The Influence of Processed Steel Slag Additive on Brick-Making Clay

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As clay deposits become scarce, the brick industry is increasingly seeking additives or substitutes. This study investigates a high-plasticity clay that requires an opening agent, for which was used 10 wt.% of processed steel slag Ekominit S1. Ceramic-technological tests were performed to determine the compressive strength, density and porosity. The addition of Ekominit S1 increased the total porosity by 5% in samples fired at 950 °C, and by 4% in samples fired at 1050 °C, while the compressive strength decreased by 36% in the samples fired at 950 °C and by 38% in those fired at 1050 °C compared to the reference material. Although the mechanical properties were lower than those of the reference, the benefit is reduced shrinkage. The processed steel slag could be incorporated successfully into bricks, which would also reduce the environmental impact of this sector by using secondary products instead of virgin materials.

Keywords:
clay bricks,
compressive strength,
opening agent,
porosity,
steel slag

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1 Introduction

As clay deposits vary in scarcity, this sector is searching constantly for potential additives or alternatives to clay. Some additives simply replace virgin clay and conserve resources, while others may have a positive effect on the process or product. When evaluating various wastes for their usability in the clay-based sector, the following parameters are important: chemical and mineralogical compositions, and the particle size of the additives.

In terms of mineralogical composition, the amount of quartz is particularly important, as it affects both the product properties and the drying process by reducing sensitivity. It also influences firing, where the phase transformation of quartz at 573 °C should be considered during the cooling phase, as it is associated with volumetric changes and can lead to cracking of the products if the cooling process is not managed properly. The carbonate content, if dispersed finely, can be as high as 20–25%; only lime inclusions larger than 1 mm can pose a problem (Ducman & Kopar, 2007, Baksa et al., 2018).

Various wastes have already been introduced successfully into the clay-based sector, including wastewater treatment sludges (Detho et al., 2024), paper sludge (Mohd Tajri and Hashim, 2025), ashes (Muñoz et al., 2023) and sediments. For the same type of clay investigated in the present paper, Božič et al.`s (2023) studied untreated Drava River sediment as a clay substitute for fired bricks, and showed that, despite reduced compressive strength, the pilot-scale bricks met all the regulatory requirements. Marine sediments are another potential material, but their chloride content can affect the brick properties negatively. Baksa et al. (2018) evaluated marine sediments from the Port of Koper, again with the same type of clay, and found them only conditionally suitable as a raw material, as they show excessive drying and firing shrinkage and high water absorption. These drawbacks can be mitigated by incorporating suitable additives, such as virgin clay or compatible waste materials. Various slags have also been investigated; Shih et al. (2004) found that slag addition reduced the required firing temperature. When the firing temperature exceeded 1050 °C and the slag content was below 10%, the bricks met the ROC National Standard CNS 3319 for third-class building bricks. As the slag content increased, quartz and kaolin decreased in the sintered samples, while magnesium aluminium silicate and calcium silicate increased. No new crystal phases were observed. In another study, Freitas et al. (2021) reported high substitution rates (up to 50%) of clay with iron ore concentrate tailings (IOT) and basic oxygen furnace (BOF) steel slag. The results confirmed that a high level of clay substitution with IOT and BOF slag can be used together to produce fired clay bricks, but some adjustments are necessary. To avoid cracking, the particle size should be adjusted, and changes in the heating and cooling stages of the firing process are recommended. Depending on the type of slag, its addition to the brick-making clay can have varying degrees of beneficial influence (Gencel et al., 2021).

The aim of this study is to evaluate the potential of processed steel slag Ekominit S1 as an additive to brick-making clay, and to assess its influence on key properties such as shrinkage, water absorption and compressive strength. Furthermore, the study enhances the understanding of these effects through detailed phase and microstructural analyses (XRD, SEM, and MIP).

2 Materials and methods

2.1 Raw material

Steel slag is the main solid co-product of steel production, accounting for about 90% by mass. Electric arc furnace (EAF) slag from stainless steel production and ladle slag from secondary metallurgical processes for stainless and carbon steel were mixed, stabilised in the slag cooling yard, and processed further on the slag processing line. The resulting products are steel granulate, which is returned to the EAF, and the mineral product Ekominit S1, which was the material investigated in this study. The reference brick-making mixture was provided by the brick factory Goriške opekarne, located in western Slovenia. It consists of marl (50 wt%), clay (48 wt%), and coal powder (2 wt%) (Žibret et al., 2025).

