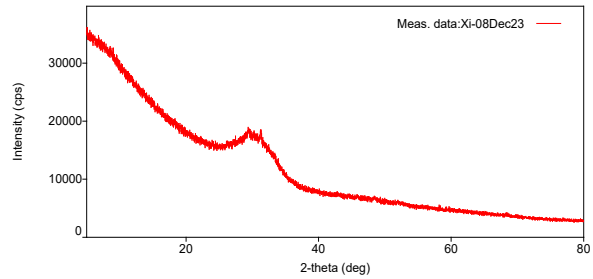

Figure 2. *XRD diagram of S95 Hoa Phat slag*

2.1.3. Glycerol

Glycerol is a polyhydric alcohol with the chemical formula $C_3H_8O_3$ and acts as a foaming agent. The glycerol used was a commercial product imported from China.

2.1.4. Liquid glass (Sodium Silicate Solution)

Liquid glass was produced by Viet Tri Chemical Joint Stock Company and used as purchased from the market. It is a light yellow solution containing SiO_2: 30 wt %; Na_2O: 11 wt %; H_2O: 59 wt %; with a density $\rho_v = 1{,}42$ g/cm^3.

2.1.5. Dolomite

Thanh Hoa dolomite was used, with a particle size passing through a 0.088 mm sieve; its chemical composition is shown in Table 3.

Table 3. *Chemical composition of Thanh Hoá dolomite (wt %)*

MgO	CaO	Al_2O_3	Fe_2O_3	P_2O_5	SO_3	MnO
19.0	32.0	0.13	0.2	0.045	0.025	0.122

Dolomite acts as a foaming agent and decomposes upon heating according to the following reactions:

$$CaMg(CO_3)_2 \leftrightarrows CaCO_3 + MgO + CO_2 \quad (1)$$

$$CaCO_3 \leftrightarrows CaO + CO_2 \quad (2)$$

Reaction (1) occurs at 800°C, and reaction (2) at 890°C; both release CO_2 gas to form the foam structure in the glass [7].

2.1.6. Agar

Commercially available agar was used in this study.

2.2. Experimental Procedure

Samples were shaped using two methods: pouring into steel molds and semi-dry pressing.

The pouring method was used to produce foam glass with high porosity, low bulk density, and low strength, targeting applications in thermal and acoustic insulation. The foaming agent was Thanh Hoa dolomite (4 wt %), and the foam stabilizer was agar [11] (used at 2 % of the total weight of waste glass and slag). First, the glass, S95 slag, and water were mixed in a mixer. Agar was dissolved in water at 80°C to form a viscous solution, which aids in stabilizing the foam and preventing collapse. The raw mixture was heated to 80°C, the agar solution was added, and the mixture was stirred thoroughly. The resulting slurry, with a moisture content of 40%, was poured into steel molds. The samples were then air-dried at room temperature for 24 hours, followed by oven drying at 80°C for another 24 hours.

The samples were subsequently fired at 800°C, 850°C, and 900°C [2, 5, 7], with a heating time of 90 minutes and a soaking time of 30 minutes (see Figure 3).

Figure 3. *Sample formed by pouring method after firing*

The semi-dry pressing method was used to produce foam glass with lower porosity, moderate bulk density, and relatively high strength, aiming at applications such as thermal and acoustic insulation panels or bricks. The foaming and foam-stabilizing agents were a mixture of glycerol and liquid glass, prepared in a ratio of glycerol/liquid glass/water = 40/40/20 wt % [5]. In addition to their roles as foaming and stabilizing agents during firing, liquid glass also acts as a binder during the pressing process.

First, the glass, S95 slag, and foaming/stabilizing additives were mixed in various proportions. Water was then added, and the mixture was homogenized to a moisture content of 5-6% before being formed by semi-dry pressing using a hydraulic press. The pressed samples were dried at 110°C to constant moisture content and then fired at 800°C, 850°C, and 900°C, with a heating time of 90 minutes and a soaking time of 30 minutes, similar to the poured samples (see Figure 4).

