Thermal properties of porous ceramics manufactured by direct foaming using silicon sludge and silica fume

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ABSTRACT
In this study, waste silica fume was used as the raw material for manufacturing porous ceramics, and its mechanical and thermal properties required for application as thermal insulators were studied. For pore formation with direct foaming, Si sludge (0.01, 0.05, and 0.1 wt%) and NaOH aqueous solution (14 N) were used as the foaming agents. The porous ceramics sintered at 900°C showed an apparent porosity of 85.9–89.8%, and the specimen with 0.1 wt% Si sludge showed the highest apparent porosity of 89.8% and a bulk density of 0.24 g/cm³. Scanning electron microscopy results showed that with increasing Si sludge substitution, an open pore structure was formed because of the increase in the pore size from several tens to several hundreds of micrometers. The compressive strength decreased from 3.82 to 2.11 MPa as the amount of added Si sludge increased from 0.01 to 0.1%, respectively. The thermal conductivity was less than 1.0 W·m⁻¹·K⁻¹ in the temperature range of 25–800°C, and the specimen with 0.1 wt% Si sludge showed a low thermal conductivity of 0.2–0.6 W·m⁻¹·K⁻¹. The thermal expansion coefficients were 17.1–22.4 × 10⁻⁶/K in the temperature range of 25–800°C.

1. Introduction
The production of industrial by-products is continuously increasing under the influence of global industrialization. In addition, the necessity of recycling industrial by-products is emerging as ecological environmental problems and economic problems such as lack of landfill space and increase in treatment costs arise [1,2]. Accordingly, research to utilize various industrial by-products is emerging. As part of this recycling research, study on the production of insulated refractories using various industrial by-products [3–5] and research on the production of insulated refractories using industrial by-products containing silica are also being actively conducted [2,6,7]. These studies on the production of insulating refractories using industrial by-products suggested the possibility of using recycled insulated refractories through meaningful result indicators [2,6,7].

Silica fume is an industrial by-product generated during the reduction of high-purity quartz using coal or coke in the production of silicon and ferrosilicon alloy [1]. Silica fume comprises mostly (90% by mass) amorphous SiO₂ particles and also it is a very reactive pozzolanic material with a specific surface area in the range of 15–25 m²/g. These are spherical particles in the range of about 0.03–0.1 μm. But it supplied in the form of small lumps or powder or liquid to solve the difficulties of handling and storage due to the low density and fine particle size. It has been mainly used as an additive to improve the physical properties of cement mortar and concrete [8–10].

Si sludge is a by-product generated during the processing of silicon wafers used in the manufacturing of semiconductor devices and solar cells. In the process of manufacturing silicon wafers by cutting a Si ingot, more than 40% of the ingot is discarded in the form of sludge [11,12]. The amount of Si sludge generated is expected to increase with the increasing use of silicon wafers, owing to the ongoing developments in the semiconductor and photovoltaic industries. However, it is difficult to dispose the Si sludge by simple storage in landfills or by incineration because of the cutting oil used for ingot cutting [13]. Various studies for recycling Si sludge have been conducted with the development of methods, such as the recovery of high-purity silicon through secondary processing or SiC production; however, the use of the current recycling methods is still limited [14–16].

Porous ceramics have a porosity of 20–95% and can be used for various applications depending on the shape and structure of the pores, the porosity, and pore size distribution [17]. Porous ceramics possess superior heat, abrasion, and corrosion resistances compared to metal and polymeric materials [18]. Hence, they are used in gas filters, catalyst supports, insulators, absorbers, and lightweight construction structures, because of their excellent thermal properties and lightweight porous structure [18]. For porous ceramics used...
as thermal insulating materials, ongoing research is focused on controlling the shape and size of the pores and enhancing the porosity to obtain high thermal insulation and excellent strength [19–22].

