Role of addition of kaolin on the firing of white clay for Korean porcelain

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ABSTRACT

The objectives of this study were to examine the role of the addition of kaolin on the firing of white clay for Korean porcelain by characterizing the fired composites at 1000–1300°C, and finally to estimate the production conditions of ancient Korean white porcelain in the Joseon Dynasty. Yanggu white clay disks composed of 57.1 wt% quartz and 38.8 wt% muscovite showed bloating phenomenon at temperatures over 1175°C due to the evolution of gas incorporated in the disk. Potassium from muscovite (\(\text{KAl}_2\text{Al}_2\text{Si}_6\text{O}_{18}\text{(F,OH)}_2\)) in Yanggu white clay played a significant role as melting agent to form a liquid phase. To produce Korean white porcelain at temperatures over 1175°C without bloating, the addition of 20–40 wt% of Korean kaolin to Yanggu white clay was necessary. Increasing the amount of kaolin added and firing temperature enhanced the formation of mullite. We estimated the manufacture of a portion of the old Korean white porcelains in the Joseon Dynasty from mixtures of Yanggu white clay and kaolin to improve the refractoriness and whiteness of the body.

1. Introduction

In the 9th–10th century, Korean potters were able to produce their first celadon and white porcelain using specific ceramic production techniques introduced from China, and the advanced technology of Korean pottery and porcelain influenced on the production of Japanese pottery and white porcelain in the northern area of Kyushu from the end of the 15th to the beginning of the 17th century [1–5]. By the 11th century of the Goryeo Dynasty (918–1391), Korean potters had developed new and unique styles, designs, and glaze colors of celadon (Goryeo celadon) compared with those of Chinese celadon. After the Goryeo Dynasty, with increased demand from the royal court and governmental officials, potters from the Joseon Dynasty (1392–1910) achieved rapid progress in the production of white porcelain [2]. The production of white porcelain was controlled at the Royal Kiln, which was established by the government in 1467 in Gwangju, Gyeonggi-do. Since the late 17th century, the Royal Kiln had used only white clays mined in specific regions of the Korea Peninsula, including mainly Hamgyeong-, Gangwon-, Chungcheong- and Gyeongsang-do provinces. According to old records of the Joseon Dynasty, white clay mined at Yanggu (Gangwon – do), Jinju and Gonyang (Gyeongsangnam – do) were used as raw materials for white porcelain production (Figure 1(a)). It is supposed that Yanggu white clay was composed of quartz and mica, whereas Jinju and Gonyang white clays were composed of kaolin, quartz, and a small amount of oxide impurities [2,3,6].

In our previous study [7], we reported that various porcelain bodies produced in the Royal Kiln in the early 18th century showed a higher content of \(\text{Al}_2\text{O}_3\) (18–24 wt%). The \(\text{Al}_2\text{O}_3\) content in Yanggu white clay mined near the old kiln site was around 15 wt% [6], so we estimated that the white porcelain body was produced from a mixture of Yanggu white clay and Korean kaolin (kaolinite and halloysite), which had higher alumina content (35–39 wt%). Several reports on the Ming and Qing Dynasties in China suggest the addition of kaolin to white clay to improve the quality of Jingdezhen white porcelain [8–10]. A large amount of Korean kaolin was used for the production of white porcelain in the Joseon Dynasty in Korea; however, there are limited scientific papers on the effect of addition of Korean kaolin on the production of white porcelain.

In this paper, we investigated the role of addition of Korean kaolin to Yanggu white clay on firing at 1100–1300°C and along with the specific properties of the fired white porcelains were investigated, and we estimated the production of old Korean white porcelains in the Joseon Dynasty.

