ORIGINAL ARTICLE

Economic analysis of the use of rice husk ash in the production of clay ceramics

G. A. Benedet[1,2]*, A. Zaccaron[1], J. M. Inocente[1], V. S. Nandi[1], S. Arcaro[1], F. Raupp-Pereira[1], D. Gorini Neto[2]
[1]*Universidade do Extremo Sul Catarinense, Post-Graduate Program on Materials Science and Engineering, Research Group on Waste Valorization as a Strategy for the Development of the Circular Economy, 88806-000, Av. Universitária 1105, Criciúma, SC, Brazil*
[2]*Universidade do Extremo Sul Catarinense, Production Engineering Department, Criciúma, SC, Brazil*

Abstract

Studies have proven that the use of waste in the production of clay ceramics is common for achieving the technical performance that is necessary for the application of these by-products. However, it is essential to analyze the feasibility of using these materials in terms of productivity and economic gains, in line with sustainability. The objective of this study is to determine the cost-benefit ratio of using rice husk ash in the production of clay ceramics. The methodological process consisted of a comparative analysis on an industrial scale between the formulation with up to 15% by volume of rice husk ash and the standard formulation previously used by the company. The economic aspects included the costs/consumption of raw materials, transport, and energy. The productivity throughout the process and technical characteristics of the final product were also evaluated. The costs of raw materials showed a financial gain of 7.0%, whereas the productivity analysis revealed that the greatest economic gain was in energy consumption during drying (13%).
Keywords: rice husk ash, clay ceramic, productivity, industrial costs.

INTRODUCTION

The world population and economy have been constantly growing over the years, resulting in challenges such as waste generation and its management. In 2016, global waste production reached 2.01 billion tons and is estimated to increase by 70% by 2050 [1]. The agroindustry generates the maximum amount of these wastes because of the activities involved in food production, such as the processing of agricultural raw materials, animal husbandry, and the manufacture of food products [2]. Within the agroindustry, rice production contributes the most to waste generation because it is one of the main foods around the world and consequently generates a large amount of waste rice husks [3]. Compared to other agricultural residues generated by the main crops in the country (sugar cane, corn, and wheat), rice husk contributes to the largest vegetable residue in ash production after combustion [4]. Therefore, considerable research is being conducted on technological and profitable means of reusing rice husk ash in industries such as civil construction, chemicals, and electrical applications, for manufacturing ceramic products and even photovoltaic cells [5].

Population growth exerts a significant influence on the production of clay ceramics because of the growing demand for housing, infrastructure, and building materials. To meet this demand, it is necessary to increase the production of clay ceramics by investing in technology, machinery, and customized raw materials. It is essential to achieve a balance between production expansion and environmental sustainability by adopting responsible and efficient production practices for natural resource use [6]. Based on this, studies that value agro-industrial waste in ceramic products are becoming increasingly common. The use of some of these wastes, such as coffee processing [7, 8], cotton waste [9], olive pomace [10], sugarcane bagasse [11], and rice husk [12] among others, have been presented in the existing literature. In most of these studies, only the technicalities of the application of waste in ceramic formulations were evaluated without analyzing the potential of these wastes in the productivity of the industry, mainly in terms of economic gains. In addition, by introducing the use of rice husk ash waste as a raw material in the ceramic industry, we can focus on a circular economy in which a productive configuration is proposed that reduces the degradation potential of activities conducted in the agroindustry, thus promoting the relationship between the economic system and the environment [13].

This study aims to analyze the cost-benefit ratio of rice husk ash on an industrial scale from an economic perspective for the production of clay ceramics with 15% by volume of rice husk ash.

EXPERIMENTAL

The methodology of this study involved the analysis using rice husk ash (RHA) in ceramics within the process on an industrial scale in the southern region of Santa

**grabenedet@outlook.com*
https://orcid.org/0000-0003-2684-6138

Table I - Chemical compositions (mass%) of the RHA as determined using X-ray fluorescence (XRF) spectroscopy.

