

Polymer waste utilization in the manufacturing of facing ceramics produced using glass cullet

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Abstract

The paper presents results on the development of a facing ceramic material produced from the low-plasticity clay with the addition of boric acid and flat window glass cullet, which serve for liquid-phase sintering and achieving a surface self-glazing effect. Additionally, polymer waste, in particular, waste from consumed non-plasticized PVC products, was introduced as a combustible additive. The research results show how the basic properties of the produced ceramics depend on the polymer waste amount added to the batch, with boric acid and cullet included in quantities that provide the maximum possible strength and frost resistance. The optimal polymer waste amount was determined, enabling production of a material that meets the requirements for ceramic facing products and qualifies as conditionally effective in terms of thermal engineering characteristics. The resulting batch composition enables the joint utilization of polymer and glass waste, while simultaneously expanding the raw material base and product range for facing ceramics production.

Keywords: Low-plasticity clay; self-glazing; liquid-phase sintering; energy efficiency.

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1. INTRODUCTION

The problem of waste recycling is becoming extremely urgent in modern society. Waste recycling, on the one hand, prevents pollution and environmental degradation, and on the other, promotes rational utilization of natural resources and reduces economic expenditure of raw materials.

An effective solution for improving waste recycling is to utilize waste materials in the production of construction materials. This approach allows for the separate and complex processing of most waste types in large quantities, utilizing relatively simple and inexpensive technologies and processes. The most effective and promising utilization methods enable the joint processing of various waste types, using them as quality-improving additives and property-modifying agents in new products [1-3].

When using waste, it is important to consider the amount generated and accumulated, as well as its potential use as a secondary resource. This paper examines batch compositions that enable comprehensive utilization of polymer waste, in particular non-plasticized polyvinyl chloride (NPVC), and sheet glass cullet. Polymer waste currently ranks among the highest-volume waste types, and its utilization is an urgent task [4-6]. Polymer waste characterized by high purity and low degradation degree is successfully processed into an additive to primary raw materials for manufacturing plastic products, while low-quality waste with many impurities is practically unclaimed [5,7,8]. A similar trend is seen with glass waste: production waste is recycled by glass manufacturers, while post-consumer waste, amounting up to 10 % of the total waste amount, is instead accumulated at disposal sites and landfills [9-11].

Previous studies explored the utilization of polymer and glass waste in developing batch compositions based on low-plastic clay, with boric acid added as a melt, window glass cullet as a fluxing and strengthening additive, and NPVC waste as a combustible additive to improve the product energy efficiency. It was found that adding 2.5 wt.% boric acid and 12.5 wt.% cullet yielded the highest strength and the lowest water absorption, which could be achieved with NPVC waste additions ranging from 2.5 to 20 wt.% [1].

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The objectives of the present work were to study the effect of polymer waste on the basic properties of self-glazing ceramics produced using cullet, and to determine the optimal amount of polymer waste in the batch so that the manufactured products meet regulatory requirements for facing ceramics while also providing enhanced energy efficiency.

2. MATERIALS AND METHODS

The basic component of the considered batch was the clay from Suvorotskoe deposit in the Vladimir region characterized by 5.2 clay plasticity in compliance with the standard method testifying of its low-plasticity and thus indicating the reason for the poor strength and high-water absorption of the products [4,12]. Therefore, introduction of special additives is required to improve the products quality. The used clay is characterized by the following composition: 67.5 wt.% SiO₂; 10.75 wt.% Al₂O₃; 5.85 wt.% Fe₂O₃; 2.8 wt.% CaO; 1.7 wt.% MgO; 2.4 wt.% K₂O; 0.7 wt.% Na₂O and loss on ignition of 8.3 wt.% [4,13].

The strengthening additive was sheet window glass cullet (Figure 1), due to its liquid-phase sintering, obtained after crushing the glass waste of the following composition: 73.5 wt.% SiO₂; 7.4 wt.% CaO; 1.9 wt.% MgO; 11.1 wt.% Na₂O; 5.1 wt.% K₂O and 0.9 wt.% Al₂O₃[1, 8].



