Porous ceramics as a sustainable solution for estuarine dredged mud

Cerâmica porosa como solução sustentável para lama de dragagem estuarina

Cerámica porosa como solución sostenible para los lodos de dragado estuarino

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Abstract: Amid ongoing environmental degradation and its unmistakable climatic impacts, there is an urgent need to enhance exploratory practices and increase the utilization of local materials capable of reducing environmental liabilities. Although some studies have incorporated small amounts of dredged sediment into conventional ceramic formulations, few have explored the use of estuarine dredged sludge as the predominant raw material, limiting the potential to reduce

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mineral extraction and ocean disposal. This study examines the potential of estuarine dredged sediment as the primary raw material for producing porous ceramics, proposing an approach that integrates thermal efficiency, circularity, and decreased reliance on mineral extraction. Samples were collected from the Port of Rio Grande complex (RS, Brazil) and thoroughly characterized chemically, physically, and mineralogically, followed by sintering at 900 °C. The resulting ceramics exhibited design thermal conductivity values between 0.23 and 0.37 W/mK and a bulk density of 1.80 g/cm³, demonstrating effective thermal insulation without compromising mechanical strength. The research is grounded in the framework of regenerative sustainability, understood as an evolution of conventional approaches, promoting the integration of human and natural systems through coevolutionary processes. Accordingly, the reuse of dredged sediment is conceived not merely as environmental mitigation but as the reintegration of material into the living cycle of the territory.

Keywords: Clayfired; Dredged Material; Beneficial use of Waste; Regenerative Sustainability; Energy Efficiency.

Resumo: O atual contexto de degradação ambiental, com impactos climáticos inequívocos, reforça a urgência de aprimorar práticas exploratórias e ampliar o uso de materiais locais capazes de reduzir passivos ambientais. Embora alguns estudos incorporem pequenas quantidades de sedimento dragado em formulações cerâmicas convencionais, poucos exploraram o uso da lama de dragagem estuarina como matéria-prima predominante, limitando o potencial de reduzir a extração mineral e o descarte oceânico. Este estudo experimental investiga a viabilidade de produzir cerâmica porosa utilizando lama de dragagem estuarina como principal matéria-prima. O material foi coletado no complexo portuário do Rio Grande (RS), caracterizado química, física e mineralogicamente, e submetido à sinterização a 900 °C. As cerâmicas obtidas apresentaram condutividade térmica de projeto entre 0,23 e 0,37 W/mK e densidade aparente de 1,80 g/cm³, demonstrando bom desempenho como isolante térmico sem perda de resistência mecânica. A pesquisa ancora-se na perspectiva da sustentabilidade regenerativa, entendida como uma evolução das abordagens tradicionais, ao promover a integração entre sistemas humanos e naturais em processos coevolutivos. Assim, o reaproveitamento do sedimento dragado é compreendido não apenas como mitigação ambiental, mas como reintegração do material ao ciclo vivo do território.

Palavras-chave: Cerâmica vermelha; Material dragado; Uso benéfico de resíduos; Sustentabilidade Regenerativa; Eficiência energética.

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CLG: Conceptualization; Data curation; Investigation; Methodology; Project administration; Supervision; Validation; Visualization; Writing – original draft; Writing – review & editing. RCGV: Conceptualization; Visualization; Writing – original draft; Writing – review & editing. MRFG: Conceptualization; Methodology; Supervision; Resources.

Conflict declaration
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Resumen: El contexto actual de degradación ambiental, con impactos climáticos evidentes, resalta la necesidad de mejorar las prácticas de explotación y ampliar el uso de materiales locales capaces de reducir pasivos ambientales. Aunque algunos estudios han incorporado pequeñas cantidades de sedimento dragado en formulaciones cerámicas convencionales, pocos han explorado el uso del lodo de dragado estuarino como materia prima predominante, limitando el potencial de disminuir la extracción de minerales y la disposición oceánica. Este estudio experimental evalúa la viabilidad de producir cerámica porosa utilizando lodo de dragado estuarino como insumo principal. El material fue caracterizado química, física y mineralógicamente, y posteriormente sometido a sinterización a 900 °C. Las cerámicas obtenidas mostraron conductividad térmica de diseño entre 0,23 y 0,37 W/mK y densidad aparente de 1,80 g/cm³, demostrando un desempeño eficaz como aislante térmico sin comprometer la resistencia mecánica. La investigación se sitúa dentro del marco de la sostenibilidad regenerativa, entendida como una evolución de los enfoques tradicionales, promoviendo la integración de los sistemas humanos y naturales mediante procesos coevolutivos. Así, la reutilización del lodo de dragado se concibe no solo como mitigación ambiental, sino como reintegración de los materiales en el ciclo vital del territorio.

Palabras clave: Cerámica cocida; Material dragado; Uso beneficioso de residuos; Sostenibilidad regenerativa; Eficiencia energética.

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1 INTRODUCTION

Regenerative sustainability advocates a paradigm shift, moving beyond conventional approaches that focus solely on mitigating environmental damage, toward achieving net-positive socio-ecological impacts (Du Plessis, 2012; Du Plessis; Brandon, 2014; Devi; Jeyaradha, 2023). This transition involves adopting a production model in which discarded materials are reintegrated into productive cycles (Lyle, 1994; Reed, 2007; du Plessis, 2012), enabling their reconfiguration into more complex structures that generate value for the common good (Garcia; Freire; Franzato, 2023; Devi; Jeyaradha, 2023).

From this perspective, the use of locally available resources, particularly those associated with clay extraction for the ceramic industry (Fonseca; Morais, 2022), becomes a relevant strategy for developing environmentally responsible production processes. Current research has therefore focused on raw materials capable of incorporating *mining tailings* (Vimieiro et al., 2024; Amaral et al., 2021; Menezes; Neves; Ferreira, 2002) and *organic or inorganic waste* (Silva et al., 2022; Vieira; Monteiro, 2009; Lima, 2023), including dredged sediments from waterways (Mesrar et al., 2021; Silva et al., 2022; Larrosa et al., 2023), as potential inputs for the production of sustainable ceramic materials.

Dredged sediments are materials extracted from the beds of water bodies, primarily composed of mineral particles ranging from sand to clay, along with organic matter and, in some cases, pollutants (Hamer; Karius, 2002; Romero *et al.*, 2008; Castro; Almeida, 2012; Barksa *et al.*, 2018; Mesrar *et al.*, 2021; Solanski *et al.*, 2023).

