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Use of waste green soda bottle-glass as an additive in the artistic ceramics production

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Abstract: This study investigates the potential use of post-consumer green soda bottle glass (GSBG) waste as a sustainable additive in artistic ceramic bodies. Composite specimens were prepared by incorporating ground GSBG into white ceramic clay at weight percentages of 20%, 30%, 40%, and 50%. The specimens were shaped using mold pressing and hand shaping techniques and sintered under various conditions to compare full vitrification with sintering. XRF analysis confirmed the potential of GSBG waste as a plasticizer due to its high Na2O content (~10.78 wt%) and CaO content (~9.26 wt%). When the GSBG was fully melted, the microstructure underwent transformation. The optimal formulation was obtained from the GSBG waste with the smallest powder size range, at 40 wt%, resulting in near-zero water absorption (~less than 1.0%) and maximum densification. XRD analysis confirmed this structural change, revealing a distinct amorphous bump not present in the pure clay body, and demonstrated successful vitrification. Conversely, lower temperatures (930 °C) and larger particles resulted in limited melting and crack formation. This approach offers an environmentally conscious recycling pathway, providing structurally stable and aesthetically pleasing green glazed surfaces suitable for artistic ceramic production.

Keywords: Sustainability; Artistic; Ceramics; Upcycling; Glass; Waste Material.

1. Introduction

Currently, sustainability and waste management are among the priority research areas in the search for solutions to environmental problems. Soda-bottle glass, one of the difficult-to-recycle inorganic wastes, poses a significant environmental threat, especially due to the substantial amount of post-consumer waste it generates. Evaluating alternative uses for glass waste not only reduces this environmental burden but also enables the production of new aesthetically pleasing and functional materials.

In ceramic art, diverse results, both aesthetic and technical, can be achieved by combining different raw materials. The literature indicates that the addition of waste or unconventional materials into ceramic bodies or glazes creates noticeable effects on both surface aesthetics and material performance. For instance, different color and texture effects have been achieved in ceramics fired in the 950°C–1100°C range, prepared by adding specific ratios of waste glass and metal powder to clay slip, which contributes to both artistic variety and sustainable material production [1]. Furthermore, studies focusing solely on glass have shown its effectiveness as a fluxing agent in red ceramic bodies. Research has found that while increasing temperature promotes densification and lowers water absorption in ceramics incorporating glass waste, excessive temperatures lead to undesirable porosity due to overfiring [2]. Similarly, the use of metal-containing industrial wastes, such as chromite enrichment slag and copper production slag, as coloring raw materials in glaze formulations has allowed for the creation of new colored glazes and shimmering surface effects [3]. The use of such alternative raw materials can also lead to changes in the material's physical properties, such as strength and water absorption.

Studies in the literature demonstrate that various types of waste can be incorporated into ceramic bodies. For instance, research on marble mining wastes has revealed that these wastes can be used as an effective component in matt glaze compositions, and can be utilized at high ratios in traditional artistic stoneware clay bodies [4] and transparent glaze recipes [5]. Likewise, it has been determined that slate wastes can be used as raw materials in ceramic clay and glaze compositions [6]. Replacing quartz with natural minerals (e.g., py-

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rophyllite) in ceramic clay has offered advantages such as low-temperature sintering, increased thermal shock resistance, and enhanced strength [7]. All these studies support the potential use of waste materials in ceramic art. The evaluation of wastes like marble and slate as raw materials and the use of glass powders for new aesthetic and artistic pursuits reinforce the importance of sustainability in this field. Indeed, some ceramic artists (e.g., David Binns) who achieve innovative surface textures by incorporating substances like glass, granite, and grog into clay bodies have addressed the resulting aesthetic and technical changes in these additive bodies [8,9]. Glass materials can remain intact in nature for at least 4000 years. Many discarded soda bottles can also be found in nature. In Türkiye, glass recycling is approximately 40%. This study also aims to contribute to the recycling of glass. It is believed that this study will also contribute to the circular economy.