Figure 1. Sheet window glass cullet

NPVC waste (Figure 2), in particular building profiles waste (docking profiles and plinths) and finishing panels, was introduced into the developed batch composition as a combustible additive. It should be noted that the NPVC combustion products are highly toxic, primarily hydrochloric acid vapors and various organochlorine compounds, including dioxins. To neutralize these substances, afterburning chambers are required to decompose the combustion products at 1200 and 1400 °C. The most effective method for eliminating hydrochloric acid vapors is dry purification, which involves introducing quicklime, magnesium oxide, or sodium hydroxide into the flue gases, where they react with hydrochloric acid to form harmless compounds [4].

Both used waste types are accumulated in sufficiently large quantities because of construction and repair, justifying the relevance of their application in the studied batch composition.



Figure 2. NPVC waste

Boric acid brand B grade 2 in compliance with standard GOST 18704-78 [14], containing basic substance of at least 98.6 wt.%, was additionally introduced into the batch. The boric acid introduction reduces the liquid-phase sintering temperature and, alongside the cullet, provides self-glazing effect and product vitrification [1].

In accordance with previous results to ensure high-quality ceramics, 12.5 wt.% glass cullet, 2.5 wt.% boric acid and 2.5 to 20 wt.% NPVC were added to the batch in this work. Adding smaller amounts of NPVC waste does not induce significant changes in thermal conductivity and other material properties. However, incorporating more than 20 wt.% NPVC results in a substantial decrease in strength and an increase in water absorption, which together reduce frost resistance. Additionally, if excessive amounts of NPVC waste are added, traces of additive burnout remain visible both within the material depth and on its surface [1].

Before using the clay, NPVC waste and cullet intended as batch components were separately crushed to a maximum particle size of 0.63 mm and then dried to a constant weight. Also, all the batch components were initially mixed dry in accordance with the intended batch compositions, followed by mixing with water at the concentration of 8 wt.% to achieve uniform molding mass. The mixing period at each stage lasted 5 min. Ceramic samples were made from the molding mass by one-sided pressing at 15 MPa, followed by firing in an oxidizing atmosphere at a heating rate of 5 °C·min⁻¹, with a 30 min hold at 1050 °C.

The samples (Figure 3) were shaped like cubes with 50 mm sides, prepared in sets of three for each batch composition, and the results were averaged for each set. For the bending strength measurements, parallelepiped samples measuring 10×10×70 mm were prepared.

Compressive strength (σ_{cmp} / MPa) has been determined by continuous and uniform load impact on the sample until its destruction with maximum load fixation. When determining the bending strength (σ_{bnd} / MPa), the sample was mounted on the supports on both sides at 25 mm middle from the center. The bending load was applied continuously and evenly through the third support installed in the sample middle. To determine the strength characteristics, a hydraulic press P6326B (JSC Hidropress, Russia) was used.



Figure 3. Sample of the developed ceramic material

Water absorption (WA, %) has been determined by measuring the sample mass increase from the dry state till saturation with water at the atmospheric pressure of 48 h.

Frost resistance (FR, cycles) of the samples has been determined after the water absorption experiment. For this purpose, water-saturated samples were kept in a KM-0,15 freezer (LLC Mayak, Russia) at -15 to -20 °C for 4 hours, then placed in water at room temperature for 2 hours and examined for cracks. If the cracks were not found, the sample underwent another freeze-thaw cycle.

The density (ρ / kg/m³) was calculated from the measured mass and volume of the air-dry sample.

To determine the total porosity (P_{tl} / %), the true density (ρ_{true} / kg m⁻³) has been determined by the pycnometric method, and then calculated according to the Equation (1):

$$P_{tl} = (\rho_{true} - \rho)100 / \rho_{true} \quad (1)$$

Open porosity (P_{opn} / %) was calculated by the Equation (2):

$$P_{opn} = WA\rho \quad (2)$$

Closed porosity (P_{clsd} / %) was calculated by the equation (3):

$$P_{clsd} = P_{tl} - P_{opn} \quad (3)$$

Thermal conductivity (λ / W m⁻¹.°C⁻¹) was determined by using MIT-1 mobile thermal conductivity meter (LLC NPP Interpribor, Russia). For this purpose, 4 cubic samples with 50mm sides were placed on top of each other. The samples' touching surfaces were thoroughly polished, and then a hole was drilled through the centers of the samples. The device's measuring probe was placed into the hole, and the expected range of thermal conductivity was set. The device was then left for 2 hours to adjust the heating power and stabilize the heat flow. Afterward, readings were recorded, ensuring that the ambient temperature was maintained between 20 to 30 °C.