Analyses aimed at improving the disposal of dredged sediments have been conducted since the 1970s (Lee, 1976), driven by concerns regarding contamination resulting from the deposition of this material on land or in water bodies (Burt, 1996). Two main research traditions stand out: (a) studies on sediment decontamination through methods that render it inert (Hamer; Karius, 2002; Becarelli *et al.*, 2023); and (b) studies on beneficial use in industry, civil construction, or agriculture (Hamer; Karius, 2002; Teixeira; Dias, 2008; Mesrar *et al.*, 2021; Villwock *et al.*, 2021; Larrosa *et al.*, 2023; Solanski *et al.*, 2023), with the latter being the primary focus of this study.

In some studies, notably the seminal work by Hamer and Karius (2002), these two research strands converge. Their findings indicate that ceramic production, as a thermal process, not only stabilizes contaminated sediments but also enables the beneficial use of dredged materials, as evidenced by the industrial-scale production of fired clay bricks. Subsequent research has further shown that dredged sediments from diverse waterways worldwide can be incorporated into ceramic mass formulations at varying percentages (Mesrar *et al.*, 2021; Slimanou *et al.*, 2020), while also highlighting the significant presence of organic matter in most sediments (Baruzzo *et al.*, 2006; Romero *et al.*, 2008; Belmonte; Bertelsen, 2016; Baksa *et al.*, 2018).

Although ceramic materials are often criticized (Del Rio et al., 2022) for the high energy required during firing, red ceramics offer significant regenerative potential. Their durability, recyclability, and capacity to incorporate waste, combined with broad cultural acceptance in Brazilian construction (Menezes; Neves; Ferreira, 2002), particularly when integrated into local production systems, (Lyle, 1994; Du Plessis, 2012;

Hes; Du Plessis, 2015), make them promising materials for regenerative practices within the built environment, a topic that warrants further investigation.

Ceramic materials have demonstrated a significant ability to incorporate both organic and inorganic waste into their raw materials, particularly in products for the construction industry (Menezes; Neves; Ferreira, 2002; Vieira; Monteiro, 2009; Lima, 2023). The incorporation of organic waste into clays used in ceramic production results in key characteristics, such as reduced density, increased porosity, and decreased thermal conductivity (Menezes; Neves; Ferreira, 2002; Vieira, Monteiro, 2009; Silva *et al.*, 2022), making these materials particularly suitable for the development of insulating materials.

Porous ceramics, as materials with insulating properties and the potential to improve energy efficiency, even in reinterpreted versions incorporating waste, do not face usage constraints related to the absence of regulatory standards, a frequent challenge for products developed from novel or certain bio-based materials (Bal; Rani, 2025).

The presence of organic compounds in the raw ceramic materials, which disappear during the firing process, is one of the factors responsible for the formation of voids (Dutra; Pontes, 2002; Areias *et al.*, 2017; Silva *et al.*, 2022; Pessanha; Holanda, 2023). This presence in dredging sediments highlights their potential for producing porous ceramics (Mesrar *et al.*, 2021; Slimanou *et al.*, 2020), with industrial applications in filtration systems, catalytic supports, or thermal and acoustic insulation (Silva *et al.*, 2022). In other words, this type of ceramic has the potential to offer environmental benefits, such as energy efficiency and pollutant decontamination (Hamer; Karius, 2002).

Although the heterogeneity of ceramic masses enables numerous compositions incorporating waste and by-products (Amaral *et al.*, 2021; Areias *et al.* 2017; Petterle *et al.*, 2018; Pessanha; Holanda, 2023), it is crucial to fully understand all the raw materials involved in both the shaping process and the firing cycle, as these are the primary factors influencing the physical-mechanical properties (Brito *et al.*, 2015; Santos *et al.*, 2017; Figueiredo *et al.*, 2018) and environmental safety, such as gas emissions or leaching of contaminants throughout the product's life cycle (Hammer; Karius, 2002).

The presence of organic matter in the extracted sediments is more pronounced in waterways located in freshwater or estuarine environments (Mesrar *et al.*, 2021; Santos *et al.*, 2017).

However, in estuarine waterways, salinity fluctuations driven by the hydrological dynamics of the environment can result in continuous variations in the composition of dredged sediments, particularly concerning salts and chlorides (Madeira; Ilha, 2023), depending on rainfall patterns and wind dynamics.

In this context, for beneficial use of the sediment in industrial processing, it is essential that the material can accommodate variability in its composition without compromising the performance of the final product (Solanski *et al.*, 2023; Lima, 2023). This need for adaptability supports the application of such sediment in the ceramic industry, given the high firing temperatures to which the raw material is exposed (Menezes; Neves; Ferreira, 2002).

The extraction of clay from traditional natural deposits for use in the ceramic industry generates numerous environmental impacts, including soil nutrients depletion, loss of biodiversity, hydrological instability, physicochemical alterations, and subsequent erosion processes (Cavalcante *et al.*, 2021; Scalco; Ferreira, 2013). In the Brazilian context, constructing with ceramic materials is particularly significant due to the widespread adoption of this technique, especially in the rapidly expanding self-built urban areas. Nationwide, millions of tons of clay are consumed monthly exclusively for the production of fired clay blocks and bricks (Brazil, EPNM, 2024).

On the other hand, the volume of dredged sediments in waterways are also highly significant. The National Dredging Program (PND) of Brazil projected that by 2020, more than 80 million m^3 of sediment would be removed (Brazil, PND, 2007). For instance, the periodic maintenance dredging at the Port of Rio Grande, located in the southernmost region of Brazil - the context selected for this study - removes up to 35 million m^3 of sediment every two years to maintain the required depth for large vessels (Villwock; Nicolodi; Calliari, 2021). This represents the largest dredged volume among the 16 Brazilian ports listed at PND (Brazil, PND, 2007).

This volume of sediment, usually disposed of in licensed offshore areas, has frequently been linked to significant periodic accumulations of mud on adjacent beaches, with numerous socio-environmental impacts arising from the suspected return of the muddy fraction present in the discarded dredged sediments (Ferreira; Freitas, 2019; Calliari *et al.*, 2020).

The use of dredging sediments in the ceramic industry, especially with the aim of minimizing the volume of material extracted from natural deposits in mass formulations, is highly relevant for potentially reducing extraction volumes and the associated impacts of the dredging process itself, making research in this area particularly important.

In the Brazilian context, “tailings” are materials whose recovery is economically or technologically unfeasible, as defined by the National Solid Waste Policy (Brazil, L. 12.305, 2010). In other words, when a feasible technological process becomes available for utilizing material that would otherwise be discarded, it could be reclassified as “waste”, highlighting the importance of academic research exploring alternatives uses. It is crucial to consider the issue of economic viability outlined in the legislation, as, depending on the context, this viability may be regarded as a socio-environmental cost, particularly in cases involving contaminated sediments.