In this study, the integration of waste glass as an additive material into the structure of ceramic bodies not only creates aesthetic surface effects but also contributes to sustainable material design. This study investigates the potential use of post-consumer green soda-bottle glass as an additive material in artistic ceramic production, by incorporating it into white ceramic clay at varying ratios (20 wt.%, 30 wt.%, 40 wt.%, 50 wt.%) and in three different particle sizes. The samples were shaped using mold pressing and hand-forming techniques and subsequently subjected to sintering at two temperatures: 930 °C and 1150 °C. These two temperature levels enabled a comparative evaluation between traditional sintering and vitrification temperatures where the glass fully integrates into the ceramic matrix. The fundamental hypothesis of the research is that the addition of glass at specific ratios and particle sizes, when combined with an appropriate shaping method and sintering temperature, can yield results that are structurally stable and aesthetically satisfying. Accordingly, this study aims to present a sustainable approach focused on upcycling in artistic ceramics production and to contribute to the creative reuse of waste green soda-bottle glass. This study will significantly contribute to the circular economy by incorporating green soda bottle waste into white ceramic clay and making this clay available to ceramic artists and fine arts faculty students.

2. Materials and Methods

The white ceramic clay utilized in this study is a commercially available ceramic body and was used without any additional components. The chemical composition of the waste green soda-bottles was determined using X-ray Fluorescence Spectrometry (XRF) analysis to identify the primary fluxing agents and main structural components [10]. The glass additive chosen was post-consumer waste green soda-bottles (Figure 1).



Figure 1. Waste green soda- bottle.

The collected green soda-bottle glass was initially washed, separated from its labels, dried and subsequently ground in a ball mill with 60 rpm rotation speed for 2 hours. Alumina balls were used in this milling process (Figure 2).



Figure 2. The grinding process of the waste glass samples using a ball mill.

The waste glass obtained after the grinding process was separated into three distinct fractions based on particle size. These fractions were classified as Large Particles (LP) (>2 μm), Medium Particles (MP) (2-16 μm) and Small Particles (SP) (<1 μm), respectively (Figure 3).

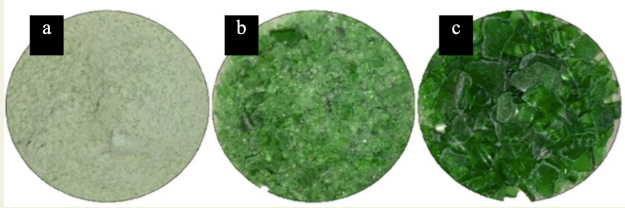


Figure 3. SP, MP and LP particle sizes, respectively.

In the experimental study, composite samples totaling 100 grams were prepared by incorporating waste glass into white ceramic clay at weight ratios of 20%, 30%,

40% and 50% (Table 1). The green soda-bottle glass and the white ceramic clay were mixed using a hand-kneading method until a homogeneous mixture was obtained. The test specimens were shaped using a mold-pressing technique with single-piece plaster molds, each measuring 3 cm im height and 5 x 5 cm in base dimension. The prepared samples were allowed to dry in a controlled manner at room temperature. The specimens were fired at two different sintering temperatures: 930 °C and 1150 °C for 15 minutes. As shown in Figure 4 (a), an electric kiln was used for both sintering cycles.

Table 1. Composition Table

White ceramic clay (WCC) (wt%)	Green soda-bottle glass (GSBG) Composition Codes		
	SP	MP	LM
80	SP20	MP20	LM20
70	SP30	MP30	LM30
60	SP40	MP40	LM40
50	SP50	MP50	LM50

The kiln diagrams illustrating the temperature-time profiles for the sample sintering are provided in Figure 4 (b), allowing for a comparative analysis of the processes.

The samples obtained after sintering were evaluated based on surface observation, form stability, crack formation and aesthetic effects. A comparative analysis of physical properties was conducted with a primary focus on water absorption rate, sintering shrinkage and color change observations.

The water absorption test was performed in accordance with ASTM C373-88. First, the dry weights (W_d) of the specimens were weighed. The samples were then kept in boiling water at 100 °C for 4 hours and subsequently soaked in the same water for an additional 24 hours. Their wet weights (W_w) were measured afterward. The water absorption percentage was calculated using the formula below (Eq. 1).

