A review on the production of porous ceramics using organic and inorganic industrial waste

***K. R. Silva*[1]**, *R. R. Menezes*[1], *L. F. A. Campos*[2], *L. N. L. Santana*[1]**
*[1]Federal University of Campina Grande, Department of Materials Engineering, 58429-900,
Campina Grande, PB, Brazil*
[2]Federal University of Paraiba, Department of Materials Engineering, 58051-900, João Pessoa, PB, Brazil

Abstract

The use of industrial waste in compositions of ceramic masses has attracted great interest from the scientific community, as they can be considered abundant and diversified alternative sources of raw materials. At the same time, there is a growing interest in the development of porous ceramics due to their wide possibilities for use in various fields of engineering. In this sense, the present work aimed to provide a literature review on the use of industrial waste as alternative raw materials in the production of porous ceramics, highlighting the innovations and technological potential of research carried out in recent years. Increasingly higher levels of industrial waste in ceramic formulations have been studied, as well as high-performance porous ceramic bodies obtained entirely from waste materials. In addition to promoting the diversification of products, the incorporation of waste in ceramic masses represents an alternative to minimize their negative effects on the environment.

Keywords: industrial waste, porous ceramics, sustainability.

INTRODUCTION

The planet is facing a serious environmental crisis, including problems such as pollution, global warming, waste generation, and depletion of natural resources [1]. In the 21st century, the exacerbated population growth, accompanied by consumerism and industrialization, resulted in a rapid increase in waste generation [2-4]. Thus, it is necessary to formulate urban, industrial, agricultural, and transport development strategies and policies that are linked to environmental protection [5]. Conventional solid waste management methods, such as incineration, landfill, and composting, are widely used around the world. However, the emergence of stricter regulations in order to slow down the exploitation of non-renewable natural resources has motivated the use of waste materials as high-quality raw materials [4, 6]. The use of wastes, after detecting their potential, contributes to product diversification, energy savings, and improvement in population health [7-11]. In recent years, several studies have demonstrated the feasibility of using industrial waste in the manufacture of ceramic products, especially porous ceramic products. Among the studied waste materials, organic [12-32] and inorganic [33-51] ones have shown promising results.

In general, ceramics are produced from natural raw materials with very heterogeneous chemical and mineralogical compositions [52], which are similar to the compositions of many types of waste. This similarity makes them very suitable to be used as alternative raw materials in the production of various ceramic materials, especially porous ceramic materials. In the last decade, porous ceramics have stood out due to their wide possibilities for use in various fields of engineering, ranging from filtration and water treatment to thermal/acoustic insulation and catalytic support [53, 54]. Traditionally, porous ceramics are classified according to the pore size: macroporosity (diameter >50 nm), mesoporosity (2 nm< diameter <50 nm) and microporosity (diameter <2 nm). However, commonly used structures present a combination of pores of different sizes in a single monolithic matrix [55, 56]. Porous ceramics can also be classified according to the way in which their basic structure is composed: open cells (or reticulated) or closed cells. This characteristic plays a key role in determining the functionalities of these materials [56, 57]. A ceramic structure composed of open cells and interconnected pores is favorable for applications where fluid transport is required, such as in filtration processes. On the other hand, isolated pores in a continuous ceramic matrix composed of closed cells offer advantages for applications where fluid flow must be restricted, such as in thermal and acoustic insulation [56, 58-61].

In recent years, an intense effort around the world has aimed at more sustainable and technically differentiated reuse for waste. In this sense, a large volume of studies has been devoted to the development of porous ceramics using different types of industrial waste. However, there is no systematic analysis of the results and a current review of the state of the art in this technology. Thus, the present work aimed to provide a review on the use of organic and inorganic industrial waste as alternative raw materials in the production of porous ceramics, highlighting the technological innovations and potential of the studies developed.

**karinaruizsilva@gmail.com*
https://orcid.org/0000-0001-8593-3114

ORGANIC WASTE

The wastes used as alternative raw materials in the production of porous ceramics can present in their composition inorganic and organic components [4], which can act in different ways, contributing to the consolidation of the ceramic matrix and to the formation of specific crystalline phases or promoting pore formation, respectively. Knowing the chemical composition of wastes is essential for planning formulations and, consequently, for obtaining desirable characteristics in the final product [62]. Organic waste has different constituents such as cellulose, hemicellulose, and lignin, which open up many opportunities to add value and can be a low-cost alternative for use as porogenic agents in the manufacture of porous ceramics [13]. According to Laksaci et al. [63], the pyrolysis of lignocellulosic materials results in the formation of three phases: coal, oils (tar), and gases. A rudimentary porosity is obtained from the carbon fraction as a consequence of the release of elements such as hydrogen, oxygen, and nitrogen in the form of gases and tar, leaving a rigid carbon skeleton formed by aromatic structures [16, 63]. The chemical compositions of some organic wastes from the agroindustry used as porogenic agents in the production of porous ceramics are listed in Table I.

Rice husks, an important by-product of the rice milling process, are an organic waste consisting of approximately 40 wt% of cellulose, 30 wt% of lignin, and 20 wt% of silica [64]. Furthermore, this waste is formed by the combination of volatile material (60-65%), fixed carbon (10-15%), and ash (17-23%) [65, 66], and can absorb water in the range of 5-16% [67]. These properties provide important benefits in the production of porous ceramic materials, as they reduce the unit weight and improve the thermal properties of the pieces. The use of rice husks in the production of clay bricks makes an economic contribution and also serves as an energy-efficient material for construction [12]. In tropical regions, significant amounts of organic waste come from banana cultivation, such as banana leaves and pseudostem [68]. Banana is one of the most consumed fruits in the world and is commercially cultivated in about 120 countries [13]. For each ton of banana produced by the agroindustry, approximately 3000 kg of pseudostem, 160 kg of stem, 480 kg of leaves, and 440 kg of peel are generated [69]. Studies carried out by Arcaro et al. [13] pointed to a moisture content of approximately 7.81 wt% in banana leaves. According to the researchers, biomass moisture is an important factor, as it directly interferes with other parameters, such as the heating value, which decreases with increasing moisture content and thermal conductivity [13, 68, 70]. They also verified the contents of volatile solids, fixed carbon, and ash corresponding to 78.16, 15.59, and 6.20 wt%, respectively. The volatile solids content indicates the presence of organic matter, represents the lignocellulosic and carbon fractions present in the samples and expresses the amount by weight of the biomass components that are first burned [13, 70, 71].

Mathematical models to predict the thermal conductivity and mechanical strength of clay ceramics containing organic additives were developed by Nigay et al. [14]. Ceramic properties were predicted from parameters such as true density, degree of swelling, particle size distribution, and particle form factor of the organic additives. According to the authors, the extent of the increase in the porosity of the bodies during the sintering process depends on the density of the added organic additives, so that the low-density ones occupy a larger volume than the high-density ones, resulting in greater porosity. They demonstrated that the addition of 8 wt% of olive stone flour promoted an increase of 12% in porosity of the ceramics, while the addition of 8 wt% of wheat straw (less dense) resulted in an increase of 20%. Nigay et al. [14] also demonstrated that organic additives that have a relatively high particle form factor, such as olive stone flour, result in the formation of round pores. Consequently, the thermal conductivity of the material is decreased due to the low thermal conductivity of the air in these pores. On the other hand, organic additives with low particle form factors, such as wheat straw, result in the formation of oriented pores. This means that heat diffusion

Table I - Chemical compositions (%) of some organic waste from agroindustry used as porogenic agents in the production of porous ceramics.

Organic waste	C	H	N	O	S	LoI	Ref.
Rice husk	44.60	5.60	-	49.30	-	-	[12]
Banana leaf	43.28	6.23	0.98	-	0.49	-	[13]
Olive stone flour	49.80	6.00	0.40	42.00	-	-	[14]
Wheat straw	43.10	5.50	0.70	28.50	-	-	[14]
Active yeast	64.12	-	-	28.12	0.75	-	[15]
Coffee waste	58.48	7.31	1.05	-	-	-	[16]
Sawdust	44.21	6.02	5.06	-	-	99.67	[17]
Grape seed	50.16	6.62	2.17	-	-	97.03	[17]
Cherrie seed	50.42	6.19	1.96	-	-	99.66	[17]

LoI: loss on ignition.

is highly limited through stacking clay sheets and porosity. Table II summarizes the properties of some porous ceramic materials that were obtained from the use of organic waste as porogenic agents. The data reveal that ceramic bodies with a high level of porosity, low thermal conductivity, and satisfactory mechanical strength can be obtained from waste such as rice husks [12], banana leaves [13], olive stones [14], wheat straw [14], yeast [15] and coffee waste [16, 72]. Additionally, it is observed that the most porous ceramic materials produced using organic waste in their composition are applied in the civil construction industry, such as porous clay bricks and foams for thermal and/or acoustic insulation. The increase in the number and size of pores after the incorporation of agricultural waste in burnt clay bricks can be attributed to the combustion of organic matter and the reduction in the amount of fluxing oxides [73] so that bodies produced with higher contents of organics have higher apparent porosity values.

