A Review of Porous Glass-Ceramic Production Process, Properties and Applications

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Abstract. Porous materials exist around our environment and play an important role in our daily lives to be used widely in many fields, among the fields are energy distribution and storage, vibration suppression, liquid filtration, heat insulation, and sound absorption. Porous glasses are materials that have pores structure using silica as the primary component in all types of standard and specialty glass mixture with a foaming agent and other additives. Porous glass is usually in the size of nanometre and micrometer range. Porous glass is usually prepared by using phase separation, sintering and sol-gel method [1]. This review paper will focus on the various properties of this porous material related to the production process used to their properties and possible applications such as filtering, lightweight concrete, heat resistance insulator, and biomaterials.

1 Introduction

The use of glass is becoming increasingly popular nowadays and very important in materials science and functional materials. Glass is a non-crystalline material that has a wide range of practical, technological, and decorative applications. Glass can be defined as every solid that has a non-crystalline structure at the atomic scale and shows the glass transition when heated to a liquid state [2]. Glass-ceramic materials have many properties with both crystalline and non-crystalline shared properties. In recent years, researchers have developed many types of glass including porous glass.

Porous glass can define as any solid material which contains cavities, channels, or interstices. According to Mejia, porous materials are defined as solids containing voids, channels, or interstices. According to the International Union of Pure and Applied Chemistry (IUPAC), porous materials are divided into three groups depending on the pore diameter ranges such as microporous, mesoporous and macroporous as shown in Table 1 [3]. The pore structure will determine the physical properties of porous glass material such as its density, thermal conductivity, and strength. In this paper, we will describe the various characteristics of this porous material related to the production process, different properties, and possible applications of porous glass that already the researcher developed.

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Table 1. Classification of pore according to pore-width according to IUPAC [3].

| Pore type     | Microporous | Mesoporous | Macroporous |
|---------------|-------------|------------|-------------|
| Pore-width (nm)| <2          | 2-50       | >50         |

2 Production process

Production of porous glass-ceramic involved different methods such as phase separation or leaching process, sol-gel method, sintering, and foaming. Based on the synthesis method, porous glass is categorized as “classical” porous glass that made by leaching, open-pore glass derived by sintering glass and porous silica prepared through sol-gel method [4, 5].

2.1 Phase separation

In the phase separation process, sodium borosilicate glass is used to produce glass-ceramics. Using phase separation, the heat-treated process of sodium borosilicate was used [6]. In the heat treatment process, two different phases was found. The first phase is an alkali-rich borate phase while the other phase is almost pure silica which is soluble and insoluble in acids respectively. Once the heat treatment done, the glass is soaked in a hot dilute acid solution [6].

Fig. 1 demonstrates the schematic diagram of phase separation process to produce porous glass. By using acid corrosion treatment such as hydrochloric acid (HCl), nitric acid (HNO₃), and sulfuric acid (H₂SO₄) in the silicate phase [7], the “weak” borate phase will dissolve and create continuous porosity. It is possible to adjust the pore size by controlling the composition and heat treatment. This process is used to prepare silica-rich glass at low temperatures. From this process, the porous glass can be sintered deeper in vitreous silica glass at temperature <1000°C, compared to classical way which is 2000°C [3, 6].

Fig. 1. Schematic diagram of phase separation process.

2.2 Sol-gel method

Homogenization of the solution is achieved at ambient temperature for the sol-gel method. The gelling procedure was used to produce cross-linking and preservation of the liquid structure further by heat treatment in order to eliminate the organic species, hydroxyl, and porosity [6]. This method is the most dynamic, reliable, and environmental friendly [8, 9]. This method are also very convenient and versatile due to its simple step procedure, economical, and diversity of high purity materials from various configurations such as monoliths, nanoparticles, thin films, foams, fibers, and others [8, 10].
2.3 Sintering process

Sintering is the process of bonding, compaction, and/or recrystallization of a powder compact which is a treatment in a green body that is transformed into a stronger monolith [6]. Glass-ceramics are developed using glass powder sintering-crystallization techniques. This method is economical and suitable for the production of a small number of articles with complex forms [11, 12]. According to Ayoob et al to produce glass-ceramics using the sintering method, raw materials such as soda-lime silicate glass and balls of clay are crushed, ground, and sieved to obtain powder form. All materials were mixed and pressed into pallet shape by hydraulic pressure at room temperature and were sintered at 750 - 950°C with a soaking time of one hour and a heating rate of 2 °C/minute and a natural cooling temperature [12].

2.4 Foaming process

Foamed glass is prepared by bubbles of nucleates in the melt and then extinguished. Bubbles are obtained by the decomposition of carbonate during the melting [6]. Nam et al. developed a porous scaffold by using an effervescent salt (ammonium bicarbonate) as a foaming agent. The effervescent salt particles was sieved from the polymer gel paste then projected in a mold to get a shape. Afterwards, it was then soaked into boiling water. The ammonia gas (NH₃) and carbon dioxide gas (CO₂) was generated and the effervescent salt particles leached out from the solidification polymer matrix. This phenomenon creates the pores with high voids linking [13]. Fig. 2 demonstrate the schematic diagram of the gas foaming process for porous glass-ceramic production.