SiO_2	Al_2O_3	CaO	MgO	K_2O	Na_2O	Fe_2O_3	TiO_2	P_2O_5	MnO	SrO	LOI
82.03	0.10	0.46	0.41	0.76	0.10	0.09	<0.05	0.71	0.12	0.08	15.09

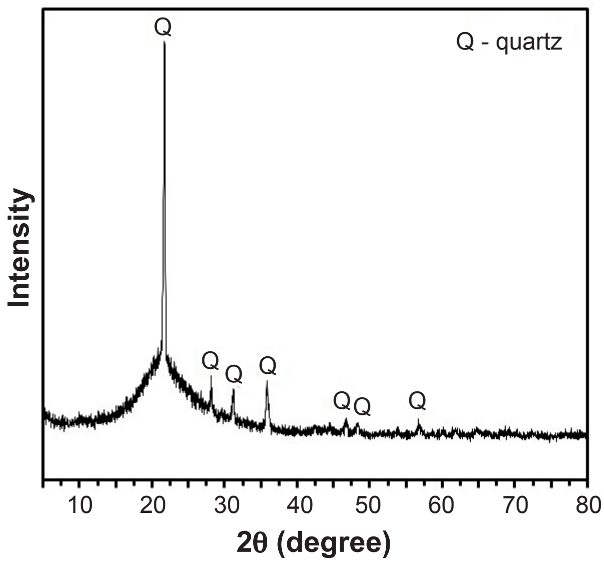

Figure 1: Result of mineralogical analysis of the RHA as determined using X-ray diffraction (XRD).

Catarina, Brazil, obtained from the combustion (at 850 °C) of rice husks to generate energy in a thermoelectric plant. RHA chemical analysis (Table I) revealed SiO_2 (silica) content >80%, which is naturally caused by the combustion of rice husks [14]. The loss on ignition (LOI) was >15% due to the high residual carbon content, which directly influences the firing color [15]. The sum of the remaining oxides was <3% and was mainly composed of K_2O and P_2O_5, where the potassium and phosphorus in RHA may be associated with the use of fertilizers in rice crops [16, 17]. Mineralogical analysis of RHA (Fig. 1) showed the presence of quartz (Q - JCPDS 00-046-1045) and amorphous silica.

The industrial production process of clay ceramics is divided into the extraction and preparation of clay, shaping of the ceramic piece, heat treatment, and shipping. The study focused on key parts of the production process. RHA can be incorporated into the process in the clay preparation stage, where two formulations were compared in volume proportion (Table II): the clay called plastic clay (PC) was a blend of yellow plastic clay (YPC) and black plastic clay (BPC) in the proportions of 90% and 10%, respectively; the SC clay corresponded to sandy clay; and the RHA corresponded to rice husk ash. When the new formulation (denominated FRHA) was created by adding 15% of the RHA waste, the SC was reduced. The mixture development process was carried out in the raw material box of a ceramics industry, using a wheel loader (bucket capacity: 2 m^3). The study by Benedet et al. [18] was a precursor to obtaining the levels of RHA applied to clay ceramics. The content of 15% by volume was adjusted to the manufacturing process. In the industrial production process, a monobloc extruder was used (MSM-350, MS Souza; production capacity 18 to 25 ton/h). Drying was carried out in an artificial dryer with a 24 h cycle and a capacity of 80 ton/day. Finally, the firing was carried out in an 80 m continuous kiln, with a capacity of 30 cars/day, or 50 to 60 ton/day, and a temperature in the firing zone of 900 °C. After the process, the standard paste (STD) of the industry and the paste developed with FRHA were compared and analyzed from technical and economic perspectives. The current study focused on the evaluation of at least four relevant conditions within the process: consumption of raw materials, productivity (outflow in extrusion), consumption of thermal energy, and weight of the blocks. These conditions were selected because they have greater economic relevance within the production process of clay ceramics. The procedural conditions were evaluated for 12 months: 6 months in the second half of 2020 (STD, without ash), and 6 months in the first half of 2021 (FRHA, with a content of 15% by volume of RHA). Subsequently, a comparison was made of the results achieved with the addition of waste to the standard paste for analyzing the technical and economic feasibility based on the data and calculations of acquisition costs with materials, transport, and energy.

Table II - STD and FRHA clay ceramic formulation (vol%).

