

Pegmatites of Ukraine as raw materials for electrical porcelain production

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Abstract

Purpose. To substantiate the feasibility of using feldspar concentrate obtained from beneficiated pegmatites of the Lozuvatka deposit as a domestic fluxing raw material for low-temperature electrical porcelain production and to determine the formulation and processing parameters for energy-efficient firing.

Methods. The chemical and mineralogical composition of the raw materials was investigated using chemical, petrographic, and X-ray diffraction analyses. The radiological properties of the pegmatites were determined by gamma-ray spectrometry. The fluxing ability of the feldspar concentrate was evaluated by graphical-analytical calculations in the Na₂O-Al₂O₃-SiO₂ and K₂O-Al₂O₃-SiO₂ systems. Body compositions were optimized using a full factorial experimental design. Specimens were shaped plastically from bodies prepared by the slip method and fired at 1150-1250°C. Sintering behavior and mechanical, thermophysical, and electrophysical properties were determined using standard methods. Structural and phase characteristics were examined by dilatometry, X-ray diffraction, optical microscopy, and scanning electron microscopy.

Findings. A rational clay : kaolin : feldspar concentrate ratio of 40:22:28 was established at a quartz sand content of 15 wt.%, with additions of 2 wt.% dolomite and 0.3 wt.% TiO₂. Firing at 1200°C produced dense electrical porcelain with zero water absorption, dielectric strength of up to 30 kV/mm, volume resistivity above 4·10¹⁴ Ω·m, flexural strength of 77 MPa, and a mullite content of approximately 30 vol.%. No signs of high-temperature deformation were observed within the range of 1150-1250°C. The firing temperature was reduced by 150°C compared with industrial counterparts.

Originality. The mechanism of accelerated electrical porcelain sintering in the presence of a feldspar melt modified with CaO and MgO and a TiO₂ mineralizing additive was established. Early melt formation, reduced melt viscosity, and intensive formation of needle-like secondary mullite were shown to promote maximum densification and improve the material's mechanical and dielectric properties.

Practical implications. The use of exclusively domestic raw materials can reduce dependence on imported feldspar for porcelain insulator production, lower firing energy consumption, and improve the competitiveness of Ukrainian electrical porcelain.

Keywords: pegmatites; feldspar concentrate; electrical porcelain; low-temperature firing; mullite; sintering; dielectric properties

1. Introduction

The full-scale war and mounting economic pressure from the aggressor state have made import substitution a particularly pressing issue for Ukrainian industry. The production of electrical porcelain, which has traditionally relied on imported feldspar, has become increasingly vulnerable due to disrupted supply chains and rising costs of imported raw materials and energy. One promising way to reduce this dependence is to increase the use of domestically sourced feldspar.

Ukraine has deposits of quartz-feldspar raw materials (QFRM) that can serve as an alternative to sodium- and potassium-bearing feldspars, which have traditionally been imported from other countries [1], [2]. Currently, 33 pegmatite fields are known in Ukraine, each containing hundreds, and in some cases thousands, of pegmatite bodies [3]. The total feldspar

raw material reserves in Ukraine are estimated at 258 million tonnes, including 51.9 million tonnes in categories A + B + C1 and 206.1 million tonnes in category C2 [4]. At present, 12 feldspar deposits are officially recorded, most of which are represented by pegmatite veins occurring within the Ukrainian Shield. The main sources of feldspar raw materials include low-iron alkaline granites, pegmatites, nepheline syenites, feldspathic sands and sandstones, microgranodiorites and porcelain stone. The distribution of feldspar raw material deposits, based on the data reported in [5], is shown in Figure 1.

The Ukrainian Shield (USh) is essentially a pegmatite province comprising seven districts: Middle Dnipro, Western Azov, Eastern Azov, Inhul, Ros-Tikych, Dniester-Buh, and Volyn [6]. Each of these districts contains known resources of ceramic-grade pegmatites that represent high-quality quartz-feldspar raw materials.