Biomass ash: biomass, considered one of the most promising sources of renewable energy [74], has great potential to provide energy for heating, electricity, and transport, being increasingly used on a world scale. The agroindustry produces huge amounts of waste around the world, most of which is composed of biomass that can be used as fuel to obtain electrical and thermal energy. However, the combustion process of this material generates a large amount of ash, and its disposal has become an environmental and economic issue [25]. Biomass ash is commonly disposed of in landfills close to power plants, but this alternative is the least attractive in environmental management [27]. The accumulation of ash can damage the soil and surroundings, contributing to air and water pollution. In addition, space limitations can make landfill disposal problematic [25, 75, 76]. There are two main types of ash: bottom ash, which corresponds to the portion of non-combustible residue found in the furnace or incinerator, and fly ash, which escapes through the chimney and must be retained to prevent its release into the atmosphere [77]. The quality and quantity of ash generated in a plant are greatly influenced by the characteristics of the biomass and the combustion technology used [78]. The potential for reusing ash is determined by its chemical and physical

Table II - Properties of porous ceramic materials obtained from the use of organic waste as a porogenic agent.

Composition	Final product	Sintering conditions	Apparent porosity (%)	Thermal conductivity (W.m^{-1}.K^{-1})	Compressive strength (MPa)	Ref.
Coarse rice husk (5-15 vol%) + brick raw material	Porous clay brick	700 °C/1 h	~34-46	~0.30-0.20	~4-1	[12]
		800 °C/1 h	~37.5-49	~0.28-0.16	~8-2	
		900 °C/1 h	~37-48	~0.34-0.17	~10-2	
		1000 °C/1 h	~37-48	~0.40-0.18	~11-2	
Ground rice husk (5-15 vol%) + brick raw material	Porous clay brick	700ºC/1 h	~36-41	~0.40-0.27	~4-2	[12]
		800 °C/1 h	~39-44.5	~0.34-0.24	~9-5	
		900 °C/1 h	~38-44	~0.39-0.25	~9.25-5.75	
		1000 °C/1 h	~37-43.5	~0.45-0.29	~9-6	
Banana leaf (30-50 wt%) + crushed glass bottle	Thermal insulating glass foam	700 °C/30 min	~75-85	~0.15-0.06	~3.50-2.25	[13]
		800 °C/30 min	~72.5-87	~0.07-0.06	~2.25-1.17	
		850 °C/30 min	~58.5-80	~0.12-0.10	~2.25-2.75	
Olive stone flour (4-8 wt%) + clay	Porous clay brick	950 °C	~36-42	~0.70-0.60	-	[14]
Wheat straw (4-8 wt%) + clay			~40-50	~0.60-0.45	-	
Active yeast (10-50 wt%) + alumina powder	Porous alumina ceramic	1600 °C/2 h	30.2-63.8	-	19.5-1.8	[15]
Coffee waste (10-30 wt%) + red clay	Porous red ceramic	1150 °C	~30-42.81	~0.53-0.37[a]; ~0.56-0.39[b]; ~0.60-0.45[c]	-	[16]
Spent coffee ground (15 wt%) + red clay	Porous clay ceramic	1000 °C/1 h (MM)	55.51 (TP)	-	-	[72]
		1000 °C/1 h (PP)	46.20 (TP)	-	-	

MM: manual pelletization; PP: powder pressing; TP: total porosity; [a]: 10 °C; [b]: 25 °C;[c]: 40 °C.

Table III - Chemical compositions (%) of ashes from different types of biomass.

Biomass ash	SiO_2	Al_2O_3	K_2O	Na_2O	CaO	MgO	Fe_2O_3	TiO_2	Others	LoI	Ref.
Rice husk ash	75.42	6.81	2.17	1.29	3.54	1.54	3.98	-	-	4.05	[20]
	77.21	6.87	2.59	1.24	3.65	1.45	4.69	-	0.37	4.71	[19]
Sugarcane bagasse ash	85.41	1.98	0.31	0.25	2.61	0.73	2.58	-	-	9.21	[20]
	87.97	1.84	0.32	0.28	2.65	0.72	2.65	-	0.15	10.45	[19]
Ash from sludge from olive oil refining industry	8.60	56.95	0.47	2.09	0.84	0.27	1.92	0.08	25.73	-	[21]
Corn cob ash	18.35	-	59.16	-	-	0.73	1.21	0.05	20.47	-	[22]
Untreated coffee husk ash	1.24	0.58	46.46	0.14	17.70	4.51	0.56	0.08	7.66	-	[23]
Brazil nut shell ash	6.38	1.94	32.86	0.82	10.84	5.36	0.67	0.93	12.44	27.50	[24]
Wood ash	48.60	5.94	1.85	0.92	18.10	3.20	3.26	1.39	1.10	15.62	[25]
Ash from pomace from olive oil extraction industry	35.77	11.32	2.99	3.08	20.94	3.93	8.71	0.49	11.73	-	[21]
Olive pomace ash	16.44	7.03	19.69	-	35.43	6.83	2.16	0.20	6.05	5.60	[26]
	10.88	1.68	38.01	0.13	13.07	1.92	1.38	0.13	7.24	25.53	[27]

LoI: loss on ignition.

properties. Ashes are composed of minerals absorbed by the biomass itself or incorporated into it during harvesting, and by unburned organic material [79]. Components of interest such as silica, potassium, chlorine, sodium, phosphorus, sulfur, iron, magnesium, calcium, and titanium can be found in biomass ash even after thermal processing [22, 80-82], as shown in Table III. Table III shows a wide variation in the chemical composition of the ashes, which is linked to the different types of biomass from which they originate. Rice husk and sugarcane bagasse ashes are mainly composed of SiO_2 [19, 20], which can be used as alternative sources of silica in the production of ceramic materials. On the other hand, corn cobs [22], coffee husks [23], and Brazil nuts [24] ashes have K_2O as the main oxide in their chemical compositions, allowing their use as sources of fluxing oxides in ceramic masses. Although wood ash and olive oil extraction process bagasse ash are mainly composed of SiO_2, they also have high CaO contents [21, 25], being considered good sources of auxiliary fluxing oxides.

Kazmi et al. [18] demonstrated, in their studies, that rice husk ash (5 wt%) can be satisfactorily incorporated into ceramic masses in order to obtain lightweight bricks for the construction industry. The reduction in the weight of the bricks, due to the greater porosity (39.71%), can result in a reduction in structural loads and, consequently, in savings. Kazmi et al. [19] also produced lightweight bricks using rice husk ash (5-15 wt%). With satisfactory values of porosity (~37.5-40%) and mechanical strength (~6.5-5 MPa), bricks showed potential to be used in building insulation, in moderate climate environments, and in the presence of sulfates. The incorporation of rice husk ash also contributed to a significant improvement in efflorescence resistance. Results obtained by Eliche-Quesada et al. [25] indicate that it is possible to obtain ceramic bricks with up to 10 wt% of rice husk ash that meet technological standards. And, when sintered at 1000 °C, they deliver the mechanical performance required by standards for clay masonry materials, while reducing thermal conductivity by more than 30%. The incorporation of rice husk ash promotes the formation of high porosity, mainly closed porosity. According to Eliche-Quesada et al. [25], the addition of this type of ash in the clay matrix can result in the formation of a liquid phase with sufficient viscosity to avoid the release of gases from the decomposition of organic matter and $CaCO_3$ present in the matrix, that would cause open porosity. This behavior is desirable, as high-porosity bricks are preferred in terms of weight and thermal performance [20, 25]. Andreola et al. [83] also observed an increase in the closed porosity as a function of rice husk ash content.

Sugarcane bagasse ash has also been extensively studied for the manufacture of lightweight bricks [84]. In the sugar-alcohol industry, the sugarcane stalk is crushed to extract the juice and the remaining fibrous waste is called bagasse [28], which composition is approximately 26.6-54.3 wt% of cellulose, 22.3-29.7 wt% of hemicellulose and 14.3-24.5 wt% of lignin [85, 86]. Currently, sugarcane bagasse is burned in boilers to produce steam, which can be used in manufacturing processes and also to drive turbines for the production of electricity [86]. As a result of this burning process, large quantities of solid waste known as sugarcane bagasse ash are generated around the world. It is estimated that each ton of bagasse produces about 25 kg of ash [86]. Kazmi et al. [19, 20] and Maza-Ignacio et al. [84] demonstrated that the partial replacement of clay with

Table IV - Properties of porous ceramic materials obtained from the use of rice husk and sugarcane bagasse ashes.