2. Experimental procedure

Yanggu white clay and Korean kaolin were used for this study. Figure 1(b,c) shows the appearances of the two...
raw materials. Yanggu white clay was mined at Yanggu-gun, Gangwon-do, and Korean kaolin was mined at Hapcheon-gun, Gyeongsangnam-do, Korea. The as-received Yanggu white clay was composed of coarse gray particles and white clay powder (Figure 1(b)). White clay powders were separated in advance from 1 to 10 mm gray particles. Fine white clay and kaolin powders were collected and sieved through a 100-mesh stainless steel sieve. Crystalline phases of the powders were characterized by powder X-ray diffraction (XRD) (CuK\textsubscript{α} radiation and operating at 40 kV and 100 mA, model D/Max, 250, Rigaku Co., Japan). For quantitative analysis of the mineral components of the fired samples, Rietveld quantitative phase analysis results were collected at room temperature using XRD (CuK\textsubscript{α} radiation and operating at 40 kV and 50 mA, SmartLab SE, Rigaku Co., Japan). Intensities were collected by step scanning in the 5° - 80° (2θ) range, with a step of 0.01° and a counting time of 0.03 s for each step. For quantitative analysis, finely powdered samples were mixed with 10.7 wt% of fine MgO powder as an internal standard. XRD patterns were analyzed using the program SmartLab Studio II (Version 4.1.0.237) which is a multipurpose profile-fitting program, including Rietveld refinement to perform phase quantification. The reliability factors for the Rietveld quantitative phase analysis were $R_{wp} = 4.43$–5.36% and $\chi^2 = 1.2$–1.4, respectively. The contents (wt%) of mullite and quartz were estimated from a comparison of MgO content using a calibration curve. The amorphous amount was calculated by subtracting the contents of the crystal phases from the total amount (100%).

Figure 1. (a) Location of royal kiln (Gwangju) and typical mining locations of white clay and Korean kaolin in the Joseon Dynasty in the 16 to 19th centuries in the Korean Peninsula. (b) Yanggu white clay and (c) Jinju kaolin powders.
The morphology of the powders and the fired composites was observed using a field emission scanning electron microscope (FESEM) (model JSM-6390, JEOL Co., Japan). To characterize fine mullite crystal in the fired composites, samples were etched with 2.5% HF for 12 min at 23°C prior to microscopic examinations. Chemical analysis of the powder was performed using an X-ray fluorescence spectrometer (XRF) (model ZSX, Rigaku Co., Japan). The average particle size and distribution of powder were measured using a particle analyzer (model; LA-950A2, HORIBA Ltd., Japan). Clay composite with Yanggu white clay and kaolin was prepared to examine the effect of addition of Korean kaolin on the properties of white porcelain. The weight ratios of Korean kaolin/Yanggu white clay were 0/100, 10/90, 20/80, 30/70, and 40/60. Kaolin and Yanggu clay powders were mixed with water for 6 h in a mixer. After mixing and drying at 80°C for 24 h, the powders were mixed with water and kneaded to form wet clay lumps. The clay composite with 13–14 wt% of moisture content was pressed at 0.1 MPa pressure for 15 min in a gypsum mold to obtain rectangular composite disks with dimensions of 25 × 25 × 5 mm. After drying at 80°C for 24 h, porosity, total pore volume, and average pore diameter of the composites were analyzed by an Hg – Porosimeter (Model: Auto Pore IV, Micrometrics Instrument Co., USA). The composite disks were fired in an electric furnace at 1000–1300°C for 1 h in air. The heating rate to the desired firing temperature was 5°C/min. Bulk density and water absorption of the fired composites were measured by the Archimedes method at 20°C, and the linear shrinkage was measured by the conventional method. The CIE Lab color parameters of the composites fired at 1150°C were analyzed by UV-visible spectroscopy (UV2600, Shimadzu, Japan). Some properties of the composites in this study were compared with those of old porcelains produced in the Joseon Dynasty in Korea.

3. Results and discussion

3.1. Characterization of Yanggu white clay and Korean kaolin

Figure 2 shows the morphologies of Yanggu white clay and Korean kaolin powders. Yanggu white clay was composed of thin platy crystals of 1–2 µm wide, whereas Korean kaolin was composed of small needle-like crystals of 0.5–1 µm long and 0.1 µm wide and granule-like crystals of 0.2 µm long. The average particle sizes of the aggregated Yanggu white clay and Korean kaolin, determined by a particle analyzer, were 8.8 and 12.6 µm, respectively.