$$\text{Water Absorption}(\%) = \frac{W_w - W_d}{W_d} \times 100 \quad (1)$$

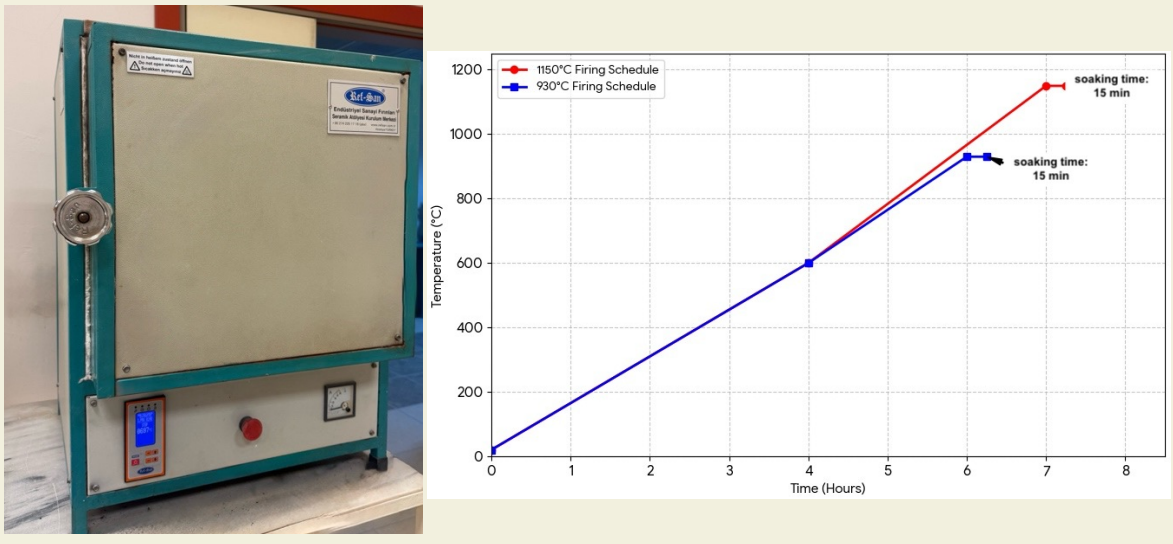
Furthermore, the microstructural and visual effects of the glass addition within the ceramic matrix were investigated through Scanning Electron Microscopy (SEM) imaging, X-ray Diffraction (XRD) and color analysis *(L*a*b*)* performed on the samples. Technical specifications and analysis conditions for the equipment used in the SEM, XRD and color analysis are presented in detail in the corresponding findings section.

As a result of these experimental analyses, the most successful glass-clay combination in terms of aesthetic appearance and structural integrity was determined, and an artistic ceramic artwork was produced using ceramic with 40 wt.% SP green soda-bottle glass content.

3. Results and Discussions

3.1. Chemical Analysis of Green Soda-Bottle Glass

Glass is an amorphous material typically produced through controlled heating and cooling processes of a silica (SiO_2) based main structure former, network modifiers and fluxing oxides (e.g., Na_2O, CaO) [10]. In



(a) (b)

Figure 4. (a) The ceramic kiln used in this study (b) Sintering diagram for the samples sintering at 930 C and 1150 C

the field of ceramics, the addition of waste glass to the composition widely investigated, particularly to promote vitrification and lower the sintering temperature. This approach not only contributes to environmental sustainability but also imparts new aesthetic qualities to artistic ceramic surfaces.

The waste green soda-bottle glass used in this study is a typical soda-lime-silica glass, primarily containing a high proportion of silica (SiO_2), significant amounts of sodium oxide (Na_2O), calcium oxide (CaO) and iron oxide (Fe_2O_3) and chrome oxide (Cr_2O_3) as a colorant. Specifically, the sodium oxide content enables the material to act as a flux, there by lowering the melting point and facilitating the formation of a liquid phase within the ceramic body [11]. The green color of the glass is typically due to trace amounts of iron oxide (Fe_2O_3) and chromium oxide (Cr_2O_3) content [12].

The chemical analysis (XRF) of the waste green soda-bottle glass revealed its oxide-based composition (Table 1). The glass was determined to have the main components of 73.96 wt.% SiO_2 and 10.78 wt.% Na_2O by weight. The high Na_2O (10.78 wt.%) and CaO (9.26 wt.%) content confirms the material's potential to increase vitrification within the ceramic body by lowering the sintering temperature.

Table 1. XRF Analysis of waste green soda-bottle glass and white ceramic clay.

