Iranian Journal of Analytical Chemistry
Volume 12, Issue 2, October 2026 (151-159) Original Research Article
مجله ایرانی شیمی تجزیه
دوره ۱۲، شماره ۲، مهر ۱۴۰۴ (۱۵۱-۱۵۹)

Development and Characterization of High-Performance Decorative Glass-Ceramics: Frit Design, Processing, and the Role of Wollastonite

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Received: 24 October 2025 **Accepted:** 11 November 2025
DOI: 10.30473/ijac.2026.80004.1361

Abstract
This study aimed to develop high-performance decorative glass-ceramics through the incorporation of specifically formulated frits into the body composition, targeting exceptionally low water absorption, enhanced mechanical strength, excellent chemical durability, and superior surface aesthetics. Two formulations were developed following more than 200 laboratory trials. Particular attention was given to the role of wollastonite ($CaSiO_3$), considered at 2–5 wt.% in candidate formulations alongside 1–3 wt.% free alumina, as a source of CaO and SiO_2 for adjusting the oxide balance and tailoring the thermal characteristics of the frits. Two optimized products, GC105 and GC178, exhibited water absorption values between 0.005% and 0.0003%. Their breaking loads reached 1820 and 2430 N, with corresponding moduli of rupture of 54 and 120 N/mm², respectively. Both products achieved Class A chemical resistance and Class 5 stain resistance. Following polishing and nano-treatment, GC178 achieved a 60° gloss value of 95–100 while retaining its marble-like appearance and light-transmitting characteristics. Industrial scale-up trials further identified granule-size distribution, binder selection, firing conditions, and cooling-profile control as critical parameters for process reliability and product consistency. These findings confirm the feasibility of developing decorative glass-ceramics through frit-assisted body formulation, achieving the targeted combination of near-zero water absorption, high mechanical strength, chemical durability, and refined surface aesthetics. Furthermore, the successful scale-up trials establish a promising foundation for transferring the optimized formulations to industrial production and expanding their application in high-performance architectural and decorative surfaces.

Keywords: Glass-Ceramics, Frit, Water Absorption, Mechanical Properties, Wollastonite.

1. Introduction

Glass-ceramics are inorganic materials in which one or more crystalline phases are developed within a residual glassy matrix through controlled crystallization. Their performance depends on the composition of the parent glass as well as the type, amount, size, and distribution of the crystalline phases formed during thermal processing [1-234]. This combination of glassy and crystalline constituents allows glass-ceramics to be designed for specific mechanical, thermal, chemical, and optical requirements, supporting their use in architectural and engineering applications [4,5,6].

The production route strongly influences the final structure and properties of glass-ceramics. In the conventional route, a parent glass is melted and formed before a controlled heat treatment promotes nucleation and crystal growth. In powder-based processing, glass powders are compacted and densified while crystallization may occur concurrently, a process commonly described as sinter-crystallization [1,3,7,8]. In these systems, densification and crystallization must be balanced: early crystal formation can limit viscous flow, whereas unsuitable firing or cooling conditions may cause residual porosity, distortion, or cracking [7–9]. Therefore, composition design and thermal-cycle optimization are central to achieving reproducible products.

Wollastonite ($CaSiO_3$) is a calcium silicate mineral with a chain-silicate structure and is used in a range of ceramic, glass, and glass-ceramic

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formulations [10,11]. In oxide batches, it can supply both CaO and SiO_2, thereby influencing the balance between network-forming and modifying oxides. Its effect is not independent of the remaining composition: phase development (see Fig. 1) and melt behaviour in CaO–Al_2O_3–SiO_2 and CaO–MgO–SiO_2 systems are governed by the combined oxide chemistry and the thermal history [2,12,13]. Phase-equilibrium relationships provide a useful basis for interpreting possible crystalline products, although the phases actually formed must be verified for each formulation and processing schedule [2,12–14].

