MINERALOGICAL–FUNCTIONAL CRITERIA FOR THE INTEGRATION OF MINING RESIDUES INTO BUILDING CERAMIC MATERIALS

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ABSTRACT

The valorisation of mining waste within the ceramic industry represents a key strategy for advancing towards more sustainable production models, reducing the consumption of natural resources and lowering the carbon footprint associated with the construction sector. However, the marked mineralogical and chemical heterogeneity of these wastes hinders their systematic incorporation into ceramic bodies intended for the manufacture of bricks and other construction products. The absence of unified criteria that define the technical role each type of residue may play within the ceramic process generates uncertainty for manufacturers and prevents the establishment of stable synergies between the extractive and ceramic industries.

The objectives of this paper are to establish a conceptual framework linking the mineralogical composition of mining residues with the ceramic functions they may perform, and to propose a functional classification comprising five categories—non-plastic fillers, fluxes, structural loads, plasticity modifiers and colourants—to guide their potential use. Technical criteria are also defined to assess the suitability of each residue for its application in ceramic construction materials, complemented by a replicable methodological tool intended to support further research and industrial feasibility studies.

The methodology is based on a critical review of scientific and technical literature combined with a conceptual synthesis of key ceramic properties. The main types of mining residues generated in extractive and metallurgical operations are identified, and their predominant mineralogical families analysed. For each residue, essential parameters are considered, including mineralogical composition, thermal behaviour, particle size distribution, potential plasticity and the presence of critical compounds. From this information, correspondences are established between residue properties and their potential ceramic functions, together with minimal environmental considerations to ensure the viability of incorporating these materials into construction products.

The main outcome is the development of a mineralogical–functional classification that allocates mining residues to the five proposed ceramic functions. Silica- and quartz-rich residues are identified as potential fillers; feldspathic materials and those with low melting temperatures function as fluxes; clay-rich residues and phyllosilicates act as structural loads or plasticity modifiers; while iron-oxide-rich or metallic-oxide-bearing materials are suitable as colourants. This classification not only evaluates technical functionality but also considers compatibility with ceramic shaping and firing processes (extrusion, pressing and sintering), alongside effects on final properties such as porosity, mechanical strength and water absorption.

This study therefore proposes a methodological approach for classifying mining residues according to specific ceramic functions, facilitating their selection and potential application in construction materials. Moreover, it enables the identification of opportunities for substituting natural raw materials, optimising ceramic formulations and supporting circular-economy strategies, including emissions reduction across the sector. Although conceptual in nature, this work provides a solid basis for future research aimed at experimentally validating the performance of each category at laboratory scale. Overall, the systematic application of this classification has the potential to make a significant contribution to the sustainability and efficiency of the ceramic production process.

KEYWORDS: mining waste valorisation; ceramic construction materials; mineralogical–functional classification; circular economy; sustainable ceramic production.

1. INTRODUCTION

The extractive industry generates millions of tonnes of mining waste each year in the form of waste rock, tailings, sludges and slags. A significant proportion of these materials remains stored in dumps and tailings ponds, with associated risks of soil, water and air contamination, particularly in the case of sulphidic wastes capable of generating acid mine drainage [1]. Several studies indicate that, within the European Union, mining and quarrying wastes represent a notable proportion of the total waste produced, highlighting the need for material valorisation strategies within the framework of the circular economy [2], [3], [4].

In parallel, the ceramic industry for construction (bricks, roof tiles, blocks and tiles) faces the challenge of reducing its environmental footprint, limiting the consumption of non-renewable natural resources, particularly high-quality clays, and consequently decreasing the emissions associated with firing processes [1], [5]. In this context, various studies have demonstrated the technical feasibility of incorporating mining wastes as secondary raw materials in the manufacture of ceramic products, both structural and facing. The literature reports experiments with sulphidic tailings, flotation residues, phosphate mining sludges, coal mine wastes, tungsten tailings, zinc processing residues and other mining by-products in ceramic formulations for bricks, roof tiles and tiles [6], [7], [8], [9], [10]..