Component (Oxide)	Green soda-bottle glass (GSBG) (wt.%)	White ceramic clay (WCC) (wt.%)
SiO2 (Silica)	73.96	71.9
Na2O (Sodium Oxide)	10.78	1.93
CaO (Calcium Oxide)	9.26	0.25
MgO (Magnesium Oxide)	2.83	0.40
Al2O3 (Aluminum Oxide)	2.24	21.2
Fe2O3 (Iron Oxide)	0.29	0.53
Cr2O3 (Chromium Oxide)	0.23	-
K2O (Potassium Oxide)	0.16	2.40
I (Iodine)	0.07	-
TiO2 (Titanium Oxide)	0.07	1.39
SO3 (Sulfur Oxides)	0.06	-
ClO2 (Chlorine Di Oxide)	0.05	-

3.2. Color Measurement Analysis

3.2.1. Green Soda-Bottle Glass (GSBG) Color Measurement Analysis

The color properties of the Waste green soda-bottle glass (GSBG) were determined using the $L^*a^*b^*$ system to establish a reference point for its aesthetic impact on the final ceramic product. The coordinates for the GSBG were found to be L^* = 36.61, a^* = -11.76 and b^* = 12.18.

The relatively low L^* value (36.61) indicates that the material possesses a dark tone. The negative a^* value (-11.76) definitively confirms that the glass color shifts significantly towards the green axis [13]. This dominant green coloration is attributed to transition metal oxides such as Fe_2^+ or Cr_3^+, which are typically used in commercial glass production. The positive b^* value (12.18), in turn, signals the presence of a slight yellowish undertone accompanying the green hue [14]. These initial data define the strong color potential and chromatic character that the GSBG will impart to the ceramic body.

3.2.2. Color Measurement Analysis of Ceramic Sample with 40 wt.% SP GSBG Additive (S40)

The post-firing surface color analysis of the optimum formulation, the ceramic sample with 40 wt.% GSBG addition (S40), yielded the following $L^*a^*b^*$ coordinates: L^* = 72.15, a^* = - 8.84 and b^* = 10.00.

The significantly high L^* value (72.15) of the sample indicates that the surface is much brighter compared to the raw glass. This brightness is a dominant effect resulting from the light-colored nature of the clay components within the ceramic matrix, despite the densification. The negative a^* value (-8.84) confirms that the green character of the GSBG was successfully transferred to the ceramic body. The b^* value (10.00) indicates the persistence of the yellowish undertone; however, this position in the green-yellow region confirms that the ceramic has a homogeneous and aesthetically attractive appearance.

3.3. Sintering Behavior and Structural Changes

In a general assessment, increasing the sintering temperature stands out as the main factor significantly reducing water absorption values across all samples, due to the more effective melting of the glass phase and its ability to fill porosity. Especially in small particle size samples sintered at 1150°C, the water absorption values approaching almost zero (below ≈1.0%) when the clay/glass ratio is 40/60 and 50/50, indicates that a high degree of vitrification and maximum densification occurred under these conditions. On the other hand, although medium and large particle sizes also benefited from the temperature increase, the lowest water absorption values at 1150°C (≈7%) remained significantly higher than the level reached by the SP, confirming that densification is more challenging for larger particles due to their lower surface-area-to-volume ratio. At the lower sintering temperature of 930°C, although water absorption values gradually decrease as the glass content increases, this reduction was limited in groups other than the SP; furthermore, a slight increase was observed after the 40/60 ratio in the large particle size, suggesting that excessive glass content at low tempera-

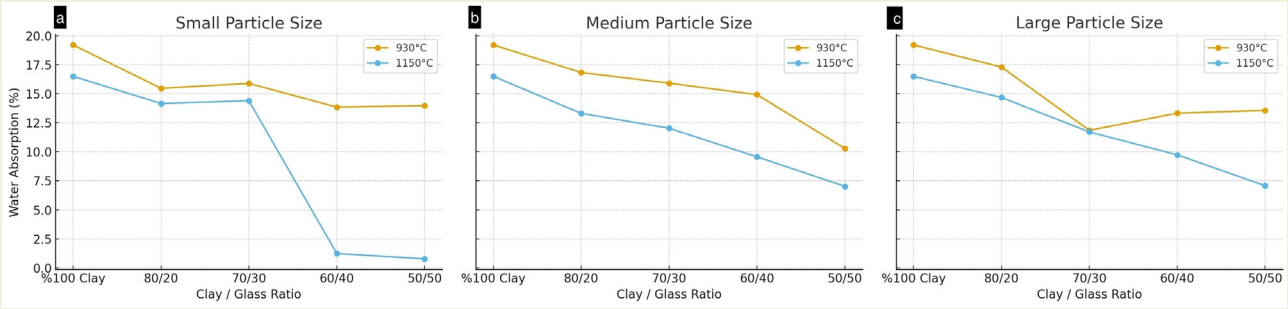


Figure 5. Comparison graphs of the water absorption values of samples containing (a) SP, (b) MP, and (c) LP glass at different white clay/glass ratios and different sintering temperatures.