Most studies, however, propose incorporating a certain percentage of waste or tailings into a ceramic mass typically used in the study region (Lima *et al.*, 2023; Menezes; Neves; Ferreira, 2002). In contrast, few studies, focus on using waste or tailings as the primary raw material, without including material extracted from natural deposits in the ceramic mass mixture (Silva *et al.*, 2022). Even fewer investigate the use of dredged sediments as the main raw material in industrial beneficial processes or explore the incorporation of other associated wastes (Hamer; Karius, 2002; Mezencevova *et al.*, 2012). Moreover, there is a notable lack of research on producing porous ceramics from dredged sediments as the primary raw material, particularly from estuarine waterways, where clay content is expected to be higher (Mesrar *et al.*, 2021; Barksa *et al.*, 2018).

The regenerative approach (Lyle, 1994; Reed, 2007 Du Plessis, 2012; Du Plessis; Brandon, 2015), which promotes the use of local materials to minimize carbon footprint while respecting construction techniques culturally established in ceramic block usage, underscores the significance of this study. By situating the reuse of dredged sediments within this framework, the research contributes to advancing discussions on regenerative material practices and their socio-environmental potential.

In this context, the environmental relevance of employing estuarine dredged mud in the production of porous ceramics lies in its capacity to foster more sustainable waste management practices, reduce the extraction of natural resources, and enhance both pollutant filtration and energy efficiency. Expanding research in this field is therefore essential, as it raises critical questions regarding the viability and performance of porous ceramics formulated with estuarine dredged mud as the primary raw material.

Accordingly, *this study aims to develop and evaluate porous ceramics, utilizing estuarine dredged mud as the primary raw material.*

2 REGENERATIVE SUSTAINABILITY VIA LOCAL MATERIAL TRANSITIONS

Regenerative sustainability, proposed by Du Plessis (2012), stands as a disruptive paradigm that challenges traditional sustainability frameworks shaped since the mid-twentieth century. Drawing on Lyle's (1994) ecological design principles, Du Plessis (2012) argues that conventional sustainability rests on a mechanistic worldview incompatible with dynamic and interdependent socio-ecological systems (Lyle, 1994; Reed, 2007; Hes; Du Plessis, 2014). She distinguishes two main strands: "*sustainability as internationally negotiated public policy"* and as *"ecological modernization of the private sector"* (Du Plessis, 2012).

Conversely, *regenerative sustainability*, or *regenerative development*, is conceived as a *co-evolutionary partnership* between human and natural systems, oriented toward resilience, adaptation, and regeneration. It moves beyond mitigation or compensation, seeking positive socio-environmental outcomes (Lyle, 1994; Reed, 2007; Du Plessis, 2012; Hes; Du Plessis, 2014).

The post-war *Era of Development* shaped international environmental discourse, where UN conferences promoted utilitarian conservation models such as *ecological economics* and *ecosystem services*, foundations of ecological modernization. Within this paradigm, uncritical adoption of Modern Movement principles fostered urban planning centered on automobiles and environmentally inefficient buildings, with some context-sensitive exceptions in Brazil, Mexico, and South Africa (Du Plessis, 2012).

A key contribution from Du Plessis (2012) shift she proposes: from "*how to sustain development*" to "*how to develop in ways that sustain the integrity of human and natural systems.*" This perspective underpins co-evolutionary design strategies grounded in local culture and ecology, providing the theoretical basis for integrating estuarine dredged sediments into ceramic production systems.

In this study's context, the predominance of sandy regional soils (Goularte; Bastos; Dias, 2016; Brazil, CPRM, 2008) limits both the production of raw earth bricks and the extraction of suitable clays, which found only in deposits located about 70 km away (Brazil, CPRM, 2008). These constraints highlight the importance of exploring *local alternative raw materials* that can support process adaptations. In cold bioclimatic zones (1R and 1M), such as the context of this study, thermal performance is critical for ensuring energy efficiency and human comfort (NBR 15220:3, 2024). In regions where, self-construction accounts for the vast majority of housing production, reaching up to 85% of dwellings built or renovated without technical assistance (Brazil, CAU, BR/ Datafolha, 2023), materials compatible with local practices that reintroduce dredged sediments into production, while improving thermal behavior through porosity, represent regenerative ceramic solutions.

The concept of local material transitions refers to the adaptive reconfiguration of construction material cycles within specific territories aligning construction practices with locally available resources while fostering ecological and cultural regeneration (Hes; Du Plessis, 2014; Garcia; Freire; Franzato, 2023). Such transitions express a shift from extractive, linear material flows toward context-responsive material systems, where waste streams and by-products, such as estuarine dredged sediments, are reintegrated into productive cycles (Lyle, 1994; Devi; Jeyaradha, 2023). Within a regenerative framework, these processes represent not only a reduction of environmental impact but also a co-evolutionary strategy that reconnects material practices with place-specific ecological dynamics (Du Plessis, 2012; Hes; Du Plessis, 2014; Du Plessis; Brandon 2015).

In territories characterized by predominantly sandy soils, as observed in the southern coastal plain of Brazil (Brazil, CPRM, 2008), the availability of fine clayey fractions suitable for ceramic production is limited. The presence of clay minerals and silt in dredged sediments thus emerges as a relevant alternative source, especially when such materials originate from estuarine environments where mineral deposition occurs under slow natural hydrodynamic conditions (Goularte; Bastos; Dias, 2016). These sediments often exhibit granulometric and chemical characteristics compatible with those of natural clays, enabling their integration into ceramic masses (Madeira; Ilha, 2023). Therefore, the reuse of locally dredged materials not only contributes to the maintenance of port operation viability, which holds significant socioeconomic relevance for local communities, but also reinforces the territorial dimension of regenerative design by reintroducing locally available resources into construction processes.

The combination of raw materials with varying grain sizes is commonly employed in the ceramic industry to optimize the workability and cohesion of the materials. This adjustment significantly influences the drying process, ultimately resulting in ceramics with enhanced density and improved physical and mechanical properties (Pracidelli; Melchiades, 1997; Prado *et al.*, 2008; Figueiredo *et al.*, 2018). The Winkler's diagram (1954) proposes an ideal granulometric composition for the production of red ceramics and serves as an effective initial tool for balancing the proportions of clay, silt, and sand in ceramics masses (Pracidelli; Melchiades, 1997; Pérez *et al.*, 2010; Goes *et al.*, 2014; Santos *et al.*, 2017).

Like clays, dredging residues are predominantly composed of silica and aluminum oxides, followed by sodium, potassium, magnesium, and calcium, with a significant presence of iron oxide (Fe_2O_3) > 3% (Hamer; Karius, 2002; Romero *et al.*, 2008; Mezencevova *et al.*, 2012; Baksa *et al.*, 2018; Slimanou *et al.*, 2020; Larrossa *et al.*, 2023). The presence of fluxing oxides suggests that firing may occur at lower temperatures, between 800°C and 1000°C, facilitating the formation of a liquid phase and promoting densification of the ceramic materials. Additionally, it contributes to the reddish tone of ceramics, which is associated with the presence of iron oxide (Santos, 1989; Dondi, 2006; Santos *et al.*, 2017; Petterle *et al.*, 2018).