Figure 4. *Sample formed by semi-dry pressing method after firing*

After firing, the following properties were determined: specific weight ρ_r (g/cm^3) by the pycnometer method, bulk density ρ_v (g/cm^3), water absorption H (%), apparent porosity X_{bk} (%), and true porosity X_t (%) using the method of weighing dry samples, water-saturated samples, and samples immersed in water (hydrostatic weighing). The results were calculated according to Archimedes' principle.

True porosity was calculated using the formula [6]:

$$X_t = (1- \rho_v/\rho_r)x100$$

Additionally, the surface morphology of the samples was examined using scanning electron microscopy (SEM).

3. Results and discussion

3.1. Foam glass mix compositions

Seven foam glass compositions, designated FSG1 to FSG7, were prepared as shown in Table 4.

Compositions FSG1, FSG2, and FSG3 were shaped by the pouring method, using Thanh Hoa dolomite as the foaming agent at a content of 4 wt % and agar as the foam stabilizer at 2 wt %. The blast furnace slag content was 0 wt % , 20 wt %, and 50 wt %, respectively.

Table 4. *Foam glass mixture composition, wt %*

Mixture	Slag	Glass	Glyxerol+ water glass+water	Dolomite	Agar
FSG1	0	94	0	4	2
FSG2	20	74	0	4	2
FSG3	50	44	0	4	2
FSG4	20	70	10	0	0
FSG5	30	60	10	0	0
FSG6	40	50	10	0	0
FSG7	50	40	10	0	0

Compositions FSG4, FSG5, FSG6, and FSG7 were shaped by the pressing method, with slag contents of 20%, 30%, 40%, and 50%, respectively. The mixture of glycerol and liquid glass was used at 10%, while the blast furnace slag content in the mix increased from 20 wt % to 50 wt %.

3.2. Technical properties of the samples

The technical properties of the samples are presented in Table 5.

Table 5. *Technical properties of the samples*

Sample	Firing temperature, °C	Bulk density (ρ_v, g/cm^3)	Specific weight (ρ_r, g/cm^3)	Water absorption (H, %)	Apparent porosity (X_{bk}, %)	Porosity (X_t, %)
FSG1	800	0.29	2.022	256.9	76.94	85.51
	850	0.34	2.038	247.2	75.57	83.32
	900	0.38	2.026	210.3	74.49	81.24
FSG2	800	0.41	2.058	202.7	74.41	80.08
	850	0.45	2.054	201.0	73.67	78.09
	900	0.49	2.035	187.2	71.07	75.92
FSG3	800	0.44	2.012	146.1	70.64	78.13
	850	0.48	2.001	128.3	68.00	76.01
	900	0.52	2.045	107.8	66.44	74.57
FSG4	800	0.78	1.552	72.06	44.51	49.74
	850	0.83	1.588	60.39	42.26	47.73
	900	0.94	1.600	57.23	35.43	41.25
FSG5	800	1.00	1.609	56.48	31.43	37.85
	850	1.05	1.706	50.44	31.53	38.45
	900	1.15	1.702	45.12	24.95	32.43
FSG6	800	1.33	1.754	39.12	17.85	24.17
	850	1.46	1.846	37.23	15.50	20.91
	900	1.49	1.788	34.12	11.66	16.67
FSG7	800	1.50	1.748	25.80	8.55	14.21
	850	1.55	1.806	16.67	9.15	14.17
	900	1.63	1.850	15.28	5.45	11.87

For the compositions FSG1, FSG2, FSG3 (shaped by pouring) and FSG4, FSG5, FSG6, FSG7 (shaped by pressing), it was found that both the firing temperature and

the slag content in the mix are two main factors influencing the material properties.

When the firing temperature was increased from 800°C to 900°C, the bulk density of FSG1, FSG2, and FSG3 samples increased from 0.29 to 0.52 g/cm^3, while that of FSG4, FSG5, FSG6, and FSG7 samples increased from 0.78 to 1.63 g/cm^3, as shown in Figure 5.