tures might lead to undesirable pore coarsening. Consequently, the combination of high temperature (1150°C) and high glass ratio, particularly when used with SP, provides the most optimum condition for achieving non-porous and most dense structures (Figure 5).

3.3.1 The Surface Features of the Samples Sintered at 930 °C

In the samples fired at 930°C for 15 minutes, it was observed that the glass particles did not melt significantly and remained stable within the ceramic matrix (Figure 6 (i), (j), (k), (l)).

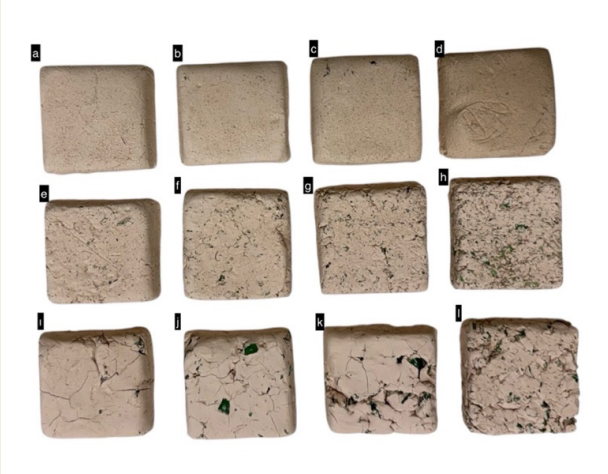


Figure 6. Produced samples sintering at 930 C, (a) SP 20 GSBG / 80 wt.% WCC, (b) SP 30 GSBG/ 50 wt.% WCC (c) SP 40 GSBG / 60 wt.% WCC, (d) SP 50 GSBG / 50 wt.% WCC (e) MP 20 GSBG / 80 wt.% WCC, (f) MP 30 GSBG / 70 wt.% WCC, (g) MP 40 GSBG / 60 wt.% WCC, (h) MP 50 GSBG / 50 wt.% WCC, (i) LP 20 GSBG / 80 wt.% WCC, (j) LP 30 GSBG / 70 wt.% WCC, (k) LP 20 GSBG / 80 wt.% WCC, (l) LP 50 GSBG / 50 wt.% WCC.

In samples with particularly high glass ratios (40 wt.% and 50 wt.%) and LP (Figure 6 (k), (l)), it was determined that the glass particles caused crack formation by leading to stresses on the surface. The water absorption value remained high in these samples.

MP (1,715 µm) created a visually attractive effect by forming green speckles on the surface after sintering.

In samples with the small particle sizes (1,010 µm), only color change occurred at 40 wt.% and 50% glass ratios (d); no distinct melting or cracking was observed (Figure 6 (a), (b), (c), (d)).

3.3.2. The Surface Features of the Samples Sintered at 1150 °C

At 1150°C, it was determined that the glass particles completely melted and interacted with the ceramic body.

The sample a show that 40 wt.% glass / 60 wt.% white clay mixture with the smallest particle size yields the most stable and aesthetically pleasing results in physical tests. A glaze-like smooth green layer formed on the surface of this sample, indicating high strength and low porosity (Figure 7, b).

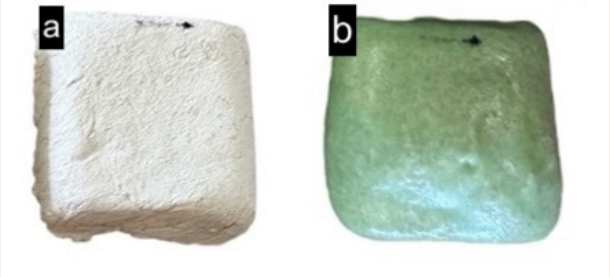


Figure 7. The state of the ceramic sample with the smallest particle size addition (a) before and (b) after sintering at 1150 C.