However, the presence of oxides such as sodium, calcium, magnesium, chlorides, and sulfates, which are also classified as soluble salts, is associated with the potential for efflorescence formation, which may compromise the durability and appearance of ceramic products (Dondi *et al.*, 1997; Menezes *et al.*, 2006; Ferreira; Bergmann, 2011; Lesovik *et al.*, 2020).

Dredging sediments, particularly estuarine or marine sediments due to their composition, often contain salts like chlorides and sulfates, which are significant factors for study because of their potential to generate toxic gases during firing and the possibility of efflorescence formation on ceramic pieces (Hamer; Karius, 2002; Belmonte; Bertelsen, 2016; Barksa *et al.*, 2018). However, literature suggests that the addition of barium compounds to ceramic masses may reduce efflorescence by converting soluble salts into insoluble ones (Pereira; Bernardin; Riella, 2000; Jindasuwan; Chakornnipit; Suorthina, 2015; Clim; Groll; Diaconu, 2016), as well as the potentially neutralizing gases generated during the firing process (Hamer; Karius, 2002).

Despite this, no direct correlation has been established between the content of soluble salts and the intensity of efflorescence (Dondi *et al.*, 1997; Menezes *et al.*, 2006). The presence of soluble salts in raw materials is not the sole determining factor for the formation of efflorescence (Belmonte; Bertelsen; Gieysztor, 2016). Other factors, such as the chemical composition of the salts and the microstructure of the ceramic pieces, also play a significant role in the occurrence of these deposits (Dondi *et al.*, 1997; Ferreira; Bergemann, 2011; Lesovik *et al.*, 2020).

Another factor to consider is the presence of organic matter observed in sediments from dredging operations (Mesrar *et al.*, 2021; Barksa *et al.*, 2018; Salin *et al.*, 2012). Organic products act as pore-forming agents and, when present in ceramic masses, alter their microstructure, increasing the material's porosity (Dutra; Pontes, 2002; Silva *et al.*, 2022, Pessanha; Holanda, 2023). In addition to organic materials, the presence of oxides such as calcium can also retard the densification process by promoting porosity through the release of carbon dioxide, which occurs during the decomposition of carbonates between 700°C and 800°C (Mesrar; Benamar; Jabrane, 2020).

The porous microstructure acts as a barrier to heat transfer, which, in ceramic materials occurs mainly through conduction, via vibration of the crystal lattice and heat transport by phonons, at temperatures up to 800°C (Petterle *et al.*, 2018). These materials, traditionally known as insulators, have low thermal conductivity, with values ranging from 0.70 to 0.90 W/mK for products such as bricks and roof tiles, according to NBR ISO 10456/2022-D (ABNT, 2022).

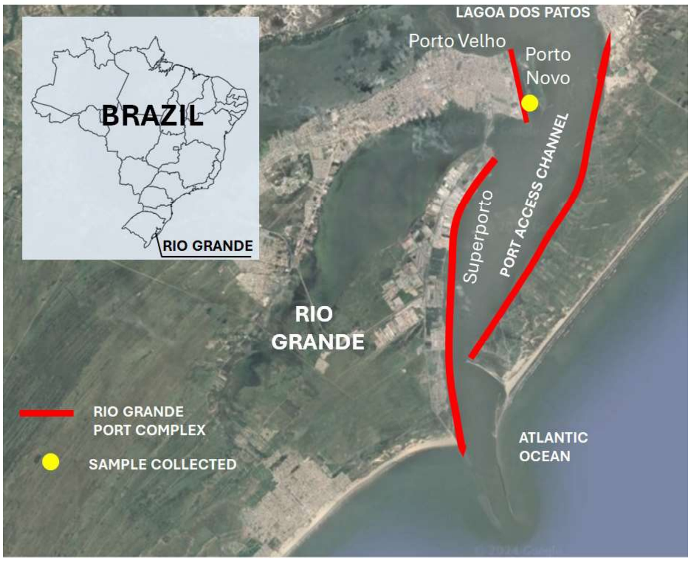
Considering the increase in porosity promoted by the addition of waste to ceramics, also observed in pieces produced with dredged sediments (Slimanou *et al.*, 2020), a significant reduction in thermal conductivity is expected in ceramics that use dredging sediments as raw material.

3 MATERIALS AND METHODS

The sediment analyzed originates from maintenance dredging operations in the access channel to the Port of Rio Grande, situated in the southernmost region of Brazil. This region is characterized by singular estuarine environment, a unique ecological system that connects *Lagoa dos Patos*, a coastal lagoon, to the Atlantic Ocean, providing a distinctive context for the study of estuarine dredge mud.

The literature indicates that the sediment from the access channel to the Rio Grande Port Complex is predominantly composed of clay (Madeira; Ilha, 2023) and exhibits high plasticity (Valério; Alves; Fontoura,

Figure 1 – The Porto of Rio Grande, Rio Grande do Sul, Brazil.



Source: Google Earth, modified by the authors.

2017; Machado; Bastos; Fagundes, 2019; Araújo; Silva; Fagundes, 2023), similar to conventional raw materials used in ceramic production (Santos, 1989; Pérez *et al.*, 2010; Goes *et al.*, 2014; Santos *et al.*, 2017). These characteristics informed the selection of this study area. The Rio Grande Port Complex comprises three sections - Porto Velho, Porto Novo, and Super Porto – extending from the estuary to the ocean, as illustrated in Figure 1.

The granulometric distribution of sediments along a dredged channel varies, with fine sediments, such as clay and silt, accumulating in deeper and low-energy areas, while coarser-grained sediments, such as sand, predominate in regions near the shore (Antiqueira; Calliari, 2005). Accordingly, for the experimental analysis conducted in the laboratory, sediment samples were collected from the area in front of Porto Novo, as indicated in Figure 1, where muddy material was obtained, as shown in Figure 2.

Figure 2 – Dredged mud sediment from the Port Access.

Source: research data.

The samples were provided by the Superintendency of the Port of Rio Grande during the dredging process of the access channel in the Porto Novo area, extracted on September 17, 2019, at the coordinates

32°07’20’ ‘S latitude and 52°05’36’ ’W longitude. The study was conducted in two phases to assess the potential of the sediment removed during the dredging process at the Port of Rio Grande for the production of porous ceramics with thermal insulation properties. In the first phase, the sediment was characterized to better understand its suitability as a raw material. In the second phase, the properties of the resulting ceramic were analyzed to evaluate its potential as a thermal insulating material.