Figure 1. Mining waste and ceramic products

Simão et al. [8] analysed the use of sulphidic tailings in the manufacture of facing bricks, demonstrating through life cycle assessment that a 40 wt.% substitution can improve the environmental performance compared with conventional bricks, while maintaining acceptable physico-mechanical properties. Likewise, other recent studies have shown the feasibility of using phosphate residues and phosphate mining waste rocks to produce eco-efficient fired bricks, achieving strength and water absorption values compatible with their use in construction [6]. Other studies employ coal mining residues and contaminated soils in the manufacture of structural ceramics, analysing physical, radiological and leaching properties [11].

In the field of cladding materials and higher value-added products, formulations of ceramic tiles and porcelain stoneware have been developed using lignite and copper mining residues, bentonite wastes and iron mining residues, as well as ceramic membranes and high-temperature materials obtained from different mining wastes [10], [12]. More recently, permeable bricks incorporating tungsten tailings and bricks containing zinc processing residues have been produced, showing suitable properties for specific construction applications [13], [14], [15].

However, despite the growing number of studies, the integration of mining wastes into the ceramic industry remains limited and largely dependent on specific projects. One of the main barriers is the remarkable mineralogical and chemical heterogeneity of these residues, which hinders their systematic use in industrial plants accustomed to relatively stable raw materials. In addition, ceramic construction products must meet strict regulatory requirements in terms of mechanical strength, water absorption, durability and dimensional stability. Industrial adoption still faces relevant obstacles; for example, uncertainties remain regarding long-term stability and the risk of leaching, which complicates confirmation of their environmental advantages [16], [17], while the strong compositional variability of tailings compromises the uniformity of ceramic formulations [18].

In this context, there is a need to establish a methodological proposal that facilitates, at an initial stage, the classification and selection of mining residues according to their technical role within ceramic bodies. Beyond the mere chemical and mineralogical description, it is useful to associate each residue with one or several ceramic functions so that industry can recognise, from early stages of investigation, their potential applications and limitations in ceramic materials for building. This study is therefore aimed at proposing a functional classification framework for mining residues as additives or substitutes for traditional raw materials in ceramic construction products.

The study carried out, based on recent literature, proposes linking the composition of mining residues with the functions they may perform in ceramic bodies for construction materials. To this end, a mineralogical–functional classification is established in five categories—fillers, fluxes, structural loads, plasticity modifiers and colouring agents—in order to systematise their integration into ceramic matrices on the basis of bibliographic knowledge, facilitating knowledge transfer between the mining and ceramic sectors and supporting decision-making for their incorporation..

2. METHODOLOGY

Given the bibliographic nature of the present study, as a basis for the development of research on mining residues for their incorporation into ceramic materials for construction, the methodology has been structured around three main axes: critical review of the scientific–technical literature, comparative analysis of key ceramic properties, and systematisation of classification criteria.

2.1. Literature review and selection of case studies

In an initial phase, a literature review was carried out focusing on:

- structural ceramics (bricks, blocks, roof tiles) produced with tailings and mining residues;
- ceramic tiles and cladding materials incorporating residues from different mining operations;
- technical ceramics (refractory materials, glass-ceramics, etc.) obtained from mining waste, used as a reference for compositions and crystalline phases of interest.

Among the analysed works are studies on different products manufactured using sulphidic tailings, coal mining wastes, phosphate mining sludges, bentonite residues, tungsten tailings and zinc processing wastes, as well as reviews on ceramics produced from iron mining residues and other mining wastes.

This review made it possible to identify the most frequent types of residues, their typical composition and the range of contents that have been used in ceramic formulations, as well as the main benefits and technical issues associated with their use (expansion phenomena, undesirable colouration, formation of secondary phases, gas emissions, etc.).

