Industrial application of sugar cane bagasse as an alternative energy source in cement production

Aplicação industrial do bagaço de cana-de-açúcar como fonte alternativa de energia na produção de cimento

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Aabstract

Among the costs involved in cement production, energy consumption is one of the most relevant factors in the production cost. The search for alternative sources can be a solution to reduce dependence on the use of fossil fuels. The objective of this work was to study the feasibility of co-processing by burning sugarcane bagasse in a pre-calciner. 98 tons of sugar cane bagasse (SCB) were used as an alternative fuel during 16 hours of production. The results showed that replacing part of the fossil fuel with sugar cane did not have a significant impact on the quality of the material produced. The use of this residue as an alternative fuel enabled a reduction in fuel-related costs of R$1,067/hour. Sugarcane bagasse can be used as co-fuel in a pre-calciner, without reducing the equipment's performance and without changing the properties of the flour.

Keywords: Waste. Co-processing. Thermal replacement. Portland Cement.

Resumo

Dentre os custos envolvidos na produção de cimento, o consumo de energia é um dos fatores mais relevantes no custo de produção. A busca por fontes alternativas pode ser uma solução para diminuir a dependência do uso de combustíveis fósseis. O objetivo deste trabalho foi estudar a viabilidade do coprocessamento pela queima do bagaço da cana-de-açúcar (BCA) em um pré-calcinador. Foram utilizadas 98 toneladas de bagaço da cana-de-açúcar como combustível alternativo, durante 16 horas de produção. Os resultados mostraram que a substituição de parte do combustível fóssil pelo bagaço da cana-de-açúcar, não teve um impacto significativo na qualidade do material produzido. O uso deste resíduo como combustível alternativo possibilitou uma redução nos custos relacionados ao combustível de R$ 1.067/hora. O bagaço de cana-de- açúcar pode ser utilizado como co-combustível em pré-calcinador, sem reduzir o desempenho do equipamento e sem alterar as propriedades da farinha.

Palavras-chave: *Resíduo. Coprocessamento. Substituição térmica. Cimento Portland.*

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Introduction

A lot of authors dedicated their studies to prove ways to mitigate CO_2 emissions or to draw attention to the effects that these gases caused. Obi, Onyekuru e Orga (2024) showed that climate change in global warming is triggered mainly by CO_2 emissions from power plants powered by fossil fuels.
In addition to emissions from the combustion of fossil fuels, the decomposition of limestone in cement production results in the emission of 0.85 tons of CO_2 per ton of clinker, contributing approximately 7% of global CO_2 generation, placing the cement industry in the second position of largest generator of CO_2 (Wi *et al.*, 2018). Similar results were observed by Shah *et al.* (2022), who analyzed all anthropogenic CO_2 emissions, which ranged from 7% to 8%.

Several authors pointed out in their studies that greenhouse gases (GHG) were in some way related to the burning of fossil fuels, and this phenomenon was directly linked to climate change (Junqueira; Medeiros; Cohim, 2022; Lobato; Rodrigues; Santos, 2021; Aguiar; Fortes; Martins, 2016; Shapiro, 2019). In this context, promoting measures that encourage thermal replacements through the use of alternative fuels could be, in this case, the great opportunity that everyone is looking for.

Prado *et al.* (2022) found that one of the alternatives to reduce GHG emissions in the cement industry is the use of alternative fuels through the co-processing of Solid Waste (SW) and the use of biomass.

Campos *et al.* (2021) examined the conversion of waste to energy, correlating the generation and composition of municipal solid waste (MSW) with income level, while Lima e Stefanutti (2023) carried out a study on co-processing techniques, fuel sources and the potential of the cement industry in reusing waste.

Legally, it is up to the CONAMA to regulate waste co-processing activities, and these must be compatible with the materials used in cement production, or replace part of the fuel used (Brazil, 2020).

According to Ajala *et al.* (2021), sugarcane bagasse (SCB) has been found in abundance globally, for this reason, it has been explored by researchers for numerous applications, including energy and environmental sustainability. Consequently, SCB is a biomass with great potential to meet global energy demand and promote sustainability.