Typical porous ceramic manufacturing methods include the replica method, partial sintering, the pore precursor method, and the direct foaming method. In the replica method, a porous ceramic is obtained by first impregnating a slurry containing ceramic powder into a sponge made of a polymeric material and then thermally decomposing the sponge through heat treatment [23]. Partial sintering is used to obtain a porous ceramic through sintering prior to complete densification by combining powder particles via evaporation-cohesion or surface diffusion through heat treatment [23]. The pore precursor method uses a mixed slurry that disperses ceramic powder with a pore-forming precursor that can control the quantity, size, distribution, and orientation of pores [23,24]. In direct foaming, porous ceramics are obtained by sintering, while maintaining the shape of the pores after their generation using methods such as mechanical mixing, gas injection, and gas generation in the liquid slurry, including ceramic powder [23]. Using this method, porous ceramics can be rapidly manufactured at a low cost [25].

In this study, direct foaming with Si sludge and silica fume was used to manufacture porous ceramics from waste resources for application as thermal insulation materials with excellent thermal properties. The mechanical and thermal properties were studied, and the possibility of recycling Si-based waste resources as thermal insulation materials was investigated.

2. Materials and methods

Silica fume (971-U, ELKEM, Norway) and Si sludge (polycrystalline silicon, WOONGJIN, Korea) were used as starting materials for this study. For pore formation in the specimen, a NaOH aqueous solution prepared with NaOH pellets (sodium hydroxide, pellet, Daejun Chemicals & Metals Co, Korea) was used. The raw material ratios are listed in detail in Table 1.

Table 1. Batch composition of the specimen.

| Solid   | Si00 | Si01 | Si05 | Si10 |
|---------|------|------|------|------|
| Solution |      |      |      |      |
| Si fume (wt%) | 100  | 99.99| 99.95| 99.90|
| Si sludge (wt%) | -    | 0.01 | 0.05 | 0.10 |
| W/S ratio | 0.3  |      |      |      |
| NaOH (N) | 14   |      |      |      |

Table 2. Chemical composition of raw materials (wt%).

| SiO₂ | Al₂O₃ | Fe₂O₃ | CaO | MgO | Na₂O | K₂O | TiO₂ | LOI | Total |
|------|-------|-------|-----|-----|------|-----|------|-----|-------|
| silica fume | 98.04 | 0.23 | 0.17 | 0.33 | 0.14 | 0.12 | 0.27 | 0.01 | 0.71 | 100 |
| Si sludge | 48.93 | 20.17 | 6.11 | 21.92 | 0.08 | 0.95 | 0.13 | 0.47 | 1.24 | 100 |

After grinding, silica fume and Si sludge with particle sizes below 75 μm and below 106 μm, respectively, were used. Each raw material was weighed and mixed, and dry ball milling was carried out for 1 h using zirconia balls. The mixed powder was stirred (400 rpm) for 5 min using a propeller-type stirrer with a 14 N NaOH aqueous solution. After stirring, the mixture was molded into an acrylic mold (5 × 5 × 7 cm³). The molded body was dried for 72 h at 50°C in a hot air dryer and then demolded in an acrylic mold. The dried body was sintered in an electric furnace with oxygen atmosphere at a heating rate of 10°C/min, maximum temperature of 900°C, and holding time of 1 h, and then naturally cooled in the furnace.

The chemical composition of the raw material was analyzed using X-ray fluorescence (XRF) (ZSX Primus, RIGAKU Co., Japan), and the particle size distribution of the raw material after sieving was analyzed using a particle size analyzer (LA-950, HORIBA, Japan). In addition, the thermal properties of each raw material were investigated using simultaneous thermal analysis-mass spectrometry (STA 409PC-QMS 403 C, NETZSCH, Germany). To examine the crystal characteristics of the prepared porous ceramic specimens, the crystal phase was determined using an X-ray diffraction (XRD) analyzer (MiniFlex II, Rigaku, Japan), and quantitative phase analysis was performed using the Rietveld method. The pore size distribution in range 0.01–100 μm, was observed using automated mercury porosimeters (AutoPore IV 9500, micromeritics, USA). The pore size distribution in range 100–3000 μm, was estimated using image analysis with open source software “image J”. The microstructure was observed using field-emission scanning electron microscopy (FE-SEM, JSM-7610 F PLUS, JEOL, Japan). The bulk density and apparent porosity of the porous ceramic specimens were measured using the Archimedes principle (KSL ISO18754, Korea standard), and the compressive strength was analyzed using a universal testing machine (DTU-900MHA, DEAKYOUNG Tech, Korea). To investigate the thermal properties of the porous ceramic specimens, the thermal conductivity and thermal diffusivity were measured using a thermal conductivity meter (LFA467, NETZSCH, Germany), and the thermal expansion coefficient was measured using a thermo-mechanical analyzer (TMA 402 F3, NETZSCH, Germany).