Formulation	PC		SC	RHA
	YPC	BPC		
STD	66.15	7.35	26.50	0.00
FRHA	66.15	7.35	11.50	15.00

PC: plastic clay; YPC: yellow plastic clay; BPC black plastic clay; SC: sandy clay; RHA: rice husk ash

The chemical analysis of the raw materials (Table III) showed contents of >80% of clay base oxides (SiO_2+Al_2O_3) [19]. Alkaline and alkaline earth oxides (K_2O+Na_2O+CaO+MgO) constituted 2.6-4.1% of the clay samples and facilitated the sintering of ceramic materials because they are mineralizers [20]. Chromophore oxides (Fe_2O_3+TiO_2) content in the clays was 4.42-5.86% and impart a reddish color to ceramic masonry products [21-23]. Finally, the LOI values of the clays were 5.12-8.74% and are attributed to silicate de-hydroxylation reactions, organic matter combustion, and carbonate decomposition [24]. The oxides of the chemical elements shown in Table III were present in their most stable form in the crystalline phases identified in the XRD patterns of the clays in Fig. 2. Quartz (Q: SiO_2, JCPDS 00-046-1045), among the phyllosilicates the identified peaks were kaolinite [K: $Al_2(Si_2O_5)(OH)_4$, JCPDS 01-089-6538], illite {I: $K[Al_4Si_2O_9(OH)_3]$, JCPDS 01-070-3754}, montmorillonite [Mt: $(Na,Ca)_{0.3}(Al,Mg)_2Si_4O_{10}(OH)_2.xH_2O$, JCPDS 00-003-0010], and feldspars, namely, microcline (Mi: $KAlSi_3O_8$, JCPDS 00-019-0932), and albite/anorthite (A: $NaAlSi_3O_8$, JCPDS 00-009-0466) were identified in the XRD patterns. The diffractogram in Fig. 2 is characteristic of clay that is typically used for the manufacture of clay ceramics.

Table III - Chemical compositions (mass%) of the used clays as determined using XRF spectroscopy.

Oxide	YPC	BPC	SC
SiO_2	66.81	62.69	68.49
Al_2O_3	17.79	21.45	16.17
CaO	0.21	0.25	0.11
MgO	0.43	0.53	0.86
K_2O	1.67	1.68	2.96
Na_2O	0.29	0.21	0.78
Fe_2O_3	4.65	3.28	4.81
TiO_2	1.21	1.14	0.61
P_2O_5	0.07	0.06	0.08
MnO	<0.05	<0.05	<0.05
LOI	6.84	8.74	5.12

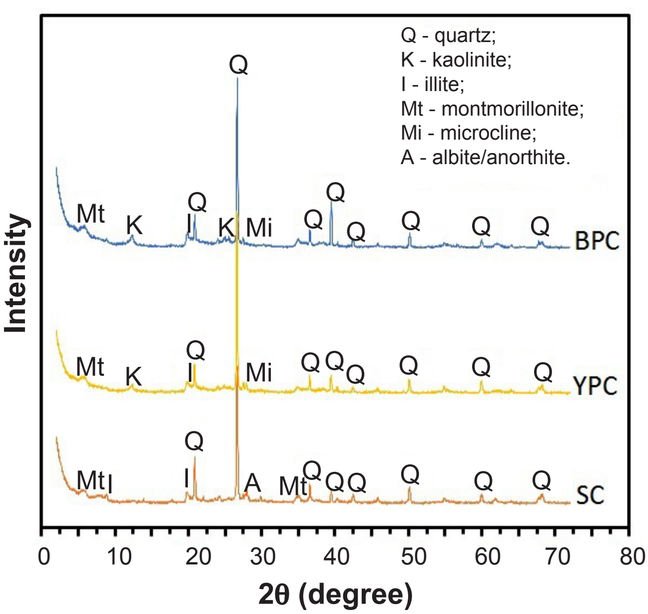

Figure 2: Results of mineralogical analysis of the clays as determined using XRD.

Technical analysis: to verify the quality of the final product, technical tests were performed on both samples and the results were measured against the technical standard ABNT NBR 15270-2 [25] in terms of the dimensional characteristics, external walls, and septum, deviation from the square, face flatness, and mechanical resistance to compression. For each sample, 13 blocks were tested for compliance with the standard. For the evaluation of water absorption, 6 blocks were tested. The water absorption index must be between 8% and 25% to be within the standard. All tests were carried out in a technical laboratory registered with the National Institute of Metrology, Quality and Technology (INMETRO). The density was obtained to evaluate the behavior of the waste based on the weight of the blocks. This test was based on Archimedes' principle [26], using a balance (AC 10 K, Marte; precision of 0.1 g), according to:

$$\rho_{app} = \frac{w_0}{w_s - w_i} \quad \text{(A)}$$

where ρ_{app} is the apparent density (g/cm^3), w_0 is the initial weight (g), w_s-w_i=V corresponds to the difference between the saturated weight and the weight immersed in the liquid and equals the volume of the immersed body (cm^3).