Lagarinhos, Espinosa and Tenório (2016), found that 62% of integrated factories installed in Brazil were licensed to carry out co-processing. According to Prado *et al.* (2022), this licensed potential represents approximately 15% of energy consumption, when incorporating alternative fuels into the energy matrix. In the European Union, more than 48% of the energy used in clinker production comes from biomass waste, considered an advantageous option. This is because CO_2 emissions from biomass combustion are considered climate neutral, resulting in a zero emission factor for this type of material (Uliasz-bochenczyk; Deja; Mokrzycki, 2021).

This study aimed to analyze the impacts resulting from the burning of SCB in the cement production process and the potential obstacles that may arise in the quality of the cement produced.

The specific objective of this work was limited to using SCB during the limestone pre-calcination stage, to prove the cost reduction generated by the partial replacement of fossil fuel by agricultural waste. Furthermore, it evaluated the standard compliance of the cement produced during the test.

Literature review

Alternative raw material

Chatterjee e Sui (2019) highlighted the evolution that has occurred in the technique of co-processing waste in cement kilns since its emergence in the 1980s. The technique, which was initially adopted as a cost reduction measure, has evolved into a prominent position worldwide, as a suitable destination for different sources of agricultural and industrial waste, minimizing the emission of greenhouse gases, especially CO_2.

Aranda Usón *et al.* (2013) addressed in their work the potential of the cement industry to reduce dependence on fossil fuels and natural resources (limestone and clay), and analyzed which are the most common wastes: municipal solid waste (MSW), animal meat and bone meal, sewage sludge, biomass and end-of-life tires.

Aprianti *et al.* (2015) presented in their studies that, after the burning process, the ash generated could be used as supplementary material, due to its chemical and physical properties, which are presented in Table 1.

Table 1 **- Chemical and physical properties of sugarcane bagasse ash**

Elements	Composition (% by mass)
SiO_2	60.0 – 65.3
Al_2O_3	4.7 – 9.1
Fe_2O_3	3.1 – 5.5
MgO	1.1 – 2.9
CaO	4.0 – 10.5
Na_2O	0.3 – 0.9
K_2O	1.4 – 2.0
SO_3	0.1 – 0.2
Physical Properties	
Particle size distribution, (μm)	66.9 – 107.9
Density	1.9 – 2.4
Specific surface area (cm_2/g)	274.0 – 943.0
Loss on ignition (% by mass)	15.3 – 19.6

Source: Aprianti *et al*. (2015).

Alternative fuels in the cement industry

Clinker kilns has utilized different energy sources, the most common being: coal, fuel oil, petroleum coke, natural gas and diesel (Madlool *et al.*, 2011). Aranda Usón *et al.* (2013) evidenced the feasibility of replacing fossil fuels and managing waste with energy potential, which were normally byproducts of other industries. Figure 1 illustrates a typical fuel co-processing process in clinker kilns.

Brazil (2020), in its Article 4, establishes that fuels obtained from waste, with the potential to replace fossil fuels, are called alternative fuels.

According to Serrano-González, Reyes-Valdez and Chowaniec (2017), alternative fuels in cement kilns, in addition to preserving non-renewable sources of fossil fuels and helping to reduce CO_2 emissions, also represent a safe option for waste management.

Several factors are responsible for the success of the co-processing technique in cement kilns. Luo *et al.* (2015) showed that cement production is one of the most energy-intensive in the world, which would serve to boost the search for substitute materials for fossil fuels. In addition to the economic incentives associated with the technique, there is also a need to mitigate CO_2 emissions of cement producers, which contribute approximately 5% to 7% of global emissions (Mikulčić *et al*., 2016; Wi *et al*., 2018). Table 2 summarizes the analysis of some fuels used in cement plants.

The authors Horsley, Emmert e Sakulich (2016), demonstrated that coal is responsible for a large part of the energy consumed in cement production units around the world, accounting for 67% of demand.