2.2 Sample preparation

To evaluate the influence of Ekominit S1 as an additive in clay brick production, 10 wt.% Ekominit S1 was added to a clay sample, and the mixtures were fired at 950 °C and 1050 °C (Figure 1).

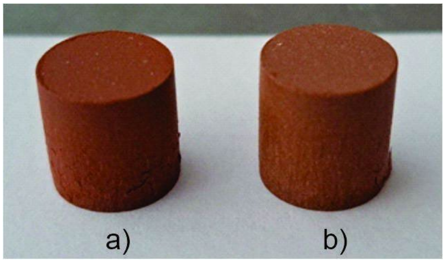

Figure 1: (a) Brick-making clay, and (b) clay with 10 wt.% Ekominit S1 after firing at 1050 °C.
Source: own.

The brick samples were ground to a particle size below 63 μm, pressed at 150 MPa with the addition of 4% moisture, and sintered in an HLF 100 laboratory furnace (Protherm) at 950 °C and 1050 °C for 2 hours, using heating and cooling rates of 150 °C/h.

2.3 Test procedures

The particle size distribution (PSD) of the raw materials (slag and clay samples) was determined by laser diffraction granulometry using a Sync+Flow-Sync laser grain size analyser (Microtrack MRB). The clay was measured with distilled water, while the slag was dispersed in isopropanol. The PSD of the raw materials is shown in Figure 2.

Before the chemical analysis the samples were dried to a constant mass in a laboratory oven at 105 °C, and ground to pass through a 125 μm sieve. The loss on ignition (LOI) of the raw materials was determined at 950 °C, according to the EN 196-2:2013 Standard. The chemical composition of the materials was determined using an ARL PERFORM'X sequential X-ray fluorescence (XRF) spectrometer (Thermo Fisher Scientific Inc., Ecublens, Switzerland) with UniQuant 5 software (Thermo Fisher Scientific Inc., Waltham, MA, USA). The analysis was performed on melted discs, prepared by melting a mixture of the ignited sample and Fluxana (Li-tetraborate and Li-metaborate mixed in a mass ratio of 1:1) at a ratio of 1:10. LiBr (aq) (50 mL H_2O and 7.5 g LiBr (s) from Sigma Aldrich) was added to the mixture to avoid gluing the melt to the Pt crucible.

The compressive strength was measured using a ToniPRAX compressive strength testing machine (ToniTechnik, Berlin, Germany) at a loading rate of 1.2 kN/s.
The shrinkage was determined by measuring the change in the pellet diameter before and after sintering. The diameter of each pressed pellet was measured with a digital calliper (±0.01 mm) before firing (d_0). After sintering at 950 °C and 1050 °C and cooling to room temperature, the final diameter (d_f) was measured using the same method. The shrinkage was calculated following the approach of Xu et al. (2025) using Equation (1):

$$\text{Shrinkage (\%)} = [(d_0 - d_f)/d_0] \times 100 \quad (1)$$

Small representative pellets with a diameter and height of 10 mm were analysed for their porosity and pore size distribution directly after sintering using the Micromeritics® Autopore IV 9500 instrument (Micromeritics, Norcross, GA, USA).

X-ray powder diffraction of the clay fired at 950 °C and 1050 °C, as well as clay containing 10 wt.% Ekominit S1 fired at the same temperatures, was conducted using a PANalytical X'Pert Pro X-ray powder diffractometer equipped with CuKα1 radiation (Johannson Ge (111) incident beam monochromator) and an X'Celerator detector at 45 kV and 40 mA. The samples were prepared by back-loading the powder into a circular sample holder with a diameter of 16 mm to minimise the preferred orientation effects. The measurements were taken in a 2θ range of 5–70° with a step size of 0.013° 2θ, using a 1° divergence slit and a 15 mm mask. Rietveld refinement was performed using the PANalytical X'Pert High Score Plus diffraction software (version 4.9), utilising structures for the phases from the ICDD PDF 4+ 2021 RDB powder diffraction files.