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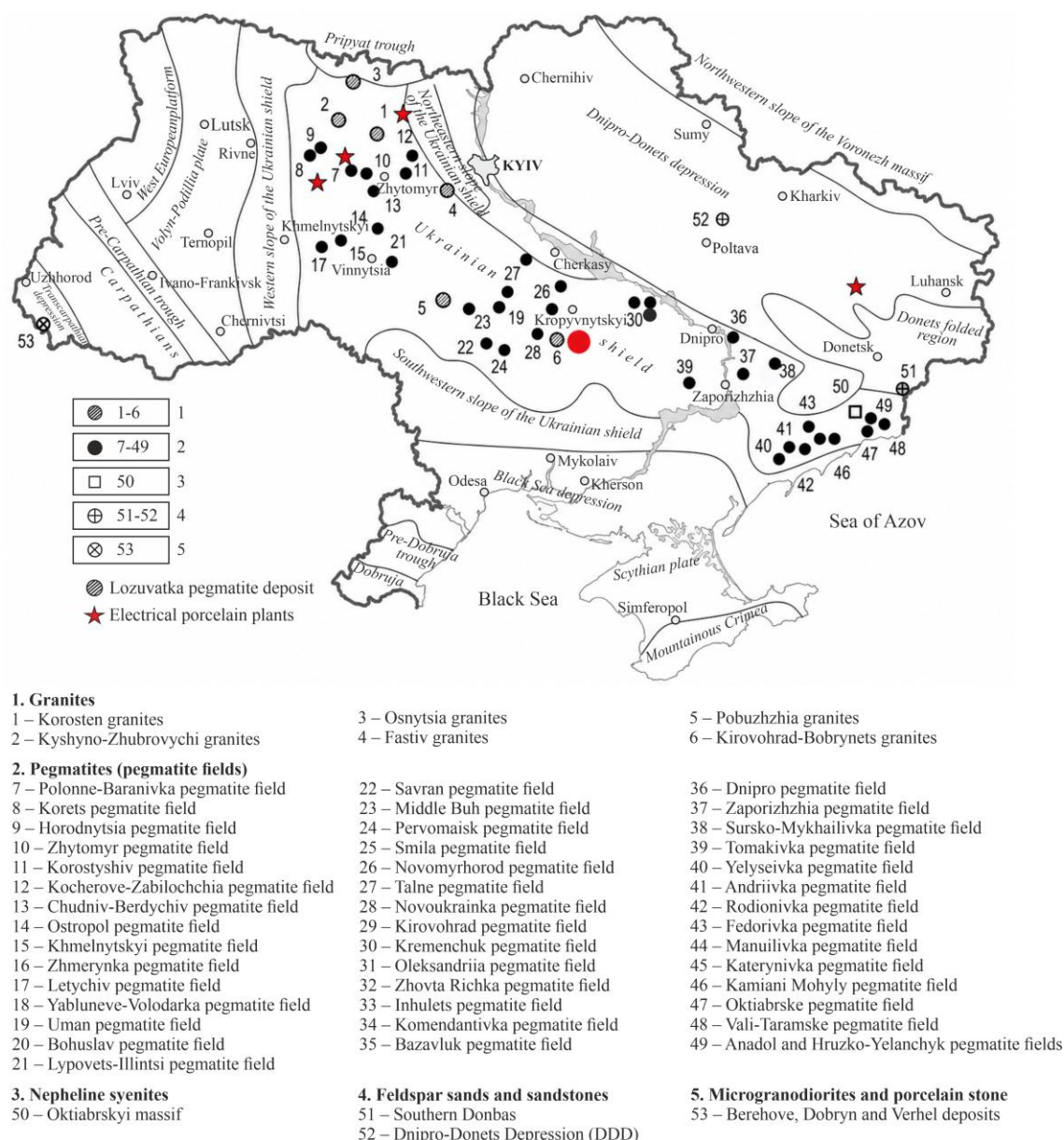


Figure 1. Distribution of feldspar raw material deposits and electrical porcelain plants (after D.S. Hurskyi et al.)

Historically, electrical porcelain manufacturers, including Sloviansk High-Voltage Insulator Plant LLC, Pershotravensk Electrical Porcelain Plant LLC, Olevsk Electrical Porcelain Plant JSC, and Poliankivskiy Porcelain LLC, were located directly within these pegmatite districts, particularly the Western Azov and Volyn districts.

Other occurrences of quartz-feldspar raw materials include the Dubryntsi deposit of “porcelain stone” (microgranodiorite) in Zakarpattia and the Novakivska site of the Maidan-Vilskyi deposit in Khmelnytskyi region, where local granitoids and their grus meet the quality requirements for porcelain production. Beneficiation products from apatite-ilmenite ores of the Nosachiv deposit in the Cherkasy region may also serve as a source of feldspar raw materials [7].

The Mazurivske deposit in the Donetsk region represents a technogenic source of feldspar. Since the beginning of the full-scale invasion, Ukraine has also lost control over one of its richest pegmatite deposits, Balka Velykoho Taboru, which was being mined in the Azov region. Nevertheless, substantial feldspar resources, particularly pegmatites, remain available in other regions of Ukraine. This study focuses on the pegma-

tites of the Lozuvatka deposit, located south of the village of Lozuvatka in the Kirovohrad region. Its reserves of approximately 2.01 million tonnes were approved in 2012. Georesurs LLC holds a special subsoil use permit for pegmatite extraction and plans to beneficiate the pegmatite raw material.

A detailed assessment of the physicochemical properties and technological suitability of domestically sourced fluxes offers considerable potential to replace imported feldspar raw materials without compromising final product quality. Such substitution may also reduce production costs associated with the transportation and customs clearance of imported materials.

It should be noted that raw materials used in the production of porcelain insulators are subject to stringent requirements regarding the content of coloring impurities, as these impurities can impair the dielectric properties of the products and cause defects such as dark specks and fused inclusions.

At the same time, the suitability of quartz-feldspar raw materials (QFRM) for electrical porcelain production depends not only on the concentration of transition elements in dark-colored compounds but also on the mineralogical forms in which these elements occur [8]. In particular, the presence

of mafic minerals in quartz-feldspar materials (QFM) determines both their suitability for various silicate technologies and the appropriate beneficiation methods. For example, unlike magnetite, pyrite is non-magnetic and hydrophobic, making flotation a suitable method for its removal. Magnetite and moderately magnetic Fe-bearing minerals, such as biotite and ilmenite, are more effectively removed by magnetic separation, whereas weakly magnetic minerals, including hematite, goethite, and siderite, as well as amorphous or poorly crystalline iron-bearing phases such as hydrogoethite, limonite, and ferrihydrite, can be removed by chemical leaching [9].