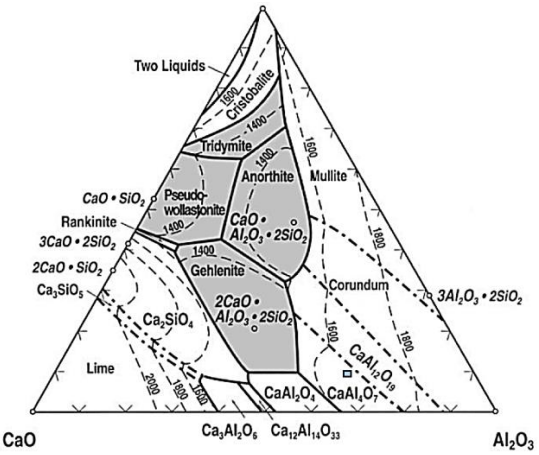


Fig. 1. Phase diagram of the Wollastonite as reported by Osborn and Muan

Previous studies have examined wollastonite-containing glass-ceramics prepared from designed oxide mixtures, natural minerals, industrial residues, and recycled glass or stone-processing wastes [2,7,15-16,17,18,19]. These studies indicate that the properties of the resulting materials depend on raw-material chemistry, particle-size distribution, densification, and the conditions under which crystallization proceeds [7,8,15,17]. Wollastonite-bearing compositions have also been investigated for stone-like and marble-like architectural products, making this material family relevant to decorative surfaces that require both visual quality and functional performance [16,18,19].

Frit design is particularly important when glass-ceramic compositions must be processed using practical industrial firing schedules. The oxide balance influences melting behavior, viscosity, softening, and the potential crystallization pathway; accordingly, the nominal content of one raw material cannot by itself predict the performance of the complete frit [2,3,12,13]. Alumina content and other minor oxides may also affect crystallization, microstructure, and mechanical response in multicomponent glass-ceramics [13,20-21,22]. A suitable frit must therefore provide not only the desired oxide chemistry but also a sufficiently broad and controllable firing window for subsequent forming and firing operations.

Despite the broad literature on glass-ceramics, the development of thin decorative products for industrial ceramic processing requires simultaneous consideration of formulation, granulation, compaction, firing, cooling, and surface finishing. A formulation that performs well in laboratory specimens may behave differently after scale-up because powder flow, granule-size distribution, product dimensions, and thermal gradients influence raw-body uniformity and residual stresses. For this reason, performance evaluation should combine chemical analysis with measurements of water absorption, mechanical strength, chemical and stain resistance, and surface finish.

In this context, the present study aimed to develop decorative glass-ceramic products by incorporating specifically designed frits into the body formulation, with particular emphasis on the role of wollastonite ($CaSiO_3$) as a source of CaO and SiO_2 in tailoring the oxide composition and thermal behavior of the frit. The study focused on selecting a suitable frit composition capable of providing favorable melting characteristics and a broad firing window while promoting the formation of highly densified glass-ceramic bodies with exceptionally low water absorption, high mechanical strength, and improved chemical and stain resistance. Two products, GC105 (30 × 30 cm) and GC178 (10 × 20 cm), were developed and evaluated to establish the relationship between frit composition, processing conditions, and final product performance. Beyond laboratory-scale formulation and characterization, particular attention was given to the practical challenges of industrial implementation, including granule-size distribution, binder selection, firing-cycle optimization, and cooling control. The ultimate objective was to establish a reproducible formulation and processing route that could be transferred from laboratory development to industrial production while maintaining the required functional and aesthetic properties of the resulting glass-ceramic products.

2. Experimental Section

2.1. Raw Materials

The raw materials used in this study included silica, feldspar, kaolin, dolomite, wollastonite, other mineral raw materials commonly used in ceramic formulations, and frit compositions designated R1, R2, and LF3. All raw materials used for the development and production of the glass-ceramic formulations were supplied from the inventory of Lotus Color and Glaze Company, Iran.

DOI: 10.30473/ijac.2026.80004.1361

2.2. Instruments and Equipment

Frit melting was carried out in a NANNETTI KL40/12 laboratory furnace (Italy). Laboratory milling was performed using a fast mill manufactured by Foshan Huayang Instrument, China. A laboratory glaze applicator (slasher) was used to apply frit–kaolin suspensions to engobed tiles manufactured by MNG, Italy. Laboratory pressing was used to shape the granulated powders into specimens; the manufacturer and country of origin of the laboratory press was NANNETTI from Italy. Laboratory specimens were dried in a Shimaz dryer (Iran). Industrial forming was conducted using an HLT press (China), and industrial drying and firing were carried out using DLT equipment (China), including an industrial dryer and a roller kiln approximately 40 m in length. Chemical compositions were determined by X-ray fluorescence (XRF) at the Zar Azma Mahan partner laboratory. Surface gloss was measured using a gloss meter at a measurement angle of 60°.