The microstructure and elemental composition (as a complementary method to confirm XRD) of the brick samples were examined using a JEOL IT500 HV Scanning Electron Microscope (SEM) equipped with an Energy Dispersive X-ray Spectrometer (EDS). The samples were cast in epoxy resin, dry polished, and coated with an approximately 17 nm thick layer of carbon.

3 Results and discussion

3.1 Raw material

Ekominit S1 is composed mainly of the oxides of calcium, iron, silicon and magnesium (Table 1). It is a fine-grained material with particle sizes mostly below 0.1 mm (Figure 2). The main minerals are C_2S, merwinite, periclase, ferrite and mayenite (Loncnar et al., 2025). Brick-making clay from regular brick production was used as a reference material. It contained illite/muscovite, chlorite, kaolinite, feldspars, calcite and quartz (Božič et al., 2023, Žibret et al., 2025).

Table 1: Chemical composition of the brick-making clay and Ekominit S1 (determined by XRF analysis, in wt.%)

	Brick-making clay	Ekominit S1
LOI 950 °C	8.9	7.5
Na_2O	0.8	0.0
MgO	1.7	14.0
Al_2O_3	16.5	10.2
SiO_2	59.4	18.3
P_2O_5	0.1	0.1
SO_3	0.0	0.3
K_2O	2.3	0.0
CaO	3.2	36.9
TiO_2	0.7	0.6
V_2O_5	0.0	0.1
Cr_2O_3	0.0	2.8
MnO	0.2	1.6
Fe_2O_3	6.0	7.2
Others	0.2	0.4

Source: own.

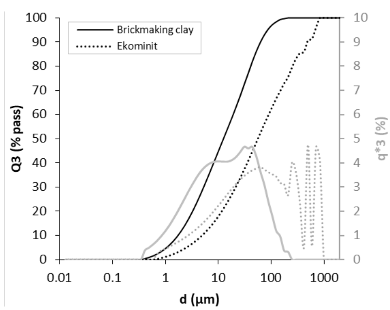

Figure 2: Particle size distribution of the Ekominit S1 and brick-making clay.

Source: own.

3.2 Evaluation after firing

The mechanical properties, shrinkage, density, and porosity were evaluated after firing at selected temperatures. The results show that adding 10 wt.% Ekominit S1 increased the total porosity of the samples fired at both temperatures. At 950 °C the porosity increased from 21.2% for the reference clay to 25.9% with the Ekominit S1. The lowest measured porosity was for the clay sample fired at 1050 °C (18.8%), which also exhibited the highest mechanical strength and density. With the addition of Ekominit S1, the porosity increased to 25.5%. A similar trend was observed at 1050 °C, where the reference sample had the lowest porosity of all the tested compositions (18.8%), while the Ekominit S1-containing sample reached 25.5% (Table 2). These changes are consistent with the mercury intrusion porosimetry (MIP) results shown in Figure 3, confirming the porosity-enhancing effect of Ekominit S1.

Table 2: Bulk density and porosity, measured with MIP, and compressive strength and shrinkage of samples fired at 950 and 1050 °C.

	Temperature (°C)	Brick-making clay	Clay with 10 wt.% Ekominit S1
Bulk density (g/cm^3)	950	2.1	2.0
	1050	2.2	2.0
Porosity (%)	950	21.2	25.9
	1050	18.8	25.5
Shrinkage (%)	950	2.0	1.0
	1050	3.9	2.0
Compressive strength (MPa)	950	235.2 ± 10.3	151.5 ± 12.7
	1050	261.2 ± 11.6	161.9 ± 4.0

Source: own.

The bulk density remained comparable between the samples, showing only a slight decrease with the addition of Ekominit S1 at both temperatures (Table 2), which reflects the increased open porosity. The shrinkage values also decreased in the presence of Ekominit S1, from 2.0% to 1.0% at 950 °C and from 3.9% to 2.0% at 1050 °C. The reduced shrinkage suggests that the additive limits densification during firing and acts as an opening agent (Ducman & Kopar, 2007), indicating that Ekominit S1 could replace quartz in the clay brick mixture.

