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PERFORMANCE ANALYSIS IN CERAMIC PORCELAIN PRODUCTION WITH THE USE OF ALTERNATIVE RAW MATERIALS AND COMPOSITION IMPROVEMENT

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Keywords

Ceramic Porcelain, Alternative Raw Materials, Composition Improvement, Thermal Expansion, Crack Resistance in Autoclave

ABSTRACT

This study investigates the use of feldspar derivatives from different regions and alternative raw materials used in ceramic porcelain production. Characterization tests performed include mineralogical analyses, XRF, XRD, dilatometer, heat microscopy, grain size distribution, water absorption and autoclave crack resistance analyses. The findings evaluate the sintering behavior, chemical composition and thermal expansion properties, identifying weak links in the manufacturing processes. In particular, mismatches in alkali oxide ratio, differences in thermal expansion and problems in melting behavior affect crack resistance. As a result, alternative raw material usage and composition improvement are suggested and various recommendations are presented to solve the problems in production.

Introduction

Ceramics are materials that are shaped with a mixture of inorganic substances and metal alloys and strengthened by firing after glazing (Erzincan et al. 2021; Kurian and Thankachan 2023). The ceramic sector has become one of the most important manufacturing fields with mass production, which has developed in the world and our country with the industrial revolution. Economic growth in the ceramic sector has increased the need for floor and wall tiles, ceramic tableware, sanitary ware, and vitrified products (Göl et al. 2021; García-Ten et al., 2024).

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Porcelain is known as a vitrified product consisting of 50% kaolin or clay, 25% quartz, and 25% feldspar (Wong, 2019; Alwi Kutty, 2020; Santos et al. 2022). The kaolin and clays in porcelain allow the product to take shape, feldspar provides sintering of the body, and quartz increases the strength of the body (Bahtli and Erdem 2021; Engels and Piribauer, 2022). Hard porcelain is formed between 1350-1450℃ firing temperature, and soft porcelain is formed at 1200℃-1250℃ (Leonelli et al. 2001; Kim, 2006; Tomalino, 2021).

The world ceramic tableware sector is worth 15 billion dollars, and consumption is increasing by 5% every year (Ministry of Development Report, 2015). China accounts for 36% of exports in the ceramic tableware sector, while Turkey accounts for 1%. According to TUIK data, the net value added in manufacturing in 2018 was approximately 750 million TL (Ministry of Industry and Technology, 2022).

Glaze material is known as the glassy layer that covers the surfaces of ceramic products and provides aesthetic and hygienic properties (Revuelta, 2021; Reinosa et al., 2022). After firing at different temperatures, ceramic products change their physical and mechanical properties with the sintering of both glaze and structure (Binhussain et al. 2014; Capatína et al. 2012; Köseoğlu, 2017; Sariisik et al. 2011; Sarıışık et al. 2013; Aurélio et al., 2015; Nam and Park, 2018; Otitoju et al., 2020; Xu et al., 2023). The proportion of materials in the glaze content is determined by grain size and firing temperature (Amorós et al. 2021; Xu et al., 2023). While some oxides (Na2O, B2O3, K2O, ZnO, PbO) decrease the melting temperature in the glaze composition, some oxides (SiO2, Al2O3) increase the melting temperature (Brosh et al. 2012; Huang et al. 2021; Taallah et al., 2021). The addition of boric acid (H3BO3) increases the strength of the ceramic products and decreases the furnace regime (Çelik, 2015;Ustunel et al. 2021). The melting temperature decreases in feldspar and alkaline-containing blends and glazes. For this reason, there is a shrinkage of firing after sintering in the base and glazes. Depending on the increase in sintering temperature, the porosities decrease as they become closer to each other with the melting of the glassy phase. Accordingly, porosity and water absorption values decrease and density increases (Dondi et al. 2002; Çelik, 2015; Öztürk et al. 2021; Zanelli et al., 2021; Altimari et al., 2023.

In literature studies, it is seen that feldspar derivatives of different regions are used in ceramic porcelain production to facilitate melting and lower the temperature (Akpinar et al., 2017;Tarhan and Tarhan 2019; Fuertes et al. 2022; Wang et al., 2023). In addition, pumice and calcined colemanite have been used as alternative raw materials to feldspar (Akpınar et al. 2017; Öztürk and Can 2023; Öksüzer, 2023). In the production of ceramic porcelain tableware, new products must be resistant to high temperatures. In particular, in the ceramic tableware sector, it is necessary to design innovative products for customer satisfaction, increase product quality, eliminate problems in the production stage to reduce costs, use alternative raw materials, and increase productivity. In this study, characterisation tests (mineralogical analysis, mineralogical analysis, XRF, XRD, dilatometer, heat microscopy and grain size distribution, water absorption analysis of the final products obtained from glaze samples A and B, and crack resistance analysis in autoclave were performed. Thus, the aim is to improve the composition of the composition in the

production of industrial ceramic tableware under operating conditions.