2.3. General Preparation Procedure for Glass-Ceramic Products

Frit preparation: The required raw materials for each frit formulation were weighed and mixed. In the design of candidate formulations, wollastonite was considered at 2–5 wt.% as a source of CaO and SiO_2, while free alumina was considered at 1–3 wt.%; the available records do not specify the exact wollastonite content of each individual frit or selected glass-ceramic batch. For laboratory preparation, a 400 g batch was heated furnace at 1450 °C for 80 min to promote melting and homogenization. The resulting melt was quenched in water to cool it rapidly and limit extensive crystallization. The quenched frit was separated from the water and dried before further use.

Frit evaluation: A suspension was prepared from frit and kaolin at a mass ratio of 90:10. Water (40 mL), carboxymethyl cellulose (CMC, 0.1 g), and tripolyphosphate (TPP, 0.2 g) were added. The mixture was milled for 14 min and applied to engobed tiles using a laboratory glaze applicator at an application weight of 0.6. The coated specimens were fired at 1150 °C using a 60 min cycle. The fired surfaces were examined for melting behavior, coating uniformity, and visible defects, and the selected frit was used in subsequent formulations.

Compound preparation and granulation: For laboratory batches, 300 g of the selected raw-material mixture was weighed according to the target formulation and combined with 35 mL of water, 0.1 g of CMC as a binder, and 0.3 g of TPP as a processing aid. The suspension was milled for 8 min until the residue on a 230-mesh sieve reached approximately 2.5–4%. The milled material was dried and ground, after which water was added gradually during granulation to adjust granule moisture to approximately 4%. Coarse particles retained on an 80-mesh sieve were removed, and the granules were classified using a 40-mesh sieve. After laboratory optimization, a 100 kg batch was prepared for industrial-scale granulation using a spray dryer.

Forming, drying, and firing: Following a one-hour conditioning period to equilibrate moisture, laboratory granules were pressed into specimens measuring 5 × 10 cm. The specimens were dried at 200 °C for 30 min in a dryer and then fired at 1150 °C. For industrial production, GC105 and GC178 were pressed into 30 × 30 cm and 10 × 20 cm products, respectively, using an industrial press. The raw products were dried for 10 min at 250 °C in industrial dryer. GC105 was fired in a roller kiln at a peak temperature of approximately 1183 °C with a cycle of about 35 min, whereas GC178 was fired at approximately 1144 °C with a cycle of about 63 min. Cooling conditions were monitored because rapid cooling was associated with thermal stress and cracking in some industrial trials.

Characterization: The chemical composition of the fired products was determined by XRF. Water absorption, breaking load, modulus of rupture, chemical resistance, and stain resistance were assessed according to the relevant Iranian national standards cited in the following sections. GC178 was polished in two stages using abrasives with grit sizes from 180 to 5000. The polishing line speed was approximately 8 m/min, and the applied pressure was 2–4 kPa. Surface gloss was measured at 60° before and after nano-treatment.

3. Results and Discussion

3.1. Frit Selection and the Formulation Role of Wollastonite

Initial screening of the available commercial frits showed that not all compositions provided suitable melting behavior or a sufficiently broad firing window for the intended glass-ceramic process. New candidate frits were therefore designed and evaluated under comparable preparation and firing conditions. Wollastonite was considered at 2–5 wt.% as a potential $CaO–SiO_2$ source, while free alumina was considered at 1–3 wt.% to adjust the oxide balance. Because wollastonite supplies calcium and silicon simultaneously, its incorporation may affect the balance between network-forming and modifying oxides and may consequently influence melt formation, viscosity, softening behavior, and crystallization. The magnitude and direction of these effects depend on the complete formulation and thermal schedule; the present dataset does not isolate wollastonite as an independent variable. Among the evaluated frits, LF3 was selected because it exhibited a higher melting temperature and a broader firing

DOI: 10.30473/ijac.2026.80004.1361

range. Its measured composition contained 20.72 wt.% CaO and 58.69 wt.% SiO_2, consistent with a CaO–SiO_2-rich chemistry. The oxide compositions of R1, R2, and LF3 are summarized in Table 1.