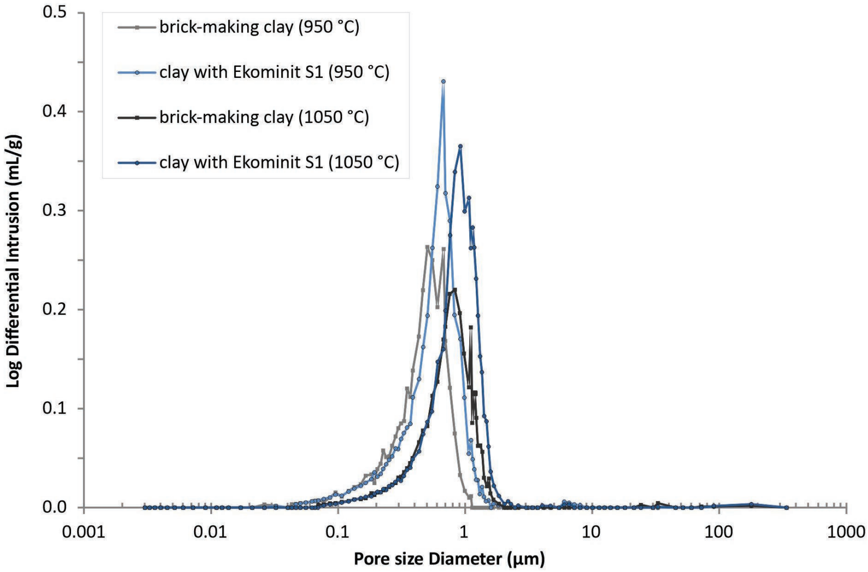

Figure 3: Pore size distribution of brick-making clay and clay sample with 10 wt.% of Ekominit S1, fired at 950 and 1050 °C.

Source: own.

The mechanical properties followed the expected relationship with the porosity (Figures 3 and 4). The reference clay samples, particularly those fired at 1050 °C, exhibited the highest compressive strength (261.2 MPa), consistent with their lower porosity. In contrast, the samples containing Ekominit S1 showed reduced compressive strength at both temperatures (151.5 MPa at 950 °C and 161.9 MPa at 1050 °C), corresponding to their higher porosity values.

Overall, the results indicate that Ekominit S1 increases porosity while reducing shrinkage and mechanical strength.

XRD analysis identified the following major phases: quartz, hematite, feldspar, an amorphous phase, and periclase as a minor phase (Figure 5). The quantitative results are presented in Table 3, which shows that the phase composition of the brick-making clay and the clay with the addition of 10 wt.% Ekominit S1 varied with the firing temperature and slag addition.

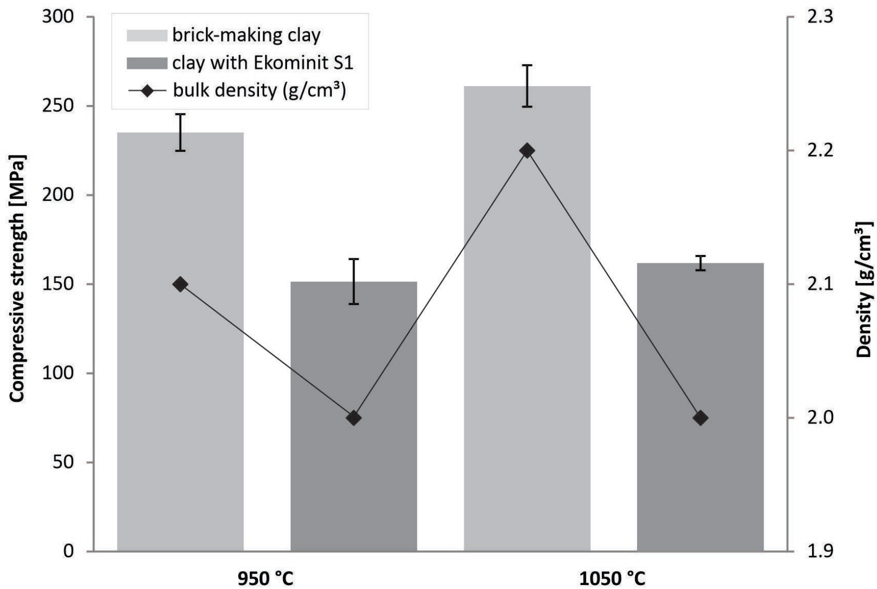

Figure 4: Compressive strength and density of brick-making clay and clay with the addition of 10 wt.% of Ekominit S1 after firing at 950 °C and 1050 °C.
Source: own.