Economic analysis: for the costs of acquiring raw materials, the costs of materials and logistics/freight were considered. The cost of raw materials (RMc, BRL/ton) was the value of each raw material multiplied by the amount used by the company (RMa, ton), according to Eq. B. The logistics/freight value (FV, BRL/km) was the multiplication of this value by the distance traveled (TD, km) between the company and the material distribution areas, according to Eq. C.

$$RMc = RMa \frac{BRL}{ton} \quad \text{(B)}$$

$$FV = TD \frac{BRL}{km(traveled)} \quad \text{(C)}$$

For determining the productivity of the process, the amount of raw material used in the ceramic formulation was evaluated as a function of the monthly addition of RHA during the periods studied. For this, the number of pieces produced per month (NPM) was considered and multiplied by the wet part weight of the pieces after forming (WPW, ton), to finally obtain the amount of clay consumed (CC, ton), according to:

$$CC = NPM.WPW \quad \text{(D)}$$

The energy consumption/cost (τc, kWh) was calculated using its relation to the drying time (t_d, h) in Eq. E. The energy consumption was calculated as only the number of h/month for which the pieces were in the dryer. The production of blocks (Pr, unit) was analyzed based on the number of cars that entered the kiln daily to fire the products (Eq. F) and expanded to monthly values. The company used a continuous kiln in the manufacturing process.

$$\tau c = t_d.kW \quad \text{(E)}$$

Pr = blocks.cars (F)

where blocks is the number of blocks per car and cars is the number of cars per kiln. For industrial landfill cost (ILc, BRL/month) calculations, the amount of RHA waste (Wa, ton/month) and values spent per ton for the correct disposal of waste (BRL100.00/ton) were analyzed using Eq. G. Thus, it was known how much was avoided spending in industrial landfills for RHA disposal.

ILc = Wa.BRL100.00 (G)

RESULTS AND DISCUSSION

Technical viability

The technical viability of the finished product is essential for proving that the product complies with regulatory specifications, in addition to controlling the industrial production process. Table IV shows a comparison of the characteristics of the finished products of STD and FRHA according to the ABNT NBR 15270-1 standard [27]. All the values were within the tolerances established in NBR 15270-2 [25]. This indicated that the addition of RHA did not interfere with the technical characteristics of the final product. In addition, there was an increase in the compressive strength value, from 3.8 to 4.4 MPa between the formulations; this effect was not attributed to the properties of the incorporated RHA but to the enlargement of the blocks walls from 139.6 to 141.0 mm which may be due to the wear and tear caused over time in the extruder mold or by the difference in the spring-back of the shaped bodies. Water absorption increased with the addition of RHA, which was associated with porosity. Considering the relationship between the apparent density and weight of the material, Table V shows a comparison between the average densities of the STD and FRHA samples. The increase in RHA in the formulation led to lower density and directly influenced the weight/mass of the ceramic block.

Table V - Average apparent density (g/cm^3): comparison between STD and FRHA.

STD	FRHA
1.80±0.03	1.60±0.03

Economic viability

Evaluation of the costs of ceramic formulations is important for economic analysis in the industry. Table VI lists the costs of the raw materials and freight involved in their supply. The PCs used in the formulations were owned by the company; therefore, their costs were already included in other demands, and there was no change in their values with the addition of RHA. Table IV shows that the addition of RHA directly influenced the decrease in the amount spent on the purchase of clay from BRL 6110.37/month to BRL 3430.64/month, reducing the consumption of this clay by 3.6 ton and general costs because the ash had no purchase cost (value to be added to the material/waste through recovery/addition). Analyzing the freight (Table VI), the FRHA paste exhibited a decrease in cost with the SC (BRL 13966.56 to 7841.47) owing to the decrease in the content in the formulation from 26.5% to 11.5%; with the distance traveled between the ceramic industry and the raw material mine, which in this case was the same for both, there was a decrease in the freight value of RHA because of its low density (ρ=0.15 g/cm^3). Finally, the comparison between the two ceramic formulations showed a 7.0% monthly cost reduction with the acquisition of raw materials used in the production of blocks.