3.1 Characterization of Mud Samples

The physical, chemical, mineralogical, and thermal properties of the dredged sediment were analyzed. In the physical characterization of the sediment, the granulometric composition was determined according to the NBR 7181/2016 (ABNT, 2016c). The plasticity index (PI) was measured using the Atterberg method, in accordance to NBR 6459/2016 (ABNT, 2016a) and NBR 7180/2016 (ABNT, 2016b).

For the tests, three samples (A, B, and C) were used, which were first air-dried and subsequently oven-dried at 60°C for 48 hours. After drying, the samples were disaggregated using a pestle and mortar. The tests were conducted at the Geotechnical and Concrete Laboratory, Prof. Dr. Cláudio Renato Rodrigues Dias, School of Engineering Federal University of Rio Grande (Furg).

The chemical characterization was performed using X-ray fluorescence (XRF) spectroscopy on a Bruker S2 Ranger device, in the Chemical Analysis Laboratory at the Federal University of Santa Maria (UFSM). The samples were prepared by grinding and sieving, using material passing through a #325 mesh sieve.

The mineralogical characterization was conducted using X-ray diffraction (XRD) at the Electron Microscopy Center of Furg, employing a Bruker D8 Advance system, operating at 40 kV and 40 mA, with a scan range from 10°to 90°(2θ), step size of 0.02°/2s, and data analysis performed with X’Pert HighScorePlus software, based on the Crystallography Open Database (COD).

Thermal analysis was carried out by thermogravimetry and differential scanning calorimetry (TGA/DSC) using a Shimadzu device, with a heating rate of 10°C/min up to 1000°C. These tests were conducted at the Thermal Analysis Laboratory of the Integrated Analysis Center at Furg. Samples for both mineralogical and thermal analyses were prepared by grinding and sieving, using material passing through a #200 mesh sieve.

3.2 Determining Ceramic Properties

The material was initially dried and disaggregated, then moistened with 8% water and sealed in plastic bags for 24 hours to ensure moisture homogenization. Ten test specimens were then subsequently formed by uniaxial pressing at pressure of 20 MPa using a Bovenau P15 ST hydraulic press. The specimens were molded with dimensions of 1,2 x 8,5 x 1,2 cm, air-dried at room temperature (23°C) for 24 hours, and then oven-dried at 110°C for an additional 24 hours.

Subsequently, the specimens were sintered at 900°C in a Pechini-type muffle furnace (model KK170.16 SO 1059). The heating processes was maintained at a rate of 2.5°C/min until 600°C and then increased to 5°C/min from 600°C to 900°C, with 30-minute hold at the maximum temperature before allowing the specimens to cool naturally.

The resulting ceramics were then characterized to determine the following properties: *linear shrinkage, loss on ignition, water absorption, apparent porosity, bulk density, flexural strength, thermal conductivity and microstructural analysis.*

Linear shrinkage (LS) was calculated by measuring the dimensions changes of the samples at two stages: **drying linear shrinkage (LSd)**, and **firing linear shrinkage (LSf)**. A caliper with a minimum sensitivity of 0,05 mm was used for the measurements.

Loss on ignition ***(LOI)",*** was determined by measuring the difference in dry mass of sample tests before and after firing.

Water absorption *(WA)* was determined according to the ABNT NBR 15310/d standard (ABNT, 2009).

Apparent porosity (AP) was determined using the gravimetric method based on Archimedes' principle.

Bulk density (ρ_a) was determined using the geometric method, which involves calculating the ratio between the dry mass and the apparent volume of the ceramic piece, with the density of water (γ) taken as 1 g/cm^3.

For **flexural strength** analysis, the rupture stress *(σ)* (N/cm^2) was based on the NBR 15310 -2009/c standard and was applied using an Instron universal testing machine, model 8801.

For thermal behavior analysis, test samples of 7 x 7 x 3 cm were molded according to the same molding and firing methodology employed for the physical-mechanical characterization.

The **thermal conductivity** (λ) of the test samples was measured in triplicate using a LaserComp FOX 304 device, employing the guarded hot plate method. The tests were conducted at the Applied Mechanics Laboratory of the Alegrete Campus of the Federal University of Pampa, at a temperature of 25°C and 57°C.

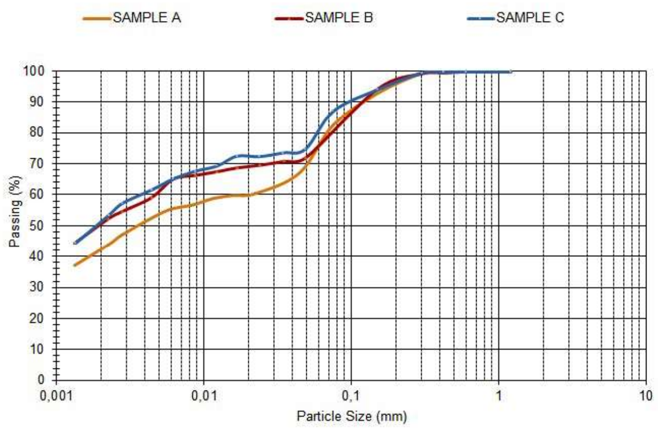
Additionally, **microstructural analysis** was performed using scanning electron microscopy (SEM) on a Jeol JSM6610LV device to examine the morphology of the sintered ceramics. For this analysis, a slice from the flat inner face of the specimen was used, which was obtained with the aid of a saw following the mechanical strength test.

4 RESULTS AND DISCUSSION

4.1 Dredged Mud Properties

The sediment's composition was determined as identified 49% clay, 19% silt, and 33% sand (Figure 3), indicating a predominantly clayey material.

Figure 3 – Particle size distribution of dredged sediment

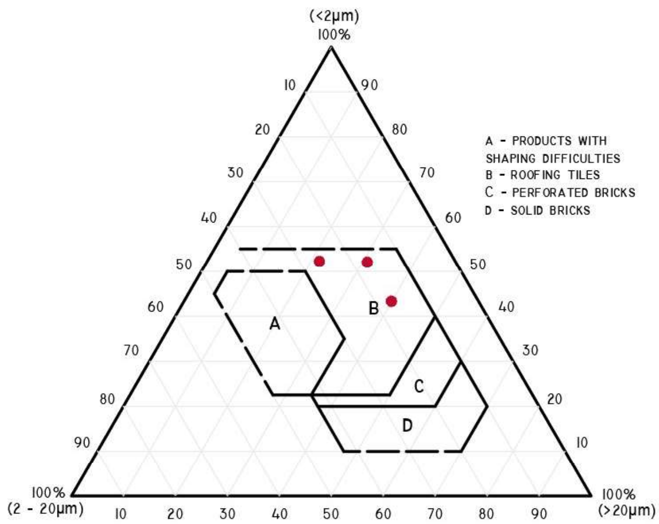


Source: research data.