The use of alternative raw materials in the ceramic industry can make significant contributions to the existing literature. In particular, materials such as pumice and calcined colemanite used as alternatives to traditional raw materials have the potential to reduce production costs and improve product quality. The aim of this research is to contribute to the development of innovative ceramic products resistant to high temperatures by examining the effects of alternative raw materials in ceramic production. This study aims to provide important information to the literature by revealing the potential benefits of the use of alternative raw materials in the ceramic industry and their effects on production processes.

MATERIALS AND METHODS

2.1. Material

The materials used in the glaze recipe were first brought to the desired grain size by wet grinding in a ball jet mill. Based on the properties of the glaze materials, ±0.01 g was weighed in the desired ratio with a precision balance. Water was added to the glaze mixture and filtered through a 100-mesh sieve. To control the fluidity of the prepared glaze, 20 l/s was measured using a viscometer. In addition, the solid-liquid ratio was checked by waiting for a while for the glaze to settle. Thus, the glaze was made ready for glazing and was applied to the body using the dippingmethod. Table 1 shows the A (Opaque) and B (Transparent) components of the glaze recipes.

Table 1. A (Opaque) and B (Clear) glaze recipes

Sır Türü	**Solid ratio**					**Liquid ratio**
	Transparent	Opaque	Flaks	Groleg	Magnesium	Water
A Glaze (%)	16.63	37.42	2.08	3.74	0.06	40.06
B Glaze (%)	43.52	0.00	1.70	3.07	0.05	51.65

Figure 1. The appearance of the clay raw material used in the production of ceramic products

The appearance of the clay raw materials used in the production of ceramic products and the composition and glaze samples used in the analysis are shown in Figure 1 and Figure 2. The glaze mixtures were first ground in a ball mill and then dried in an oven at 105 ºC. The body was also dried in an oven at 105ºC for 1.5 h.

2.2. Experimental Conditions

For a more detailed understanding of the properties of the materials used and the experimental conditions, the following specifics are provided:

- Grain Size Reduction: The initial step involved wet grinding the glaze materials

in a ball jet mill to achieve the desired grain size. This process ensured a uniform particle size distribution, crucial for consistent glaze application.

Figure 2. Appearance of the composition and glaze samples used in the analysis

- Weighing and Mixing: The precise ratio of materials was weighed using a precision balance with an accuracy of ±0.01 g. Water was then added to the glaze mixture, which was subsequently filtered through a 100-mesh sieve to ensure a homogenous mixture.
- Viscosity Measurement: The fluidity of the glaze was controlled by measuring 20 l/s using a viscometer. This step ensured that the glaze had the appropriate consistency for application.
- Solid-Liquid Ratio: The solid-liquid ratio was monitored by allowing the glaze to settle for a period, ensuring the correct balance for optimal application.
- Drying Conditions: Both the glaze mixtures and the body were dried in an oven at 105 ºC. The glaze mixtures were dried until they reached a constant weight, while the body was dried for 1.5 hours to remove any residual moisture.

2.3. Production of Ceramic Products using Classical and Digital Printing Technology

The steps followed in the production of ceramic products are shown in Figure 3. In the classical method of the production of ceramic products moulds of new products are prepared in the model shop. The raw material mud (clay) is vacuumed and sent to the press for shaping. The edges of the material that takes the shape of the mold are cleaned. The cleaned products are dried, and the burrs and excesses on the edges are removed in the retouching section. In ceramic production, isostatic powder pressing, plastic forming, ram pressing, and casting methods are used. Isostatic powder pressing is the most preferred method according to the geometric structure of the product to be produced. In this study, the isostatic powder-pressing method was also used according to the product variety. The retouched products were biscuits baked in a chamber-type electric oven and sent to the glazing department. If the product is to be decorated, it is decorated in the decorating section before the glazing section. The glazed and decorated products are fired in a tunnel oven for the second firing. The final products are quality-controlled and packaged. Decorating and pattern printing methods used in the ceramic industry include decal printing, pad printing, and digital inket printing. In this study, the production processes in digital inkjet printing machines were used. The digital inkjet printing machine consists of a product input section, height photocells centering, with the help of a camera, warning lamp, touch control screen, band, printing area, product output area, and band washing chamber. The semi-

finished product (glazed biscuit) is sprayed onto the semi-finished product moving from the production line and the previously designed pattern is processed. The semi-finished product is removed from the production line, and directed to the benches where other processes will be performed. The process of dropping the semi-finished product on the production line and removing it from the production line is performed manually. Manual control of the digital inkjet printing machine, adjustments of the printing head, and other adjustments related to the head plate are made from the control panel. The appearance of ceramic kitchenware before and after glazing is shown in Figure 4 and Figure 5.