Table 1. Oxide composition of the reference frits and selected frit LF3; values are reported as oxide wt.%.

Oxide	R1 (wt.%)	R2 (wt.%)	LF3 (wt.%)
SiO_2	63.0	59.0	58.69
Al_2O_3	10.0	6.8	8.12
BaO	4.5	4.3	3.52
CaO	8.0	19.1	20.72
Fe_2O_3	0	1.7	0.20
K_2O	3.0	0	2.15
MgO	4.5	0	0.10
Na_2O	5.6	0	0.84
B_2O_3	1.0	0.6	> 0.01
TiO_2	0.4	0	> 0.01
ZnO	0	6.8	6.80

3.2. Chemical Composition of the Glass-Ceramic Products

XRF analysis was performed by the Zar Azma Mahan partner laboratory to compare the developed glass-ceramic products with the reference bodies. GC105 contained 55.23 wt.% SiO_2 and 18.13 wt.% Al_2O_3, whereas GC178 contained 57.32 wt.% SiO_2 and 16.93 wt.% Al_2O_3. The ZnO contents were 1.44 wt.% and 2.75 wt.% for GC105 and GC178, respectively, while the corresponding CaO contents were 15.18 wt.% and 14.86 wt.%. The differences between the two products show that their final oxide compositions were not identical, particularly with respect to MgO, Na_2O, BaO, and ZnO. Such compositional differences may influence densification, the residual glass composition, and the surface response. Calcium and silicon are relevant to the discussion of wollastonite-containing formulations because both elements contribute to the oxide balance.The measured compositions are presented in Table 2.

Table 2. XRF oxide composition of the reference bodies and glass-ceramic products.

Oxide	Reference 30 × 30	Reference 10 × 20	GC105 (wt.%)	GC178 (wt.%)
SiO_2	71.75	71.37	55.23	57.32
Al_2O_3	14.59	13.99	18.13	16.93
BaO	0.02	0.02	0.01	1.73
CaO	1.86	2.08	15.18	14.86
Fe_2O_3	1.14	1.45	0.51	0.61
K_2O	1.45	1.87	1.62	1.72
MgO	1.37	0.87	4.76	2.04
Na_2O	2.99	4.18	2.32	1.35
P_2O_5	0.07	0.02	0.24	0.21
SO_3	0.05	0.05	0.06	0.11
TiO_2	0.24	0.18	0.13	0.13
ZnO	0.01	0.01	1.44	2.75
LOI	4.45	3.95	0.29	0.21

3.3. Granule Characteristics and Industrial Scale-Up

Particle-size assessment of the GC178 granules showed that a considerable fraction passed through the 120-mesh sieve, indicating a relatively high proportion of fine particles. A high fines content can alter powder flowability and die filling and may produce nonuniform density across a pressed body. These effects can become more pronounced during scale-up, where variations in moisture and granule distribution can affect pressing consistency and the formation of defects during firing. The observations therefore emphasize the need to control granule-size distribution, moisture content, and conditioning time before pressing. Following laboratory optimization, a 100 kg batch was prepared for industrial granulation, making powder handling and consistency important process-control parameters.

The industrial trials also demonstrated the importance of the cooling profile. Cracking was observed in some trials associated with rapid cooling, whereas slower cooling in the laboratory furnace helped maintain specimen integrity. This behavior is consistent with the development of thermal gradients and residual stresses, which can become more significant as product dimensions and cooling rates increase. Peak temperature, cycle duration, and cooling conditions should therefore be optimized together rather than treated as independent parameters. Additional controlled industrial trials are needed to define a robust thermal window for each product geometry. The photo of GC178 and Reference 10 × 20 tile are presented in Fig 2.