Figure 3 shows the XRD patterns of two raw samples of Yanggu white clay and Korean kaolin. Yanggu white clay was composed of quartz and muscovite (PDF: 06–0263, M1 type: KAl₃[AlSi₃O₁₀](F,OH)₂) without kaolin and feldspar. Gray particles (Figure 1(a)) were also composed of quartz and muscovite phases, as determined by XRD analysis. The ground in Yanggu district is covered with granite as mother rock and white clay and gray particles are considered to have been formed by the weathering of the granite. Korean kaolin was mainly composed of halloysite (7A type; Al₂O₃·2SiO₂·2H₂O; 2α = 12.1–12.2, 20.1, 25.0, 35.1, 36.0, 38.4° in Figure 3(b)), hydrated halloysite (10A type; Al₂O₃·2SiO₂·4H₂O; 2α = 8.7–8.8, 20.1, 26.7, 35.0° in Figure 3(b)), anorthite (CaO·Al₂O₃·2SiO₂), and a small amount of quartz and feldspar.

Table 1 shows the chemical composition of Yanggu white clay and Korean kaolin. The contents of Fe₂O₃ in Yanggu white clay and Korean kaolin were 0.57 and 0.47 wt%, respectively. These lower contents of Fe₂O₃ are expected to result in the high whiteness of porcelain after firing. From the XRD results shown in Figure 3 and the values in Table 1, the mineral composition of Yanggu clay, based on normative calculation, was found to be 57.1 wt% quartz, 38.8 wt% muscovite, and negligible amounts of Fe-, Ca-, and Mg-containing oxide impurities. On the other hand, Korean kaolin was composed of 94–96% kaolin (a
mixture of halloysite and hydrated halloysite) and 2–4 wt% anorthite. In this research, the addition of kaolin gradually decreased the plasticity of Yanggu white clay with 13–14 wt% water content.

3.2. Firing properties of the composites

After drying at 25°C for 48 h, the average linear shrinkage of the composites was 4.3%, and the green densities of the composites after drying at 80°C were 2.05 (0 wt%), 2.04 (10 wt%), 1.93 (20 wt%), 1.94 (30 wt%), and 1.86 g/cm³ (40 wt% of kaolin). After drying, the porosity, total pore volume, and average pore diameter of disks prepared from Yanggu white clay were 22.7%, 0.11 cm³/g, and 0.02 µm, respectively; those values for Yanggu clay with an addition of 40 wt% Korean kaolin were 27.6%, 0.15 cm³/g and 0.03 µm. A small volume of large pores of around 100 µm, formed by small air bubbles incorporated during kneading of the clay, were observed in both disks.

Figure 3. XRD patterns of (a) Yanggu white clay and (b) Korean kaolin.

Figure 4 shows the lateral views of all composite disks fired at 1100–1300°C for 1 h, in which several composites fired at 1175–1300°C showed abnormal bloating phenomenon in the bodies. However, the addition of kaolin depressed the bloating and increased the refactoriness.