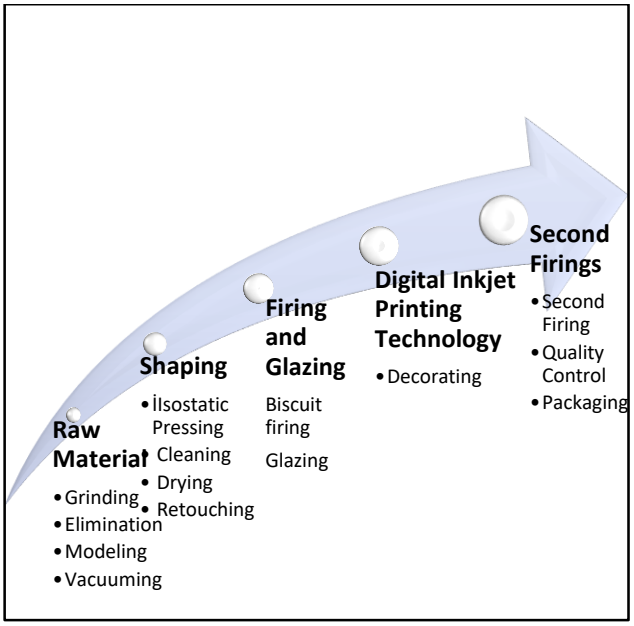

Figure 3. Steps in the Production of Ceramic Products

Figure 4. Before and After Glaze Appearance in Classical Ceramic Products

Figure 5. Post-glaze appearance of ceramic products produced with digital printing technology

A REF-SAN brand REF-SAN electric chamber-type kiln with a kiln volume of 0.5 m3 was used for the heating process of the impregnation and glaze application. The impregnated and glazed

product was fired at 1055 °C. The kiln regime for the firing process of impregnation and glaze application is shown in Figure 6.

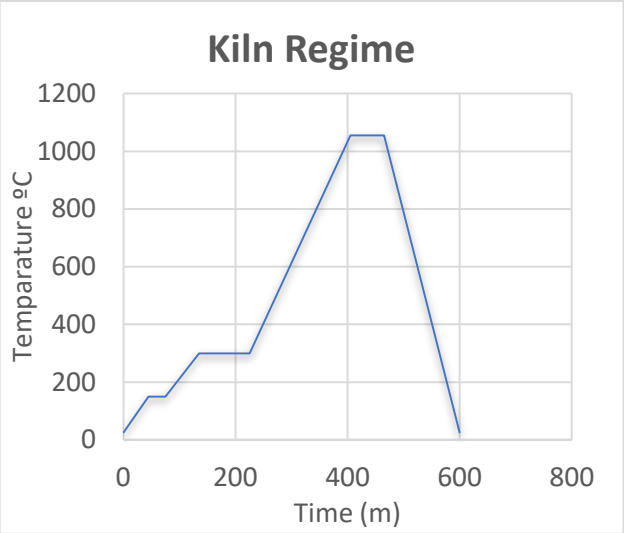

Figure 6. Kiln regime during the heating process of composition and glaze application

2.4. Characterization Tests

Characterization tests on composition, A glaze, and B glaze samples (mineralogical analysis, XRF, XRD, dilatometer, heat microscopy, and grain size distribution) were conducted at SEM (Ceramic Research Center) laboratories.

Grain Size Measurement: The grain sizes of raw materials, clays, and glazes ranging from 0.2 to 2000 pm were measured using laser diffraction.

Chemical Composition Analysis: The chemical properties of the composition and glaze samples were analyzed using XRF (ICP-ES) method to determine the oxide compounds.

Crystal Structure and Phase Analysis: Samples were analyzed with a Rigaku brand Miniflex 600 model XRD device within a scanning range of 2Θ=5º-70º, identifying the crystal structures and phases present in the materials.

Thermal Analysis: Dilatometer analyses were performed using a Netzsch brand 402PC model device at a heating rate of 10ºC/min up to 700ºC. This analysis determined the thermal expansion properties of the materials.

Melting Behavior: The melting behavior of the samples was analyzed using a Misura ODHT HSM 1600-80 heat microscope device. The sintering, softening, full sphere, half sphere, and yield temperature points were determined.

Water Absorption and Crack Resistance: Water absorption determination and autoclave crack resistance analysis of the products made from glaze samples A and B were performed at the Ceramic Research Center (SAM) laboratories.

3. RESULTS

3.1. Grain Size Distribution Analysis Results

Grain size distribution analyses of liquid clay, opaque glaze, and transparent glaze samples were performed by the laser method at the Ceramic Research Center (SAM) laboratories. Because of the measurement, d10, d50, and d90 values, size distribution percentage values in terms of volume or surface were determined. 10% of the d (0.1) µm sample, 50% of the d (0.5) µm sample, and 90% of the d (0.9) µm sample are below this size. The grain size distribution analysis results for composition, A, and B rows are given in Table 2.