Composition (wt%)	Final product	Sintering conditions	Apparent porosity (%)	Thermal conductivity (W.m^{-1}.K^{-1})	Compressive strength (MPa)	Ref.
Rice husk ash (5%) + sugarcane bagasse ash (5%) + clay	Porous clay brick	Fired in coal kiln/45 days	39.71	-	5.10	[18]
Rice husk ash (5-15%) + clay	Porous clay brick	800 ºC/36 h	~37.5-40	-	~6.50-5	[19]
Rice husk ash (10-50%) + alumina powder	Porous alumina ceramic	1600 ºC/2 h	42.9-49	-	69.7-53.9	[15]
Rice husk ash (10-30%) + clay	Porous clay brick	900 ºC/4 h	~37.5-46	-	~30-13.5	[25]
		1000 ºC/4 h	~37-45	0.7-0.68	~35.9-17.5	
Rice husk ash (5-15%) + clay	Porous clay brick	800 ºC/36 h	~32-35	~0.50-0.37	~7.3-5.5	[20]
Carbonized rice husk (5-30%) + tabular alumina + α-Al_2O_3 powder	Highly porous alumina ceramic	1600 ºC/2 h	26.8-82.4	0.82-0.19 (200 ºC)	32-45	[88]
Sugarcane bagasse ash (5-15%) + clay	Porous clay brick	800 ºC/36 h	~42-44	-	~7-4	[19]
Sugarcane bagasse ash (5-15%) + clay	Porous clay brick	800 ºC/36 h	~35-40	~0.45-0.35	7.2-5	[20]
Sugarcane bagasse ash (30%) + kaolinite clay	Ceramic membrane	800 ºC/2 h	32.4	-	-	[87]
		900 ºC/2 h	37.4	-	-	
		1000 ºC/2 h	30.8	-	-	
Sugarcane bagasse ash (40%) + clay	Resistant lightweight fired brick	900 ºC/6 h	~49	-	~7.5	[84]
		1000 ºC/6 h	~50	-	~8	

sugarcane bagasse ash results in lighter bricks compared to conventional ones. According to the researchers, this behavior may be related to the lower content of fluxing oxides and higher content of organics present in these ashes in comparison to clay, and also to the presence of calcite, which undergoes thermal decomposition during the sintering process, generating gases that contribute to increased porosity. Ashes from the combustion of rice husks [15, 18-20, 25] and sugarcane bagasse [18-20, 84, 87] have shown great potential to be used as alternative raw materials in the production of porous ceramic materials, in particular, lightweight bricks for applications in the construction industry, as shown in Table IV.

In general, ash that has significant levels of fluxing oxides (K_2O, Na_2O) and auxiliary fluxing oxides (CaO, MgO) in its composition tends to reduce the sintering temperature because the melting capacity of the waste lowers the melting point of the clay matrix. In this sense, the greater amount of alkaline oxides-rich ash incorporated in the clay matrix contributes to the formation of a liquid phase at lower temperatures and, consequently, adequate viscosity is reached more quickly, avoiding the release of gases resulting from the thermal decomposition of organic material and other compounds of carbon, causing open porosity. According to Eliche-Quesada and Leite-Costa [27], high amounts of ash (>20 wt%) can lead to the formation of too much open porosity, as well as larger macropores and small particles that become isolated and nearly spherical, characteristics of the viscous flow sintering mechanism. The joining of the pores and the increase in their size indicate the beginning of a coalescence process. Table V presents works that were carried out aiming at the use of ash rich in fluxing and auxiliary fluxing oxides together with clay mixtures to obtain porous ceramics.

Corn cob ash with good properties is generally derived from natural green corn cob through a controlled combustion process [22, 80, 82]. This is a material with a large amount of potassium compounds (KCl, K_2SO_4, and $KHCO_3$) that help to reduce the sintering temperature of a ceramic body [82], making it suitable as a fluxing additive in ceramics technology. Furthermore, the ability of potassium compounds to diffuse easily into water [89] or any other solvent [90, 91] made it a potential material for use in membrane applications [22]. Kamarudin et al. [22] used corn cob ash as a porogenic agent and sintering additive, together with metakaolin, in order to obtain hollow fiber ceramic membranes to be applied in water filtration and oil-water separation processes. The authors found that, compared to standard hollow fiber membranes made entirely from metakaolin, those made from ash had significant

Table V - Properties of porous ceramic materials obtained from the use of ash rich in fluxing and auxiliary fluxing oxides from biomass burning.

Composition (wt%)	Final product	Sintering conditions	Apparent porosity (%)	Thermal conductivity (W.m^{-1}.K^{-1})	Compressive strength (MPa)	Ref.
Corn cob ash (0-50%) + kaolin powder	Ceramic hollow fiber membrane	1200 ºC/3 h	~19.4-62	-	-	[22]
Brazil nut shell ash (0-30%) + diatomaceous earth	Porous brick material	750 ºC/1 h	~25-60	-	~2.5-9	[24]
		850 ºC/1 h	~7.5-52	~0.23-0.76	~7.5-19	
		900 ºC/1 h	~5-42.5	-	~9-17	
Pomace ash from olive oil extraction industry (0-30%) + clay	Lightweight clay brick	950 ºC/4 h	~28-35	~1-0.90	~47.5-22.5	[21]
Milled washed olive pomace ash (5-10%) + clay	Lightweight clay brick	1025 ºC	-	~0.68 (10%)	-	[26]
Micronized washed olive pomace ash (5-10%) + clay			-	~0.71 (5%)	-	
Olive pomace bottom ash (10-50%) + clay	Porous clay brick	950 ºC/4 h	28.3-39	0.99-0.82 (20%)	47.96-10.2	[27]
Wood ash (10-30%) + clay	Porous clay brick	900 ºC/4 h	~33-37	-	~53-34.3	[25]
		1000 ºC/4 h	~32-34	1-0.75	~55-40	

advantages over the porous membrane configuration. The dissolution behavior of corn cob ash during the preparation of the ceramic suspension was favorable to increasing the viscosity, inducing the formation of sponge-like structures with high performance for filtration applications. The studies demonstrated the feasibility of producing highly porous (62.03%) hollow fiber ceramic membranes, with good flexural strength (41.61 MPa) and permeability (1359.93 L.m^{-2}.h^{-1}), and efficient oil/water removal (74.73%) at a relatively low sintering temperature (1200 °C).

Brazil nut shell ash is a waste resulting from the direct combustion of the nut's shell. This ash, rich in alkaline elements such as potassium and calcium, has the potential to lower melting points during sintering and therefore can be an inexpensive and attractive waste material to replace traditional flux materials used in ceramic production, namely feldspars. The Brazil nut-based industry is an important emerging local business in the Amazon region, Brazil. In this region, large amounts of nutshell waste are produced, which are often used as biofuel for heating and electricity generation, resulting in the production of 80 to 150 ton of ash over a period of approximately six months [24]. Escalera et al. [24] demonstrated that it is possible to obtain highly porous ceramic bricks (up to 60% porosity) at relatively low sintering temperatures (750-950 ºC) by using Brazil nut shell ash. Olive pomace comes from the oil production process and consists of components present in the fruit, with the exception of oil, such as crushed stone pieces (15 wt%), pulp with residual oil (20 wt%), and water (65 wt%) [92]. The residual oil is normally recovered by solvent extraction after drying the bagasse, and this process generates another waste called dry olive cake or 'orujilo' [26]. Both bagasse and dry olive cake are rich in organic material and potassium [93], and both can be used as fuel for the generation of thermal and electrical energy in industries, producing a large amount of ash (4-8% of waste burned) [26,

Table VI - Chemical compositions (%) of eggshell and mollusk shell wastes.

Waste	SiO$_2$	Al$_2$O$_3$	K$_2$O	Na$_2$O	CaO	MgO	Fe$_2$O$_3$	Others	LoI	Ref.
Avian eggshell waste	-	-	-	0.20	52.40	0.60	-	0.30	46.50	[28]
	-	-	0.80	-	52.51	-	-	1.09	45.60	[29]
	0.09	0.03	-	0.19	50.70	0.01	0.02	1.02	47.80	[94]
Oyster shell waste	0.60	<0.10	<0.10	-	53.70	0.90	<0.10	-	44.50	[30]
	0.69	0.42	-	0.98	52.57	0.65	-	0.20	44.49	[31]
Mollusk shell powder	0.40	0.16	-	-	53.80	-	-	1.34	44.30	[32]

LoI: loss on ignition.

Table VII - Properties of porous ceramic materials obtained from the use of eggshell and mollusk shell wastes.

Composition (wt%)	Final product	Sintering conditions	Apparent porosity (%)	Thermal conductivity (W.m^{-1}.K^{-1})	Compressive strength (MPa)	Ref.
Avian eggshell waste (1-30%) + crushed glass bottle	Glass foam	900 °C/30 min	60-95	0.18-0.06	1.50-0.15	[28]
Avian eggshell waste (1-5%) + crushed cathode ray tube glass (PG, FG)	Glass foam	600-800 °C/15 min	-	-	0.76-5.88 (97% FG^{a}); 1.26-14.82 (97% PG^{a})	[95]
Raw avian eggshell waste + chamotte	Thermal insulation construction material	1100 °C/24 h	-	0.25	0.45	[29]
Calcined avian eggshell waste + chamotte			-	0.29	0.35	
Avian eggshell waste (15%) + red clay + quartz	Wall tile material	1150 °C/1 h	37.53	-	-	[94]
Oyster shell waste (1-15%) + crushed glass bottle	Vitro-crystalline foam	800-900 °C/30-120 min	81-91 (9% waste)	0.08-0.06 (9% waste)	2.3-0.7 (9% waste)	[30]
Oyster shell waste (0-40%) + low-grade diatomite	Porous ceramic	700 °C/3.5 h	~52-49	-	~0-5	[31]
		800 °C/3.5 h	~49.5-47	-	~0-19	
		900 °C/3.5 h	~48.5-45	-	~0-25	

PG: panel glass; FG: funnel glass; ^{a}: +3% waste.