3. RESULTS AND DISCUSSION

The results obtained in this research show that the overall porosity of the developed material increases rapidly and almost linearly with increasing waste content in the batch. This is due to the burnout of the waste during firing, which leads to the formation of pores and voids formation within the samples (Figure 4).

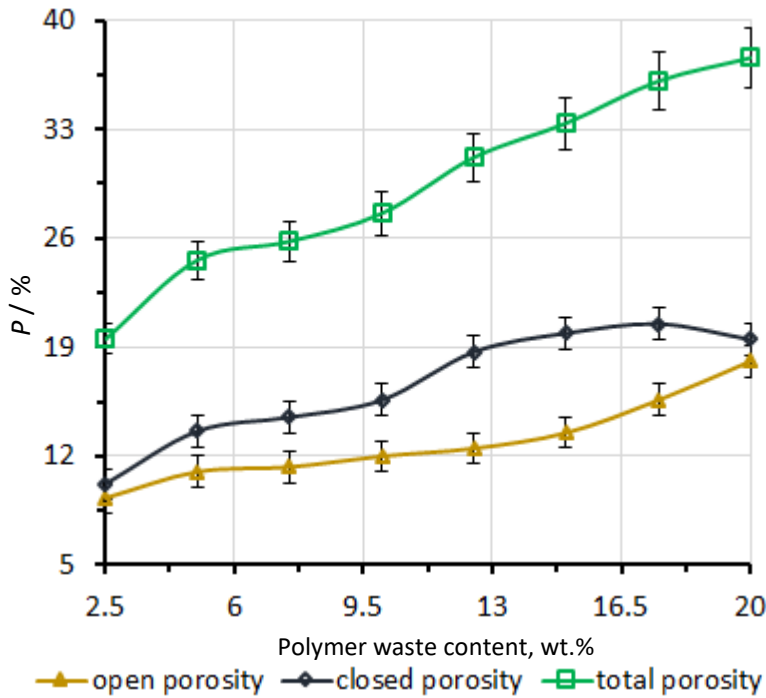


Figure 4. Porosity of the developed ceramics as a function of the polymer waste content

Open porosity also increases linearly, but when more than 10 wt.% NPVC waste is added, the rate of open pore formation accelerates. At the same time, closed porosity increases with NPVC content up to 17.5 wt.%, but higher amounts of polymer waste led to a decrease in closed porosity.

The observed increase in open porosity and decrease in closed porosity at NPVC contents above 17.5 wt.% NPVC can be attributed to the development of a porous structure, during which pores begin to connect at both the surface and within the depth of the ceramics once a certain amount of additive is reached.

The results also revealed an almost linear decrease in ceramics compressive and bending strengths with the increase in polymer waste content (Figure 5).