This characteristic was also reported by Madeira and Ilha (2023), Larrossa *et al.* (2023), and Valério, Alves, and Fontoura (2017) for sediments extracted from the same study area.

According to Calliari and Fachin (1993), the navigation channel leading to the port predominantly contains clay and silt in deeper areas, while fine sand in more prevalent in shallower areas. This distribution accounts for variation in the granulometric composition of the dredged material from the channel, as described by Araújo *et al.* (2023), Villwock, Nicolodi, and Calliari (2021), as well as Machado, Bastos, and Fagundes (2019).

Figure 4 – Granulometric suitability of raw materials for red ceramics production



Source: research data, adapted from Winkler (1954).

Granulometric analysis was conducted using the Winkler diagram (Figure 4). All samples fell within area B of the diagram, indicating the suitability of the dredged sediment for red ceramic production. As noted by Santos et al. (2017) and Prado (2008), beyond the specific processing methods of ceramic raw materials, the granulometric composition of a ceramic mass plays a crucial role on the workability and particle packing, directly influencing the density of the final ceramic pieces.

The sediments's workability was assessed through the Atterberg consistency limits, revealing a plasticity index (PI) of 25%. This value classifies the material as *highly plastic* (PI > 15%) with a plastic limit (PL) ranging between 39% and 44%. Such plastic behavior suggests that the sediment is well-suited for extrusion, a shaping method widely used in blocks and tiles production (Dondi, 2006; Santos *et al.*, 2012). However, the higher moisture content required for shaping may pose challenges during the drying process (Pracidelli; Melchiades, 1997).

Additionally, Barksa *et al.* (2018) and Mesrar *et al.* (2021) highlight that the plasticity is not solely determined by the granulometric composition but also by other factors, such as the organic matter content in the dredged sediments. The presence of organic matter can increase plasticity and contribute to greater porosity in the ceramic after firing.

The chemical analysis of the dredged sediment (Table 1) reveals a predominant composition of silica (SiO_2), followed by alumina (Al_2O_3) and iron oxides (Fe_2O_3), along with other oxides such as potassium oxide (K_2O) and calcium oxide (CaO). This composition is consistent with the raw materials typically employed in red ceramic production, as reported by Santos (1989) and Silva and Pereira (2021).

Table 1 – Chemical composition of the dredged sediment determined by X-ray fluorescence (% by mass)

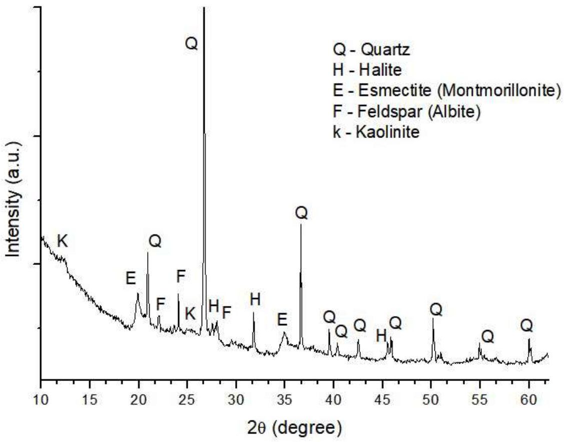
Oxide	Content (%)
SiO_2	54.28
Al_2O_3	16.08
Fe_2O_3	14.37
K_2O	4.12
CaO	2.35
Cl	2.35
SO_3	2.25
TiO_2	1.58
P_2O_5	1.24
Others	< 0.3

Source: research data.

The high content of fluxing oxides, such as iron, potassium, and calcium (greater than 20% by weight), observed in the sediment, contributes to the formation of the liquid phase and reduces the refractoriness of the raw materials, enabling firing temperatures below 1000°C. This is advantageous in terms of reducing energy consumption and minimizing environmental impacts. Moreover, the significant presence of iron oxide (Fe_2O_3) suggests that the resulting ceramic would exhibit a reddish color after firing (Mezencevova *et al.*, 2012).

The presence of soluble salts, including potassium, calcium, chloride, and sulfate, was also observed in other dredged sediments (Mesrar *et al.*, 2021; Barksa *et al.*, 2018) as well as in certain traditional ceramic bodies (Macedo *et al.*, 2008; Pérez *et al.*, 2010; Goes *et al.*, 2014; Silva; Pereira, 2021), albeit at varying percentages, depending on the location material's extraction location. The presence of soluble salts is generally associated

Figure 5 – X-ray Diffractogram of the dredged sediment sample



Source: research data.

with the potential for efflorescence formation, though no direct relationship exists, as this phenomenon also depends on factors such as granulometry, drying, and firing conditions (Dondi *et al.*, 1997; Menezes *et al.*, 2006).

Studies have shown that addition of barium carbonate ($BaCO_3$) or barium chloride ($BaCl_2$) to raw materials can help mitigate efflorescence in ceramic pieces (Pereira; Bernardin; Riella, 2000; Mezencevova *et al.*, 2012; Jindasuwan; Chakornnipit; Sitthisuntorn, 2015). However, the presence of chlorides identified in the sediment is *atypical* for traditional ceramic raw materials and, according to Barksa *et al.* (2018), may lead to damage in kilns due to the formation of acidic gases during firing. This issue remains an area for further investigation.

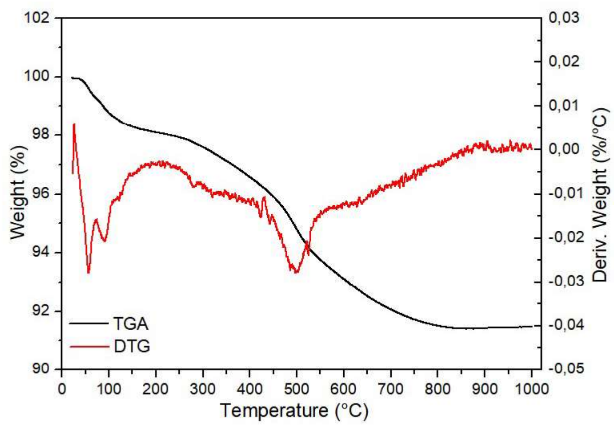
The mineralogical analysis, based on the diffractogram presented in Figure 5, identifies the following phases: quartz (Q) (COD 01-085-0794), halite (H) (COD 01-07-0751), albite (F) (COD 00-041-1480), montmorillonite (E) (COD 00-029-1499), and kaolinite (K) (COD 00-029-1488).

These crystalline phases are consistent with the chemical composition of the sediment, presented in Table 1, as well as with those identified by Larrosa *et al.* (2023) in sediments from the Rio Grande port access channel.