The water absorption value showed a significant decrease due to strong vitrification and the formation of the glassy surface. Sample B (SP 50 /50 wt.% WCC) exhibited excessive melting of the glass phase. This caused the body to collapse and spread on the surface, making it unsuitable for shaping (Figure 7).

It was noted that some larger particles vaporized at this temperature, which led to surface irregularities (Figure 8).

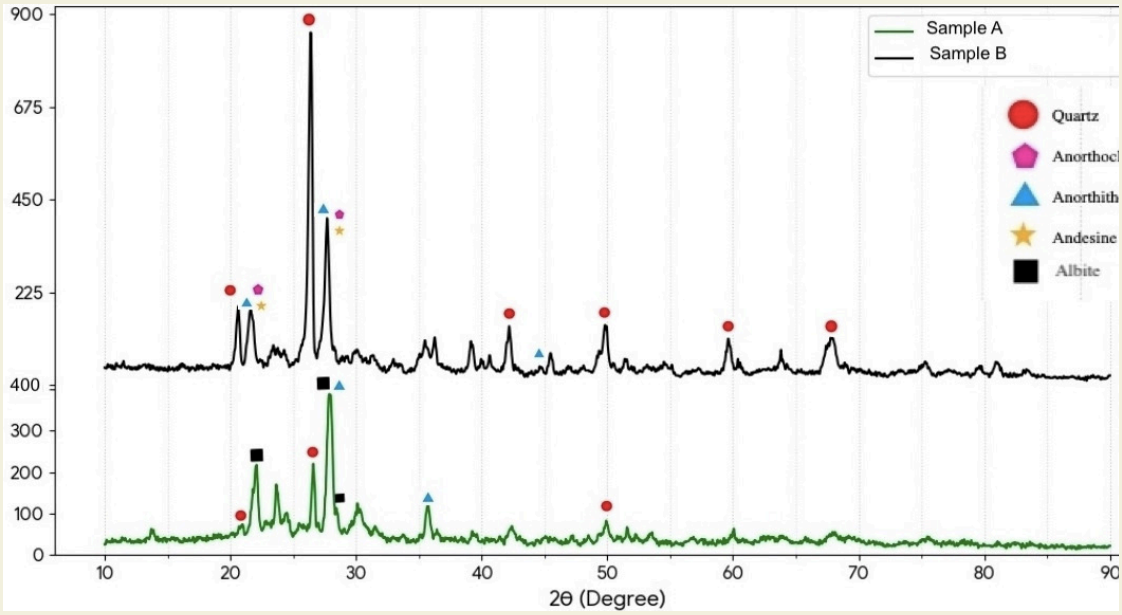


Figure 9. XRD Analysis of Sample A and B sintered at 1150°C

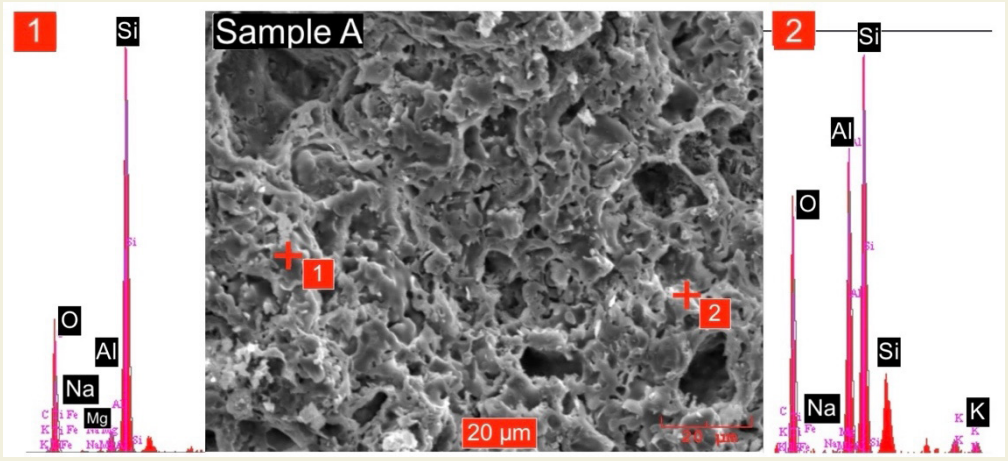


Figure 10. The SEM-EDS images of the WCC (Sample A).