3. Results and discussion

Table 2 shows the results of the chemical composition analysis of the raw material. Silica fume was mainly composed of 98.04 wt% SiO₂. Si sludge was composed
48.93 wt% SiO$_2$ and Al$_2$O$_3$, CaO, et al. Silica fume is an industrial by-product of silicon that reduces high-purity silica and generally possesses a SiO$_2$ particle content of more than 90% [1]. Si sludge is also an industrial by-product of silicon wafer, containing SiO$_2$ component of silicon wafer, Fe$_2$O$_3$ by saw used in wafer cutting process, Al$_2$O$_3$ by coagulant used to obtain Si sludge from suspension, and CaO component.

Figure 1 shows the particle size distribution analysis of the silica fume and Si sludge. In the case of silica fume sieved below 75 μm, the particles with sizes below 1 μm accounted for 2.26%, and particles with sizes in the range of 1–75 μm accounted for 97.74%. In the case of Si sludge sieved below 106 μm, the particles with sizes below 10 μm accounted for 24.5%, and particles with sizes in the range of 10–106 μm accounted for 75.5%.

The results of the XRD analysis of the silica fume and Si sludge are shown in Figure 2. In the case of silica fume, a low-intensity cristobalite (SiO$_2$) peak was observed along with a typical amorphous peak. Cristobalite, a SiO$_2$ crystal phase, was partially observed along with an amorphous peak due to a high process temperature of 1800°C or higher during silicon manufacturing [1]. Si sludge exhibited a typical silicon crystal phase as a byproduct of the silicon wafers.

Figure 3 shows the thermogravimetry and differential thermal analysis results for the silica fume and Si sludge. A constant weight reduction was observed with increasing temperature of the silica fume, with a final weight reduction of approximately 3.7 wt%. This is judged to be a weight reduction due to the dehydration reaction of adsorb and crystallized water (below 200°C), and combustion of carbon generated in the silica fume manufactured process [26,27]. In the case of Si sludge, a rapid weight increase was observed above 600°C, which is attributed to the oxidation reaction where Si combines with oxygen in the atmosphere [11,28].
Figure 4 shows the optical image of the porous ceramic specimen surface with varying amounts of Si sludge substitution. As the amount of Si sludge substitution increased, pores of various sizes were formed. In contrast to the Si01 (0.01 wt%) and Si05 (0.05 wt%) specimens, many macropores were formed uniformly for the Si10 sample with 0.1 wt% substituted Si sludge. This was attributed to another reaction that occurred due to the addition of the Si sludge. In the case of silica fume and Si sludge, pores are formed through the release of hydrogen gas during the reaction with the aqueous NaOH solution according to the following equations [29,30]:

\[
\begin{align*}
2\text{NaOH} + \text{SiO}_2 & \rightarrow \text{Na}_2\text{SiO}_3 + \text{H}_2\text{O} \quad (1) \\
\text{Na}_2\text{SiO}_3 + 2\text{H}_2\text{O} & \rightarrow 2\text{NaOH} + \text{SiO}_2 + \text{H}_2\text{O} \quad (2) \\
2\text{NaOH} + \text{Si} + \text{H}_2\text{O} & \rightarrow \text{Na}_2\text{SiO}_3 + 2\text{H}_2 \quad (3)
\end{align*}
\]

For the Si00 sample, it was found that additional hydrolysis and a reaction rate increase with the thermal energy resulted in an exothermic reaction of the silica fume, forming a non-uniform porous structure due to rapid pore formation and pore merging [30]. However, by controlling the reaction rate with Si sludge substitution, it was possible to manufacture porous ceramic specimens with uniform macropores, as shown in Figure 4(c).