DOI: 10.30473/ijac.2026.80004.1361



a) b)

Fig. 2. The Photo of a) unpolished GC178 and b) Reference 10 × 20 tile

3.4. Water Absorption and Mechanical Properties

Water absorption was determined in accordance with Iranian National Standard INSO 9169-3, corresponding to ISO 10545-3, using the vacuum impregnation method. Five specimens were tested for each product. The specimens were initially dried to constant mass and weighed to determine their dry mass (m_1). They were subsequently impregnated with distilled or deionized water under vacuum conditions. After saturation, excess surface water was removed using a damp cloth, and the saturated mass (m_2) was measured.

Water absorption (E_v) was calculated using the following equation:

$$E_v = \left(\frac{m_2 - m_1}{m_1} \times 100\right)$$

where m_1 and m_2 represent the dry and saturated masses of the specimen, respectively. The measurements were performed using a balance with a readability of 0.01 g. This instrumental resolution was considered when interpreting the very low water absorption values.

E_v was 5×10^{-3} % for GC105 and 3×10^{-4} % for GC178, substantially below the values reported for the conventional reference bodies (approximately 9.73% for the 30 × 30 cm body and 10.78% for the 10 × 20 cm body). The very low measured absorption is consistent with highly densified products under the applied test conditions. The difference between GC105 and GC178 should be interpreted in the context of their distinct compositions, geometries, and firing schedules.

The breaking load and modulus of rupture were determined according to Iranian National Standard INSO 9619-4, corresponding to ISO 10545-4. The test was performed using a three-point bending configuration. The breaking force (F) was recorded for each specimen, and the breaking strength (S) and modulus of rupture (R) were calculated according to the following equations:

$$S = \frac{Fl_2}{B}$$

$$R = \frac{Fl_2}{B}$$

where F is the breaking force (N), l is the distance between the supporting rods (mm), B is the specimen width (mm), and h is the minimum thickness at the fracture section (mm).

The breaking load was expressed in newtons (N), whereas the modulus of rupture was expressed in N/mm². The number of specimens tested was recorded, and the results were evaluated using the individual measurements obtained for each specimen.

The mechanical results also showed higher measured performance for the developed products than for their corresponding reference tiles. GC105 exhibited a breaking load of 1820 N and a modulus of rupture of 54 N/mm², compared with 1106 N and 27 N/mm² for the 30 × 30 cm reference. GC178 reached 2430 N and 120 N/mm², whereas the 10 × 20 cm reference showed 816 N and 21.7 N/mm². The particularly high modulus of rupture measured for GC178 is notable given its reported thickness of approximately 5 mm. These comparisons indicate that the developed formulations achieved a combination of very low water absorption and improved measured mechanical strength. The results are summarized in Table 3.

Table 3. Average breaking load and average modulus of rupture of reference tiles and glass-ceramic samples.

Sample	Average breaking load (N)	Average Modulus of rupture (N/mm²)
Reference tile, 30 × 30 cm	1106	27
GC105	1820	54
Reference tile, 10 × 20 cm	816	21.7
GC178	2430	120

DOI: 10.30473/ijac.2026.80004.1361

3.5. Effect of Binder Modification on Raw-Body Strength

Binder evaluation was conducted to assess the effect of binder modification on the mechanical integrity of the pressed raw bodies. The specimen prepared without binder exhibited a breaking load of 36.6 N and a flexural strength of 16.5 N/mm². Use of the powder binder increased these values to 77.3 N and 23.4 N/mm². The citric-acid-modified binder produced the highest measured values, with a breaking load of 86.6 N and a flexural strength of 39.9 N/mm². By comparison, the combined citric- and boric-acid modification resulted in lower values of 61.6 N and 28.6 N/mm². These results indicate that binder selection can substantially affect raw-body strength and that combining modifiers does not necessarily provide an additional benefit. Improved raw strength may support handling and transfer before firing, although the selected binder should also be assessed for its influence on drying, burnout, and final product quality. The measured values are presented in Table 4.

Table 4. Raw-body mechanical properties for the evaluated binder conditions.