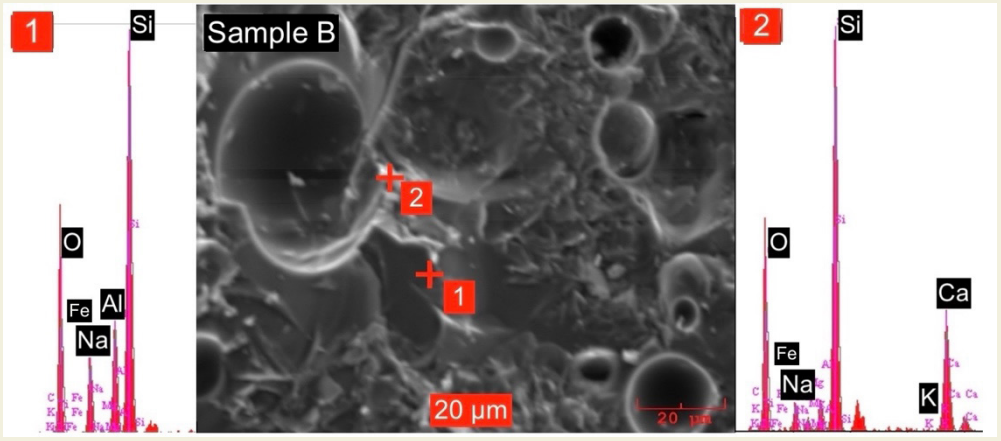


Figure 11. SEM-EDS images of the SP 40 added WCC sample (Sample B).

3.4. Microstructural Analysis

3.4.1 XRD Analysis

Comparative XRD pattern of Sample A displays a significant decrease in intensity for all crystalline peaks when compared to Sample B. This clearly demonstrates that the 40 wt.% amorphous glass phase added to the system has diluted the crystalline matrix, resulting in a reduction of the overall crystallinity. While the peak intensities of the dominant quartz (SiO_2) and anorthoclase ($(Na,K)AlSi_3O_8$) / andesine ($(Na,Ca)(Si,Al)_4O_8$) phases observed in Sample B have decreased, the strongest reflections in this sample now correspond to the albite ($NaAlSi_3O_8$) and anorthite ($CaAl_2Si_2O_8$) phases.

The XRD pattern of Sample B exhibits relatively high intensity and sharp peaks compared to the other sample. The most intense peak is associated with Quartz (SiO_2) (≈27°), the main component of the ceramic clay. Additionally, reflections corresponding to the primary crystalline phases, Anorthoclase ($(NaK)AlSi_3O_8$) and Andesine ($(AlSi)_4O_8$) are observed. These phases are the typical main crystalline components of feldspathic ceramic materials fired at high temperatures without glass addition. This sample represents the highly crystalline reference ceramic matrix for comparison with the effects of glass incorporation.

The emergence of sodium-rich (Albite) and calcium-rich (Anorthite) feldspar types in Sample A, replacing the dominant feldspar types (Anorthoclase and Andesine) observed in Sample B, suggests that the glass addition formed a liquid phase during sintering. This liquid reacted with the ceramic matrix, altering the chemical composition of the feldspar phases or promoting the formation of different secondary crystallization products. These findings confirm that the glass additive not only dilutes the crystalline phase but also influences the phase transformation mechanisms.

3.4.2 SEM-EDS Analysis

The comprehensive SEM/EDS analysis of Samples A and B quantitatively and morphologically proves the transformative effect of glass addition on the ceramic microstructure and chemical reactivity. The high porosity, rough, and heterogeneous morphology dominating the SEM image of Sample A indicates a solid-state sintering regime where sufficient liquid phase formation was not achieved. EDS points in Sample A confirm the presence of aluminum-rich regions (~20.7 wt.%) alongside unreacted silicon-rich residues (~58.3 wt.%), verifying that the raw materials did not fully homogenize even at high temperatures. In contrast, the SEM image of Sample B displays a distinctly denser and smoother matrix with lower porosity, courtesy of the abundant liquid phase sintering provided by the glass additive. This morphological change suggests a significant improvement in the ceramic's ultimate mechanical strength and resistance to water absorption. EDS analyses clarify a dramatic increase in the concentration of alkali and alkaline earth elements such as sodium (Na) and calcium (Ca) in Sample B (Na content reaches ~8.5 wt.% at 1); these elements act as powerful fluxing agents, lowering the sintering temperature and accelerating densification. Microstructural phase separation is most strikingly observed in the point 2 analysis of Sample B, where the Calcium content (~17.2 wt.%) becomes dominant. This -rich region represents the local accumulation of new crystalline Ca-silicate phases that precipitated from the glass melt upon cooling, observed as needle-like or rod-like structures in the microstructure. This finding demonstrates that the glass additive is a critical optimization factor that fundamentally alters the ceramic's microstructural phase composition by promoting the formation of desired new mineralogical phases, rather than merely driving physical densification. (Figure 10,11).