27]. De La Casa and Castro [26], Eliche-Quesada et al. [21], and Eliche-Quesada and Leite-Costa [27] demonstrated the feasibility of using olive pomace ash in the production of lightweight masonry bricks. For this, they replaced the clay (10%, 30%, and 50%), usually used in the manufacture of bricks, with ash. The systematic analysis of the results in the aforementioned works shows that there was a reduction in the bulk density of the pieces and, consequently, in the thermal conductivity in relation to bricks produced entirely with clay.

Egg and mollusk shells waste: Table VI presents the chemical compositions of wastes from egg and mollusk shells. All of them are mainly composed of CaO (>50%) and have a high loss on ignition (>40%), which means a high content of organic material. The eggshell corresponds to approximately 10 wt% of the egg and contains about 94 wt% of calcium carbonate ($CaCO_3$) in its composition [28], while the shell of an oyster corresponds to more than 70 wt% of this mollusk and is composed of approximately 96 wt% $CaCO_3$ [30]. Although both are not considered hazardous wastes, their inadequate disposal can result in considerable environmental disturbances due to the large volume that is produced [28, 30]. Considering that the thermal decomposition of calcium carbonate generates CO_2, the possibilities for reusing this waste include its use as a porogenic agent in the production of low-density ceramic materials [17], as shown in Table VII. According to Teixeira et al. [30], oyster shell waste was shown to be a strong candidate as an alternative porogenic agent to replace mineral calcium carbonate (commercial), since the release of CO_2 by it corresponds to a sufficient amount to produce the expansion of a soda-lime glass at its softening temperature for the production of vitreous foams.

INORGANIC WASTE

Table VIII lists the chemical compositions of various inorganic industrial wastes used as alternative raw materials in the production of porous ceramics. Among them, those from the brewing [33, 34], ornamental rocks [35-37], ceramic [35, 38-42], metallurgical [43, 44] and mining [45-49] industries, thermal power plants [96-98] and others [13, 50, 51, 99] stand out. It is observed that the vast majority of these wastes are mainly composed of SiO_2, that is, they can be used satisfactorily as sources of silica in ceramic technology. Exceptions are some mineral tailings, which have high CaO and MgO contents [46-49].

Diatomaceous earth waste from the brewing industry: diatoms are single-celled organisms, abundant in fresh and salt water, that produce complex-shaped cytoskeletons made of silica. When diatoms die, their silica shells accumulate on the sea floor and thick layers of these shells are fossilized into diatomaceous earth or diatomite [101, 104-106]. Diatomaceous earth, a fine-grained material with a porous structure, is rich in hydrated amorphous silica and has low thermal conductivity, high melting point, high surface area, and low density, in addition to being essentially inert to most chemical liquids and gases [33, 106]. Diatomaceous earth is commonly used by the brewing industries during the beer filtration and clarification steps. When applied in this way, it has a very short shelf life, as it becomes saturated with organic material, derived from the beer fermentation

Table VIII - Chemical composition of inorganic industrial wastes used in the production of porous ceramics.

Industry	Inorganic waste	SiO_2	Al_2O_3	K_2O	Na_2O	CaO	MgO	Fe_2O_3	TiO_2	Others	LoI	Ref.
Brewing industry	Diatomaceous earth waste	91.02	1.23	0.59	-	1.99	-	4.40	-	0.73	-	[33]
		74.61	5.48	1.45	1.32	0.48	0.12	0.73	0.30	0.54	13.40	[34]
Ornamental rock industry	Granite scrap	66.13	15.15	1.32	1.83	3.75	3.05	3.04	-	-	7.58	[35]
		73.77	13.37	3.92	3.52	1.38	0.23	2.57	-	0.14	0.64	[36]
	Quartzite waste	79.62	12.43	4.44	-	0.63	0.95	1.11	0.13	0.69	-	[37]
Ceramic industry	Ceramic tile polishing waste	68.77	21.74	2.39	2.64	1.32	1.02	0.79	0.49	0.12	0.95	[38]
	Porcelain polishing waste	64.30	17.70	1.25	3.51	1.55	2.14	0.65	0.34	-	0.80	[39]
	Porcelain tile polishing residue	67.10	20.50	2.40	3.00	1.80	1.40	1.70	0.70	0.70	0.50	[100]
	Stoneware polishing residue	64.10	16.50	2.10	4.40	1.40	4.60	0.50	0.50	1.90	4.00	[40]
	Ceramic waste	78.62	10.56	1.48	3.37	0.99	0.97	1.00	-	-	2.36	[41]
	Fired clayey material residue	47.14	28.22	0.91	4.59	1.37	1.98	11.44	-	-	3.47	[35]
	Ceramic sludge	56.45	15.68	2.82	1.37	7.79	2.24	0.52	0.12	9.79	3.20	[101]
	Porcelain sludge	66.83	16.84	1.52	0.55	2.08	1.83	1.06	-	0.08	9.20	[42]
Metallurgical industry	Chromium slag	33.78	26.33	0.22	0.18	4.99	21.67	3.75	-	7.95	0.17	[43]
	Nickel smelting slag	50.97	5.02	0.18	2.59	1.36	29.97	7.76	-	-	0.95	[44]
Mining industry	Germanium tailing	66.68	10.82	2.56	4.69	6.55	3.66	3.54	0.92	0.58	-	[45]
	Lead-zinc mine tailing	14.30	4.52	-	-	28.0	1.72	25.09	-	23.67	2.61	[46]
	Extracted titanium tailing	21.30	8.90	-	0.50	35.2	9.50	2.50	11.00	11.10	-	[47]
	Asbestos tailing	36.05	0.71	0.11	-	6.03	44.64	11.28	-	1.18	-	[48]
		31.30	0.62	0.10	-	5.28	38.99	8.42	-	0.07	14.35	[49]
	Vitrified asbestos-containing waste	35.70	7.40	0.10	<0.05	35.1	12.60	7.00	1.50	-	0.60	[40]
	Iron tailing	60.11	6.79	1.56	0.32	6.60	8.66	14.73	0.58	0.63	-	[102]
Power plant	Coal fly ash	52.30	28.60	0.06	0.40	5.80	1.60	4.10	-	2.40	4.60	[96]
		48.49	41.20	-	-	3.31	0.20	3.37	1.30	-	2.13	[97]
		55.05	31.97	-	-	1.58	-	-	-	1.68	-	[98]
	High alumina fly ash	42.59	48.27	0.56	-	2.14	0.41	2.36	2.41	1.26	-	[103]
Others	Investment casting* waste	36.20	53.30	0.90	0.40	-	-	1.70	1.40	6.10	-	[50]
	Cathode ray tube glass	58.72	3.72	5.56	7.01	4.03	3.32	-	-	17.95	-	[45]
	Glass waste	70.95	2.16	0.02	16.76	9.60	-	0.10	0.05	0.03	0.33	[13]
		70.00	0.90	-	11.50	12.7	3.90	0.40	-	0.60	-	[47]
	Silicon kerf waste	75.01	0.09	0.02	-	0.50	-	5.27	-	19.13	-	[51]
	Coal gangue	52.70	18.10	2.51	2.00	1.57	1.50	4.77	0.75	0.76		[99]
	Coal slime	58.29	23.85	2.69	1.90	3.62	1.51	4.64	0.76	1.19		[99]

*LoI: loss on ignition; *: lost-wax process.*

Table IX - Properties of porous ceramic materials obtained from the use of diatomaceous earth waste from the brewing industry.

Composition (wt%)	Final product	Sintering conditions	Apparent porosity (%)	Compressive strength (MPa)	Ref.
Diatomaceous earth waste (10-16%) + ignimbrite + bentonite	Ceramic foam	1100 ºC/1 h	79.76-81.62	0.11-0.80	[33]
Diatomaceous earth waste (1-5%) + clay	Porous clay brick	950 ºC/6 h	~35.1-39.4	18.2-22.4	[34]

process, making its reuse as filtering material unfeasible. A large brewing company can generate approximately 30,000 kg/month of this waste [33, 107]. Diatomaceous earth waste, as well as other inorganic materials rich in amorphous silica, is convenient and promising for the production of porous ceramics due to its properties [108]. According to studies carried out in recent years (Table IX), highly porous ceramic materials can be obtained from the use of diatomaceous earth waste as porogenic agents. Using formulations containing ignimbrite, bentonite, and only 10 to 16 wt% of diatomaceous earth waste, Huanca and Nunes [33] produced highly porous ceramic supports (porosity of 79.76-81.62%) capable of reducing approximately 85% of the pollutants emitted by burning bricks and tiles from the red ceramic industry. Mateo et al. [34] produced ceramic bricks with high porosity (35.1-39.4%) using only 1 to 5 wt% of diatomaceous earth waste. The addition of the waste promoted an increase in open porosity and, consequently, a reduction in the bulk density of the bricks, contributing to their insulating characteristics. According to the researchers, the use of this waste as secondary raw material in the manufacture of ceramic bricks can present advantages from an economic and technological point of view.