Table 2. Grain size distribution analysis results of composition, A and B glazes

Sample	d (0.1) µm	d (0.5) µm	d (0.9) µm
Composition	1.2	6.1	31.8
A glaze	1.9	11	30.8
B glaze	2	10.3	29.3

The sintering behaviour and physico-mechanical properties of the ceramic body affect the grain size distribution of the raw body. In this study, the grain size distributions of the body, A, and B glaze samples were

investigated. The sintering behaviour of the composites varies as the grain size of the hard raw materials in the composite decreases. The sintering temperature can be reduced by further grinding the core and glaze samples.

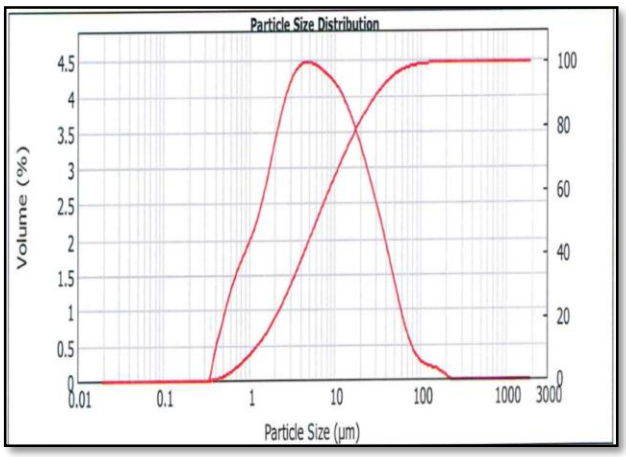

Figure 7. Grain size curve of the impregnation

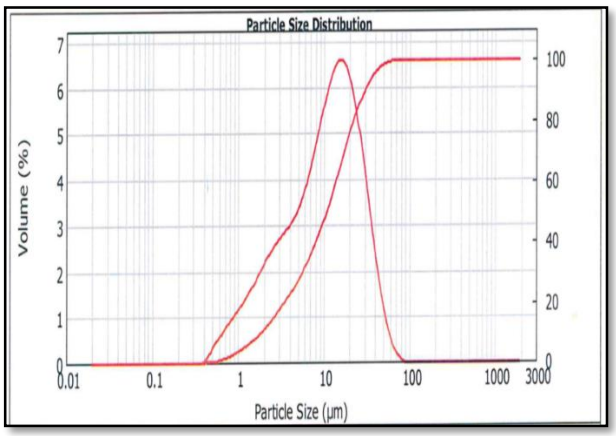

Figure 8. Glaze grain (A) size curve

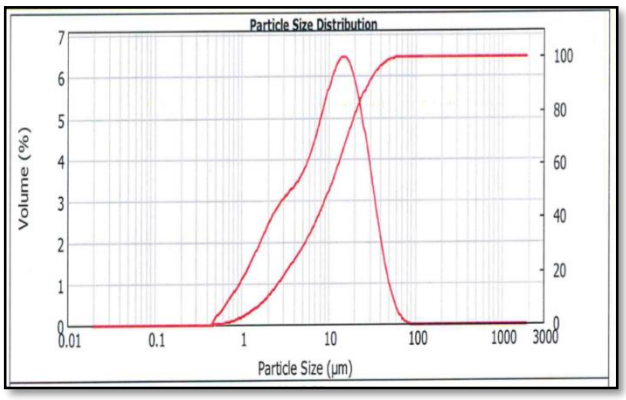

Figure 9. Glaze grain (B) size curve

The data indicates that the A glaze has a slightly larger d50 value compared to B glaze, suggesting a coarser particle size distribution. Composition shows the smallest particle sizes, which might contribute to its different sintering behavior compared to glazes A and B.

3.2. XRF (X-Ray Fluorescence) Analysis Results

The results of the XRF semi-quantitative analysis of the ceramic body, A glaze, and B glaze samples are given in Table 2. SiO2 was between 60.87 and 964.59%, Al2O3 was between 10.51 and 20.92%, and CaO was between 7.14 and 99.98% in the samples of the ceramic body. A glaze, and B glaze. The alkaline oxide ratio (Na2O, K2O, TiO2) was determined to be 3.06–9.01% in the composition, A glaze, and B glaze samples. There are also small amounts of Fe2O3 (0.22–91.26%), MgO (0.26–92.12)%, ZrO2 (0.01–8.88%) and ZnO (0.01–93.20%).