Table 3: Main phase composition of brick-making clay fired at 950 °C and 1050 °C, and clay with the addition of 10 wt.% Ekominit S1, fired at 950 °C and 1050 °C.

	Temperature (°C)	Brick-making clay	Clay with 10 wt.% Ekominit S1
Quartz	950	36.3	41.0
	1050	35.5	26.7
Hematite	950	10.4	9.9
	1050	11.1	10.8
Feldspar	950	9.8	8.7
	1050	18.4	24.2
Amorphous	950	42.7	40.4
	1050	34.9	37.4

Source: own.

For pure clay, increasing the firing temperature from 950 °C to 1050 °C decreased the quartz content slightly (from 36.3 to 35.5 wt.%) and the amorphous phase (from 42.7 to 34.9 wt.%), while promoting feldspar crystallisation (from 9.8 to 18.4 wt.%) and increasing the hematite slightly (from 10.4 to 11.1 wt.%). This indicates that higher temperatures facilitate the transformation of amorphous material into crystalline phases, particularly feldspar, consistent with enhanced fluxing and partial melting. The addition of 10 wt.% Ekominit S1 also resulted in different phase evolution. At 950 °C, quartz content increased slightly (from 36.3 to 41 wt.%), while the feldspar decreased slightly (from 9.8 to 8.7 wt.%). At 1050 °C, the Ekominit S1 addition promoted feldspar formation (from 18.4 to 24.2 wt.%) while decreasing quartz (from 35.5 to 26.7 wt.%). The amorphous content in the mixture remained slightly higher than in pure clay (37.4 wt.% vs 34.9 wt.%), suggesting that the slag stabilises part of the glassy phase at elevated temperatures. Overall, Ekominit S1 acts as a flux, accelerating the feldspar crystallisation at high temperatures while modifying the balance between the crystalline and amorphous phases, which could influence the sintering behaviour and final properties of the fired material.

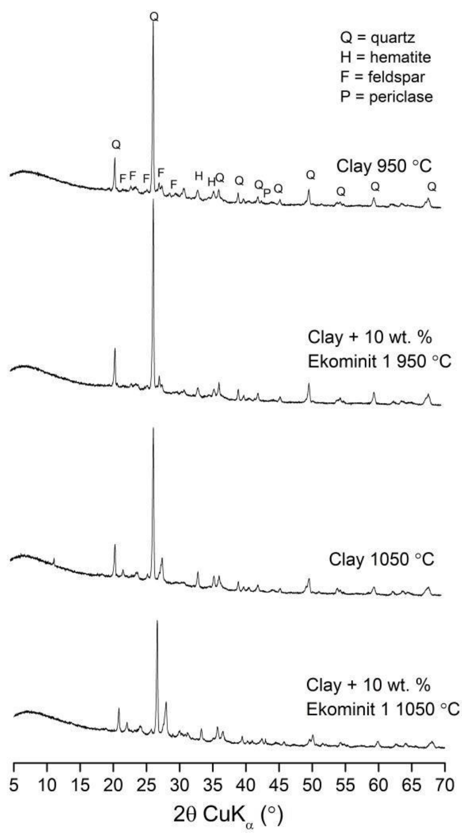

Figure 5: X-ray diffraction patterns of brick-making clay fired at 950 °C and 1050 °C, and clay with the addition of 10 wt.% Ekominit S1, fired at 950 °C and 1050 °C.

Source: own.

Further microstructural evaluation confirmed the presence of the phases identified by XRD, with feldspars enriched in K (K-feldspars) (Figure 6). At both firing temperatures, the porosity was higher in the mixtures containing 10 wt.% Ekominit S1 than in the pure clay bricks. Additionally, the SEM images show a reduction in matrix porosity with the increased firing temperature, resulting in larger pore diameters. This is consistent with the MIP results, which indicate that the pore diameter for samples fired at 1050 °C shifted to higher values (Figure 3).