Tables 2 and 3 show the bulk density and water absorption of the composites after firing. The values of the bloating phenomenon are shown in the shaded region of the tables. As the firing temperatures increased, the bulk density of the composites with 0–40 wt% of Korean kaolin powders reached 2.2–2.3 g/cm³, whereas the bulk density decreased with the addition of Korean kaolin to Yanggu white clay. However, in samples that did not exhibit the bloating phenomenon, the water absorption decreased with firing temperature and increased with the addition of Korean kaolin (Table 3). Kaolin is a hydrous aluminosilicate mineral with a chemical formula of Al₂Si₂O₅(OH)₄ or Al₂O₃·2SiO₂·2H₂O. The ideal loss of ignition of pure kaolin after firing at temperatures over 1000°C is 13.95 wt%. In this study, the loss of ignition from Korean kaolin was 13.48 wt% (Table 1). This loss of ignition value indicates the removal of all H₂O and -OH from the halloysite structure during firing. From Table 1, the loss of ignition of the composite due to the addition of Korean kaolin increased from 2.99 wt% (0 wt% of kaolin), to 4.04 wt% (10 wt% of kaolin), 5.09 wt% (20 wt% of kaolin), 6.14 wt% (30 wt% of kaolin), and 7.19 wt% (40 wt% of kaolin). The increased addition of kaolin to Yanggu white clay causes porous structures (low bulk density and high water absorption as shown in Tables 2 and 3) by high ignition loss in the fired body. The water absorptions of the composites at 1100°C were 2.8 (0), 6.9 (20), and 12.9 (40 wt% of kaolin), respectively. However, the bloating was suppressed by addition of 30 and 40 wt % kaolin at 1300°C (Figure 4). It was supposed that Al₂O₃ in kaolin reacted with a liquid phase in Yanggu white clay to form mullite phase and the sintering of the composites was promoted without bloating by the increased addition of kaolin.

Figure 5 shows SEM images of a polished section of the disk prepared from Yanggu white clay at 1100°C. The absence of bloating was confirmed at 1100°C and two types of pores were formed in the body. Coarse pores, 50–120 µm in size (Figure 5(a)), were uniformly distributed and originated from air bubbles incorporated during kneading of the clay. In contrast, it was supposed that the small, irregular and elongated pores (small bloating pores) of 0.5–20 µm in size (Figure 5(b))

Table 1. Chemical composition of Yanggu white clay and Korean kaolin (wt%).

| Sample            | SiO₂ | Al₂O₃ | Fe₂O₃ | TiO₂ | CaO | MgO | Na₂O | K₂O | Loss of Ig. |
|-------------------|------|-------|-------|------|-----|-----|------|-----|-------------|
| Yanggu white clay | 74.61| 15.95 | 0.57  | 0.01 | 0.54| 0.44| tr.   | 4.59| 2.99        |
| Korean kaolin     | 45.26| 38.56 | 0.47  | 0.12 | 1.23| 0.13| 0.31  | 0.11| 13.48       |
were introduced into the clay by absorbed surface water and dihydroxylation of muscovite in Yanggu white clay, as well as by $O_2$ gas generated by the conversion of a small content of $Fe_2O_3$ to $Fe_3O_4$ ($6Fe_2O_3\rightarrow4Fe_3O_4+O_2$) in white clay during firing [11–13]. These small and coarse pores in the body decreased the bulk density of the fired body produced by Yanggu white clay at 1100°C and 1150°C (Table 2).

When Yanggu white clay disk was fired at 1200°C, a large cavity was formed by bloating (Figure 6). As the firing temperature increased, the small pores changed from an irregular elongated shape to a more spherical one, and aggregation of the pores accelerated. As the pores grew large and spherical, they eventually caused bloating in the body. A large cavity with several millimeter-size instances of bloating was formed in the composite at 1200°C. Many large round pores, 100–400 µm in diameter, were observed within the composite (C region in Figure 6(b)), whereas small round pores 10–50 µm in diameter existed in the surface layer (S region in Figure 6(b)). A continuous vitreous layer was formed on the surface, as shown in Figure 6(b,c).

Previous studies have reported some basic bloating mechanisms of white porcelain during firing at temperatures over 1000°C [14–17]. For instance, the first source of bloating was the formation of a liquid phase with

![Figure 4](image)

**Figure 4.** Cross sections of disks fired from the mixture of Yanggu white clay and Korean kaolin at 1100–1300°C for 1 h in air.