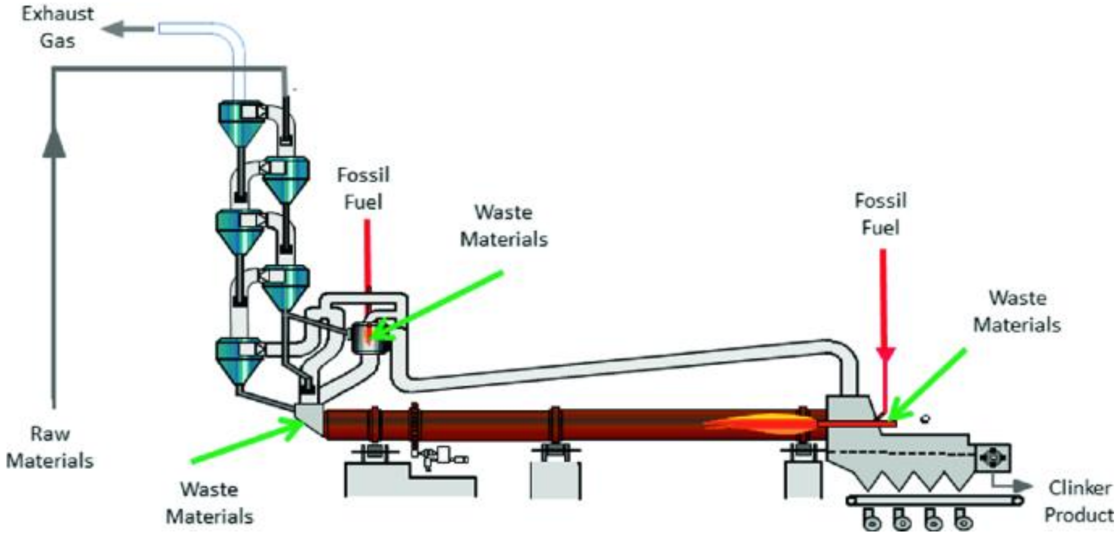
In its report entitled, co-processing panorama 2022, the Brazilian Portland Cement Association, disclosed that the cement industry's thermal replacement rate was 26%, and of these replacements, the tire deserves to be highlighted, occupying 45.48% of use, Figure 2 shows the increase in this consumption in recent years.

Waste-Derived Fuels (WDF)

In their studies, Zhang *et al*. (2021), registered concern about the complexity of problems related to the generation of Municipal solid waste (MSW) and estimate generation of 2.2 billion tons in 2025, based on publications from the World Bank.

For Rahman *et al*. (2015), the high availability of Municipal solid waste (MSW) makes it attractive to replace up to 30% of traditional fuel, as long as it is previously characterized, becoming known as Solid Recovered Fuel (SRF).

Figure 1 - **Co-processing of wastes as alternative fuels in cement kilns**



Source: Ghosh, Parlikar e Karstensen (2022).

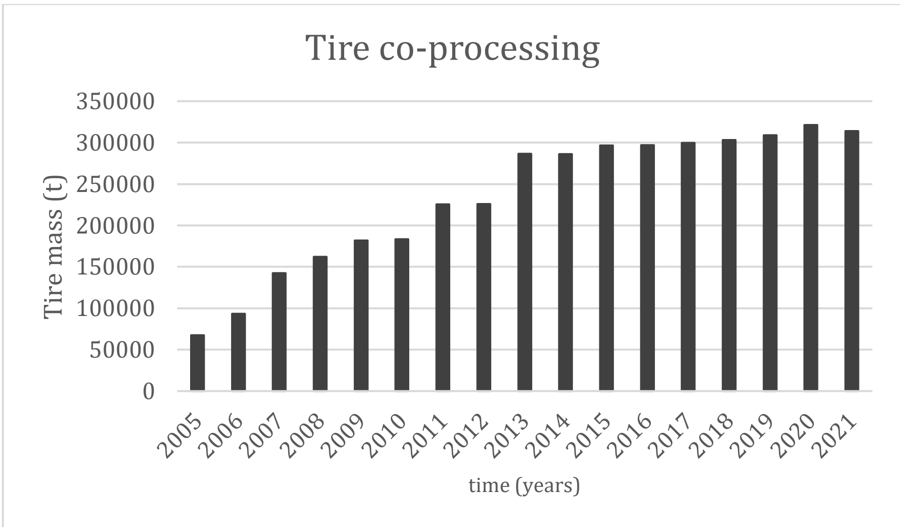
Table 2 - **Comparative fuel analysis**

Analysis	Pet-coke	Coal	TDF
Volatile (%)	13.0	36.8	72.0
Ash (%)	7.1	14.0	7.0
Carbon (%)	82.6	80.6	84.0
Hydrogen (%)	3.4	4.6	5.0
Sulfur (%)	4.9	0.7	2.0
Nitrogen (%)	1.75	0.3	1.75
LHV (kJ/kg)	32,480	27,430	31,400

Source: Pipilikaki *et al*. (2005).