Quartz (SiO_2) is predominantly identified, reflecting the 32% sand content observed in the granulometric analysis. Along with *albite* ($(Na,Ca)Al(Si,Al)_3O_8$), a fluxing feldspar, these minerals contribute to the reduction of plasticity (Macedo *et al.*, 2008). However, the sediment was classified as a highly plastic material (PI > 15%). This high plasticity is attributed to the presence of clay minerals such as montmorillonite ($Na_{0.3}(Al,Mg)_2Si_4O_{10}(OH)_2 \cdot 8H_2O$), as well as kaolinite ($Al_2Si_2O_5(OH)_4$), which, according to Santos (1989), contribute to the high plasticity of the materials, in addition to the influence of organic matter.

The presence of halite (NaCl), although uncommon in traditional ceramic raw materials, is likely attributable to the estuarine origin of the dredged sediment. Despite the identification of a significant amount of

Figure 6 – Curve TGA/DTG of the dredged sediment



Source: research data.

iron oxide (Fe_2O_3) in the chemical composition, as shown in Table 1, no crystalline phases such as hematite or goethite were detected in the mineralogical diffractogram. This suggests that the iron may be present in an amorphous form or be incorporated into other mineral phases.

Thermal analysis of the material was conducted up to a maximum temperature of 1000°C, with the thermogravimetric curves presented in Figure 6.

Initial mass loss peaks are observed at 80°C, 114°C, and 150°C, which are likely associated with the loss of free and adsorbed water, as described by Santos (1989) and identified by Brito *et al.* (2015). Between 200°C and 300°C, the peak is probably related to the combustion of organic matter and the initial alteration of clay minerals, with changes intensifying around 500°C. This behavior may be attributed to the dehydroxylation of clay minerals, a process described by Santos (1989) that occurs in iron-rich smectites between 500°C and 550°C, while in kaolinites, it begins at 450°C and ends around 600°C.

The differential curve, presented in Figure 6, indicates a total mass loss of 8%, which is likely attributed to a combination of free and adsorbed water loss, organic matter combustion, and dehydroxylation of clay minerals. The material reaches stability between 850°C and 900°C.

Similar to how the properties of clays are influenced by geology and extraction location, dredged sediments – often regarded as waste - are shaped by factors such as local hydrodynamics, depth, and the heterogeneity of the transported soil. This explains the distinctiveness of dredged materials from different ports or even from various areas within the same port, cove, or bay (Calliari; Fachin, 1993).

4.2 Properties of the obtained ceramic

The ceramic produced using dredged mud as a predominant raw material (Figure 7) exhibited a ***reddish hue***, likely due its high iron oxide (Fe_2O_3) content, which accounts for 14,37% of the material. Its physical and

Figure 7 – Porous ceramic predominantly from Dredged Mud

Source: research data.

mechanical properties are detailed in Table 2 and further analyzed below.

The observed ***linear shrinkage*** was 2,38% (0,69% during drying and 1,69% during firing), which is lower than the values that reported for ceramics produced from dredged sediments in previous studies (Mezencevova *et al.*, 2012; Mesrar *et al.*, 2021). Nevertheless, the identified dimensional variation falls within the typical range for red ceramics, which varies from 1,5% to 5% (Brito *et al.*, 2015; Santos *et al.*, 2017).

The ***mass variation*** during firing ranged from 7,5% to 8,4%, aligning with the 8% mass loss observed in the thermogravimetric analysis (Figure 6). This reduction in mass is primarily associated with water elimination and the combustion of organic matter, which is commonly present in dredged sediments (Barksa *et al.*, 2018; Mesrar *et al.*, 2021).

The combustion of organic matter reduces the apparent density to the ceramic bodies by promoting porosity formation. The measured ***apparent density*** was 1,80 g/cm^3, lower than that reported by Petterle *et al.* (2018) for ceramics formulated with sludge and rice husk ash, but comparable to the value obtained by Pessanha and Holanda (2023) in the development of lightweight ceramic tiles incorporating organic waste as pore-forming agents.

The ***apparent porosity*** of the ceramic obtained from the dredged sediment, in conjunction with their density, aligns with findings from studies on porous ceramics material (Pizzatto *et al.*, 2021; Pessanha; Holanda, 2023). An apparent porosity of 28,96% was recorded, attributed to the thermal decomposition of the organic matter within the sediment, which plays a key role in pore formation (Silva *et al.*, 2022).

Water absorption was measured at 16,15%, which is higher than the values observed in porous ceramics analyzed by Petterle *et al.* (2018) and Pessanha and Holanda (2023). The results for porosity and water absorption indicate the presence of *open porosity*, characterized by interconnected pores, which facilitates higher water absorption. Nevertheless, the identified absorption rate remains within the limit set by NBR 15270-2/2017(ABNT, 2017) standard for traditional red ceramics and shows lower values when compared to studies on dredged waste (Barksa *et al.*, 2018; Mesrar *et al.*, 2021).

Moreno, Bartolomeu, and Lima (2009) highlight that the microstructure of ceramic materials is closely linked to densification, which is influenced by factors as particle packing (determined by granulometry), fluxing agent content, temperature, and the firing process. While porous ceramics are known for their excellent thermal performance (Silva *et al.*, 2022), they tend to exhibit increased fragility in terms of mechanical behavior.

Nevertheless, the ***mechanical behavior***, assessed through the bending rupture test, resulted in a flexural strength of 3,28 MPa, demonstrating a performance above the minimum required by the NBR 15270-2/2017 standard (ABNT, 2017) for non-structural red ceramics. Additionally, the mechanical strength of the ceramic produced *entirely from estuarine dredged mud* aligns with the values observed in porous ceramics *made from waste* (Menezes; Neves; Ferreira, 2002), as well as those made from traditional raw materials (Santos *et al.*, 2017).

The ***thermal conductivity*** *(λ)* of the ceramic material produced exclusively from dredged sludge was analyzed at two temperature ranges, 25 °C and 57 °C. At 25 °C, an average value of 0.249 W/m·K was obtained, whereas at 57 °C the mean conductivity was 0.218 W/m·K. Based on these results, the design thermal conductivity was estimated to range between 0.365 W/m·K and 0.228 W/m·K, considering the reference temperature of 10 °C, in accordance with NBR ISO 10456:2022-D.