| Content of kaolin (wt%) | 1100°C | 1150°C | 1175°C | 1200°C | 1250°C | 1300°C |
|------------------------|--------|--------|--------|--------|--------|--------|
| 0                      | 2.28   | 2.2    | 1.47   | 1.57   | 1.34   | 1.14   |
| 10                     | 2.23   | 2.24   | 1.67   | 1.77   | 1.48   | 1.52   |
| 20                     | 2.1    | 2.2    | 2.23   | 2.21   | 1.92   | 1.73   |
| 30                     | 1.99   | 2.1    | 2.14   | 2.17   | 2.23   | 2.25   |
| 40                     | 1.92   | 2.02   | 2.07   | 2.1    | 2.18   | 2.25   |

**Table 2.** Effect of addition of Korean kaolin on bulk density (g/cm$^3$) of composites fired at 1100–1300°C. Bloating phenomenon is shown in gray zone of table.

| Content of kaolin (wt%) | 1100°C | 1150°C | 1175°C | 1200°C | 1250°C | 1300°C |
|------------------------|--------|--------|--------|--------|--------|--------|
| 0                      | 2.8    | 1.4    | 7.8    | 11.6   | 3.5    | 2.2    |
| 10                     | 3.5    | 1.9    | 16.1   | 4.5    | 1.5    | 3.2    |
| 20                     | 6.9    | 5.5    | 3.2    | 1.8    | 1.4    | 1.9    |
| 30                     | 10.5   | 7.3    | 6.2    | 4.6    | 2.5    | 1.8    |
| 40                     | 12.9   | 9.6    | 8.6    | 7.1    | 4.6    | 4.3    |

**Table 3.** Effect of addition of Korean kaolin on water absorption (%) of composites fired at 1100–1300°C.

![Figure 5](image)

**Figure 5.** SEM images of a polished section of disk fired from Yanggu white clay at 1100°C for 1 h.
a sufficiently high viscosity high capable of trapping gases. The second proposed mechanism was due to the presence of a material that releases gas at the temperature at which the glassy phase forms. Bhattarai et al. reported that bulk densities decreased with the additional firing at high temperatures, which can be explained by the expansion of closed pores and ultimately bloating in the fired body [18]. Furthermore, Kobayashi et al. studied the densification of a porcelain body in a triaxial alumina – feldspar – kaolin system, and found that bloating occurred more readily as the amount of kaolin decreased; the ratios of feldspar (as flux) and kaolin were found to be strongly related to the bloating temperature [19]. From these previous studies, the bloating phenomenon in this study was suggested to occur as follows: (1) Yanggu white clay was composed of 57.1 wt% of quartz and 38.8 wt% of muscovite. The content of K2O in the body was 4.59 wt%. Higher content of muscovite acted as a flux and formed a viscous liquid phase at the firing temperature. Densification of porcelain was basically driven by progressive melting of muscovite and quartz at 1175°C; (2) the green disk prepared from Yanggu white clay had 22.7% porosity, 0.11 ml/g total pore volume, and 0.02 µm average pore diameter. During firing at temperatures over 1175°C, the porous structure of the disk led to the formation of large interconnected pores via coalescence of pores and cavities in the body. Finally, the evolution of gas from inside the body during firing was blocked by a continuous glassy layer formed on the surface of the composite (Figure 6(c)).

Quantitative analysis of the F ions in muscovite (KAl2(Si3O10)(F,OH)2) of Yanggu white clay and of the effect of F gas on bloating is in progress. The influence of heating rate on the bloating phenomenon of disks prepared from Yanggu white clay was investigated at 1100–1300°C. However, the identical bloating was observed under slow heating conditions (2°C/min).

From Figure 4 and Table 2, it can be seen that the addition of 20–40 wt% of Korean kaolin to Yanggu white clay was required to produce well-sintered white porcelain at temperatures over 1175°C without bloating. The addition of Korean kaolin to Yanggu white clay facilitated suppression of bloating. In addition, firing at temperatures over 1175°C enhanced the refractoriness of the body.