As the firing temperature increased from 800°C to 900°C, the true porosity of FSG1, FSG2, and FSG3 samples decreased from 85.51 to 74.57 g/cm^{3,} while that of FSG1, FSG2, FSG3, FSG4 samples decreased from 49.74 to 14.17 g/cm^3, as shown in Figure 6. Structurally, open pores account for a significant proportion of the true porosity, as evidenced by the apparent porosity X_{bk}, which ranges from 5.45% to 76.94%. For example, the FSG1 sample fired at 800°C exhibited an apparent porosity of 76.94%, with open pores clearly visible to the naked eye (see Figure 7).

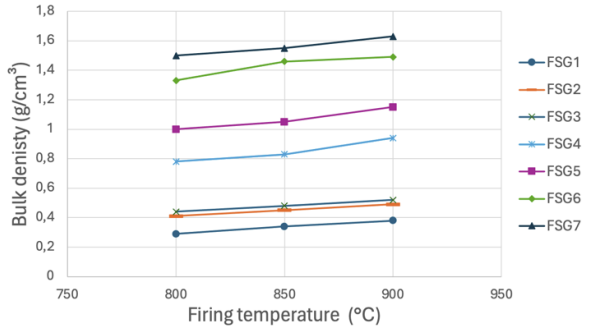

Figure 5. *Dependence of bulk density of foam glass samples FSG1-FSG7 on firing temperature*

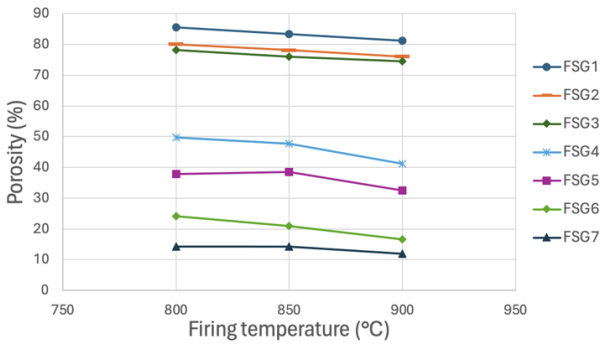

Figure 6. *Dependence of porosity of foam glass samples FSG1-FSG7 on firing temperature*

Figure 7. *FSG1 sample image*

With increasing firing temperature from 800°C to 900°C, the water absorption of all samples decreased from 256.9% to 15.28%.

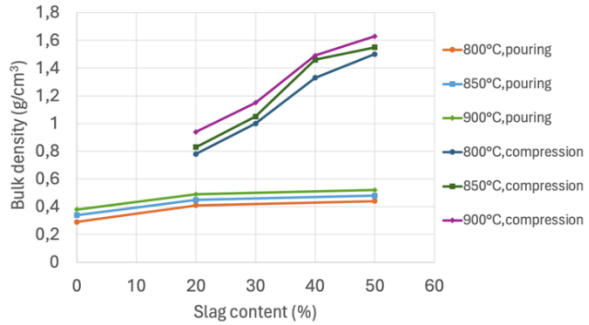

Figure 8. *Dependence of samples bulk density on slag content at different firing temperatures and forming methods*

Regarding the effect of slag content, as the slag content in the mix increased, the bulk density of the samples increased, while water absorption and true porosity decreased. The graph in Figure 8 shows that as the slag content increased from 0% to 50%, the bulk density of FSG1, FSG2, and FSG3 (poured samples, fired at 800, 850, and 900°C) increased from 0.29 to 0.52 g/cm^3; similarly, as the slag content increased from 20% to 50%, the bulk density of FSG4, FSG5, FSG6, and FSG7 (pressed samples, fired at 800, 850, and 900°C) increased from 0.78 to 1.63 g/cm^3.

Thus, with both pouring and pressing shaping methods and firing temperatures ranging from 800°C to 900°C, foam glass samples with bulk densities from 0.29 to 1.63 g/cm^3, and true porosities from 85.51% to 11.87% were produced. All compositions from FSG1 to FSG7, with a wide range of bulk density and porosity, are suitable for different application requirements. From the perspective of maximizing blast furnace slag utilization and producing foam glass with low bulk density, we propose composition FSG3 (slag content 50%, bulk density 0.44 g/cm^3, pouring method, fired at 800°C) as optimal. Conversely, if the aim is to maximize slag use and obtain foam glass with higher strength, composition FSG7 (slag content 50%, bulk density 1.63 g/cm^3, pressing method, fired at 900°C) is optimal.