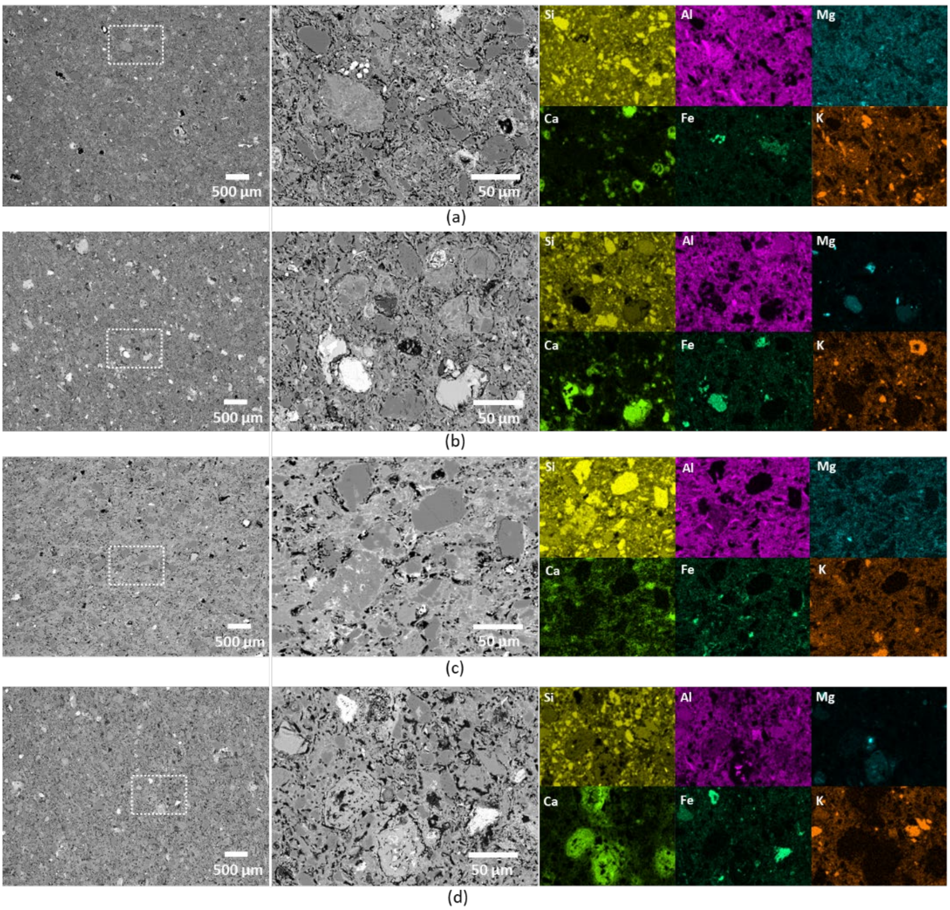

Figure 6: SEM images and EDS elemental maps of Si, Ca, Al, Fe, Mg, and K for the laboratory brick samples, where (a) is pure clay fired at 950 °C, (b) is clay with 10 wt% Ekominit S1 fired at 950 °C, (c) is pure clay fired at 1050 °C, and (d) is clay with 10 wt% Ekominit S1 fired at 1050 °C.

Source: own.

4 Conclusions

The investigated clay is classified as high-plasticity clay and requires the addition of an opening agent, in this case Ekominit S1. Adding Ekominit S1 (up to 10 wt.%) reduced the density, which, consequently, led to decreased mechanical properties. However, the beneficial effect of Ekominit S1 is the reduction in shrinkage, which is important from a technological perspective.

In regular production an extrusion process is used, and, as hollow bricks are produced, the compressive strength of laboratory-made samples cannot be compared directly with that of regular production. Nevertheless, the study showed that processed steel slag can be incorporated into bricks, reducing the environmental impact of both sectors by using secondary products instead of virgin materials. The next step should be pilot production at the brick-making company, which will provide a comprehensive insight into the additive's impact on the process and final properties.

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