Transition elements in minerals that adversely affect QFM quality are primarily Fe^{2+} , Fe^{3+} , and Ti^{4+} . Fe^{3+} can isomorphically substitute for Al^{3+} in the crystal lattice of natural alkali aluminosilicates. Bound forms of iron also include hematitic coatings on mineral surfaces, commonly referred to as “iron coatings”. Their removal requires a combination of beneficiation methods, such as mechanical or ultrasonic scrubbing followed by chemical treatment with oxalic, hydrochloric, or sulfuric acid. Although this approach can provide high beneficiation efficiency, it is economically unattractive for large-scale ceramic production [10]. Titanium in feldspar-bearing rocks, in turn, occurs predominantly as rutile and/or anatase, both of which are sparingly soluble and non-magnetic.

As reported in [11], the content of iron oxides in quartz-feldspar materials (QFM) suitable for electrical porcelain production should not exceed 0.3 wt.%. The free quartz content is also limited to 30%. Therefore, the main objectives of quartz-feldspar raw material (QFRM) beneficiation are the removal of coloring oxides and dark-colored minerals, as well as the separation of excess quartz. However, separating quartz from QFM is challenging because both quartz and feldspars are non-magnetic, have very similar electrophysical properties, and exhibit only a small difference in density – 2.65 and 2.55 g/cm³, respectively [12].

The beneficiation behavior of various quartz-feldspar rocks from Ukrainian deposits was investigated in [13]. The results demonstrated that electromagnetic separation can effectively reduce the content of Fe-bearing impurities while offering a relatively simple and economically viable beneficiation method. When the total content of iron- and titanium-bearing inclusions does not exceed 4.0 wt.%, combined beneficiation involving air, electrical, and magnetic separation can reduce the content of coloring oxides to the level required for QFRM used in electrical porcelain production. The recommended parameters for dry electromagnetic separation are a magnetic field strength of $H = 200\text{--}225$ A/m and a magnetic flux density of $B \approx 1.4$ T. Under these conditions, weakly magnetic inclusions of dark-colored minerals can be effectively removed, while beneficiation products with the required proportions of quartz and feldspar components can also be obtained.

Another important challenge, particularly in the context of the European transition toward resource and energy efficiency and the instability of the natural gas market, is the development and implementation of energy-efficient technologies for producing electrical porcelain entirely from domestic raw materials. In our view, one effective way to reduce energy consumption in porcelain insulator production is to use technological additives that intensify sintering and phase formation. This approach can promote the formation of a homogeneous electrical porcelain structure with the re-

quired phase composition at lower firing temperatures. Considerable research attention is currently focused on this issue [14]–[17]. At the same time, the search for alternative natural and technogenic raw materials to replace expensive, scarce, or rare materials remains equally relevant [18]–[22]. Growing environmental awareness is also driving the adoption of more sustainable manufacturing practices to reduce emissions and waste [23]–[26].

Compared with alternative dielectric materials such as polymers and glass, electrical porcelain offers high performance and stable electrical, thermal, and electromechanical properties, together with resistance to environmental exposure, including high humidity, temperature fluctuations, ultraviolet and solar radiation, and aggressive chemical emissions from industrial facilities. Electrical porcelain is widely used in high-voltage engineering to manufacture insulators for power transmission lines, transformers, and other high-voltage equipment. Typical products include pin, disc, suspension, post, and bushing insulators, as well as components for circuit breakers and fuses [9], [27].

The properties of porcelain insulators play a crucial role in ensuring electrical safety and reliable operation in various electrical applications. Among the most important are their dielectric and mechanical properties [27], which depend on the phase composition of the ceramic body, particularly the ratio of mullite to glassy phases formed during firing [28], [29]. This relationship should be taken into account when developing compositions for low-temperature electrical porcelain.

Conventional electrical porcelain consists of three main components:

- the clay component, which provides plasticity and contains the principal phase-forming oxides;
- the quartz component, which acts as a filler and reduces shrinkage and high-temperature deformation during firing;
- the feldspar component, which promotes densification through the formation of a liquid phase during firing.

Alumina is sometimes added as a partial replacement for quartz to improve the dielectric properties of porcelain; however, this approach requires higher firing temperatures.

Since the beginning of the war, and particularly following the full-scale invasion, many deposits of high-quality clay, feldspar, and dolomite have been located in temporarily occupied territories. Consequently, current research on the formulation and processing parameters of electrical porcelain is increasingly focused on raw materials from other domestic deposits.

The search for effective solutions to replace imported raw materials is not only a technical challenge but also an economic and strategic priority. Given that feldspar imports have exceeded 300 thousand tonnes over recent decades [30], a thorough assessment of domestic quartz-feldspar raw materials (QFRM) and their suitability for electrical porcelain production is particularly important. Expanding the raw material base by using quartz-feldspar materials (QFM) from currently undeveloped deposits, together with alternative mineral resources, is essential for developing domestic electrical porcelain production and reducing the industry's dependence on imports. Therefore, domestic sources of feldspar materials that can replace raw materials traditionally imported from Turkey, Finland, India, and other countries need to be identified, while maintaining the high quality of porcelain insulators.