3.3. Surface morphology characteristics (SEM)

The surface morphology of the foam glass was investigated using a Jeol JSM-6010 Plus/L scanning electron microscope (SEM). The results are shown in Figures 9.

Examining the SEM images of FSG4 samples (slag content 20%) fired at 800, 850, and 900°C, it is evident that as the firing temperature increases, both the number and size of pores decrease (see Figures 9a, 9b, and 9c). Similarly, SEM images of FSG7 samples (slag content 50%) fired at 850 and 900°C show that with increasing temperature, the number and size of pores decrease, and the samples become denser (see Figures 9d and 9e). These results are entirely consistent with the bulk density and porosity data analyzed in Table 5.

Notably, Figure 9f shows the SEM image of the FSG7 sample fired at 900°C at 150x magnification, where rounding of grain boundaries is observed, indicating the onset of a molten glass phase. Therefore, the samples should not be fired at temperatures higher than 900°C.

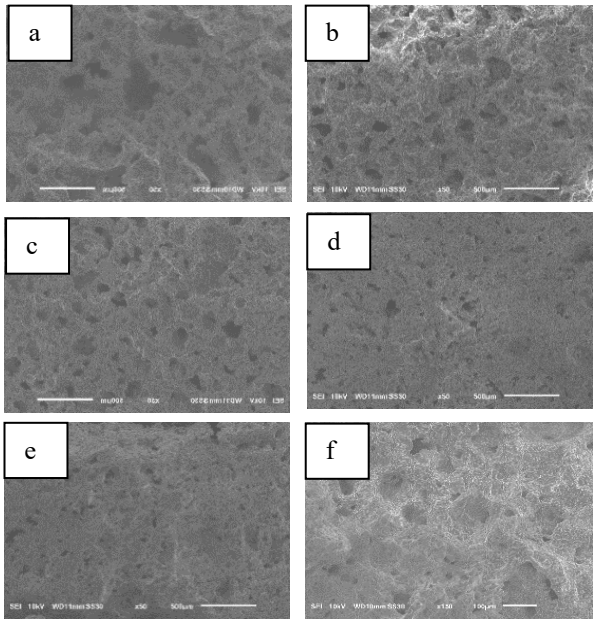

Figure 9. *SEM images at 50x and 150x magnification a) FSG4 sample fired at 800°C, b) FSG4 sample fired at 850°C, c) FSG4 sample fired at 900°C, d) FSG7 sample fired at 850°C, e) FSG7 sample fired at 900°C, f) FSG7 sample fired at 900°C, magnification 150x*

4. Conclusion

The study successfully developed a process for producing foam glass using two shaping methods: pouring and pressing, with firing temperatures ranging from 800°C to 900°C. The resulting foam glass exhibited bulk densities from 0.29 to 1.63 g/cm^3, and true porosities from 85.51% to 11.87%, meeting a variety of application requirements.

The results indicate that the two most significant factors affecting the technical properties of foam glass are firing temperature and slag content. As both firing temperature and slag content increase, bulk density increases while true porosity decreases.

From the perspective of maximizing blast furnace slag utilization, composition FSG3 (slag content 50%, bulk density 0.44 g/cm^3, pouring method, fired at 800°C) is proposed as optimal.

Alternatively, if both high slag utilization and higher material strength are desired, composition FSG7 (slag content 50%, bulk density 1.63 g/cm^3, pressing method, fired at 900°C) is optimal.

Foam glass is an environmentally friendly product with a simple, highly feasible production technology. This initial research into foam glass production contributes to diversifying lightweight material options, with the potential to partially replace current products on the market such as lightweight concrete, foam concrete bricks, and autoclaved aerated concrete.

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