Legend: LHV- Lower heating value; and Tire derived fuel (TDF).

Figure 2 - **Evolution of tire coprocessing**



source: ABCP Report (Coprocessing outlook 2022).

Given the benefits reported by researchers who dedicated their studies to SRF, as an alternative source of energy in cement kilns, there remains concern about restrictions on sulfur and chlorine compounds, with chlorine at this stage being more harmful to the process (Aranda Usón *et al*., 2013; Rahman *et al.*, 2015; Chatziaras; Psomopoulos; Themelis, 2016).

This possible interference in the production unit is due to encrustation in the equipment. To minimize this effect, it is advisable to keep the chlorine content below 0.2% and the sulfur content below 2.5% (Horsley; Emmert; Sakulich, 2016; Rahman *et al.*, 2015; Madlool *et al*., 2011).

Other solution to minimize the impacts generated by chlorides is the application of a bypass system on rotary kiln, an approach known for interrupting the internal recirculation of the chlorine element. This method consists of directing combustion gases from the furnace to an air pollution control system (Tsiliyannis, 2016; Wang *et al*., 2023).

Meat-Bone Meal (MBM)

Present in the ABCP's co-processing outlook and in the study accomplished by Bourtsalas *et al.* (2018), animal bones are viable sources of alternative fuels, Silva (2016), sought to understand the environmental, commercial and technical viability of co-processing what he called meat and bone meal (MBM), the author concluded that the destination of animal by-products is viable under the conditions of your work

Municipal sludge or sewage sludge

For Husillos Rodríguez *et al.* (2013), proper disposal of sludge is expensive and environmentally complicated, but its use as fuel and alternative raw material provides a safe disposal method. Comprehensively, his research evidenced the advantage of using dry sludge in cement production, showing a reduction of up to 66% in the consumption of fossil fuel and up to 14% of clay.

Despite its high moisture, the sludge is dried with residual heat from the furnace before its introduction to the process, and non-combustible parts are used as raw material (Chatziaras; Psomopoulos; Themelis, 2016).

The studies by Liu *et al.* (2015), evaluated the performance of sludge as a source of fuel or alternative raw material, the calorific value recorded was between 13,800 -14,650 kJ/kg of dry matter. The main components identified were SiO_2, Fe_2O_3 e Al_2O_3, similar to the components of clay, one of the inputs used in cement production.

Biomass

Nakashima *et al*. (2017), defined biomass as a non-fossil organic material of biological origin, Pires *et al.* (2018) judged it to be from renewable sources, coming from plantations, agricultural waste, pruning or sawmills.

Despite being available in a large part of the national territory, Scalet *et al.* (2018) report that this energy resource from organic sources represented only 8.2% of electrical energy production in Brazil in 2017, however, there is still potential for growth, according to Sette Junior *et al.* (2018), Brazil has the potential to increase the participation of biomass in the energy matrix, among other factors, due to the large amount of waste generated in the agricultural and forestry sectors, both in the field and in industry.

This literature review showed that in several studies, whether with agricultural, urban or industrial waste, the waste can be used as a partial source of thermal energy, in some cases, and can even replace part of the raw material used for clinker production. And it was these considerations that reinforced the idea to diversify the energy matrix in cement production, especially after considering the carried by Molin Filho (2020) with eucalyptus bark, which also studied the practical feasibility associated with using this residue as a source of energy on an industrial scale.

Material and methods

Material

The sugar cane bagasse (SCB) used was supplied by a company in the sugar and alcohol sector, located approximately 90 km from the factory where the experiments and industrial analyzes were conducted.

Methods

In the stage of incorporating biomass into the production process, it was decided to feed it mainly through the pre-calciner, positioned below the pre-heater and above the rotary kiln. Before introducing biomass into the production system, a characterization was carried out, in which thermal analyses, immediate analysis and determination of the material's heat value were carried out.

Was incorporated into the production process 17% of SCB to replace the reference fuel, approximately 98 tons of SCB as a replacement for pet-coke.

To ensure that the partial replacement of the fuel did not cause variations in the cement produced, analyzes were carried out at different moments of production. Sampling T0 referred to the average cement production using reference fuel and sampling T1 referred to cement production using SCB as part of the fuel.