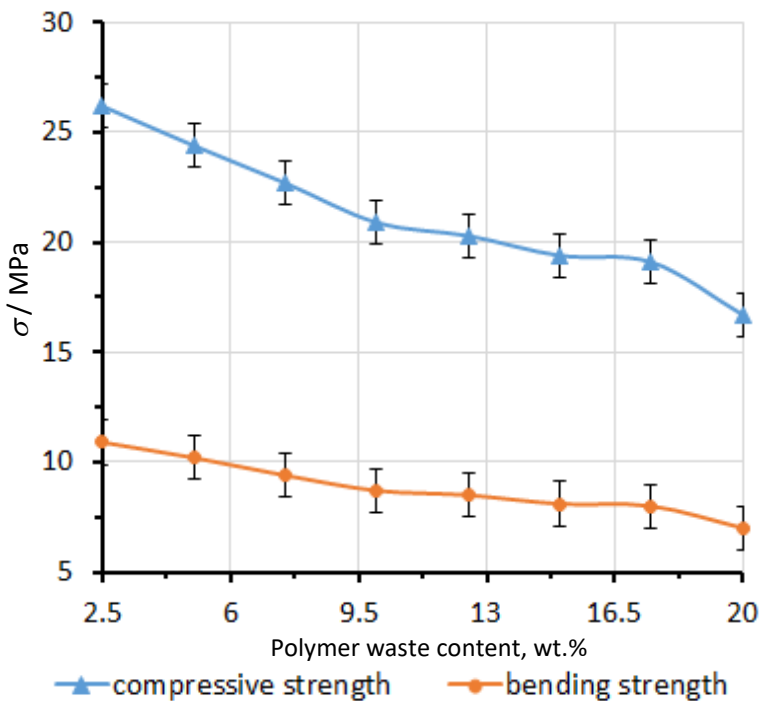


Figure 5. Dependence of the ceramic strength on the polymer waste content

Such dependence is related to the formation of pores during NPVC combustion causing a decrease in the contact area between the crystalline and vitreous phases throughout the entire material volume. As a result, the framework of ceramic particles within the glassy phase layer is disrupted. At the same time, a more significant decrease in material strength characteristics occurs as the NPVC waste content increases from 2.5 to 10 wt.%, likely due to greater disruption of the ceramic particle framework.

The ceramics water absorption increased almost linearly with the increase in the NPVC waste content, which in turn causes a similar linear decrease in the frost resistance (Figure 6). This relationship can be explained by the increase in material porosity and the higher fraction of open pores resulting from the formation of a developed porous structure. Figure 7 shows dependences of density and thermal conductivity of the developed ceramics on the NPVC waste content. Both properties are found to decrease rapidly as the NPVC waste content is increased, which corresponds again to the formation of an open porous material structure.

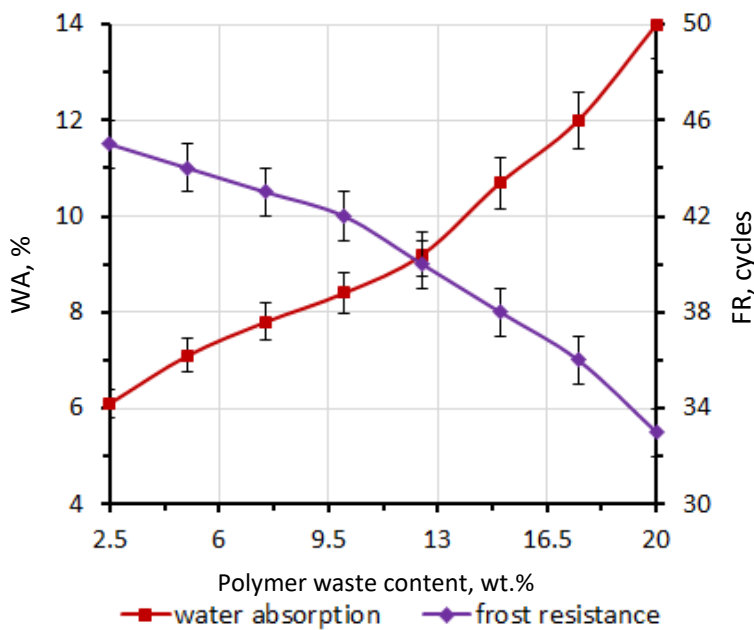


Figure 6. Water absorption and frost resistance of the developed ceramics as functions of the polymer waste content