Binder type	Breaking load (N)	Flexural strength (N/mm²)
No binder	36.6	16.5
Powder binder	77.3	23.4
Citric-acid-modified binder	86.6	39.9
Citric- and boric-acid-modified binder	61.6	28.6

3.6. Chemical Resistance

Chemical resistance was evaluated according to Iranian National Standard INSO 9169-13. Both GC105 and GC178 were classified as Class A, whereas the reference tile was classified as Class B. Under the specified test conditions, this classification indicates improved chemical resistance for the developed glass-ceramic surfaces. The result is relevant to decorative products that may be exposed to household or maintenance chemicals during service.

3.7. Stain Resistance

Stain resistance was assessed according to Iranian National Standard INSO 9169-14. GC105, GC178, and the reference samples all achieved Class 5, the highest class in the applied classification, indicating that the specified stains could be removed using the mildest cleaning method included in the test. Thus, the glass-ceramic products maintained stain-removal performance comparable to the reference tiles while also exhibiting substantially lower water absorption and higher measured mechanical strength.

3.8. Polishability and Optical Appearance of GC178

The surface of GC178 was polished in two stages using abrasive grits ranging from 180 to 5000. The polishing-line speed was approximately 8 m/min, and the applied pressure was reported as 2–4 kPa. Surface gloss was measured at a 60° measurement geometry. Before nano-treatment, the measured gloss was 50–65; following nano-treatment, it increased to 95–100. This increase indicates a marked improvement in surface gloss under the applied finishing conditions.

Visual examination showed that polished GC178 retained a light-transmitting appearance while developing a marble-like finish. The combination of a stone-inspired visual effect, high gloss, and light transmission suggests potential for decorative architectural panels and other high-value interior applications.

4. Conclusion

This study successfully demonstrated the development of two high-performance decorative glass-ceramic products, GC105 and GC178, through the incorporation of specifically formulated frits into the body composition. Following more than 200 laboratory trials, optimized formulations were identified to achieve a combination of exceptionally low water absorption, high mechanical strength, excellent chemical and stain resistance, and superior surface aesthetics. The results highlight the potential of frit-assisted body formulation as an effective approach to producing highly densified glass-ceramics with properties suitable for demanding architectural and decorative applications.

The incorporation of frit into the body formulation provided a promising route to promoting densification, reducing residual porosity, and improving the mechanical performance of the resulting products. Among the evaluated frits, LF3 exhibited a higher melting temperature and a broader firing window than the other candidates. Wollastonite ($CaSiO_3$), considered at 2–5 wt.% in the candidate formulations alongside 1–3 wt.% free alumina, served as a source of CaO and SiO_2 for adjusting the oxide balance and tailoring the thermal characteristics of the frit compositions. These findings emphasize the importance of optimizing the overall frit chemistry to achieve favorable processing behavior and the desired properties in the final glass-ceramic body.

The developed products exhibited outstanding physical and mechanical performance. Water absorption values of 0.005% for GC105 and 0.0003% for GC178 confirmed their highly densified structures. Their breaking loads reached 1820 and 2430 N, while their moduli of rupture

DOI: 10.30473/ijac.2026.80004.1361

were 54 and 120 N/mm², respectively. Both formulations achieved Class A chemical resistance and Class 5 stain resistance, demonstrating their potential for applications requiring high resistance to moisture penetration, staining, and chemical exposure. These properties are particularly advantageous for premium wall and floor coverings, decorative architectural panels, interior cladding, and other high-quality surfaces where durability and ease of maintenance are essential. Applications in exterior environments may also be feasible, provided that additional requirements, including frost resistance, thermal cycling, and weathering durability, are verified.

Beyond their functional performance, the developed glass-ceramics exhibited promising optical and decorative characteristics. Following polishing and nano-treatment, GC178 achieved a 60° gloss value of 95–100 while retaining its marble-like appearance and light-transmitting characteristics. This combination of high gloss, stone-inspired aesthetics, and excellent functional properties offers opportunities for developing premium decorative surfaces and architectural elements that combine the visual appeal of natural stone with the performance advantages of engineered glass-ceramic materials.