Sugarcane bagasse moisture

The preparation of samples for analysis followed the guidelines established by the NBR 10007 (ABNT, 2004) standard, which guides the removal of samples from at least three distinct sections of the mound or pile of waste, covering its upper, central and lower portions.

In each of these sections, four aliquots were collected equidistantly, ensuring representativeness of the analyzed material, contributing to the precision and reliability of the results obtained in the analysis.

Moisture determination was conducted by drying the material in a model 515 bench oven, manufactured by FANEM. The temperature was 105 ± 3 °C, until a constant weight was reached, as prescribed by the standard NBR 16550 (ABNT, 2018a). The moisture calculation was carried out using Equation 1.

$$M = \frac{mi - mf}{mi} x100 \quad \text{Eq. 1}$$

M = Moisture (%);

mi = initial mass (g); and

mf = final mass (g).

Bulk density of sugar cane bagasse

The bulk density calculation was carried out as determined by ISO 17828 (ISO, 2015). A cylindrical metal container with a known volume (5L = 0.005 m³) was used. To record the mass, a Toledo 2098/38 electronic scale was used with a precision of 10 g and a maximum capacity of 60 kg.

The calculation to determine the density in bulk was carried out according to Equation 2.

$$\rho g = \frac{m2 - m1}{V} \quad \text{Eq. 2}$$

ρg = density in bulk ($kg.m^{-3}$);

m1 = mass of empty container (kg);

m2 = mass of full container (kg); and

v = container volume (m³).

Ash content of sugar cane bagass

The ash content was determined in accordance with the standard (ABNT, 2018a). A porcelain crucible was used with 1g of sugarcane bagasse on a dry basis. The crucible was inserted into a muffle furnace for a period of 4 hours at a temperature of 575±25 °C. To record the mass, a Mettler Toledo electronic analytical balance was used with a precision of 0.10 mg and a maximum capacity of 220g.

The calculation to determine the ash content was carried out according to Equation 3

$$N = 100\text{x}\frac{MN}{MB} \quad \text{Eq. 3}$$

N = Total ash content, expressed as a percentage mass by mass (% m/m);

MN = mass of ash, expressed (g); and

MB = mass of sugarcane bagasse, on a dry basis, expressed (g).

Higher Heating Value (HHV)

For the Higher Heating Value (HHV) test, the sample was subjected to a quartering and drying process as described in Sugarcane bagasse moisture. After the sample had completely dried, a precise amount of 0.5g of material was selected.

The tests to determine the HHV of sugarcane bagasse were carried out on a dry basis, following D5468 (ASTM, 2017) stundart specifications. For this purpose, was used a calorimeter Parr model 6200.

The standardization of the calorimeter was carried out by burning a known quantity of standard benzoic acid pellets (C6H5COOH).

Lower Heating Value (LHV)

The Lower heating value (LHV) was determined following the same model used by Aló *et al*. (2017) e Grotto *et al*. (2021), assuming 7% hydrogen content in sugarcane bagasse, based on Equation 4, which was used by the authors.

$$LHV = \text{HHV} - \left(\frac{600 \text{ x } 9\text{H}}{100}\right) \quad \text{Eq. 4}$$

HHV - Higher Heating Value (kcal/kg);

LHV - Lower heating value (kcal/kg); and

H - Percentage obtained in the elemental analysis stage (%).

Chlorine content

The chloride ion test was conducted following the normative parameters established by the standard (ABNT, 2022a). The entire sample preparation procedure was administered in the same way as described in the HHV section.

The test began with the preparation of a sodium carbonate solution (Na_2CO_3) by adding 5g of this salt to a beaker. Then, the salt was dissolved in distilled water with the help of a glass rod to facilitate dissolution. Subsequently, this solution was transferred to a 250mL volumetric flask using a simple funnel and the volume was adjusted until reaching the mark indicated on the flask. And the prepared solution was stirred until complete homogenization was achieved.

To ensure an effective response to the chloride ions formed during combustion, 10 ml of the prepared sodium carbonate (Na_2CO_3) solution was added to the calorimeter container. This solution was used to impregnate the internal walls of the container before the analysis began, ensuring an interaction between chloride ions and sodium ions, which resulted in the formation of sodium chloride (NaCl) in solution, which was subsequently analyzed. by the selective ion method, using a multiparameter potentiometer equipped with chlorine ion electrodes.