3.5. Artistic Application

The suitability of the white clay-glass mixtures for different shaping techniques was tested, revealing varying degrees of applicability depending on the particle size and glass content:

Mixtures containing medium and large particle sizes were determined to be unsuitable for wheel-throwing and hand-building methods, as the rough glass particles could potentially cause injury to the hands during the shaping process (Figure 12). For hand-shaping high-glass ratio samples with the smallest particle size, thicker and more massive forms were recommended to prevent structural collapse from excessive melting (Figure13).



Figure 12. Hand-formed ceramic sample sintering at 1150 C, with 50 wt.% glass content.



Figure 13. Hand-formed massive sample with 50 wt.% glass content.

The final work (Figure 14) was produced using the op-

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timized composition, which featured 60 wt.% white clay and 40 wt.% recycled green soda-bottle glass (the smallest particle size), as this blend demonstrated the best overall performance in both physical and chemical tests. The sample was shaped using the press molding technique. The sintered body, fired at 1150°C, successfully acquired the natural green hue of the green soda-bottle glass. The final product exhibited smooth surfaces with minimal porosity. This result validated the successful enhanced vitrification and structural integrity achieved through the optimized composition. Aesthetically, the final product was described as providing a smooth, soap-like green surface with excellent

durability, confirming the material's high suitability for artistic and functional ceramic applications.



Figure 14. The final work.

4. Conclusions

This study conclusively established the potential of waste green soda-bottle glass (GSBG) as a highly effective and environmentally sustainable fluxing agent within white ceramic matrices.

The incorporation of the glass fundamentally transformed the firing response of the ceramic body. While the control sample maintained its crystalline and porous structure, GSBG-containing formulations exhibited significant vitrification. Chemical analyses confirmed that the GSBG, owing to its high alkali Na_2O and CaO content, functioned as a powerful flux, promoting liquid phase formation and consequently lowering the sintering temperature.

Microstructural investigations demonstrated that liquid phase sintering resulted in a denser and smoother matrix, led to maximum structural densification and negligible water absorption values. This success was critically achieved through the optimal combination of the small particle size and 40 wt.% GSBG ratio. Furthermore, EDS and XRD findings proved that the glass addition not only drove physical densification but also fundamentally altered the ceramic matrix's mineralogical composition by promoting the formation of new crystalline Ca-silicate phases in Ca-rich regions.

Aesthetically, the optimized formulation successfully transferred the natural green hue of the GSBG to the ceramic surface, resulting in a smooth, lustrous, and aesthetically appealing finish.

These results demonstrate that waste green soda-bottle glass is a valuable, environmentally sustainable raw material that enables the production of high-performance and aesthetically valuable products in ceramics manufacturing. This work thus makes a significant contribution to the creative and sustainable approach of upcycling in artistic ceramics production.

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Research ethics

Ethical approval not required.

Artificial Intelligence Use

I hereby declare that Artificial Intelligence tools (ChatGPT and Gemini) were used in this study exclusively for the verification of references.

Author contributions

Conceptualization: [Berfin Arıkan, Nermin Demirkol], Methodology: [Berfin Arıkan, Nermin Demirkol], Formal Analysis: [Berfin Arıkan, Nermin Demirkol], Investigation: [Berfin Arıkan], Resources: [Berfin Arıkan, Nermin Demirkol], Data Curation: [Berfin Arıkan], Writing - Original Draft Preparation: [Berfin Arıkan, Nermin Demirkol], Writing - Review & Editing: [Berfin Arıkan, Nermin Demirkol], Visualization: [Berfin Arıkan, Nermin Demirkol], Supervision: [Nermin Demirkol], Project Administration: [Nermin Demirkol], Funding Acquisition: [Berfin Arıkan, Nermin Demirkol]

Competing interests

The author(s) declare that there are no conflicts of interest.

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Data availability

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