This study aims to develop formulation and processing parameters for the production of high-voltage electrical

porcelain using exclusively domestically sourced alternative fluxing mineral raw materials, and to investigate the properties and structural and phase characteristics of the resulting products produced under energy-efficient firing conditions.

2. Materials and methods

2.1. Geological characteristics of the raw material base

Considering the raw material quality requirements for porcelain insulator production, readily available natural raw materials of Ukrainian origin with minimal contents of variable-valence oxides (FeO , Fe_2O_3 , TiO_2) were selected for the production of low-temperature electrical porcelain. These included kaolin from the Pyshchyky deposit in Kyiv region, Vesco-Extra kaolinite-hydromica clay (Vesco PJSC), quartz sand from the Novoselivka deposit in Kharkiv region, feldspar concentrate obtained by beneficiation of pegmatites from the Lozuvatka deposit in Kirovohrad region, and dolomite from the Nehrebivka deposit in Zhytomyr region. These raw materials have stable reserves and are comparable in quality to domestic materials traditionally used by the industry, particularly before 2014.

The Pyshchyky secondary kaolin deposit represents a major reserve base of high-quality kaolin raw material, with explored reserves of 14.8 million tonnes in categories A + B + C1 and 33.4 million tonnes in category C2. The

secondary kaolin occurs as three lenses of varying thickness, with an average thickness of approximately 4.5 m for the commercial-grade layer. The kaolins are classified as high-alumina materials: according to previous studies, the Al_2O_3 content is 27-30 wt.% in one lens and exceeds 40 wt.% in the other two [31].

Dolomite from the Nehrebivka deposit is comparable in quality to that from the Olenivka and Stylske deposits, which were developed by the Dokuchaievsk Flux and Dolomite Plant in the Donetsk region and have been located in temporarily occupied territory since 2014. Nehrebivka dolomite can be used in the production of electrical insulating ceramics, flat glass, container glass, and other types of glass at Ukrainian plants. Commercial reserves of 36.2 million tonnes of carbonate rocks were approved in 1986 [5].

Pegmatites from the Lozuvatka deposit are light beige with gray inclusions and have a massive, homogeneous texture. The feldspar concentrate (hereafter, FSC) is produced from these pegmatites by dry electromagnetic separation.

2.2. Chemical and mineral composition of the raw materials

The chemical composition of the raw materials, determined by chemical analysis of representative samples, is presented in Table 1.

Table 1. Chemical composition of the raw materials

Materials	Component content, wt.%								
	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	K_2O	Na_2O	LOI
Vesco-Extra clay (Vesco PJSC)	53.94	30.56	0.80	1.44	0.45	0.54	1.89	0.49	9.89
Kaolin from the Pyshchyky deposit	48.53	35.60	0.71	0.44	0.42	0.18	0.89	0.22	13.01
Feldspar concentrate (FSC)*	68.09	18.15	0.1	0.04	0.65	0.21	8.27	3.96	0.53
Dolomite from the Nehrebivka deposit	2.00	1.00	0.50	–	28.00	22.00	–	–	46.50
Quartz sand from the Novoselivka deposit	99.12	0.39	0.04	–	0.20	0.04	–	–	0.21

*Beneficiation product of the Lozuvatka pegmatites

2.3. Experimental methods

The mineral composition of the Lozuvatka pegmatites was investigated by petrographic analysis and X-ray diffraction (XRD) using a DRON-3M diffractometer. The specific activities of the natural radionuclides ^{226}Ra , ^{232}Th , ^{132}Cs , and ^{40}K in the investigated pegmatites were determined by gamma-ray spectrometry using an SEG-001 “AKP-S” scintillation spectrometer. The effective specific activity (C_{eff}) was also calculated. According to the Radiation Safety Standards of Ukraine, this parameter is used as a criterion for assessing the suitability of raw materials for industrial applications.

The fluxing ability of the feldspar concentrate (FSC) was evaluated using a graphical-analytical calculation method [32]. Based on the rock's chemical composition, this method allows a preliminary assessment of melt formation, including the amount, composition, and properties of the liquid phase that governs sintering at a given firing temperature.

The specimens were prepared by plastic forming from a body produced by the slip method, followed by partial dewatering. After drying to a residual moisture content below 1%, the specimens were fired in a muffle furnace at 1150, 1200, and 1250°C, with a 1 h soak at the maximum temperature.

In accordance with GOST 7030-75 requirements for silicate porcelain containing less than 30 wt.% Al_2O_3 , the following properties of the laboratory specimens were deter-

mined: water absorption (W), apparent density (ρ_{app}), compressive strength (σ_c), flexural strength (σ_f), tensile strength (σ_t), coefficient of linear thermal expansion (CLTE, α), and electrophysical properties, including volume resistivity (ρ_V), dielectric strength (E_{br}), dielectric permittivity (ϵ), and dielectric loss tangent ($\tan \delta$).

The compressive strength of the specimens was measured using a GMS-50 testing press with a maximum load capacity of 500 kN. Flexural strength was determined on rectangular specimens measuring $35 \times 120 \times 10$ mm using an MP-100 laboratory testing device. For tensile strength testing, the specimen was secured in grips and subjected to a uniformly increasing tensile load. The load was monitored using a DPU-0.5/2 No. 1874 dynamometer. Upon reaching 30 MPa, the load was held at that level for 1 min, then gradually increased until specimen failure. The reported strength values represent the arithmetic mean of measurements obtained for five specimens of each experimental composition.