![Diagram of gas foaming process](image)

Fig. 2. Schematic diagram of gas foaming process.

3 Properties and Applications

The porous glass-ceramic has many advantages such as high strength, good thermal stability, large specific surface areas, and a greater pores volume that are commonly chosen for various applications [14, 15]. The application such as biomaterials, lightweight concrete, heat and sound insulation and filter are introduced based on the properties of porous glass-ceramic produced.
3.1 Biomaterials

Nowadays, porous glass-ceramics are widely used in biomedical applications because of their high biocompatibility and bioactive materials properties. An example application of biomaterials is bone prosthesis melting from foamed glasses [6]. Sindut et al. produce a bioactive porous glass-ceramic to use as the implant for plastic surgery and other application. According to microstructure observations, the porous structure was demonstrated by sinters at 1200°C heated at rate of 1.5°C/min has a good microstructure from the point of view of implant applications which has close pores structure using cast slip deposition on polymer sponges [16].

Iatsenko et al. reported that the strength of the sample increased from 0.8 to 10.5 MPa with an increase in temperature due to the formation of closed porosity and vitrification of the sample surface (Table 2). The volume shrinkage, total and open porosity on the sintering temperature in Table 2 shows that sharp increases in the volume shrinkage of the glass-ceramic samples from 8 to 76% with increasing sintering temperature causes a decrease in the total and open porosity. The pore structure transformation from an open into the closed type and optimal structural mechanical properties obtained can use as materials for the replacement of defective cancellous bone [17].

| Temperature (°C) | 800  | 900  | 1000 | 1100 |
|-----------------|------|------|------|------|
| Compressive Strength (MPa) | 0.8  | 1.0  | 3.3  | 10.5 |
| Volume Shrinkage (%) | 8    | 12   | 45   | 76   |
| Total and open porosity (%) | 84   | 78   | 60   | 24   |

3.2 Insulation and lightweight building

An environmentally safe thermal insulation materials that have high strength, are fire-resistant, durable, low density, and high-quality macrostructure of material will be a great interest in the future [18]. According to Hartung et al., the utilization of capillary suspension as processing route provides the variables to control the pore network, porosity, mechanical properties and chemical resistance of the porous body. This lightweight porous glass capillary suspension has a low density (200 kg/m³) and good compressive strength (0.6 MPa) suitable for the lightest construction or insulation materials [19].

Bernardo et al. in their study was produced the crystallized glass foams from waste glass by using direct treatment at temperature from 900 to 1050°C. MnO₂ effectively encourages the oxidation of SiC hence employed as foaming agent for soda-lime glass at relatively low temperatures (<1000°C) within 60 min of soaking time. They found that the density decreases as soaking time increases (15-60 min) at temperature from 950-1050°C due to gas released during the process. It was elucidated that the beginning of the coalescence of small cells into larger. These glass foams are suitable to use as aggregates in lightweight concrete since it is light, simple, and economic because its sinter at a lower temperature [20].

3.3 Filter

Porosity and pore size properties are important aspect that needs to control in producing filtering product from porous glass-ceramic. The properties such as thermal characteristic, particle size, percentage of binder used and compressive strength are influencing the type of porosity and size of pore in the resulting filter sample. Typically, the porous materials in
development of filter are producing the open pore type. The average size of pore for is in range of 0.01 - 100µm according to the desired filter application.

Sadighzadeh et al. in their study was produced porous glass bodies using partial sintering of waste glasses. They found that the porosity of samples produced was in range of 15.5-32%. Accordingly, the sintering time and temperature will affect the porosity value. The samples showed higher shrinkage and lower porosity (8%) when sintered at temperature 750 and 800°C. However, when sintered at lower temperature (700°C) for 2 hours, the porosity of sample produced increased (16 – 20%) with no cracking structure but the porosity value was considered as low. Hence, to get the higher porosity sample, the sintering time was decrease into 75 min using the sample with particle size range of 40 - 63 µm. The porosity found was 30% with 5.4µm of pore size. This finding was fulfilled the filtration needed in the drug industry [21].

4 Conclusions

Porous glass-ceramics can be produced in various methods that associated with different properties and applications. Through the different production processes, the porous glass-ceramic structure can be adjusted for different applications according to their properties. The pore structure classification also can determine the application of porous glass-ceramics which for biomaterials need the pore structure transformation from an open into the closed type and optimal structural mechanical. For insulation materials and lightweight buildings need high strength, low density, and high-quality macrostructure of the materials. Filter application needs an open-pores structure. The sintering time and temperature will affect the porosity value. Long soaking time will increase density. To produce lightweight materials and filters, density and porosity need to control. Sintering time need to be shorter (lower than 2 hours) and temperature need to be higher (higher than 700°C).

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