Table 2. XRF Analysis Results

Chemical Components (%)	Composition	A Glaze	B Glaze
Na_2O	0.57	5.76	5.28
MgO	2.12	0.26	0.4
SiO_2	63.37	60.87	64.59
Al_2O_3	20.92	10.51	14.28
P_2O_5	0.01	0.01	0.13
SO_3	1.46	0.01	0.12
K_2O	1.74	2.18	3.56
CaO	7.14	7.75	9.98
TiO_2	0.75	0.15	0.17
ZrO_2	0.01	8.88	0.49
Fe_2O_3	1.26	0.22	0.31
ZnO	0.01	3.20	0.62
A.Z.	0.66	0.20	0.07

After the biscuit firing of the semi-finished products, the second firing occurs in the tunnel-type kiln by glazing. Scorching and glaze cracks were examined in the products produced in the second firing process to ensure interlocking of

the base and glaze. According to the results of the analysis, the alkali oxide ratio in the core, A glaze, and B glaze samples was determined to be 3.06–9.01%. In this case, while the alkali oxide rate is between 8.09–9.01% in glaze samples A and B, it is at a low level with 3.06% in the body. Because of the low alkali oxide ratio in the body, the bonding and interlocking points between the body and t glaze may be weaker. In this case, in addition to clay minerals, improvement studies should be conducted out by adding different industrial raw materials to increase the alkali oxide ratio. In this way, cracks and scorching are prevented, especially when the products to be obtained are exposed to temperature, impact, and chemical materials.

The high SiO2 content in A and B glazes indicates a high silica content, which is common in glazes to improve their durability and hardness. The alkali oxides (Na2O, K2O) are relatively higher in glazes A and B compared to the body, which contributes to better fluxing and a lower sintering temperature.

3.3. XRD (X-Ray Diffraction) Analysis Results

XRD (X-ray diffraction) analyses were performed on the samples of the base, A glaze, and B glaze, and their mineralogical components are shown in Figure 5.3. Because of the XRD mineralogical analyses of the composition, A glaze, and B glaze samples, the mineralogical analysis results between 20º and 30º are given below (Figure 7-Figure 9).

XRD mineralogical analysis revealed that quartz (SiO_2), anorthite, and mullite ($Al_6Si_2O_{13}$) are prominent minerals in the samples. These minerals significantly influence the mechanical properties and thermal behavior of the ceramics. In glaze sample A, high-intensity peaks between 20º and 30º were observed for quartz (SiO_2), anorthite, sodian, mullite, and $ZrSiO_4$. For glaze sample B, high-intensity peaks in the same range were predominantly due to quartz (SiO_2).

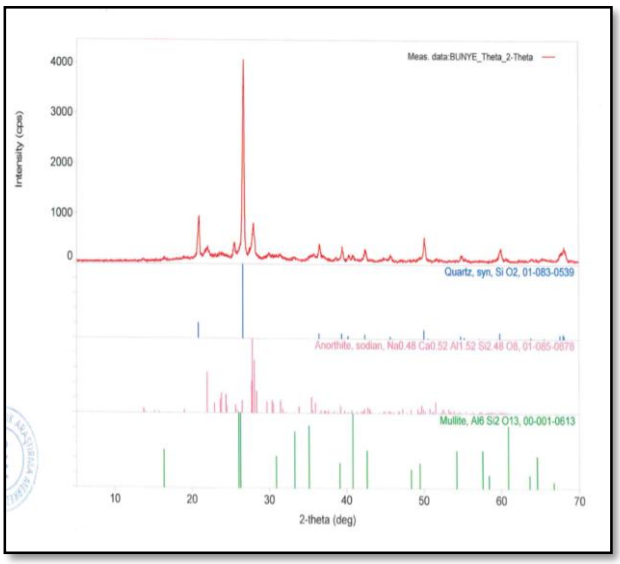

Figure 7. XRD Mineralogical Analysis Results of Earthenware

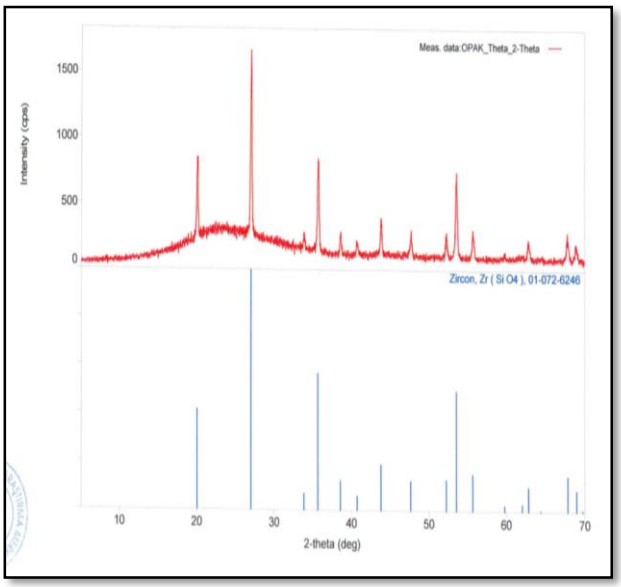

Figure 8. XRD mineralogical analysis results of glaze sample (A)