The analysis of clay consumption also directly influences the cost of the industrial production process. Table VII presents a comparison of the two formulations. The addition of 15% by volume of RHA waste exhibited a 1.2% increase amount of clay, as observed from the comparisons between the STD and FRHA formulations. Table VIII shows the Atterberg limits [28] for STD and FRHA. It is possible to verify that the plastic limit of FRHA increased, which required more water for forming, and in this sense,

Table IV - Results of technical characterization of ceramic blocks with STD and FRHA formulations (average values).

Technical data	STD	FRHA	Tolerance [25]
Width^{dc} (mm)	113.9±0.8	114.8±0.2	Individual ±5 mm; average ±3 mm
Height^{dc} (mm)	139.6±0.6	141.0±0.3	
Length^{dc} (mm)	240.8±1.1	240.7±2.6	
Septum^{dc} (mm)	7.1±0.5	7.3±0.5	-0.5 mm
External wall^{dc} (mm)	8.2±0.5	8.3±0.5	<7 mm
Square deviation (mm)	1.4±0.7	1.4±0.3	≤3 mm
Flatness of faces (mm)	-0.2±0.6	-0.2±0.4	≤3 mm
Compression strength (MPa)	3.8±0.5	4.4±0.4	≥1.5 MPa
Water absorption (%)	16.5±0.3	17.2±0.3	Between 8% and 25%

dc: dimensional characteristic.

Table VI - Cost data for the acquisition of raw materials used in STD and FRHA formulations.

Data			STD		FRHA	
Distance (km)	R.M.	(BRL/ton)	R.M. (BRL/month)	Freight (BRL/month)	R.M. (BRL/month)	Freight (BRL/month)
30	YPC	4.44	12202.29	28159.14	12202.29	28159.14
30	BPC	3.33	1016.86	3128.79	1016.86	3128.79
40	SC	5.56	6110.37	13966.56	3430.64	7841.47
40	RHA		-	-	-	4251.43
	Total		19329.52	45254.49	16649.79	43380.83
	Grand total		64584.01		60030.62	
	Cost reduction		7.0%			

R.M.: raw materials.

Table VII - Productivity in the extrusion stage: comparison between STD and FRHA formulations.

Characteristic	STD	FRHA
Clay consumption (ton/month)	4150	4201
Increase (%)	1.2	

Table VIII - Atterberg limit for STD and FRHA formulations.

Characteristic	STD	FRHA
Liquid limit	41	40
Plastic limit	24	28
Plasticity index	17	12

the water acted as a lubricant, increasing the flow during extrusion. Consequently, this led to an improvement in the extrudability/forming capability of the parts/blocks.

Drying during the ceramic process significantly influences the occurrence of major defects in the ceramic blocks. Table IX shows the productivity as a function of energy consumption in kWh during the drying stage. One of the biggest benefits for the company with the addition of RHA in the ceramic formulation was reflected in the drying process; the ash improved the drying speed of the ceramic pieces, which is one of the main objectives in the process. The FRHA resulted in a decrease in the energy consumption compared to STD as the drying time of the dryer was reduced by 3 h, leading to a decrease of 13% in the consumption (from 31740 to 27600 kW/month). This demonstrated that the use of ash in ceramic formulation contributes to an increase in the processing speed and consequently improves productivity. This factor may be caused by the increase in granulometry. Coarse particles (obtained by 325 mesh sieve) increased from 16% in STD to 20% in FRHA, aiding moisture outflow during drying [29, 30]. Table X shows a comparison between the formulations based on the energy consumed. It was evident that if the company had continued with the STD formulation, it would have increased expenses related to energy consumption by approximately 5.4%.

The monthly production of the industry considered the number of blocks produced, in comparison between the production with STD and FRHA formulations. The introduction of RHA waste into the composition of the ceramic paste improved the block processing speed and consequently increased the monthly production of the company by 16.7% (from 972,000 to 1,134,000 pieces). The technical feasibility data showed that the apparent density decreased with the addition of RHA (STD=1.8 g/cm^3 and FRHA=1.6 g/cm^3), causing the final weight of the pieces to reduce by 1.6%; this proved that the partial replacement of clay by the waste decreased the clay mass. This confirmed the improvement of some aspects related to logistics: i) lower weight loaded on the truck; ii) improvement in average fuel consumption; and iii) lower maintenance costs (less wear of tires).