3.3. XRD and SEM analysis of fired composites

Figure 7 shows the XRD patterns of Yanggu white clay and Korean kaolin fired at 1000, 1100, 1200, and 1300°C. The formation of mullite and quartz was observed in Yanggu white clay bodies fired at temperatures over...
1000°C, and a small peak of muscovite (2α = 19.7–19.8°) remained (Figure 7(a)). However, this peak was not observable at temperatures over 1050°C. The formation of mullite from Yanggu white clay with 4.59 wt% of K₂O (Table 1) was promoted by an increase in firing temperatures due to the fluxing action of muscovite. The XRD intensity ratios of mullite ([hk] = 110)/quartz ([hk] = 100) were 0.08 at 1000°C, 0.13 at 1100°C, and 0.22 at 1200°C. From these results, it is observed that 4.59 wt% of K₂O in Yanggu white clay promoted vitrification of the clay and increased the formation of mullite at 1000–1200°C (Figure 7(a)). Muscovite, sericite, and illite are K-containing mica minerals. Theoretically, high K content can cause a large amount of melt to be superimposed onto the mullite formation in illite (K-deficient mica; K₀.₃₈Al₂(Si₁₃₂Al₆₈₈O₁₀₆)(OH)₂, nH₂O) rich clay-based ceramic bodies [20–22]. However, Korean kaolin is known to have higher refractoriness and lower vitrification temperature than those of Yanggu white clay. Cristobalite and mullite were formed by the thermal decomposition of kaolin at 1200°C, as expected (Figure 7(b)). The anorthite (CaOAl₂O₃·2SiO₂) phase in the kaolin was stable up to 1300°C.

Figure 8 shows XRD patterns of the composites fired at 1200, and 1300°C. The addition of Korean kaolin to Yanggu white clay was changed from 10 to 30 wt%. Mullite, quartz and amorphous phases were detected in all fired samples, but anorthite phase was not detected in the composites after the addition of Korean kaolin.

Table 4 shows the results of the quantitative analysis of mullite, quartz, and amorphous phases by the Rietveld XRD method. At 1200°C and 1300°C, the formation of mullite was promoted by the addition of kaolin. The contents of mullite formed from Yanggu white clay without kaolin addition were 10.0 and 9.1 wt% at 1200°C and 1300°C, and it increased to 19.4 wt% at 1200°C and 18.4 wt% at 1300°C by the addition of 30 wt% Korean kaolin. The formation of glass was depressed with the addition of Korean kaolin at 1200°C and 1300°C. The content of glass decreased from 57.8 wt% (no addition of kaolin) to 54.5 wt% (30 wt% of kaolin) at 1200°C, and from 70.5 wt% (no addition of kaolin) to 64.6 wt% (30 wt% of kaolin) at 1300°C.

Lecomet et al. studied the influence of muscovite on the thermal transformation of kaolinite from room temperature to 1100°C [23]. They pointed out that the interaction of muscovite and kaolinite at temperatures over 900°C was mainly correlated with the diffusion of potassium ions from muscovite platelets into the metakaolinite structure. The diffusion of potassium ions into metakaolinite structure facilitated an early (1050°C) mullite crystallization and growth of mullite needles.

In general, significant amounts of cristobalite are formed at temperatures over 1100°C by the expulsion of excess SiO₂ from the Al – Si spinel (Si₃Al₄O₁₂) formed from the thermal transformation sequence of kaolin [24]. From the results in Figures 8 and 9, the formation of cristobalite was completely suppressed at 1300°C in the mixtures of Korean kaolin and Yanggu white clay. It is estimated that the fluxing action of potassium ions of muscovite in Yanggu white clay inhibited the formation of cristobalite from Korean kaolin in this study.