Table 2 – Physical and mechanical properties of the ceramic produced from dredged sediment

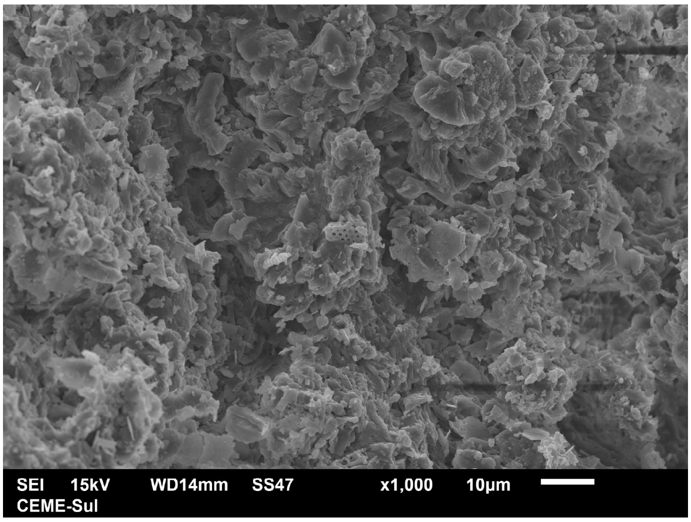
Physical and mechanical properties	Value
Drying shrinkage (%)	0.69 ± 0.24
Firing shrinkage (%)	1.69 ± 0.24
Loss on ignition (%)	8.10 ± 0.34
Water absorption (%)	16.15 ± 1.38
Apparent porosity (%)	28.96 ± 1.74
Bulk density (g/cm^3)	1.80 ± 0.04
Flexural strength (MPa)	3.28 ± 0.63

Source: research data.

The thermal behavior of the material reveals a heat conduction rate significantly lower than that of conventional ceramics used in civil construction, whose normative thermal conductivity values, according to NBR ISO 10456:2022-D, range from 0.70 to 1.05 W/m·K. Consequently, the developed material exhibits up to approximately 50% higher thermal insulation performance compared to traditional ceramics.

The average thermal conductivity values obtained were employed to determine the thermal transmittance (U), considering the typical dimensions of a solid ceramic brick. The results, summarized in Table 3, indicate U values ranging from 1.77 to 2.40 W/m^2·K, consistent with the performance of porous ceramics reported in the literature. In comparison, the calculation performed using the normative thermal conductivity of conventional ceramics (ISO 10456/2021) resulted in transmittance values between 3.35 and 3.91 W/m^2·K,

Figure 8 – microstructure of ceramic obtained entirely from estuarine dredged mud



Source: research data.

demonstrating an approximate 50% reduction in heat flux through the element.

Figure 8 shows the microstructure of the ceramic bodies after thermal treatment, in which a microporous network composed predominantly of irregular and interconnected pores can be observed. This apparent porosity mainly results from the decomposition of clay minerals and the combustion of organic matter present in the sediment during the sintering process.

The developed morphology may account for the good thermal performance observed, since the air retained within the pores acts as a thermal barrier, hindering heat transfer by solid conduction and, consequently, reducing the thermal conductivity values.

On the other hand, the high interconnectivity of the porous network contributes to a reduction in mechanical strength and an increase in the material's permeability, facilitating the transport of saline solutions. This behavior may promote the migration and deposition of soluble salts on the surface, leading to the formation of efflorescence.

These findings demonstrate the high thermal efficiency of the ceramic produced from dredged sludge, as the transmittance values are below the maximum limit of 2.7 $W/m^2 \cdot K$ established by NBR 15575-4:2021 for external walls in bioclimatic zones equivalent to the material's region of origin, demonstrating its potential application as a masonry component with adequate thermal performance.

This behavior is directly related to the porous microstructure of the material, since heat conduction in ceramic solids occurs predominantly through lattice vibrations and phonon-mediated energy transfer (Petterle et al., 2018). In this regard, the increase in porosity contributed significantly to the reduction in thermal conductivity, positioning the material as a promising alternative for applications requiring enhanced thermal resistance.

Table 3 – Thermal behavior of ceramic materials obtained from the use of organic wastes

Composition	**Final product**	**Firing temperature**	**Thermal conductivity λ ($W.m^{-1}.K^{-1}$)**	**Bulk density (kg/m^3)**	**Thermal transmittance U* ($W/m^2.K$)**	**Reference**
Dredged mud	Porous red ceramic	900°C	0.228–0.365	1800	1.77–2.40	Study material
Clay 100%	Red ceramic bricks	Not specified	0.70–1.05	1000–2000	3.35–3.91	Traditional ceramics (ABNT NBR ISO 10456:2022)
Clay + dredged sediment (0–100 wt%)	Bricks	850°C–950°C	0.22–0.35	1764–1853	1.73–2.34	Slimanou et al. (2020)
Red clay + coffee waste (10–30 wt%)	Porous red ceramic	1150°C	0.37–0.53	–	2.42–2.94	Silva et al. (2022)
Clay + water treatment sludge (10–50 wt%) + rice husk ash (20–50 wt%)	Ceramic tiles	1300°C	0.26–0.33	1090–2230	1.94–2.26	Petterle et al. (2018)
Clay + waste glass (70wt%) + sludge from sewage treatment (30wt%) + CaCo3 (5wt%)	Thermal insulators	750°C–1000°C	0.50–1.25	–	2.86–4.13	Arcaro et al. (2016)
Clay + wood ash (10–30 wt%)	Porous clay brick	1000°C	0.75–1.00	–	3.45–3.85	Silva et al. (2022)

* Thermal transmittance values were calculated according to ABNT NBR 15220-2 — Thermal performance of buildings, considering solid bricks with a thickness of 9 cm.

Source: research data

5 FINAL CONSIDERATIONS

The sediment from the dredging process exhibits physical, chemical, and mineralogical characteristics similar to those traditional raw materials used in red ceramic production. However, the presence of certain soluble salts is uncommon in conventional raw materials, warrants further investigation to evaluate their potential impact on efflorescence formation in the resulting ceramics and the effect of gases released during firing, particularly due to the presence of chlorine (Cl) identified in the dredged sediment. The organic matter present in the sediment served as a pore-forming agent, enhancing the porosity of the produced ceramic. The physical and mechanical properties obtained were in line with the developed porous microstructure, significantly contributing to the excellent thermal performance, with thermal conductivity 73% lower than the maximum limit for blocks and tiles, thus *providing insulating properties to the ceramic produced entirely from estuarine dredged mud.*

The application of dredged sediment as a predominant raw material for the ceramic industry proves to be promising approach, offering economic benefits, such as costs reduction related to traditional raw materials, as well as environmental advantages by promoting sustainable management of dredging waste and reducing the need for natural resource extraction.

To optimize the environmental and economic benefits, it is essential to prioritize the environmental considerations. The integration of dredging and ceramic production responsibilities could help mitigate environmental impacts, and this shift should be encouraged by public authorities through stricter policies and the enforcement of integrated process between industries as a form of socio-environmental compensation.

For future studies, it is recommended to explore the potential for enhancing thermal insulation while maintaining physical and mechanical properties through formulations that incorporate not only dredged sediment but also other associated waste materials. This approach aims to further improve the material's already remarkable insulating properties, contributing to the development of more sustainable and efficient ceramic solutions.

Similarly, the presence of chlorides, identified in the sediment, as an uncommon component in traditional ceramic raw materials, warrants further investigation.

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