The electrophysical properties of the specimens were determined in specialized laboratories of the Research Institute of High Voltages and Kharkivelektronaladka. Dielectric strength was measured using specimens of standard dimensions in accordance with DSTU 2203-93. Volume resistivity was determined using a Zahner Elektrik IM6e instrument after depositing thin gold films on the specimen surfaces to serve as

electrodes. The reported values were calculated as the arithmetic mean of five measurements for each batch of specimens.

Shrinkage behavior of the porcelain bodies during heating from 20 to 1200°C was investigated using a DIL 402 PC dilatometer with Proteus Software for Thermal Analysis. The thermal treatment program consisted of heating from 20 to 1200°C at 8°C/min, holding at the maximum temperature for 60 min, and cooling to 30°C at 7°C/min.

The phase composition of the specimens was examined by X-ray diffraction, optical microscopy, and scanning electron microscopy. Microstructural features were studied using a REMMA-101Az scanning electron microscope. Prior to examination, the glassy phase was removed from the specimens by etching with a 5% hydrofluoric acid solution, allowing the microstructural features to be observed in greater detail.

3. Results and discussion

The study investigated the composition and technological properties of pegmatites from the Lozuvatka deposit and their beneficiation products, and developed a process for producing low-temperature porcelain using these materials.

The qualitative mineral composition of the pegmatites, determined by X-ray diffraction analysis, is shown in Figure 2.

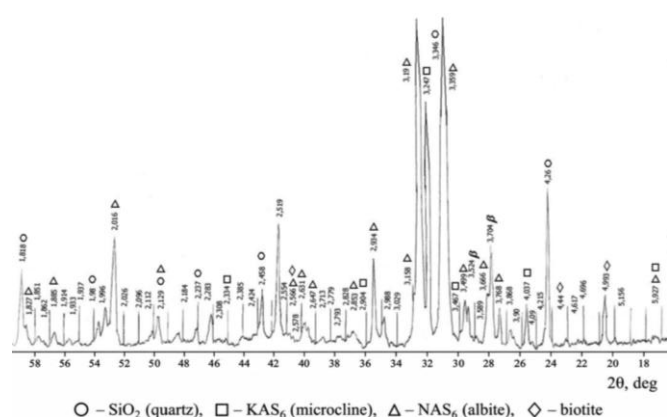


Figure 2. X-ray diffraction pattern of pegmatite from the Lozuvatka deposit

Georesurs LLC has developed a beneficiation process that not only removes mafic Fe-bearing minerals that adversely affect the quality of the pegmatite raw material, but also produces concentrates with a desired mineral composition. By varying the proportions of albite, orthoclase, and quartz during beneficiation, concentrates can be obtained that

meet the chemical and mineralogical requirements of fluxing raw materials for different ceramic industries.

The fluxing ability of the Lozuvatka pegmatites and their beneficiation product (FSC) was evaluated using graphical-analytical calculations in the ternary systems of the major rock-forming oxides ($\text{Na}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2$ and $\text{K}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2$). These calculations were used to determine the onset and complete melting temperatures of the investigated materials, as well as the amount (Q_m) and chemical composition of the melt formed at 1100, 1150, and 1200°C.

Based on the calculated chemical composition of the melts, the properties governing the intensity of ceramic body sintering were determined: viscosity (η , Pa·s), surface tension (σ , N/m), and activity coefficient (K_{act}), which characterizes the ability of the melt to dissolve residual clay minerals and quartz. The dielectric properties of the glassy phase, namely dielectric permittivity (ϵ) and dielectric loss tangent ($\tan \delta$), were also calculated. The fusibility and radiological properties of the investigated materials were determined experimentally. The results are summarized in Table 2.

Given the need to reduce the firing temperature of electrical porcelain, it was considered appropriate to modify the properties of the feldspar melt using alkaline-earth metal oxides acting as modifiers. Dolomite from the Nehrebivka deposit, whose composition is given in Table 1, was used as a source of CaO and MgO.

The porcelain body compositions were designed within the following ranges of raw materials (wt.%): 35-55 kaolin-hydromica clay, 10-25 kaolin, 25-35 feldspar concentrate, 13-17 quartz sand, and 2-4 dolomite. Experimental results showed that adding 4 wt.% dolomite, calculated as an addition above 100% of the dry batch, led to the formation of closed pores, which adversely affected the mechanical and electrophysical properties of the specimens.

Using a planned factorial experiment (2^2 full factorial design), the following rational component ratio was established: clay : kaolin : FSC = 40:22:28, with a fixed quartz sand content of 15 and 2.0 wt.% dolomite added above 100% of the dry batch (Fig. 3).

Maintaining the specified proportions of raw materials in the experimental bodies and adding 0.3 wt.% TiO_2 as a mineralizer (above 100% of the dry batch) enables, at a firing temperature of 1200°C, the production of a material whose overall properties (Table 3) meet the requirements for electrical porcelain (Group 110) according to the existing classification. No signs of high-temperature deformation were observed in the specimens over the firing temperature range of 1150-1250°C.