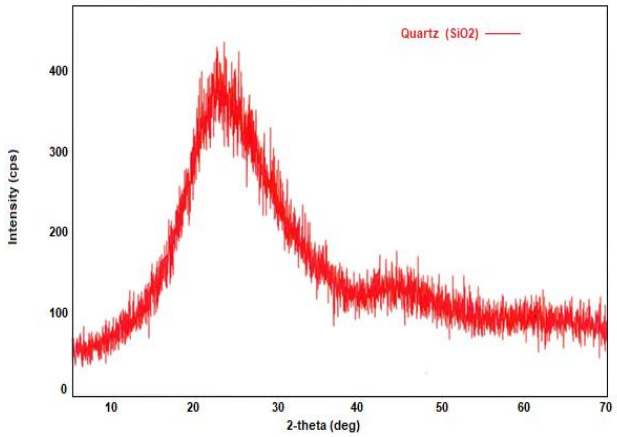

Figure 9. XRD mineralogical analysis results of glaze sample (B)

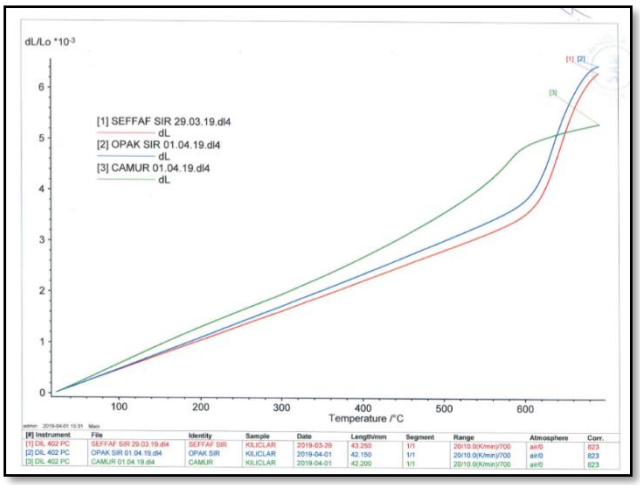

Figure 10. Composition, A and B glaze optical dilatometer curves (dL)

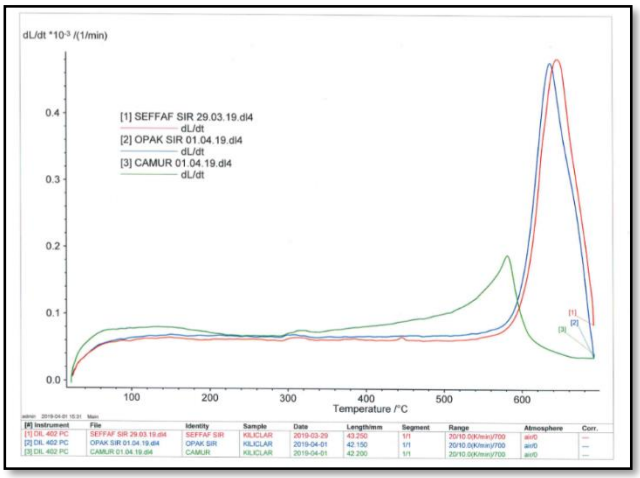

Figure 11. Composition, A and B row optical dilatometer curves (dL/dt)

3.4. Optical Dilatometer Analysis Results

The results of the thermal expansion behaviour of the core, A glaze, and B glaze samples by optical dilatometer analysis are given in Table 3. In the dilatometer measurement, the size change of the material in response to heat was analysed. Thermal expansion values are generally given in terms of linear expansion coefficient (α). The sample was kept at room temperature and allowed to stabilise. A standard firing period of up to 700ºC with a heating rate of 10ºC/min was applied to the samples. The dimensional change and expansion coefficients of the samples at 50ºC and dilatometer curves between ~50ºC-650ºC are given in Figure 10 and Figure 11.

Table 3. Non-contact optical dilatometer analysis results for the compositions of, A and B glazes

Sample	$\alpha 300x10^{-7}$	$\alpha 400x10^{-7}$	$\alpha 500x10^{-7}$
Composition	69.7	70.7	74.4
A Glaze	57.8	58.4	58.8
B Glaze	61.3	62	62.8

The ceramic body exhibits a higher thermal expansion coefficient compared to the glazes, which suggests potential mismatch issues that could lead to cracking during firing or use. The thermal expansion behavior of the raw body and the A and B glaze samples was measured from 50ºC to 700ºC. The coefficient of thermal expansion is crucial for ensuring strong bonding between the raw body and glaze. Analysis of the optical dilatometer curves indicates that the ceramic body has a lower coefficient of thermal expansion compared to the A and B

glazes, which could result in compatibility issues and potential cracking.

3.5. Melting Behavior Analysis Results with Thermal Microscopy

Melting behaviour analyses of glaze samples A and B by heat microscopy were performed at the Ceramic Research Center (SAM) laboratories. Table 4 shows the results of the melting behaviour analysis of glaze samples A and B by heat microscopy.