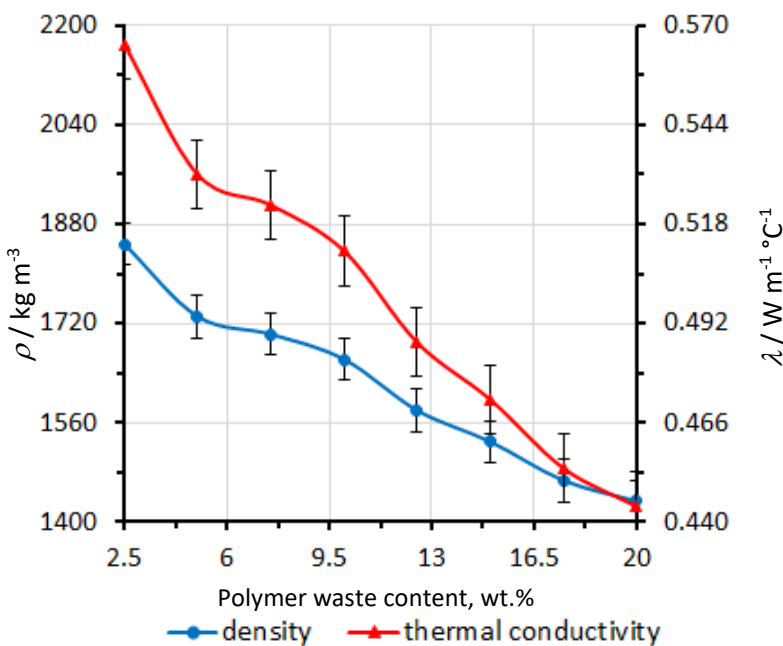


Figure 7. Dependence of the developed ceramics density and thermal conductivity on the polymer waste content

Overall, the results obtained in the research revealed that the pore-forming effect of NPVC waste burning during the ceramics firing negatively affects certain material properties such as strength, water absorption and frost resistance. At the same time, the material's density and thermal conductivity decrease, resulting in a lighter product with improved energy efficiency. Because all properties change almost linearly with increasing NPVC waste content in the batch, it is recommended to limit the amount of this additive to achieve sufficient energy efficiency.

According to the standard GOST 530-2012, energy efficiency is achieved when thermal conductivity does not exceed $0.46 \text{ W m}^{-1} \cdot \text{°C}^{-1}$. Introducing 17.5 wt.% of NPVC waste into the batch results in a thermal conductivity of $\lambda = 0.454 \text{ W m}^{-1} \cdot \text{°C}^{-1}$ allowing the final products to be classified as conditionally effective. Increasing the NPVC content further is not rational, since it significantly worsens the basic performance properties of the developed ceramics. Conversely, lower polymer waste content leads to thermal conductivity above the required level for energy-efficient materials.

4. CONCLUSION

This study contributed to developing a batch composition based on low-plasticity clay with additions of 2.5 wt.% boric acid, 12.5 wt.% cullet and 17.5 wt.% polymer waste. This batch composition enables the production of a ceramic material that can be classified as conditionally effective ($\lambda < 0.46 \text{ W m}^{-1} \cdot \text{°C}^{-1}$) in compliance with the standard GOST 530-2012 [15]. In terms of compressive and bending strength values (19.1 and 8 MPa, respectively), the resulting ceramics is comparable to facing bricks and stones of the M175 brand ($\sigma_{\text{cmp}} > 17.5 \text{ MPa}$). However, in terms of frost resistance it corresponds to the F35 brand (FR > 35), which is used for manufacturing facing construction products.

Thus, the developed batch composition ensures the combined processing of glass and polymer waste as functional additives in the production of high-quality facing ceramics. This approach, on the one hand, provides the solution to the problem of waste accumulation, while on the other, it expands the range of construction materials, products, and available raw materials.

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Korišćenje polimernog otpada u proizvodnji keramike za oblaganje napravljene od staklene šljake

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Izvod

U radu su predstavljeni rezultati razvoja keramičkog materijala za oblaganje proizvedenog od gline niske plastičnosti uz dodatak borne kiseline i staklene šljake poreklom od ravnog prozorskog stakla, za primenu za sinterovanje u tečnoj fazi i postizanje efekta samoglaziranja površine. Dodatno je kao zapaljivi aditiv uveden polimerni otpad, otpad od potrošenih neplastificiranih PVC proizvoda. Rezultati istraživanja pokazuju da osnovna svojstva proizvedene keramike zavise od količine polimernog otpada dodatog u smesu, pri čemu su borna kiselina i staklena šljaka dodati u količinama koje obezbeđuju maksimalnu moguću čvrstoću i otpornost na mraz. Određena je optimalna količina polimernog otpada, što omogućava proizvodnju materijala koji ispunjava zahteve za keramičke proizvode za oblaganje i kvalifikuje se kao uslovno efikasan u pogledu termotehničkih karakteristika. Dobijeni sastav smese omogućava zajedničko korišćenje polimernog i staklenog otpada, uz istovremeno proširenje sirovinke baze i asortimana proizvoda za proizvodnju keramike za oblaganje.

Ključne reči: Glina niske plastičnosti; samoglaziranje; sinterovanje u tečnoj fazi; energetska efikasnost.