Sulphur Content

The method used for sulfur detection was guided by international standards ISO 20847 (ISO, 2004) and D4294 (ASTM, 2021). These standards recommend the use of the X-ray fluorescence (XRF) technique for the quantitative analysis of sulfur in fuels.

To make the tablet, a sample of the material was burned until 13g of ash was produced for analysis. Then, 1g of micropulverized wax was added to the ashes. All material was pressed using a Herzog hydraulic press.

After molding, any excess sample material was removed with the help of a vacuum cleaner, before the tablet was sent for XRF analysis.

Granulometry

The tests were conducted in accordance with the procedure established by standart NBR 17054 (ABNT, 2022), adapting to the low density of the material. To conduct the test, 1kg of dry material was used.

The process was carried out with the aid of a sieve shaker, with a test time set at 5 minutes and adjusted to 10 vibrations per second.

Due to the limited capacity of the shaker in relation to the maximum number of sieves supported, the test was divided into two sets, as shown in Figure 3.

Thermogravimetric analysis (TGA)

The characteristics related to the thermal study of sugarcane bagasse were analyzed in duplicate, using a Perkin Elmer Pyris 1 TGA thermogravimetric analyzer. During the experiment, 1.233 mg of sample was evaluated, varying the temperature of the control zone between 30 °C and 900 °C. The heating rate used was 20 °C/min, with a synthetic air flow of 20 mL.min-1 of gas.

Differential thermogravimetric analysis (DTG)

Thermogravimetric differential analysis (DTG) was obtained from the data generated by thermogravimetric analysis (TGA). For this purpose, the OriginPro 2024 software was used in its learning version, made available free of charge by the company Originlab on its official website. DTG allowed a more precise identification of the deflection points in the TG curves of the analyzed samples, indicating the temperatures where occurred decomposition of the material.

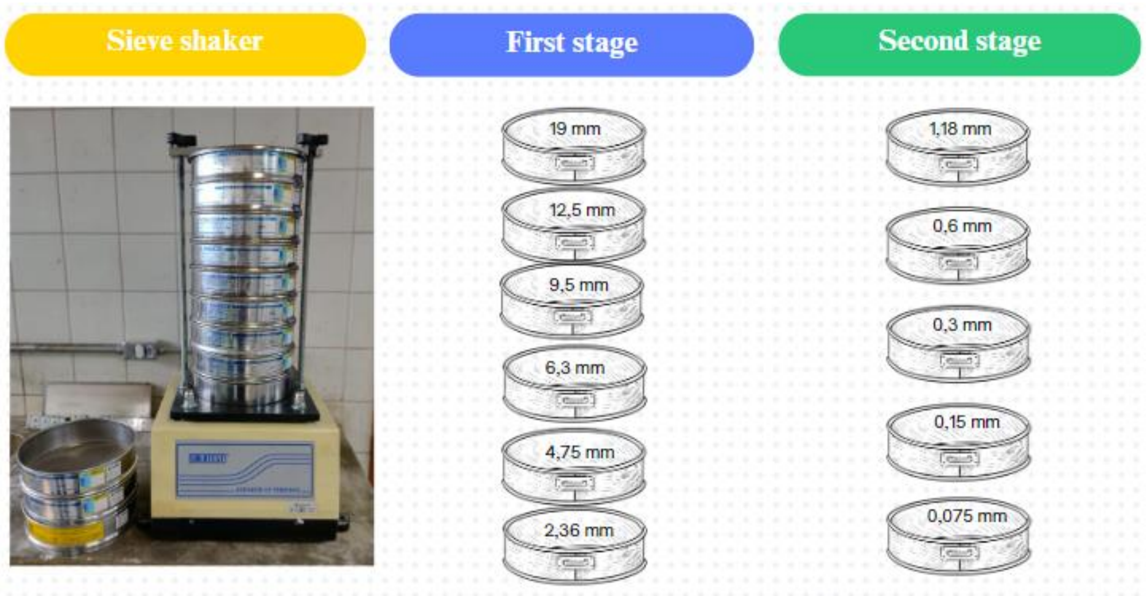
Industrial tests

To evaluate the cement produced during the tests, were carried out that characterized all the material in this study, providing guidance on possible impacts on the production process. Performing physical, chemical and mechanical analyses to ensure that during the testing period, the material complied with the technical standards defined by the factory, in addition to complying with all current standards and legislation. In general, the main objective was to ensure that the cement produced met the minimum necessary requirements, even with the use of sugarcane bagasse as an energy source, without compromising the factory's efficiency.