Table 4. Melting behavior analysis results of glaze samples A and B

Sample	A Glaze	B Glaze
Sintering Temperature (ºC)	738	730
Softening Temperature (ºC)	880	882
Full Sphere Temperature (ºC)	952	956
Hemisphere Temperature (ºC)	962	1080
Flow Temperature (ºC)	1006	1114

The similar temperature ranges observed for glazes A and B suggest that their melting behaviors are comparable. Based on the melting behavior analysis using heat microscopy, it was found that the sintering temperature for both glazes ranged from 730 to 738°C, the softening temperature was between 880 and 882°C, the hemispherical temperature ranged from 952 to 956°C, the full sphere temperature varied from 962 to 1080°C, and the melting temperature was between 1006 and 1114°C. Therefore, the application temperature should be set around 900°C to align with these ranges. Figure 12 presents the melting behavior of glazes A and B, with separate graphs and animation images illustrating the melting behavior and characteristic temperature points, including sintering, softening, hemispherical, full sphere, and melting temperatures.

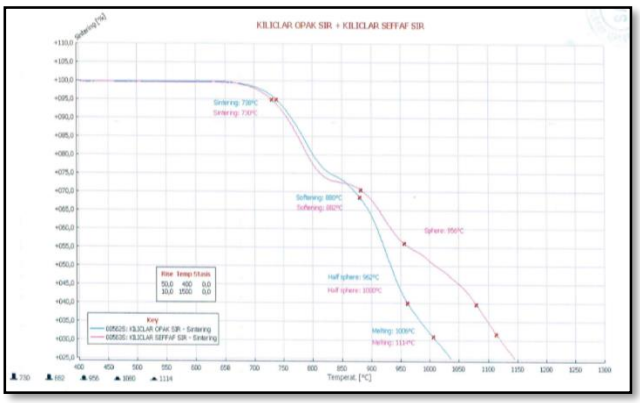

Figure 9. Glaze A and Glaze B Heat Microscopy Curves

In glaze materials, as the temperature increases, the viscous flow passes beyond the activation phase into the sintering phase. The size of the sample decreases, but the actual shape does not change. In the case of a glaze, the driving force of sintering is the surface tension of the glassy phase. In the process of sintering the material, the glassy grains get closer to each other and deform due to surface tension. The sintering phase ends when the sample reaches its maximum density. The size of the material does not change by 6% until it reaches a fluid glassy phase within a certain sintering temperature range. In the study, the furnace regime was taken as 1050ºC for firing before and after glazing. According to the heat microscopy analysis results, since the sintering temperature of glazes A and B is approximately 730-738ºC and the softening temperature is approximately 880-882ºC, the application temperature should be applied at 900 ºC. In this case, it was determined that there was heat loss at 150ºC in the tunnel kiln application.

3.6. Water Absorption Analysis Results

Water absorption analysis of the final products obtained from glaze samples A and B was

performed at the Ceramic Research Center (SAM) laboratories. The relevant standard for this analysis is TS EN 1217. The results of the water absorption analysis of the samples are presented in Table 5.

Table 5. Water absorption analysis results for glazed samples A and B

Sample	*A Glaze*	*B Glaze*
Water Absorption (%)	23.85	23.13
Apparent Porosity (%)	38.85	37.77
Apparent Relative Density (kg/m^3)	2660	2620
Bulk Mass (kg/m^3)	1630	1630

Because of the water absorption analysis, water absorption percentages were determined to be 23.85% for the opaque glazed sample, 23.13% for the transparent glazed sample, and 22.1% for the semi-transparent glazed sample. According to the TS EN 14411 standard, glazed products were classified as Group AIII and BIII because the water absorption test was E>10%.

3.7. Analysis Results of Crack Resistance Determination in an Autoclave

Autoclave cracking resistance analyses of glaze samples A and B were performed at the Ceramic Research Center (SAM) laboratories. The results of the autoclave cracking resistance analysis of the samples are presented in Table 6.

Table 6. Autoclave cracking resistance analysis results for opaque-glazed, transparent-glazed, and semi-transparent-glazed samples

Sample	Cracking and/or Discoloration of the Sample (Yes/No)
A Glaze	Damaged
B Glaze	Damaged

As shown in Table 6, because of the cracking strength analysis of the glaze according to the TS 10850 standard, hair-thin cracks were detected in all three glazed samples. The main reason for these cracks is that the bond between the composition and glaze is very weak. In this context, new composition studies should be conducted using alternative raw materials (such as kaolin, wollastonite, marble powder, calsite, dolomite (Karaogul, 2019; Karaoğul & Alma, 2019) and ground biscuit crumbs) in addition to the clay minerals in the composition.