Waste from the ornamental rock industry: the ornamental rock industry is of great importance to the world economy [109]. Its activities are mainly based on the extraction, cutting, and polishing of rocks such as granite, quartzite, marble, slate, and gneiss. The techniques used for this type of industry produce continuously high amounts of mineral waste, which are normally disposed of in landfills or directly into the environment, without any prior treatment [11, 110-112]. The inadequate disposal of mineral waste leads to the deterioration of flora and fauna and represents risks to human health since the fine mineral particles can be deposited in the lungs through breathing [11, 109, 112, 113]. In the granite processing industry, more specifically, it is estimated that 25% of the material is rejected during the sawing process, around 15% during the cutting and polishing steps, and 1% during the finishing process. The quartzite transformation industry, which involves fewer processing steps, produces approximately 1% of waste [109]. Granite and quartzite wastes are mainly composed of silicon oxide (SiO_2), but also contain aluminum (Al_2O_3), alkaline (K_2O and Na_2O), alkaline earth (CaO and MgO), and iron (Fe_2O_3) oxides in their chemical compositions [11, 35-37]. The silica present in these wastes largely comes from the quartz crystalline phase, while the alkaline and alkaline earth oxides are generally from impurities in the form of feldspar and micaceous mineral [11, 37]. The K_2O and Na_2O contents can act as fluxes, which, in reaction with silica and alumina, promote the formation of a liquid phase by eutectic reaction, which improves the sintering process [113].

Considering that some natural raw materials used in the manufacture of traditional ceramics derive from the decomposition of rocks, a similar mineralogical composition between them and the waste generated by the ornamental rock industry should be expected [11, 109, 114]. This means that waste from the extractive activity of ornamental rocks is a good substitute for raw materials with a high added value used in the production of ceramic materials, including porous ones. Table X presents works that were carried out aiming at the use of waste from the ornamental rock industry, together with clay mixtures, to obtain porous ceramics. Studies performed by Jiang et al. [35] demonstrated that it is possible to produce ceramic foams with a predominance of closed porosity using granite waste as the main raw material. With a ceramic mass consisting of 85 wt% of granite waste, the researchers obtained foams with suitable properties to be applied to the thermal insulation of buildings. According to Liu et al. [36], who also studied the use of granite waste (0-100 wt%) in the production of ceramic foams, the referred waste contributes to improving the uniformity of the pore size distribution. In a study carried out by Oliveira et al. [37], hollow fiber ceramic membranes were obtained from a mixture of 40 wt% of quartzite waste and 60 wt% of alumina. The results revealed that the quartzite waste, together with alumina, has chemical and mineralogical properties suitable for the formation of the mullite crystalline phase, which is desirable in porous ceramic materials as it contributes to the increase in mechanical strength.

Waste from the ceramic industry: the ceramic industry generates a considerable amount of wastewater in many steps of the manufacturing process, especially in the preparation of glazes and screen printing paints, slip preparation, and decoration. In an industrial plant that produces 300,000 m^2 of ceramic tiles per month, approximately 192 m^3 of wastewater is generated. After the filtering process, approximately 30 ton of solid waste (ceramic sludge) are left. Thus, it is estimated that approximately 10 ton of sludge per 100,000 m^2 of ceramic tile is produced [94]. Due to the continuous production of this sludge by the ceramic industry, its disposal has become a major problem from an environmental point of view [42]. It is reported that the annual production of ceramic sludge is around 86,660 ton in Brazil [94]. The polishing residue is another type of waste from the ceramic industry that deserves attention.

Table X - Properties of porous ceramic materials obtained from the use of waste from the ornamental rock industry.

Composition (wt%)	Final product	Sintering conditions	Apparent porosity (%)	Thermal conductivity (W.m^{-1}.K^{-1})	Compressive strength (MPa)	Ref.
Granite scraps (85%) + clay tailing	Closed-pore ceramic foam	1250 ºC/30 min	83.31	0.05	0.85	[35]
Granite scraps (10-100%) + turmeric residue	Ceramic foam	1115 ºC/1 h (10%)	-	~0.080	~0.40	[36]
		1130 ºC/1 h (20%)	-	~0.087	~0.40	
		1145 ºC/1 h (30%)	-	~0.088	~0.50	
		1160 ºC/1 h (40%)	-	~0.092	~0.50	
		1175 ºC/1 h (50%)	-	~0.100	~0.60	
		1190 ºC/1 h (60%)	-	~0.110	~1.0	
		1205 ºC/1 h (70%)	-	~0.120	~1.5	
		1220 ºC/1 h (80%)	-	~0.135	~2.2	
		1235 ºC/1 h (90%)	-	~0.150	~2.8	
		1250 ºC/1 h (100%)	-	~0.165	~4.5	
Quartzite waste (40%) + alumina powder	Hollow fiber membrane	1100 ºC/1 h	~27.5	-	-	[37]
		1200 ºC/1 h	~23.0	-	-	
		1300 ºC/1 h	~12.5	-	-	
		1400 ºC/1 h	~7.5	-	-	
		1500 ºC/1 h	~7.0	-	-	

It consists of fine powders from cutting and polishing or lapping processes [40]. It is usually reused as a by-product in the ceramic process for complete cycle industries, but in some cases, it is still discarded in landfills [40, 115, 116]. According to Zhu et al. [41] the contents of Al_2O_3 and SiO_2, together, are almost 90 wt% in this type of material.

Due to the chemical and mineralogical compositions of the aforementioned residues, they have been identified as having great potential to be used as alternative sources of raw materials in the production of ceramic products, especially ceramic products with high porosity. Table XI shows some studies that demonstrate the feasibility of using waste from the ceramic industry in the production of porous ceramic materials. Monich et al. [40] produced high porous ceramics (74%) using only porcelain stoneware polishing residue as raw material. Zhu et al. [41] and Jiang et al. [35] produced ceramic foams with apparent porosity of up to 83% using ceramic wastes. De Silva and Hansamali [42] evaluated the progressive replacement of clay by porcelain ceramic sludge (20 to 60 wt%) in the production of porous bricks, obtaining promising results. According to the authors, the replacement of 40 wt% of clay with porcelain ceramic sludge resulted

Table XI - Properties of porous ceramic materials obtained from the use of waste from the ceramic industry.

Composition (wt%)	Final product	Sintering conditions	Apparent porosity (%)	Thermal conductivity (W.m^{-1}.K^{-1})	Compressive strength (MPa)	Ref.
Polishing stoneware residue (100%)	Highly porous glass-ceramic	900 ºC/1 h	74.0	-	3.1	[40]
Polishing stoneware residue (90%) + soda-lime glass			75.1	-	2.5	
Ceramic waste (80%) + flux+cement+clay	Ceramic foam	1000 ºC/3 h	~40-83	~0.08-0.21^a ~0.12-0.23^b	~0-9.3	[41]
Residue of fired clayey material from ceramic plant (14%) + granite scrap (85%)	Closed-pore ceramic foam	1250 ºC/30 min	83.31	0.05	0.85	[35]
Porcelain ceramic sludge (20-60%) + clay	Porous clay brick	850 ºC/1 week	-	-	~2.2-2.9	[42]

^{a}: 10 wt% clay; ^{b}: 10 wt% foam.

Table XII - Properties of porous ceramic materials obtained from the use of tailings from the mining industry.

Composition (wt%)	Final product	Sintering conditions	Apparent porosity (%)	Thermal conductivity ($W.m^{-1}.K^{-1}$)	Compressive strength (MPa)	Ref.
Germanium tailing (40%) + cathode ray tube glass + SiC	Glass-ceramic foam	880 ºC/30 min	-	0.68	3.32	[45]
Lead-zinc mine tailing (20%) + fly ash + red mud + sodium borate	Glass-ceramic foam	920 ºC/1 h	34.8	-	25.3	[46]
		950 ºC/1 h	54.3	-	16.8	
		980 ºC/1 h	69.2	-	7.4	
		1000 ºC/1 h	78.5	-	4.6	
Extracted titanium tailing + glass waste (2:8)	Glass-ceramic foam	760 ºC/30 min	78.4	0.15	3.3	[47]
		770 ºC/30 min	82.4	0.11	1.3	
		780 ºC/30 min	88.0	0.06	1.0	
		790 ºC/30 min	84.0	0.09	1.0	
Asbestos tailings (10-30%) + coal fly ash	Porous glass-ceramic	1000-1220 ºC/1 h	41-51	-	-	[49]
Vitrified asbestos-containing waste (70-90%) + soda-lime glass	Highly porous glass-ceramic	900 ºC/1 h	80.9-87.3	-	0.20-2.4	[40]
Iron tailing (45%)	Porous brick	1070 ºC/3 h	88.8	0.036 (porosity 88.8%)	0.38-7.58	[102]
		1080 ºC/3 h	87.4			
		1090 ºC/3 h	87.0			
		1100 ºC/3 h	85.5			
		1110 ºC/3 h	82.6	0.13 (porosity 70.5%)		
		1120 ºC/3 h	71.6			
		1090 ºC/3-11 h	70.5-86.7			

in a decrease of 6% in brick density, an increase of 32% in compressive strength, and an improvement in thermal performance compared to bricks produced entirely with clay. At 12:30 p.m., when a higher room temperature is expected, a temperature difference of 10 ºC was observed between the external and internal environments, isolated with bricks produced with 40 wt% of ceramic sludge, while a difference of only 4.20 ºC was observed for tests with conventional bricks.