Figure 5 and 6 show the pore size distribution results with diameters of 0.01–100 μm and 100–3,000 μm, respectively. In the case of pores in the range of 0.01–100 μm analyzed through mercury porosimetry, a large amount of pores of 3 μm or less were formed as the Si sludge was substituted. In the case of pores in the range of 100–3,000 μm analyzed through optical images, the Si00 specimen without Si sludge substitution showed non-uniform pore sizes, whereas the Si01 specimen did not show pores larger than 1,100 μm and showed a relatively uniform pore size. Thereafter, as the amount of Si sludge substitution increased, the distribution of macropores increased, and in the case of Si10, in particular, it was confirmed that the number of macropores exceeding 500 μm significantly increased.

Figure 7 shows the microstructural changes observed by scanning electron microscopy (SEM) for different amounts of Si sludge substitution. As the
amount of Si sludge increased, the pore size increased. In the case of Si01, pores with sizes of several tens of micrometers dominated, whereas for Si10, pores with sizes of several hundred micrometers were predominant. It was observed that the pores formed an open-pore structure, enabling passage between the pores.

Figure 8 shows the XRD results for the crystal phase according to changing amounts of Si sludge substitution. In all specimens, SiO$_2$ polymorphs (quartz, tridymite, and cristobalite) were observed. Quantitative phase analysis using the Rietveld method showed that as the Si sludge substitution amount increased, the weight fraction of the cristobalite crystal phase did not change significantly, the quartz crystal phase content decreased, and the tridymite crystal phase content increased. For the Si00 sample in which the Si sludge was unsubstituted, there was 26 wt% of quartz; however, as the Si sludge substitution amount increased, the weight fraction of quartz decreased to 14, 7, and 3 wt%.

In the silica-alkali oxide system, quartz-tridymite transformation occurs at a temperature lower than 900°C, and tridymite formation occurs easily as the amount of alkali increases [31]. The reduction of the quartz weight fraction in Figure 8 can be judged as the result of inducing quartz-tridymite transformation by helping the uniform pore distribution and pore coalescence that help the NaOH aqueous solution alkali component to spread smoothly throughout the system according to the Si sludge substitution.

Figure 9 shows the apparent porosity and bulk density with changing amounts of Si sludge substitution. The bulk density showed a tendency to decrease as the amount of added Si sludge increased, and the lowest value of 0.24 g/cm$^3$ was obtained for Si10. The apparent porosity increased as the amount of Si sludge substitution increased, indicating the highest value of
Figure 4. OM image of porous ceramics with varying Si sludge substitution; (a) Si00, (b) Si01, (c) Si05 and (d) Si10.

Figure 5. Pore size distribution in rage 0.01–100 μm of porous ceramics with varying Si sludge substitution; (a) Si00, (b) Si01, (c) Si05 and (d) Si10.
Figure 6. Pore size distribution in rage 100–3000 μm of porous ceramics with varying Si sludge substitution; (a) Si00, (b) Si01, (c) Si05 and (d) Si10.

Figure 7. SEM image of porous ceramics with varying Si sludge substitution; (a) Si00, (b) Si01, (c) Si05 and (d) Si10.
Figure 8. X-ray diffraction patterns of porous ceramics with varying Si sludge substitution; (a) Si00, (b) Si01, (c) Si05 and (d) Si10.

Figure 9. Apparent porosity and Bulk density of porous ceramics with varying Si sludge substitution.
**Figure 10.** Compressive strength of porous ceramics with varying Si sludge substitution.

**Figure 11.** (a) Thermal conductivity and (b) Thermal diffusivity of porous ceramics with varying Si sludge substitution.
89.81% in Si10. This showed a similar tendency to the optical microscopy and SEM analysis results presented in Figure 4 and 7.