Table 2. Properties of the Lozuvatka pegmatites and their beneficiation products

Material	Effective specific activity of radionuclides* (C_{eff}), Bq·kg ⁻¹	Melt properties at a firing temperature of 1200°C				Glassy-phase properties		Fire-test specimen
		Q_m , %	η , Pa·s	σ , N/m	K_{act}	ϵ	$\tan \delta$	
Pegmatite	199.7	98.86	$10^{3.52}$	0.279	0.103	7.91	0.11	
FSC		95.44	$10^{3.42}$	0.285	0.155	7.91	0.01	

*Gamma-ray spectrometry identified the radionuclides ²³²Th, ²²⁶Ra, and ⁴⁰K

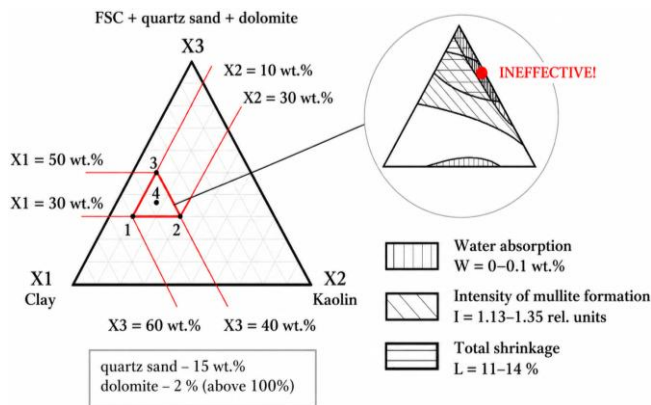


Figure 3. Investigated range of raw material compositions and the optimal composition of the low-temperature electrical porcelain body

For comparison with the low-temperature electrical porcelain developed in this study, previous research on alternative fluxing raw materials aimed at reducing the energy consumption associated with firing porcelain insulators was reviewed. The authors of [19] demonstrated that high mechanical and dielectric properties can be achieved at lower firing temperatures using a porcelain body based on kaolin from the Djebbel Debbagh deposit (Guelma, Algeria) and high-purity quartz from the Tamanrasset deposit (Algeria), with Spanish feldspar partially replaced by waste automotive glass. The glass contained, wt.-%: SiO_2 – 70.22; CaO – 12.09; Na_2O – 13.13; MgO – 1.55; and Al_2O_3 – 1.08. After firing at 1150–1200°C, the specimens contained residual quartz, anorthite, primary short-columnar mullite, and a glassy phase. The measured dielectric properties of the glass-ceramic material ($\epsilon = 2.5$ –4.0, $\tan \delta = 0.55$ –0.06) indicate its suitability for use as an electrical insulator.

Table 3. Properties of specimens fired at 1200°C

Properties	Sample code				GOST 20419 / IEC 672-3 (Group 110)
	NEF-1	NEF-2	NEF-3	NEF-4	
Dielectric strength* (E_{br}), kV/mm	26	27	29	30	≥ 25
Volume resistivity** (ρV), $\Omega \cdot \text{m}$	$3.0 \cdot 10^{-14}$	$3.3 \cdot 10^{-14}$	$4.0 \cdot 10^{-14}$	$4.2 \cdot 10^{-14}$	10^{12}
Relative permittivity*, ϵ	3.37	3.06	2.95	2.70	6.0–7.0
Dielectric loss tangent*, $\tan \delta \cdot 10^3$	12.3	12.2	12.0	11.5	≤ 25
Compressive strength (σ_c), MPa	125	152	163	170	–
Flexural strength (σ_f), MPa	63	68	71	74	≥ 60
Tensile strength (σ_t), MPa	30	31	33	34	≥ 30
Water absorption (W), %	0	0	0	0	0
Apparent density (ρ), kg/m^3	2820	2835	2850	2870	≥ 2300
Coefficient of linear thermal expansion, $\alpha \cdot 10^6$ 1/°C	5.05	4.97	4.94	4.90	3.0–6.0

*Values determined at a current frequency of $f = 50$ Hz;

**Values determined at 20°C.

The glass-containing specimens had a higher proportion of crystalline phases than conventional porcelain, which was attributed to their higher dielectric strength. Although these results are of interest for high-voltage insulation applications, the authors did not address deformation during firing. Given the substantial shrinkage (18%) in specimens containing waste glass, such deformation appears quite likely. Moreover, implementation of the proposed approach would require either an additional high-temperature glass-melting operation or the collection of waste automotive glass accompanied by control of its composition.

Dilatometric analysis was performed for the optimal NEF-1 composition. Analysis of the dilatometric curve (Fig. 4) showed that changes in the specimen's linear dimensions during heating remained relatively small until the material approached its maximum degree of densification. During both heating and cooling, the curve representing the rate of linear dimensional change (dL/dt) showed minor deviations from the baseline in the temperature range of 550–600°C. These deviations correspond to a dimensional change of approximately 0.3% associated with the polymorphic transformation of quartz ($\beta \leftrightarrow \alpha$). As the temperature increases, liquid-phase sintering of the porcelain begins, as reflected in a further decrease in the specimen's linear dimensions. The relatively low sintering onset temperature, at about 920°C, is attributed to earlier melt formation from a combined fluxing system consisting of feldspar and dolomite. With further heating, the sintering rate increases; however, between 980 and 1060°C, the process slows due to crystallization of the primary mullite phase.