Tailings from the mining industry: in general, tailings from the mining industry contain abundant compounds based on Si and Al, which are essential elements for ceramic materials [46], in addition to other compounds similar to those found in ceramic phases, such as CaO, MgO, Fe_2O_3, and TiO_2 [47]. The high contents of SiO_2 and CaO are similar to those found in glassy phases [117]. Thus, they are good alternative raw material options for the manufacture of glass-ceramic foams [47] and/or porous vitreous ceramics, as shown in Table XII. Liu et al. [46] used lead-zinc mine tailings (20 wt%) together with fly ash (48 wt%), red clay (12 wt%), and sodium borate (20 wt%) in order to produce glass ceramic foams. At 980 ºC, foams with a glassy phase belonging to the Ca-Al-Si-O system were obtained, a structure that allows the solidification of some heavy metals (Pb, Cr, etc.) present in the tailings, since stable chemical bonds can be formed between them [110]. Xi et al. [47] also produced glass-ceramic foams with satisfactory properties, but using tailings from the extraction of titanium in combination with glass waste, in a ratio of 2:8.

Asbestos tailings are considered hazardous solid waste due to their carcinogenicity [48], and their accumulation represents a serious threat to the health of the population and also to the environment [49]. Chemically, they are mainly composed of SiO_2, MgO, and Fe_2O_3, but also have small amounts of CaO and Al_2O_3 [118]. When subjected to a heating process, this waste undergoes a series of decomposition reactions that lead to the release of CO_2 [119]. This behavior can favor the formation of pores in low-density ceramic materials. It is believed that MgO and CaO produced by thermal decomposition of the crystalline phases of asbestos tailings, such as dolomite and brucite, provide higher liquid phase content and reduce the melting temperature of the glassy phase of aluminum silicate. As a result, porous glass-ceramics prepared with the addition of this type of waste present greater porosity and lower densification temperature [49, 120]. Zeng et al. [49] prepared porous vitreous ceramics using asbestos tailings together with coal fly ash, in proportions of 10:90, 20:80, and

Table XIII - Properties of porous ceramic materials obtained from the use of coal ash from thermal power plants.

Composition (wt%)	Final product	Sintering conditions	Apparent porosity (%)	Thermal conductivity (W.m^{-1}.K^{-1})	Compressive strength (MPa)	Ref.
Coal fly ash + SiC powder (0.2:0.8 wt ratio) + pore former (PMMA, graphite)	Mullite bonded SiC ceramic membrane	850 ºC/2 h + 1000 ºC/1 h	36.36 (no pore former); 42.03 (graphite); 45.96 (PMMA)	-	-	[96]
Coal fly ash (40%) + bauxite (60%) + SiC (0-15%) + potassium feldspar (0-16%)	Porous mullite ceramic	1450-1550 ºC/2 h	35.87-27.42[a] 29.29-13.23[b] 13.23-4.03[c]	~1.85-2[a] ~1.90-3[b] ~2.95-2.5[c]	~130-164[a] ~150-260[b] ~270-165[c]	[97]
Coal fly ash + $Al(OH)_3$ (3:1 M Al:Si ratio) + MoO_3 (0-20%)	Highly porous mullite ceramic membrane	1100-1500 ºC/2 h	41.65-29.75 (0%)[d]; 52.54-28.91 (5%)[d]; 55.71-29.58 (10%)[d]; 58.14-40.66 (20%)[d]	-	-	[98]
Fly ash hollow sphere (30-60%) + aluminum silicate powder + egg white protein powder (12%)	Porous mullite ceramic	1450 ºC/4 h	62.66-80.06 (TP); 27.84-54.87 (OP); 34.82-25.19 (CP)	0.29-0.76	-	[125]

[a]: 0-15 wt% SiC; [b]: 1450-1550 ºC; [c]: 0-16 wt% feldspar; [d]: wt% MoO_3; TP: total porosity; OP: open porosity; CP: closed porosity.

30:70. The researchers demonstrated that after adding the tailings, the composition of the raw materials changed from the $CaO-Al_2O_3-SiO_2$ system to the $CaO-Al_2O_3-SiO_2-MgO$ system, which is beneficial for the formation of the indialite crystalline phase ($2MgO.2Al_2O_3.5SiO_2$). Furthermore, they observed that the produced glass-ceramics underwent a sudden self-expansion during the sintering process and that their porosity significantly increased with the incorporation of the waste, reaching values from 41% to 51%. Highly porous vitreous ceramics (apparent porosity of 80.9% to 87.3%) were also produced by Monich et al. [40], but in this case, the researchers used waste containing vitrified asbestos (70-90 wt%) together with soda-lime glass.

Coal ash from power plants: coal ash is generated in large quantities as a by-product of thermal power plants [96], and is considered to be highly hazardous to the environment due to its persistently toxic trace elements [98]. In this sense, environmentally friendly use of this type of waste is an important issue for the prevention of environmental pollution [96]. The main chemical components of coal fly ash (silica, alumina) are similar to those of clays and kaolin, which are used as starting materials to fabricate porous ceramics [98]. Thus, many works have been done over the last few years aiming at the production of porous ceramics using this type of waste [96-98, 121-124], as shown in Table XIII.

FINAL COMMENTS

The incorporation of industrial wastes in production processes to obtain porous ceramic materials is an alternative way to minimize their negative effects on the environment, contributing to the formulation of more sustainable development strategies and policies. In this sense, in recent years, increasingly higher levels of industrial waste in ceramic formulations have been studied, reaching up to 50 wt% for organics, mostly used as porogenic agents, and up to 100 wt% for inorganics, used as porogenic agents but also as silica and/or fluxing oxides providers. Thus, currently, highly porous ceramic materials can be entirely obtained using a single type of industrial waste or a mixture of two or more. In general, there is a tendency to use industrial waste for the production of lightweight ceramic bricks for structural applications, glass-ceramic foams for thermal and/or acoustic insulation in buildings, and membranes for filtration/separation processes.

ACKNOWLEDGMENT

The authors acknowledge the financial support received from CAPES, Brazil.

REFERENCES

[1] S.K. Hubadillah, M.H.D. Othman, T. Matsuura, A.F. Ismail, M.A. Rahman, Z. Harun, J. Jaafar, M. Nomura, Ceram. Int. **44** (2018) 4538.

[2] K. Stoeva, S. Alriksson, Waste Manage. **68** (2017) 732.

[3] A. Minelgaite, G. Liobikiene, Sci. Total Environ. **667** (2019) 86.

[4] S.Z. Salleh, A.A. Kechik, A.H. Yusoff, M.A.A. Taib, M.M. Nor, M. Mohamad, T.G. Tan, A. Ali, M.N. Masri, J.J. Mohamed, S.K. Zakaria, J.G. Boon, F. Budiman, P.T. Teo, J.