Figure 10 shows the results for compressive strength as a function of the amount of Si sludge substitution. The highest strength was 3.82 MPa in Si01, and the compressive strength decreased with increasing amount of Si sludge, such that the compressive strength for the Si10 sample was 2.11 MPa. The mechanical properties of porous ceramics are predominantly influenced by the microstructural characteristics such as pore size distribution, shape, and open-closed pore ratio [21,22,32,33]. In this study, it was found that the bulk density decreased, the porosity increased, and the compressive strength decreased due to the formation of macropores with increasing amount of Si sludge substitution.

Figure 11 shows the results of the thermal conductivity (λ) and thermal diffusivity (κ) with changing amounts of Si sludge substitution. All the Si sludge-substituted specimens showed a low thermal conductivity of 1.0 W·m⁻¹·K⁻¹ or less in the temperature range of 25–800°C. Especially, as the amount of Si sludge substitution increased, the thermal conductivity decreased at all temperatures, with the lowest thermal conductivity of 0.2–0.6 W·m⁻¹·K⁻¹ obtained for Si10. These values indicate that the samples possess the characteristics of microporous materials and refractories [34]. The Si00 sample with no Si sludge substitution tended to exhibit a decreased thermal conductivity up to 400°C, which was attributed to the effect of the higher quartz contents observed in the XRD analysis shown in Figure 8. It is known that among the SiO₂ polymorphs, the quartz crystal phase decreases the thermal conductivity with increasing temperature [35–38]. The thermal diffusivity also showed a tendency to decrease with increasing amount of Si sludge substitution. This is attributed to an increase in the porosity due to an increase in the amount of Si sludge substitution. Because the heat capacity of the pores is negligible compared to that of the solid, in the case of a porous ceramic with a high porosity, the heat capacity per unit volume (C) decreases, resulting in a decrease in the thermal conductivity and thermal diffusivity [39,40].

Figure 12 shows the results obtained for the linear thermal expansion coefficient (α) as a function of the amount of Si sludge substitution. For Si sludge substitutions of 0.01, 0.05, and 0.1% in the temperature range of 25–800°C, the thermal expansion coefficients were 17.16, 18.25, and 22.44 × 10⁻⁶/K, respectively. It is concluded that the various changes in lengths for each temperature section are due to the phase transitions of SiO₂, as observed from the results presented in Figure 8.

4. Conclusions

In this study, porous ceramics were manufactured using silica fume, a process by-product, and their mechanical and thermal properties related to their application as thermal insulators were analyzed. Si sludge (0.01, 0.05, and 0.1%) and NaOH aqueous solution (14 N) were used as foaming agents for pore formation using the direct foaming method. The porous ceramic sintered at 900°C showed non-uniform pore size distribution in which 2000–3000 μm pores occurred in the Si00 specimen prepared only through silica fume. However non-uniformity was resolved with substituting 0.01 wt% Si sludge, thereafter as the

![Figure 12. Thermal expansion coefficient of porous ceramics with varying Si sludge substitution.](image-url)
amount of substitution of Si sludge increased, the amount of 1000–1500 μm pores by pore coalescence increased. The prepared specimens exhibited an apparent porosity of 85.9–89.8%; in particular, the 0.1 wt% Si sludge-substitution specimen exhibited the highest porosity of 89.8% and a volume density of 0.24. The SEM results confirmed that as the amount of Si sludge substitution increased, the pore size increased from several tens of micrometers to several hundreds of micrometers to form an open-pore structure. When the Si sludge substitution increased from 0.01 to 0.1 wt%, the compressive strength decreased from 3.82 to 2.11 MPa, respectively. The thermal conductivity (λ) values of the prepared porous ceramic specimens were less than 1.0 W·m⁻¹·K⁻¹ in the temperature range of 25–800°C, and in particular, the Si01 sample with 0.1 wt% Si sludge substitution showed a low thermal conductivity of 0.2–0.6 W·m⁻¹·K⁻¹. The thermal expansion coefficient (α) was 17.1–22.4 × 10⁻⁶/K in the temperature range of 25–800°C. Porous ceramics with a thermal conductivity of 0.4 W·m⁻¹·K⁻¹ (at 25°C) or less fabricated by direct foaming using low-cost silica fume and Si sludge are suitable for use as lightweight structural, sound, and thermal insulation materials. Through the analysis results, it was confirmed that the application of silica fume in the manufacture of waste recycling thermal insulation material can be considered as a sufficient consideration