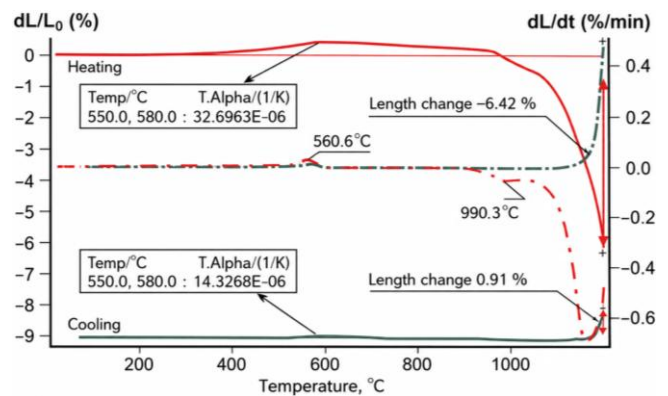


Figure 4. Dilatometric curve of the optimal composition (NEF-1)

As reported in [33]–[35], the formation of a crystalline phase increases the melt viscosity and therefore retards porcelain densification.

The highest sintering rate is observed at 1160°C, where the dL/dT curve shows the largest deviation from the baseline. The maximum degree of densification, corresponding to zero water absorption ($W = 0\%$), is reached at 1200°C. The total decrease in specimen dimensions during heating to 1200°C and holding at this temperature is 6.42%. During cooling from 1200 to 1150°C, the specimen undergoes an additional 2.61% dimensional decrease, indicating continued densification due to thermal inertia. No extrema are observed on the dL/dT curve during cooling, which suggests that the phase-formation processes have been completed.

The structural and phase characteristics of the resulting low-temperature electrical porcelain are shown in Figure 5. According to quantitative X-ray diffraction and petrographic analyses, the bulk of the low-temperature porcelain body (sample NEF-1) consists of colorless isotropic aggregates of a glass-mullite matrix. The crystalline phase consists mainly of mullite (~30 vol.%) and quartz (~12 vol.%). The predominant size of newly formed mullite crystals is approximately 0.007–8.0 μm .

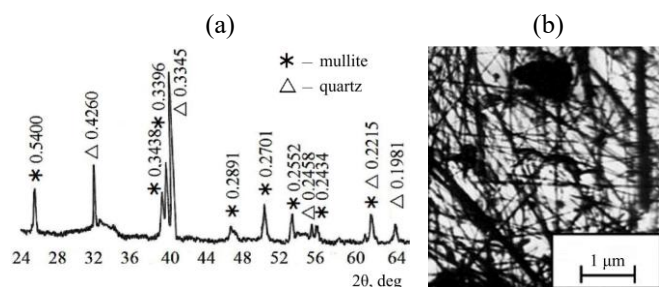


Figure 5. X-ray diffraction pattern fragment (a) and SEM micrograph of the NEF-1 specimen (b)

The low-temperature porcelain produced using the developed formulation underwent comprehensive testing at the certified laboratories of the Research Institute of High Voltages and Kharkivelektronadka (Kharkiv). Based on the test results, the developed material was recommended for the manufacture of products requiring enhanced electrophysical and physicomachanical properties, including high-voltage pins and suspension insulators.

Table 4 presents a comparative analysis of the properties of the developed electrical porcelain and its industrial counterparts manufactured in Ukraine.

As shown by the data, the electrical porcelain produced using the developed body composition achieves complete densification, a volume resistivity exceeding $4 \cdot 10^{14} \Omega \cdot \text{m}$, and improved dielectric and mechanical strength, making it a promising material for the production of high-voltage insulators. Thus, the use of feldspar concentrate from the Lozuvatka deposit with the addition of 2 wt.% dolomite from the Nehrebiivka deposit intensifies the formation and densification of electrical porcelain while reducing the firing temperature by 150°C compared with industrial counterparts.

Table 4. Properties of electrical porcelain produced using the developed and conventional technologies

Properties	Developed low-temperature electrical porcelain	Olevsk Porcelain Plant LLC	Poliankivskiy Porcelain Plant JSC
Firing temperature, °C	1200	1350	1350
Volume resistivity (ρV), $\Omega \cdot \text{m}$ ($f = 50 \text{ Hz}$)	$4.4 \cdot 10^{14}$	$1 \cdot 10^{14}$	$2.5 \cdot 10^{14}$
Dielectric strength (E_{br}), kV/mm ($f = 50 \text{ Hz}$)	30	25	25
Relative permittivity, ϵ	3.4	6.5	6.1
Dielectric loss tangent, $\tan \delta$	$10.5 \cdot 10^{-3}$	–	–
Tensile strength (σ_t), MPa	35	30	–
Flexural strength (σ_f), MPa	77	65	62
Water absorption (W), %	0	0	0
Apparent density (ρ), kg/m ³	2875	2450	2400
Coefficient of linear thermal expansion, ($\alpha \cdot 10^6$), 1/°C	$4.92 \cdot 10^{-6}$	$4.50 \cdot 10^{-6}$	$4.60 \cdot 10^{-6}$

The results also provide insight into the mechanism of structure and phase formation in low-temperature porcelain. It involves accelerated sintering and complete densification in the presence of a feldspar melt modified with CaO and MgO, accompanied by intensive formation of needle-like secondary mullite. The mullite content reaches approximately 30 vol.% when the established optimal ratio of raw materials (clay : kaolin : FSC = 40:22:28) is maintained and 0.3 wt.% TiO₂ is added as a mineralizer.