Finally, the scale-up trials established a practical basis for transferring the developed formulations from laboratory research to industrial ceramic processing. Granule-size distribution, binder selection, firing conditions, and cooling-profile control were identified as important parameters for ensuring processing stability, product uniformity, and reproducible quality. Overall, this work demonstrates the feasibility of developing advanced decorative glass-ceramics through frit-assisted body formulation and establishes a promising pathway toward industrial production of materials combining near-zero water absorption, high mechanical strength, chemical durability, and refined surface aesthetics. Further industrial validation and long-term durability testing will help establish their suitability for broader architectural and decorative applications.

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DOI: 10.30473/ijac.2026.80004.1361

توسعه و تعیین مشخصات شیشه-سرامیک‌های تزئینی با عملکرد بالا: طراحی فریت، فرآوری و نقش ولاستونیت

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تاریخ دریافت: ۰۲ آبان ۱۴۰۴ **تاریخ پذیرش:** ۲۰ آبان ۱۴۰۴

چکیده

هدف از این پژوهش، توسعه سرامیک شیشه‌ای تزئینی با عملکرد بالا از طریق افزودن فریت‌هایی با فرمولاسیون ویژه به ترکیب بدنه بود؛ به‌گونه‌ای که ویژگی‌هایی نظیر جذب آب بسیار ناچیز، استحکام مکانیکی ارتقا یافته، دوام شیمیایی عالی و زیبایی ظاهری ممتاز حاصل شود. پس از انجام بیش از ۲۰۰ آزمایش آزمایشگاهی، دو فرمولاسیون توسعه یافت. در این میان، توجه ویژه‌ای به نقش ولاستونیت – ($CaSiO_3$) با سهم ۲ تا ۵ درصد وزنی در فرمولاسیون‌های پیشنهادی، در کنار ۱ تا ۳ درصد وزنی آلومینای آزاد – معطوف شد. این ترکیبات به‌عنوان منبعی برای تأمین CaO و SiO_2 عمل کرده و امکان تنظیم تعادل اکسیدی و تعدیل ویژگی‌های حرارتی فریت‌ها را فراهم کردند. دو محصول بهینه‌شده، میزان جذب آبی بین ۰.۰۰۵٪ تا ۰.۰۰۰۳٪ نشان دادند. بار شکست این نمونه‌ها به ترتیب ۱۸۲۰ و ۲۴۳۰ نیوتن بود که متناظر با مدول گسیختگی ۵۴ و ۱۲۰ نیوتن بر میلی‌متر مربع است. هر دو محصول در آزمون‌های مقاومت شیمیایی به رده A و در آزمون مقاومت در برابر لکه‌پذیری به رده ۵ دست یافتند. پس از انجام عملیات پرداخت (پولیش) و اعمال پوشش نانو، میزان براقیت (در زاویه ۶۰ درجه) به ۹۵ تا ۱۰۰ رسید، در حالی که ظاهر مرمرمانند و ویژگی عبور نور در آن‌ها حفظ شد. آزمایش‌های مقیاس صنعتی نشان داد که توزیع اندازه دانه‌ها، انتخاب ماده چسباننده (بایندر)، شرایط پخت و کنترل پروفیل سرمایش، پارامترهای حیاتی برای تضمین قابلیت اطمینان فرآیند و یکنواختی کیفیت محصول هستند. این یافته‌ها امکان‌پذیری توسعه سرامیک شیشه‌ای تزئینی را از طریق فرمولاسیون بدنه با کمک فریت‌ها تأیید می‌کنند و دستیابی به ترکیبی مطلوب شامل جذب آب نزدیک به صفر، استحکام مکانیکی بالا، دوام شیمیایی و زیبایی ظاهری ممتاز را محقق می‌سازند. علاوه بر این، موفقیت در آزمایش‌های مقیاس صنعتی، بستری نویدبخش برای انتقال فرمولاسیون‌های بهینه‌شده به خط تولید صنعتی و گسترش کاربرد آن‌ها در سطوح معماری و تزئینی با عملکرد بالا فراهم می‌آورد.

کلیدواژه‌ها

سرامیک شیشه ای، فریت، جذب آب، خواص مکانیکی، ولاستونیت.

DOI: 10.30473/ijac.2026.80004.1361