Clean. Prod. **306** (2021) 127264.
[5] M.S. Savadkoohi, M. Reisi, J. Clean. Prod. **266** (2020) 121973.
[6] M.F.M. Ahmad Zamri, R. Bahru, R. Amin, M.U.A. Khan, S.I.A. Razak, S.A. Hassan, M.R.A. Kadir, N.H.M. Nayan, J. Clean. Prod. **290** (2021) 125792.
[7] B.C.A. Pinheiro, J.N.F. Holanda, Ceram. Int. **39** (2013) 57.
[8] W.P. Gonçalves, V.J. Silva, R.R. Menezes, G.A. Neves, H.L. Lira, L.N.L. Santana, Appl. Clay Sci. **137** (2017) 259.
[9] V.J. Da Silva, M.F. Da Silva, W.P. Gonçalves, R.R. De Menezes, G.A. Neves, H.L. Lira, L.N.L. Santana, Ceram. Int. **42**, 14 (2016) 15471.
[10] R.D.C. da Rocha, H.E. Zorel Jr., T. Lando, Cerâmica **63**, 365 (2017) 1.
[11] K.R. Silva, L.F.A. Campos, L.N.L. Santana, Mater. Res. **22**, 1 (2019) 1.
[12] O. Gorhan, O. Simsek, Constr. Build. Mater. **40** (2013) 390.
[13] S. Arcaro, B.G.O. Maia, M.T. Souza, F.R. Cesconeto, L. Granados, A.P.N. De Oliveira, Mater. Res. **19** (2016) 1064.
[14] P.M. Nigay, R. Sani, T. Cutard, A. Nzihou, Mater. Sci. Eng. A **708** (2017) 375.
[15] M.S. Ali, M.A.A. Hanin, S.M. Tahir, C.N.A. Jaafar, M. Norkhairunnisa, K.A. Matori, J. Ceram. Soc. Jpn. **125**, 5 (2017) 402.
[16] A. Manni, A.E. Haddar, I.E.E.A.E. Hassani, A.E. Bouari, C. Sadik, Bol. Soc. Esp. Ceram. V. **58**, 5 (2019) 211.
[17] F. Andreola, I. Lancellotti, T. Manfredini, L. Barbieri, Int. J. Appl. Ceram. Technol. **17** (2019) 22.
[18] S.M.S. Kazmi, S. Abbas, M.J. Munir, A. Khitab, J. Build. Eng. **7** (2016) 372.
[19] S.M.S. Kazmi, S. Abbas, M.A. Saleem, M.J. Munir, A. Khitab, Constr. Build. Mater. **120** (2016) 29.
[20] S.M.S. Kazmi, M.J. Munir, I. Patnaikuni, Y.F. Wu, U. Fawad, Energy Build. **158** (2018) 1117.
[21] D. Eliche-Quesada, R.A. Da Cunha, F.A. Corpas-Iglesias, Appl. Clay Sci. **114** (2015) 202.
[22] N.H. Kamarudin, Z. Harun, M.H.D. Othman, T. Abdullahi, S.S. Bahi, N.H. Kamarudin, M.Z. Yunos, W.N.W. Salleh, Ceram. Int. **46**, 2 (2020) 1512.
[23] W. Acchar, E.J.V. Dutra, A.M. Segadães, Appl. Clay Sci. **75-76** (2013) 141.
[24] E. Escalera, G. García, R. Terán, R. Tegman, M.L. Antti, M. Odén, Constr. Build. Mater. **98** (2015) 257.
[25] D. Eliche-Quesada, M.A. Felipe-Sesé, J.A. López-Pérez, A. Infantes-Molina, Ceram. Int. **43** (2017) 463.
[26] J.A. De La Casa, E. Castro, Constr. Build. Mater. **61** (2014) 320.
[27] D. Eliche-Quesada, J. Leite-Costa, Waste Manage. **48** (2016) 323.
[28] M.T. Souza, B.G.O. Maia, L.B. Teixeira, K.G. De Oliveira, A.H.B. Teixeira, A.P.N. De Oliveira, Process Saf. Environ. Prot. **111** (2017) 60.
[29] F.H.G. Leite, T.F. Almeida, R.T. Faria Jr., J.N.F. Holanda, Ceram. Int. **43** (2017) 4674.
[30] L.B. Teixeira, V.K. Fernandes, B.G.O. Maia, S. Arcaro, A.P.N. De Oliveira, Ceram. Int. **43** (2017) 6730.
[31] L. Hao, W. Gao, S. Yan, M. Niu, G. Liu, H. Hao, Mater. Chem. Phys. **235** (2019) 121741.
[32] E.B.G.A. Fulgêncio, F.K. de Medeiros, J.M. Cartaxo, R.P.S. Dutra, D.A. Macedo, L.F.A. Campos, Cerâmica **64**, 371 (2018) 381.
[33] K.Z. Huanca, A.B. de A. Nunes, Cerâmica **62**, 362 (2016) 110.
[34] S. Mateo, M. Cuevas, M.D. La Rubia, D. Eliche-Quesada, Adv. Appl. Ceram. **116**, 2 (2016) 77.
[35] C. Jiang, S. Huang, G. Li, X. Zhang, X. Cheng, Ceram. Int. **44** (2018) 3469.
[36] X. Liu, B. Ma, H. Tan, S. Jian, Z. Lv, P. Chen, T. Zhang, H. Qi, P. Wang, W. Lu, J. Clean. Prod. **278** (2021) 123825.
[37] S.S.L. Oliveira, R.S.B. Ferreira, H.L. Lira, L.N.L. Santana, E.M. Araújo, Mater. Res. **22** (2019) 1.
[38] H. Wang, Z. Chen, L. Liu, R. Ji, X. Wang, Ceram. Int. **44** (2018) 10078.
[39] Y. Guo, Y. Zhang, H. Huang, X. Meng, Y. Liu, S. Tu, B. Li, Constr. Build. Mater. **125** (2016) 1093.
[40] P.R. Monich, A.R. Romero, E. Rambaldi, E. Bernardo, Constr. Build. Mater. **261** (2020) 119971.
[41] L. Zhu, S. Li, Y. Li, N. Xu, Constr. Build. Mater. **180** (2018) 291.
[42] G.H.M.J.S. de Silva, E. Hansamali, Constr. Build. Mater. **228** (2019) 116754.
[43] X. Ge, M. Zhou, H. Wang, Z. Liu, H. Wu, X. Chen, Ceram. Int. **44** (2018) 11888.
[44] Q. Wu, Q. Chen, Z. Huang, B. Gu, H. Zhu, L. Tian, Ceram. Int. **46** (2020) 4581.
[45] Q. Zhang, F. He, H. Shu, Y. Qiao, S. Mei, M. Jin, J. Xie, Constr. Build. Mater. **111** (2016) 105.
[46] T. Liu, C. Lin, J. Liu, L. Han, H. Gui, C. Li, X. Zhou, H. Tang, Q. Yang, A. Lu, Ceram. Int. **44** (2018) 14393.
[47] C. Xi, F. Zheng, J. Xu, W. Yang, Y. Peng, Y. Li, P. Li, Q. Zhen, S. Bashir, J.L. Liu, Constr. Build. Mater. **190** (2018) 896.
[48] W.M. Zheng, H.J. Sun, T.J. Peng, L. Zeng, J. Non Crystal. Solids **517** (2019) 26.
[49] L. Zeng, H. Sun, T. Peng, W. Zheng, Waste Manage. **106** (2020) 184.
[50] A.C. Carvalho, F. Raupp-Pereira, J.B. Rodrigues Neto, A.P. Novaes de Oliveira, Cerâmica **61**, 359 (2015) 383.
[51] Y. Han, L. Zhou, Y. Liang, Z. Li, Y. Zhu, Mater. Chem. Phys. **240** (2020) 122248.
[52] L. Barbieri, F. Andreola, I. Lancellotti, R. Taurino, Waste Manage. **33** (2013) 2307.
[53] V.C. Colonetti, M.F. Sanches, V.C. De Souza, C.P. Fernandes, D. Hotza, M.G.N. Quadri, Ceram. Int. **44** (2018) 2436.
[54] L.N.R.M. Santos, J.M. Cartaxo, J.R.S. Silva, A.M. Rodrigues, E.L.A. Dantas, F.B. De Sousa, G.A. Neves, R.R. Menezes, J. Eur. Ceram. Soc. **41**, 14 (2021) 7111.
[55] T. Ohji, M. Fukushima, Int. Mater. Rev. **57**, 2 (2012) 115.
[56] Y. Chen, N. Wang, O. Ola, Y. Xia, Y. Zhu, Mater. Sci. Eng. R **143** (2021) 100589.