2.2. Identification of mining families

Based on the information collected, mining residues were grouped into the following most common mineralogical families:

- siliceous/quartz–feldspathic residues (tailings from metal mining operations, feldspar residues, washing sands);
- clayey residues/phyllosilicates (washing sludges, residual clays, residual bentonites);
- carbonate residues (waste from carbonate mines, marble powders, limestones);
- residues rich in iron oxides and other metallic oxides (iron and manganese tailings, zinc processing residues, phosphate sludges containing Fe);
- mixed or complex residues (sulphidic tailings composed of mixtures of silicates, sulphides, carbonates and oxides).

2.3. Key classification parameters

The key parameters identified in the literature review that allow the suitability of residues to be determined correspond to the following:

- mineralogical composition (generally identified by X-ray diffraction, XRD);
- overall chemical composition (major oxides, determined by XRF or equivalent methods);
- thermal behaviour (mass loss, decomposition processes, formation of liquid or vitreous phases, according to differential thermal and thermogravimetric analysis);
- particle size distribution and particle morphology, with a direct impact on paste rheology and densification;
- presence of potentially problematic elements (sulphides, heavy metals, volatiles)..

2.4. Definition of ceramic functions

Determining the potential usefulness of residues requires assigning one or more ceramic functions within the formulation in order to recognise their role. The most relevant functions are:

1. Temper: material essentially inert at the firing temperature, with low plasticity, which reduces drying and firing shrinkage, limits cracking and controls porosity.
2. Flux: material that lowers the sintering temperature and promotes the formation of a liquid or vitreous phase, improving densification.
3. Structural load: main component of the body, providing volume and structure and combining with the base clay.
4. Plasticity modifier: material that increases or reduces the plasticity of the raw body, adjusting its behaviour during shaping (extrusion, pressing).
5. Colouring agent: residue that provides chromophore oxides (Fe_2O_3, MnO, etc.), modifying the colour of the fired product. In some cases this function is desirable (reddish or ochre tones), while in others it may be limiting..

3. RESULTS

In the context of this study, the results obtained through the analysis of the existing literature on ceramics incorporating mining residues are presented below.

3.1. Proposed Mineralogical–Functional Classification

Table 1 presented below summarises the functional allocation of the main families of mining residues, proposing a classification that is not closed but flexible, in which a single residue may simultaneously perform several functions within the ceramic matrix.

Table 1. Mineralogical–Functional Classification of Mining Residues

Residue family	Dominant mineralogy	Main ceramic functions	Expected effects on the product	Precautions / difficulties
Siliceous / quartz–feldspathic [19][20][21]	Quartz, feldspars (K, Na), micas	Filler; flux	Reduction of shrinkage; improved sintering	Particle size control; possible brittleness
Clayey / phyllosilicates [1][22]	Illite, kaolinite, smectite/bentonite, chlorite	Structural load; plasticity modifier (major component of the body)	Improved workability; aluminosilicate phase formation	Risk of high shrinkage
Carbonate-rich [2][9][23]	Calcite, dolomite (marble powders, waste limestone rocks)	Porosity modifier; moderate flux	Increased porosity; lower sintering temperature	CO_2 release control; strength loss if excessive
Fe-rich [7][9][19]	Hematite, goethite, magnetite, Mn oxides and other metal oxides	Colouring agent; secondary flux	Intense colouration; improved densification	Chromatic variability
Mixed / sulphidic [12][20]	Mixture of silicates, sulphides (pyrite, pyrrhotite), carbonates and oxides	Combination of previous functions: filler + flux + colourant	Improved densification; raw material savings	SOx emissions; risk of microcracking

3.2. Applications of Residues in Ceramic Products

The proposed functional allocation is established on the basis of the main results obtained in experimental studies reported in the literature.

3.2.1. Bricks and roof tiles with siliceous and sulphidic tailings

In bricks and roof tiles, sulphidic tailings incorporated in proportions of 5–20% maintain or improve mechanical strength and comply with water absorption limits when particle size distribution and firing conditions are optimised [1]. They are interpreted as filler–flux materials due to their quartz–feldspathic composition, although the presence of sulphides requires control of emissions and aesthetic effects [19].