Table IX - Productivity data in the drying step: comparison between STD and FRHA formulations.

Characteristic	STD	FRHA
Engine power (hp)	63	63
Energy consumption (kWh)	46	46
Drying time (h)	23	20
Consumption (kW/month)	31740	27600
Gain (%)	13.0	

Table X - Energy consumption data during drying: comparison between STD and FRHA formulations.

Characteristic	STD	FRHA
kW/month	77013	72873
Value/month	R$ 52662.38	R$ 49831.40
R$ kWh	R$ 0.6838	R$ 0.6838
Gain (%)	5.4	

Waste generated by the supplier industry must be disposed of appropriately in response to environmental issues. The cost to send this waste to an industrial landfill is BRL 100.00/ton and RHA generation is approximately 80 ton/month. Currently, almost 75% is used in the production of clay ceramics, and the rest is sent to farmers for use in crops/soils. As a result, the company could properly dispose of all the waste generated from burning rice husks, that is, from the processing of rice. Thus, the company saves approximately BRL 72000.00/year on disposal in landfills for ceramic production. This proves that the valorization of RHA through its addition to the ceramic formulation contributes to sustainable development with significant environmental, economic, and social gains. The concept of effective mineral circularity strategies based on the use of residual materials as raw materials (alternative mineral sources) with less energy consumption, reduction in the extraction of natural resources, and generation of environmental liabilities is fundamental for ensuring productive activities.

CONCLUSIONS

It was proved that the addition of up to 15% of rice husk ash (RHA) resulted in economic gains for the clay ceramic industry that produces ceramic blocks. The analysis of the technical characteristics showed that the ceramic material continued to exhibit the same technical characteristics established by the NBR 15270-2 standard, with water absorption and mechanical resistance values of 17.2% and 4.4 MPa, respectively. The economic gain for the industry was represented by the 7.0% reduction in cost with the acquisition of raw materials. In addition, an increase in productivity was estimated, especially during the drying stage, which is a significant bottleneck during the production process. Moreover, the 13.0% decrease in energy consumption in terms of logistics was caused by the decrease in density, which led to the lower weight of the finished product and thus contributed to improvements in transport and a 16.7% gain in the monthly production. Finally, it is expected that the implementation of a circular economy in industrial processes, such as the valorization of RHA in the production of clay ceramics, can have a positive impact on the environment.

ACKNOWLEDGMENTS

The authors are grateful to the Coordination for Higher Education Improvement (CAPES) and the National Council for Scientific and Technological Development (CNPq) for financial support for this study: CAPES/Brazil process n. 88887.502321/2020-00, CAPES/Brazil process n. 88887.356961/2019-00, CNPq/Brazil process n. 381504/2023-9, CNPq/Brazil process n. 306897/2022-9, and the APL Mineral Project CNPq/Brazil Process n. 408799/2022-6. The authors are also grateful to Cerâmica Guarezi Ltda., the Technical Ceramics Laboratory (CerTec)/Parque/UNESC, and Alimentos Fumacense for their development support. Note: a study on the application of rice husk ash in ceramic bricks was presented at COP27 and won the Best Mineral Practice Award from the Mineral-based Local Productive Arrangement Network (Rede APL-Arranjos Produtivos Locais de Base Mineral - Program of the Brazilian Ministry of Science, Technology and Innovation).

REFERENCES

[1] P. Lisbona, S. Pascual, V. Pérez, Chem. Eng. J. Adv. **14** (2023) 100494.

[2] L. Agnusdei, M. Krstić, P. Palmi, P.P. Miglietta, Sci. Total Environ. **882** (2023) 163441.

[3] H.K. Tchakouté, C.H. Rüscher, S. Kong, E. Kamseu, C. Leonelli, Constr. Build. Mater. **114** (2016) 276.

[4] D.A. Dafico, "Estudo da dosagem do concreto de alto desempenho utilizando pozolanas provenientes da casca de arroz", Dr. thesis, Univ. Fed. Santa Catarina, Florianópolis (2001).