4. DISCUSSION

The glaze material, characterized by its glassy layer, plays a crucial role in enhancing the aesthetic and hygienic properties of ceramic products. Firing temperatures and grain sizes significantly influence sintering behavior, ultimately affecting the final properties of ceramics (Revuelta, 2021; La Torre et al., 2021; Reinosa et al., 2022). Specific oxides such as Na_2O and B_2O_3 lower the melting temperature, whereas SiO_2 and Al_2O_3 increase it, thus impacting the glaze composition (Brosh et al., 2012; Huang et al., 2021). Boric acid (H_3BO_3) is known to enhance ceramic strength while reducing the firing temperature (Çelik, 2015; Ustunel et al., 2021; Karataş and Şimşek 2022). Incorporation of feldspar and alkaline substances in glazes lowers the melting temperature, reduces porosity and water absorption, and increases density post-sintering (Dondi et al., 2002; Öztürk et al., 2021; Zanelli et al., 2021).

Based on the study's data, the grain size distribution analysis of mud, opaque, and transparent glazes revealed that the percentage of grain size distribution determines the amount of particles of certain sizes in terms of volume or surface. X-ray fluorescence analysis determined the

composition of the ceramic body and glazes, revealing crucial properties like thermal behavior, mineralogical composition, and crack resistance.

The study found that the glazes exhibited weak bonding with the body, leading to cracks. Therefore, it is suggested to explore new compositions using alternative industrial raw materials such as kaolin, wollastonite, marble powder, and ground biscuit crumbs instead of traditional clay minerals. This approach could help prevent crack formation when the products are exposed to temperature variations, impact, and chemicals.

Additionally, the thermal behavior of various glazes was examined using optical dilatometer analysis and thermal microscopy, determining appropriate application temperatures. For example, given the sintering temperature of the glazes ranged between 730-738 ºC and the softening temperature between 880-882 ºC, the application temperature should be set around 900 ºC.

The results of water absorption and autoclave cracking resistance tests indicated that the products met specific standards, classifying them as Group AIII and BIII according to the water absorption test.

Future research should carefully study the long-term effects of using alternative feedstocks such as kaolin, wollastonite, and marble powder. Although these materials can enhance glaze properties, they may also introduce challenges related to compatibility with existing raw materials, cost implications, and firing process modifications. Key challenges in industrial applications include ensuring a reliable supply of these alternatives, adjusting firing schedules or kiln configurations, and evaluating the economic feasibility of their incorporation. Future research should focus on optimizing both composition and processing conditions to overcome these challenges and improve the performance and durability of ceramic products.

5. CONCLUSIONS

The study aimed to identify and address the issues encountered in blooms and glazes by examining various analyses. The results of the tests and analyses performed on the composite and glazes are summarized as follows:

The grain size distributions of the core, A, and B glaze samples were analyzed. It was observed that finer grinding of raw materials used in the core and glaze samples could potentially lower the sintering temperature and improve the quality of the final product.

The X-ray fluorescence analysis revealed that the bonding and interlocking between the base and glaze were weaker due to an incompatible alkali oxide ratio. To improve adhesion and reduce defects, future studies should focus on increasing the alkali oxide ratio.

The X-ray diffraction analysis identified key minerals such as quartz (SiO2), anorthite, sodian, mullite (Al6Si2O13), and ZrSiO4 in glaze sample A, and quartz in glaze sample B, with significant peaks between 20º and 30º. These findings confirm the presence of expected minerals in the samples.

The dilatometer analysis indicated that the coefficient of thermal expansion of the raw body is lower than that of the glaze samples, suggesting a mismatch that could lead to issues during firing or use. Ensuring compatibility in thermal expansion coefficients is crucial for achieving strong bonding between the body and glaze.

Based on heat microscopy analysis, it was found that the firing temperature should be adjusted

to approximately 900 ºC, instead of the initially applied 1050 ºC. This adjustment accounts for the 150 ºC heat loss observed in the tunnel kiln, optimizing the firing process.

Final product tests classified the glazed products as Group AIII and BIII, based on water absorption rates (E>10%) according to TS EN 14411. This classification indicates that the products have relatively high porosity, which may affect their strength and durability.

The cracking resistance analysis showed the presence of hair-thin cracks in the glazed samples as per the TS 10850 standard. To minimize these cracks, it is essential to strengthen the bonding between the ceramic body and glaze.

The findings suggest that improvements in the formulation and processing of ceramic glazes could significantly enhance product performance. Practical applications of this research include refining glaze compositions and optimizing firing conditions to achieve better adhesion and durability. Future research should focus on:

Investigating the use of different materials such as kaolin, wollastonite, marble powder, and ground biscuit crumbs to increase the alkali oxide ratio and improve glaze bonding.

Developing glazes with thermal expansion coefficients that match closely with the ceramic body to prevent cracking and ensure strong adhesion.

Further studies should refine firing temperatures and kiln conditions to minimize heat loss and achieve optimal glaze melting behavior.

Conducting long-term tests to evaluate the performance of improved glaze formulations under various conditions, including temperature fluctuations, mechanical stress, and chemical exposure.

By addressing these areas, the ceramic industry can enhance the quality, durability, and functionality of ceramic products.

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