Figure 9 shows the morphologies of mullite crystals in the composites fired at 1100°C and 1300°C for 1 h. Yanggu white clay was fired without Korean kaolin at 1100–1300°C, as shown in Figure 9(a,c), and fired with 20 wt% of Korean kaolin at 1100–1300°C, as shown in Figure 9(b,d). The growth of mullite crystals from Yanggu white clay was enhanced by the firing temperatures (Figure 9(a,c)). The crystal sizes were 0.2–0.5 µm long and 0.08–0.1 µm thick at 1100°C, and 0.4–1.5 µm long and 0.2–0.4 µm thick at 1300°C. On the other hand, mullite crystals of 0.1–0.3 µm long and 0.05–0.08 µm thick formed at 1100°C and crystals of 0.2–0.7 µm long and 0.08–0.1 µm thick formed at 1300°C by the addition of 20 wt% of Korean kaolin (Figure 9(b,d)). With the

![Figure 7. XRD patterns of (a) Yanggu white clay and (b) Korean kaolin fired at 1000, 1100, 1200, and 1300°C for 1 h. m: mullite, q: quartz, c: cristobalite, a: anorthite, u: unknown](image-url)
addition of Korean kaolin to Yanggu white clay, the crystal growth of mullite was inhibited within the temperature range of 1100°C to 1300°C. It was estimated that the formation of mullite was enhanced by the addition of Korean kaolin, whereas the increased nucleation of mullite inhibited the crystal growth of mullite in the liquid phase.

3.4. Whiteness of fired composites

Table 5 shows the effect of the addition of Korean kaolin to Yanggu white clay on the whiteness of composites fired at 1150°C. The chemical composition of fired composites is also shown in Table 5. With the addition of Korean kaolin, the whiteness (L) increased from 81.1 (no addition of kaolin) to 91.3 (40 wt% of kaolin added). With the addition of Korean kaolin to Yanggu white clay, the content of Fe₂O₃, which decreased the whiteness of white porcelain, decreased from 0.57 wt% (no addition of kaolin) to 0.42 wt% (40 wt% of kaolin). From these results, the whiteness of Yanggu clay after firing can be improved by the addition of Korean kaolin, as expected.

3.5. Estimation of production of white porcelain in the Joseon Dynasty

In our previous study, alumina content in old white porcelain shards produced in the 15th – 19th centuries in Gwangju, Korea, was found to have increased from 17 to 24 wt%, with no bloating structures in the bodies [7]. If Yanggu white clay were only used as a raw material for old white porcelain at that time, the final content of alumina in the porcelain body would be calculated at 16.4 wt%, as shown in Table 5. Old white porcelain shards had content of alumina higher than that of Yanggu white clay. In this study, the content of alumina in white porcelain produced from the mixture of Yanggu white clay and Korean kaolin was controlled from 18.87 wt% to 27.49 wt% via the addition of 10–40 wt% kaolin, as shown in Table 5. From these results and those from our previous study [7], it was estimated that old white Joseon Dynasty porcelain with 24 wt% of Al₂O₃ was produced to improve whiteness and refractoriness (to prevent bloating) using a mixture of 70 wt% Yanggu white clay and 30 wt% Korean kaolin. However, further research is required to investigate the firing temperature of white porcelain in olden times.

4. Conclusions

In this study, the role of the addition of Korean kaolin on the firing of Yanggu white clay for Korean porcelain,
and specific properties of the composites produced at 1000–1300°C from Yanggu white clay and Korean kaolin were studied. Yanggu white clay was composed of 57.1 wt% quartz and 38.8 wt% muscovite, whereas Korean kaolin was composed of 93–95 wt% kaolin and 4–6 wt% anorthite. Yanggu white clay showed the bloating phenomenon at temperatures over 1175°C. The bloating was introduced by small air bubbles incorporated during kneading of the clay, by the absorbed surface water and dehydroxylation of muscovite in Yanggu white clay, and additionally O₂ gas generated by the conversion of a small amount of Fe₂O₃ to Fe₃O₄ in white clay during firing. K from muscovite (KAl₂(AlSi₃O₁₀)(F,OH)₂) in Yanggu white clay played a significant role as melting agent to form a liquid phase. The addition of 20–40 wt% of Korean kaolin to Yanggu white clay showed the decreased content of Fe₂O₃ enhanced the whiteness of the fired composites. From this research, we estimated that a portion of old Korean white porcelains in the Joseon Dynasty was produced from a mixture of Yanggu white clay and Korean kaolin, which improved the refractoriness and whiteness of the bodies.

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