[5] I.C. Bigno, "Geopolímeros à base de resíduos agrícolas e agroindustriais", Dr. thesis, Inst. Militar Eng., Rio Janeiro (2008).

[6] V. Agopyan, V.M. John, *O desafio da sustentabilidade na construção civil*, Blucher, São Paulo (2011).

[7] W. Acchar, E.J.V. Dultra, A.M. Segadães, Appl. Clay Sci. **75-76** (2013) 141.

[8] M.B. Farias, A.J.M. Araújo, V.S. Medeiros, D.A. Macedo, A. de Miranda, C.A. Paskocimas, R.M. Nascimento, Ceram. Int. **48** (2022) 23145.

[9] T. Xue, Z.J.W. Wang, Mater. Sci. Eng. A **527** (2010) 7294.

[10] E. Bonet-Martínez, L. Pérez-Villarejo, D. Eliche-Quesada, P.J. Sánchez-Soto, B. Carrasco-Hurtado, E. Castro-Galiano, Mater. Lett. **229** (2018) 21.

[11] Z. Li, W. Liu, S. Yao, Y. Yang, Q. Li, S. Zhou, Ceram. Int. **47** (2021) 28744.

[12] G. Görhan, O. Şimşek, Constr. Build. Mater. **40** (2013) 390.

[13] J.L. Alves, I.B. Borges, M.A. Ramos, J. de Nadae, R.R. Grangeiro, Rev. Prod. Online **20** (2020) 449.

[14] J.A. Santana Costa, C.M. Paranhos, J. Clean. Prod. **192** (2018) 688.

[15] P.J. Ramadhansyah, A.W. Mahyun, M.Z.M. Salwa, B.H. Abu Bakar, M.A. Megat Johari, M.H. Wan Ibrahim, Procedia Eng. **50** (2012) 101.

[16] J.-I. Lee, J.-S. Oh, S.-C. Yoo, E.H. Jho, C.-G. Lee, S.-J. Park, J. Environ. Chem. Eng. **10** (2022) 107367.

[17] S.K. Rautaray, B.C. Ghosh, B.N. Mittra, Bioresour. Technol. **90** (2003) 275.

[18] G.A. Benedet, A. Zaccaron, J.M. Inocente, V. de Souza Nandi, S. Arcaro, F. Raupp-Pereira, D.G. Neto, Process Saf. Environ. Prot. **176** (2023) 716.

[19] E. Tiffo, A. Elimbi, J.D. Manga, A.B. Tchamba, Braz. J. Sci. Technol. **2** (2015) 4.

[20] D. Tsozué, A.N. Nzeugang, J.R. Mache, S. Loweh, N. Fagel, J. Build. Eng. **11** (2017) 17.

[21] M. Dondi, M. Raimondo, C. Zanelli, Appl. Clay Sci. **96** (2014) 91.

[22] F. Pardo, M.M. Jordan, M.A. Montero, Appl. Clay Sci. **157** (2018) 158.

[23] T.V. Vakalova, I.B. Revva, Constr. Build. Mater. **255** (2020) 119324.

[24] D. Eliche-Quesada, J.A. Sandalio-Pérez, S. Martínez-Martínez, L. Pérez-Villarejo, P.J. Sánchez-Soto, Ceram. Int. **44** (2018) 4400.

[25] ABNT, NBR 15270-2, "Componentes cerâmicos: blocos e tijolos para alvenaria, parte 2: métodos de ensaio", Ass. Bras. Normas Técn., Rio Janeiro (2017).

[26] P. Mohazzabi, J. Appl. Math. Phys. **5** (2017) 836.
[27] ABNT, NBR 15270-1, "Componentes cerâmicos: blocos e tijolos para alvenaria, parte 1: requisitos", Ass. Bras. Normas Técn., Rio Janeiro (2017).
[28] A. Atterberg, Int. Mitt. Bodenkd. **1** (1911) 10.
[29] A. Zaccaron, V.S. Nandi, A.M. Bernardin, J. Build. Eng. **33** (2021) 101877.
[30] V.S. Nandi, A. Zaccaron, F. Raupp-Pereira, S. Arcaro, A.M. Bernardin, O.R.K. Montedo, Clay Miner. **58** (2023) 26.
(Rec. 05/07/2023, Rev. 28/08/2023, Ac. 19/10/2023)