Implementation of the developed approach in porcelain insulator production would enable the use of alternative mineral raw materials readily available in unoccupied regions of Ukraine while reducing industrial energy consumption during firing. This is particularly important for reducing Ukrainian manufacturers' dependence on imported raw materials and advancing energy-efficient production of electrical porcelain.

Further research will focus on refining the processing parameters for shaping porcelain products by plastic forming and slip casting, which is necessary to optimize the complete production cycle of porcelain insulators.

4. Conclusions

The results of this study are of considerable practical importance for sustainable development, the technical modernization of national production capacities, and the supply of strategic industries with domestically sourced mineral raw materials.

Based on the analysis of the fluxing ability of pegmatites from the Lozuvatka deposit and their beneficiation product (FSC), the conditions for their effective use in porcelain insulator production were established. The chemical and mineralogical composition of the alternative fluxing raw material was determined, and the possibility of modifying the properties of the feldspar melt, which govern sintering intensity and phase formation, was demonstrated using FSC in combination with 2 wt.% dolomite. The mechanism of electrical porcelain formation under energy-efficient firing conditions, with the firing temperature reduced by 150°C, was established for a combined fluxing system consisting of FSC and dolomite together with 0.3 wt.% TiO₂ as a mineralizer.

The structure of the low-temperature electrical porcelain is formed through accelerated sintering and maximum densification in the presence of a modified feldspar melt. This effect is associated with earlier melt formation, lower melt viscosity, and an enhanced ability of the liquid phase to dissolve residual clay minerals and quartz grains. At the same time, the mineralizing additive improves the phase composition of the porcelain by increasing the mullite content to approximately 30 vol.%. Mullite microfibers form a felt-like network that reinforces the glassy phase, improves structural homogeneity, and contributes to the high mechanical and dielectric properties of the resulting products.

The findings support the development of domestic porcelain production for electrical applications and help strengthen Ukraine's raw material and technological independence, while also creating new employment opportunities in the mining sector. The results are particularly relevant to manufacturers seeking to optimize production costs amid rising energy prices and the increasing cost of imported feldspar raw materials. Implementation of the proposed technological solutions could reduce dependence on feldspar imports and enable more energy-efficient production of electrical porcelain, thereby supporting the stable operation and further development of domestic manufacturers.

Author contributions

Conceptualization: OF, IN, SS; Investigation: KB, IN, SS; Methodology: OF; Project administration: RK; Resources: RK; Supervision: RK; Validation: VV; Visualization: KB, VV; Writing – original draft: OF, KB, IN, SS; Writing – review & editing: OF, RK, VV. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Пегматити України як сировина для виробництва електротехнічного фарфору

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Мета. Обґрунтування можливості використання польовошпатового концентрату, одержаного зі збагачених пегматитів Лозуватського родовища, як вітчизняної флюсуючої сировини для виробництва низькотемпературного електротехнічного фарфору та визначення рецептурно-технологічних параметрів його енергоощадного випалу.

Методика. Хімічний і мінеральний склад вихідної сировини досліджували методами хімічного, петрографічного та рентгенофазового аналізів. Радіаційні властивості пегматитів визначали гамма-спектроскопічним методом. Флюсуючу здатність польовошпатового концентрату оцінювали графоаналітичними розрахунками у системах $\text{Na}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2$ і $\text{K}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2$. Склади мас оптимізували методом повного факторного експерименту. Зразки формували пластичним способом із мас, одержаних шлікерним методом, і випалювали при температурі 1150-1250°C. Спікання, механічні, теплофізичні та електрофізичні властивості визначали стандартними методами. Структурно-фазові особливості вивчали методами дилатометрії, рентгенівської дифракції, оптичної та сканувальної електронної мікроскопії.

Результати. Встановлено раціональне співвідношення глини, каоліну та польовошпатового концентрату 40:22:28 при вмісті 15 мас. % кварцового піску, 2 мас. % доломіту і 0.3 мас. % TiO_2 . За температури 1200°C одержано щільний електрофарфор із нульовим водопоглинанням, електричною міцністю до 30 кВ/мм, питомим об'ємним опором понад 41014 Ом·м, міцністю при згинанні 77 МПа та вмістом муліту близько 30 об.%. Ознак високотемпературної деформації в інтервалі 1150-1250°C не виявлено. Температуру випалу знижено на 150°C порівняно з промисловими аналогами.

Наукова новизна. Встановлено механізм прискореного спікання електрофарфору в присутності польовошпатового розплаву, модифікованого CaO і MgO, та мінералізуючої добавки TiO_2 . Показано, що раннє утворення розплаву, зниження його в'язкості та інтенсивне формування голчастого вторинного муліту забезпечують максимальне ущільнення і підвищення механічних та діелектричних властивостей матеріалу.

Практична значимість. Використання виключно вітчизняної сировини дає змогу зменшити імпортозалежність виробництва фарфорових ізоляторів, скоротити енерговитрати на випал і підвищити конкурентоспроможність українського електрофарфору.

Ключові слова: пегматити; польовошпатовий концентрат; електротехнічний фарфор; низькотемпературний випал; муліт; спікання; діелектричні властивості

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