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Disclosure statement

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References

[1] Siddique R, Kunal. Nonconventional and vernacular construction materials. In: Chapter 7, Utilization of industrial by-products and natural ashes in mortar and concrete: development of sustainable construction materials. 2nd ed. Patiala(PB): Elsevier; 2016. p. 159–204.
[2] Hossain SS, Bae CJ, Roy PK. A replacement of traditional insulating refractory brick by a waste-derived lightweight refractory castable. Int J Appl Ceram Technol. 2021;00:1–9.
[3] Hassan AM, Moselhy H, Abadir MF. The use of bagasse in the preparation of fireclay insulating bricks. Int J Appl Ceram Technol. 2019;16(1):418–25.
[4] Ramezani A, Emami SM, Nemat S. Effect of waste serpentine on the properties of basic insulating refractories. Ceram Int. 2018;44(8):9269–75.
[5] Ahmadi PF, Ardeshir A, Ramezanianpour AM, et al. Characteristics of heat insulating clay bricks made from zeolite, waste steel slag and expanded perlite. Ceram Int. 2018;44:7588–98.
[6] Hossain SS, Roy PK. Fabrication of sustainable insulation refractory: utilization of different wastesFabricación de aislantes refractarios sostenibles: utilización de diferentes residuos. BOL SOC ESP CERAM V. 2019;58(3):115–125.
[7] Papa E, Medri V, Kpogbemabou D, et al. Porosity and insulating properties of silica-fume based foams. Energy Build. 2016;131:223–232.
[8] Zhao S, Zhang Q. Effect of silica fume in concrete on mechanical properties and dynamic behaviors under impact loading. Materials. 2019;12(19):3263–3279.
[9] Pedro D, de Brito J, Evangelista L. Evaluation of high-performance concrete with recycled aggregates: use of densified silica fume as cement replacement. Constr Build Mater. 2017;147:803–814.
[10] Adil G, Kevern JT, Mann D. Influence of silica fume on mechanical and durability of pervious concrete. Constr Build Mater. 2020;247:118453.
[11] Kim SK, Kim HK, Chang HK, et al. One-step formation of silicon-graphene composites from silicon sludge waste and graphene oxide via aerosol process for lithium ion batteries. Sci Rep. 2016;6(1):33688.
[12] Bahrami A, Schiering G, Nielisch K. Waste recycling in thermoelectric materials. Adv Energy Mater. 2020;10:19.
[13] Iowa Waste Reduction Center. Cutting fluid management: small machining operations. Cedar Falls(IA). Iowa Waste Reduction Center(US); 2003.
[14] Drouiche N, Cueliar P, Kerkar F, et al. Recovery of solar grade silicon from kerf loss slurry waste. Renew Sust Energy Rev. 2014; 32: 936–943.
[15] Drouiche N, Cueliar P, Kerkar F, et al. Hidden values in kerf slurry waste recovery of high purity silicon. Renew Sust Energy Rev. 2015;52: 393–399.
[16] Hachichi K, Lami A, Zemmouri H, et al. Silicon recovery from kerf slurry waste: a review of current status and perspective. Silicon. 2018;10(4):1579–1589.
[17] Liu P, Chen GF. Porous Materials: processing and applications. In: Chapter 1, General Introduction to Porous Materials, In Porous Materials. 1st ed. Oxford (UK): Butterworth-Heinemann; 2014. p. 1–20.
[18] Somiya S. Handbook of advanced ceramics: materials, Applications, Processing, and Property. 2nd ed. Cambridge (MA): Academic Press; 2013. p. 1131–1148.
[19] Liu P, Chen GF. Porous Materials: processing and applications. In: Chapter 1, General Introduction to Porous Materials, In Porous Materials. 1st ed. Oxford (UK): Butterworth-Heinemann; 2014. p. 303–344.
[20] Huo W-L, Zhang X-Y, Chen Y-G, et al. Highly porous zirconia ceramic foams with low thermal conductivity from particle-stabilized foams. J Am Ceram Soc. 2016;99(11):3512–3515.
[21] Fukushima M, Yoshizawa Y. Thermal insulators with macroscopic and microscopic pore anisotropy created by gelation-freezing with alumina platelets. J Ceram Soc JAPAN. 2020;128(9):582–588.
[22] Rezaee S, Ranjarb K. Thermal conductivity of porous Alumina-20 wt% zirconia ceramic composites. Ceram Int. 2020;46(10):16564–16571.
[23] Chen Y, Wang N, Ola O, et al. Porous ceramics: light in weight but heavy in energy and environment technologies. Mater Sci Eng R Rep. 2021;143:100589.
[24] Kim K-S, Song K-Y, Park S-Y, et al. Properties of Low Temperature Sintered Porous Ceramics from Alumina-Zinc Borosilicate Glass. J Korean Ceram Soc. 2009;46(6):609–614. Korean.