3.2.2. Ceramics with coal mining residues

Coal mining residues require adjustments in formulation and thermal cycle due to gas emissions and trace elements. Nevertheless, they allow the production of bricks with properties that meet regulatory requirements [11]. They are classified as partially fluxing structural loads.

3.2.3. Bentonite residues and sludges in tiles

Bentonite residues improve densification and reduce porosity without affecting strength, acting as structural loads and plasticity modifiers [10]. Mining sludges enable savings in virgin raw materials and energy, functioning as fluxes or structural loads depending on their composition.

3.2.4. Phosphate, tungsten and zinc residues

Phosphate residues allow the manufacture of eco-efficient bricks with suitable properties, acting as structural loads, fluxes and colouring agents [7]. Tungsten tailings and zinc processing residues facilitate the adjustment of porosity and permeability, being classified as specialised fillers/fluxes [29]..

Table 2. Applications of Mining Residues in Structural Ceramics

Type of residue (with references)	Ceramic product	Main function	Substitution range (%)	Observed properties (summary)
Siliceous tailings (quartz–feldspar) [24][25][26][27][28]	Bricks, roof tiles, ceramic tiles	Filler + (flux if feldspars are present)	5–40	Reduction of shrinkage; adequate compressive strength; water absorption comparable to commercial products (depending on formulation and firing cycle).
Sulphidic/metalliferous tailings with sulphides [8][16][17][18][29]	Bricks, roof tiles	Filler + flux + colouring agent (dependent on Fe/S content)	5–20	Acceptable densification; colour development due to Fe oxidation; need for control of emissions (SOx) and surface defects.
Coal mining residues / waste rock and by-products [11][20][1][19][5]	Structural bricks	Structural load (partial)	10–30	Mechanical properties compatible with regulatory requirements in optimised formulations; requires adjustment of firing conditions and radiological control when applicable.
Phosphate mining sludges / tailings and waste rocks [1][9][19][1][21]	Bricks	Structural load + flux	10–50	Adequate mechanical strength; controllable water absorption; potential improvement in eco-efficiency depending on formulation (including carbonate additions).
Bentonite residues / special clays (including fine fractions) [1][19][21]	Ceramic tiles / stoneware	Plasticity / rheology modifier	5–20	Improved workability and densification; reduction of open porosity in fine formulations; sensitivity to shrinkage if the clay fraction increases.

4. CONCLUSIONS

This work presents a proposal for the classification of mining residues for their use in ceramic materials intended for building applications. Based on a review of recent literature on different ceramic products manufactured with tailings, sludges and residues from diverse origins, the main mineralogical families of residues have been identified and specific ceramic functions have been assigned to them.

The main conclusions can be summarised as follows:

1. The available evidence demonstrates that numerous mining residues are technically viable as secondary raw materials in construction ceramics, provided that their composition and thermal behaviour are controlled and that the regulatory requirements of the products are respected.
2. The proposed mineralogical–functional classification provides researchers and industry with a conceptual tool to anticipate the role of a residue within a ceramic formulation, guide the selection of priority tests and anticipate possible problems (emissions, defects, undesirable colouration).
3. The assignment of functions (filler, flux, structural load, plasticity modifier and colouring agent) is consistent with the experimental results reported and helps to interpret the effects of residues on key properties such as compressive strength, water absorption and microstructure.
4. The systematic integration of mining residues into ceramic production requires linking mineralogical and chemical characterisation with regulatory requirements, so that innovation in formulations is accompanied by demonstrations of regulatory compliance and environmental assessments (LCA, leaching tests and radiological analyses when appropriate).
5. The bibliographic study provides a solid basis for the design of future laboratory and pilot-scale studies. These studies should validate the proposed classification with real cases, quantify optimal substitution limits and evaluate environmental and economic impacts in comparison with conventional products.

In summary, the proposal presented contributes to structuring the dispersed knowledge on ceramics incorporating mining residues, facilitating dialogue between the mining and ceramic sectors and supporting the transition towards more sustainable manufacturing models aligned with the principles of the circular economy in the building sector.

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