[57] M.V. Twigg, J.T. Richardson, Ind. Eng. Chem. Res. **46** (2007) 4166.
[58] C. Galassi, J. Eur. Ceram. Soc. **26**, 14 (2006) 2951.
[59] A.R. Studart, U.T. Gonzenbach, E. Tervoort, L.J. Gauckler, J. Am. Ceram. Soc. **89** (2006) 1771.
[60] J.H. Eom, Y.W. Kim, S. Raju, J. Asian Ceram. Soc. **1** (2013) 220.
[61] N. Vitorino, J.C.C. Abrantes, J.R. Frade, Mater. Lett. **98** (2013) 120.
[62] G. Scarinci, G. Brusatin, L. Barbieri, A. Corradi, I. Lancellotti, P. Colombo, S. Hreglich, R. Dall'Igna, J. Eur. Ceram. Soc. **20** (2000) 2485.
[63] H. Laksaci, A. Khelifi, M. Trari, A. Addoun, J. Clean. Prod. **147** (2017) 254.
[64] J. He, Y. Jie, J. Zhang, Y. Yu, G. Zhang, Cem. Concr. Compos. **37** (2013) 108.
[65] P.C.W. Kwong, C.Y.H. Chao, J.H. Wang, C.W. Cheung, G. Kendall, Atmos. Environ. **41**, 35 (2007) 7462.
[66] S. Hu, J. Xiang, L. Sun, M. Xu, J. Qiu, P. Fu, Fuel Process. Technol. **89**, 11 (2008) 1096.
[67] K.G. Mansaray, A.E. Ghaly, Energy Sources **19**, 9 (1997) 989.
[68] N. Sellin, B.G. De Oliveira, C. Marangoni, O. Souza, A.P.N. De Oliveira, T.M.N. De Oliveira, Chem. Eng. Trans. **32** (2013) 349.
[69] R.H. Bello, P. Linzmeyer, C.M.B. Franco, O. Souza, N. Sellin, S.H.W. Medeiros, C. Marangoni, Waste Manage. **34**, 8 (2014) 1501.
[70] E.R.K. Fernandes, C. Marangoni, O. Souza, N. Sellin, Energy Convers. Manag. **75** (2013) 603.
[71] R. García, C. Pizarro, A.G. Lavín, J.L. Bueno, Bioresour. Technol. **103**, 1 (2012) 249.
[72] F. Andreola, I. Lancellotti, R. Sergi, V. Cannillo, L. Barbieri, Materials **14**, 1 (2021) 167.
[73] C.B.E. Abi, Constr. Build. Mater. **59** (2014) 195.
[74] K. Ericsson, Energy **32**, 10 (2007) 1838.
[75] S.V. Vassilev, D. Baxter, L.K. Andersen, C.G. Vassileva, Fuel **105** (2013) 19.
[76] S.V. Vassilev, D. Baxter, L.K. Andersen, C.G. Vassileva, Fuel **105** (2013) 40.
[77] M. Cabrera, A.P. Galvin, F. Agrela, M.D. Carvajal, J. Ayuso, Constr. Build. Mater. **58** (2014) 234.
[78] L.L. Baxter, T.R. Miles, T.R. Miles Jr, B.M. Jenkins, T. Milne, D. Dayton, R.W. Bryers, L.L. Oden, Fuel Process. Technol. **54**, 1-3 (1998) 47.
[79] R. Pode, Renew. Sust. Energy Rev. **53** (2016) 1468.
[80] R. Xiao, X. Chen, F. Wang, G. Yu, Renew. Energy **36** (2011) 244.
[81] A. May, V.F. De Souza, G.A. Gravina, P.G. Fernandes, Ciên. Rural **46**, 3 (2016) 434.
[82] X. Yao, K. Xu, Y. Liang, Bioresources **12**, 2 (2017) 3222.
[83] F. Andreola, I. Lancellotti, T. Manfredini, F. Bondioli, L. Barbieri, Waste Biomass Valorization **9** (2018) 2529.
[84] O.T. Maza-Ignacio, V.G. Jiménez-Quero, J. Guerrero-Paz, P. Montes-García, Constr. Build. Mater. **234** (2020) 117314.
[85] K.S. Shanmukharadhya, K. Ramachandran, J. Energy Inst. **82**, 2 (2009) 120.
[86] K.C.P. Faria, J.N.F. Holanda, Cerâmica **59**, 351 (2013) 473.
[87] R.M. Andrade, N.G. Jaques, J. Sousa, R.P.S. Dutra, D.A. Macedo, L.F.A. Campos, Cerâmica **65**, 376 (2019) 620.
[88] J. Liu, B. Ren, Y. Lu, X. Xi, Y. Li, K. Liu, J. Yang, Y. Huang, Ceram. Int. **45** (2019) 13964.
[89] Y. Zhang, X. Tong, B. Zhang, C. Zhang, H. Zhang, Y. Chen, J. Membr. Sci. **548** (2018) 32.
[90] L. Fan, Y. Xu, X. Zhou, F. Chen, Q. Fu, Polymer **153** (2018) 61.
[91] Y.-T. Chen, C.-C. Tseng, H.-J. Tsai, W.-K. Hsu, Chem. Phys. Lett. **714** (2019) 202.
[92] D. Montané, J. Salvadó, C. Torras, X. Farriol, Biomass Bioenergy **22**, 4 (2002) 295.
[93] J.A. Alburquerque, J. Gonzálvez, D. García, J. Cegarra, Bioresour. Technol. **91**, 2 (2004) 195.
[94] V.S. Nandi, F. Raupp-Pereira, O.R.K. Montedo, A.P.N. Oliveira, J. Clean. Prod. **86**, 1 (2015) 461.
[95] H.R. Fernandes, F. Andreola, L. Barbieri, I. Lancellotti, M.J. Pascual, J.M.F. Ferreira, Ceram. Int. **39** (2013) 9071.
[96] D. Das, N. Kayal, G.A. Marsola, D.G.P. Filho, M.D.M. Innocentini, J. Eur. Ceram. Soc. **40** (2020) 2163.
[97] B. Ma, C. Su, X. Ren, Z. Gao, F. Qian, W. Yang, G. Liu, H. Li, J. Yu, Q. Zhu, J. Alloys Compd. **803** (2019) 981.
[98] M. Fu, J. Liu, X. Dong, L. Zhu, Y. Dong, S. Hampshire, J. Eur. Ceram. Soc. **39** (2019) 5320.
[99] H. Xu, H. Du, L. Kang, Q. Cheng, D. Feng, S. Xia, J. Renew. Mater. **9**, 12 (2021) 2129.
[100] I.V. de Souza, L.J.J. Nieves, A.G. Dal-Bó, A.M. Bernardin, Clean. Eng. Tech. **6** (2022) 100381.
[101] H. Arik, J. Eur. Ceram. Soc. **23**, 12 (2003) 2005.
[102] R. Li, Y. Zhou, C. Li, S. Li, Z. Huang, Constr. Build. Mater. **213** (2019) 43.
[103] B. Xia, Z. Wang, L. Gou, M. Zhang, M. Guo, Ceram. Int. **48** (2022) 10472.
[104] S. Martinovic, M. Vlahovic, T. Boljanac, L. Pavlovic, Int. J. Miner. Process. **80**, 2-4 (2006) 255.
[105] H. Hadjar, B. Hamdi, M. Jaber, J. Brendlé, Z. Kessaissia, H. Balard, J.B. Donnet, Micropor. Mesopor. Mat. **107**, 3 (2008) 219.
[106] F. Akhtar, Y. Rehman, L. Bergstrom, Powder Technol. **201** (2010) 253.
[107] M.R. Goulart, C.B. Da Silveira, M.L. Campos, J.A. De Almeida, Quím. Nova **34**, 4 (2011) 625.
[108] A.A. Reka, B. Pavlovski, P. Makreski, Ceram. Int. **43** (2017) 12572.
[109] P. Torres, R.S. Manjate, S. Quaresma, H.R. Fernandes, J.M.F. Ferreira, J. Eur. Ceram. Soc. **27** (2007) 4649.
[110] F. Raupp-Pereira, D. Hotza, A.M. Segadães, J.A. Labrincha, Ceram. Int. **32** (2006) 173.
[111] A.J. Souza, B.C.A. Pinheiro, J.N.F. Holanda, J. Mater. Process. Technol. **210** (2010) 1898.
[112] A. Jain, R. Gupta, S. Chaudhary, Constr. Build. Mater. **262** (2020) 120516.

[113] L.F. Amaral, J.P.R.G. De Carvalho, B.M. Da Silva, G.C.G. Delaqua, S.N. Monteiro, C.M.F. Vieira, J. Mater. Res. Technol. **8**, 1 (2019) 599.

[114] J.A. Junkes, P.B. Prates, D. Hotza, A.M. Segadães, Appl. Clay Sci. **69** (2012) 50.

[115] E. Rambaldi, L. Esposito, A. Tucci, G. Timellini, J. Eur. Ceram. Soc. **27**, 12 (2007) 3509.

[116] F. Andreola, L. Barbieri, I. Lancellotti, C. Leonelli, T. Manfredini, Ceram. Int. **42**, 12 (2016) 13333.

[117] H.T. Gao, X.H. Liu, J.Q. Chen, J.L. Qi, Y.B. Wang, Z.R. Ai, Ceram. Int. **44**, 6 (2018) 6044.

[118] C. Leonelli, P. Veronesi, D.N. Boccaccini, M.R. Rivasi, L. Barbieri, F. Andreola, I. Lancellotti, D. Rabitti, G.C. Pellacani, J. Hazard. Mater. **135**, 1-3 (2006) 149.

[119] A.F. Gualtieri, A. Tartaglia, J. Eur. Ceram. Soc. **20**, 9 (2000) 1409.

[120] T. Liu, Y. Tang, L. Han, J. Song, Z. Luo, A. Lu, Ceram. Int. **43**, 6 (2017) 4910.

[121] B. Ma, X. Ren, Y. Yin, L. Yuan, Z. Zhang, Z. Li, G. Li, Q. Zhu, J. Yu, Ceram. Int. **43**, 15 (2017) 11830.

[122] L. Zhu, Y. Dong, L. Li, J. Liu, S.-J. You, RSC Adv. **5** (2015) 11163.

[123] L. Zhu, Y. Dong, S. Hampshire, S. Cerneaux, L. Winnubst, J. Eur. Ceram. Soc. **35**, 2 (2015) 711.

[124] J. Cao, X. Dong, L. Li, Y. Dong, S. Hampshire, J. Eur. Ceram. Soc. **34**, 13 (2014) 3181.

[125] Z. Yang, F. Yang, S. Zhao, K. Li, J. Chen, Z. Fei, G. Chen, J. Eur. Ceram. Soc. **41** (2021) 299.

(Rec. 23/01/2022, Rev. 03/04/2022, Ac. 06/04/2022)