[25] Pokhrel A, Seo DN, Lee ST, et al. Processing of porous ceramics by direct foaming: a review. J Korean Ceram Soc. 2013;50(2):93–102.

[26] Chen J, Li T, Li X, et al. Morphological evolution of low-grade silica fume at elevated temperature. High Temp Mater Proc. 2017;36(6):607–613.

[27] Nedeljković A, Stojmenović M, Guličovski J, et al. Waste slag from heating plants as a partial replacement for cement in mortar and concrete production. Part I-physical-chemical and physical-mechanical characterization of slag. Minerals. 2020;10(11):992.

[28] Li C, Liu C, Ahmed K, et al. Kinetics and electrochemical evolution of binary silicon–polymer systems for lithium ion batteries. RSC Adv. 2017;7(58):36541–36549.

[29] Deng X, Chen K, Tüysüz H. Protocol for the nanocasting method: preparation of ordered mesoporous metal oxides. Chem Mater. 2017;29(1):40–52.

[30] Volochko AT, Podbolyotov KB, Zhukova AA. Preparation of porous ceramic materials based on wollastonite using silicon-containing components. Refractories and Industrial Ceramics. 2011;52(3):186–190.

[31] Holmquist SB. Conversion of quartz to tridymite. J Asian Ceram Soc. 1961;44(2):82–86.

[32] Ali MS, Ariff AHM, Jaafar CAN, et al. Factors affecting the porosity and mechanical properties of porous ceramic composite materials. In: Hashmi Seditor. Reference module in materials science and materials engineering. Oxford: Elsevier; 2017. p. 1–54.

[33] Liu J, Li Y, Li Y, et al. Effects of pore structure on thermal conductivity and strength of alumina porous ceramics using carbon black as pore-forming agent. Ceram Int. 2016;42(7):8221–8228.

[34] Chen Z, Wang Y, Yu S. A new low thermal conductivity high temperature vacuum insulation composites with SiC foam core. Int J Adv Mater Prod. 2016;1(1):28–33.

[35] Molaei F, Siavoshi H. Molecular dynamics studies of thermal conductivity and mechanical properties of single crystalline α-quartz. Solid State Commun. 2020;320:114020.

[36] Powell RW, Ho CY, Liley PE. Thermal conductivity of selected materials. Gaithersburg (MD): National Bureau of Standards; 1966.

[37] Lappin AR. Thermal conductivity of silicic tuffs: predictive formalism and comparison with preliminary experimental results. Albuquerque (NM): Sandia National Labs; 1980.

[38] Olson DH, Gaskins JT, Tomko JA, et al. Local thermal conductivity measurements to determine the fraction of α-cristobalite in thermally grown oxides for aerospace applications. Scr Mater. 2020;177:214–217.

[39] Sumirat I, Ando Y, Shimamura S. Ando y, Shimamura S. Theoretical consideration of the effect of porosity on thermal conductivity of porous materials. J Porous Mater. 2006;13(3–4):439–443.

[40] Živciová Z, Gregorová E, Pabst W, et al. Thermal conductivity of porous alumina ceramics prepared using starch as a pore-forming agent. J Eur Ceram Soc. 2009;29(3):347–353.