The industrial tests were carried out over 16 hours on the site of a cement plant. During this period, around 98 tons of sugarcane bagasse and petroleum coke were used in the pre-calciner. This period of time was considered adequate to stabilize the process, making it possible to carry out the collections and measurements necessary for this investigation.

During the testing period, there was constant monitoring of environmental indicators, which are already routinely controlled by the company, and any reading that presented values outside the typical monitored range would result in an interruption of the test. Despite full-time monitoring, it is important to claim that data relating to these indicators will not be discussed in this work.

Figure 3 - **Arrangement of sieves used in the two test stages**



To evaluate the cement produced during the tests, tests were carried out that characterized all the material in this study, providing guidance on possible impacts on the production process. T0 and T1 sampling followed the company's internal procedures, these procedures are based on current standards and follow the suggestions of the Brazilian Portland Cement Association.

Characterization was carried out using X-ray Fluorescence (XRF), proving compliance with the limits established by the standard (ABNT, 2018b). To conduct the test, the cement samples were initially converted into tablets, with the aid of a Herzog hydraulic press, a test step similar to that described in the topic on sulfur content. These tablets were then subjected to chemical analysis. Subsequently, the material was sent to the physical laboratory to continue regulatory tests, considered specific requirements for Portland cement.

The physical and mechanical requirements recorded in this study were conducted taking into account the type and class of cement. All tests were guided by a set of specific Brazilian standards (ABNT, 2019, 2012, 2016, 2015, 2018c, 2018d).

Reducing fuel costs through the adoption of bagasse

At this stage, the study focused only on evaluating the potential for cost reduction using biomass, evaluating only the difference in mass fed into the Pre-Calciner and the corresponding market prices.

The Agro2Business website provided the freight cost for transporting the bagasse to the manufacturing unit, estimating it at R$98.00 per ton. To calculate the cost reduction potential, the value of R$100 per ton FOB (Free on Board) was considered, since the material was located in the same state where the industrial test was conducted.

The assumptions adopted for the calculation were the following:

(a) value per ton of coke (FOB): R$ 1,227.21 – average for the last quarter (Investing, 2024); and

(b) value per ton of sugarcane bagasse (FOB): R$100 (Agro2Business, 2024).

Results and discussion

Sugarcane bagasse moisture

The Moisture analyzes carried out are presented in Table 3, demonstrating that the average value obtained is in accordance with the values indicated by Leal *et al.* (2013). This agreement reinforces the reliability and consistency of the results obtained.

Moisture was an evaluated parameter, because it was directly linked to energy consumption during the burning process. The higher the moisture of the SCB, the lower the amount of energy supplied during burning. Correia *et al.* (2020), associated moisture with ignition temperature and stated that the energy required to dry 1kg of bagasse with 80% moisture would be close to 14%, obtained by combustion of the raw material itself, inside the equipment itself.

Carvalho (2012), correlated the thermal behavior at different moisture levels, showing that for values above 50% the temperature required for ignition should be between 500 and 600 °C. A temperature that was exceeded by the equipment used in the research, which recorded an average temperature of 912 °C.

When compared to data available in the literature, the moisture results obtained were similar, taking into account the operating conditions of the equipment.

Table 3 - **Moisture analysis of sugarcane bagasse**

Identification	Moisture Content (%)
Sample 1	49.51
Sample 2	50.94
Sample 3	49.26
Average value	49.90
Standard deviation	0.91
Minimum	49.26
Maximum	50.94
Number of analyzes	3.00

Physical-chemical properties of the material analyzed

The results of the tests on the material used as an energy substitute in this research are presented in Tables 4 and 5.

Although Brazilian legislation limits the emission of pollutants from waste co-processing activities for cement production to up to 10% chlorine and 11% sulfur, the values practiced were much lower, guaranteeing a safe application of the waste (Brazil, 2020).

Corroborating with these practiced values, Chatterjee (2011), observed that the characteristics of the raw material can influence the performance of the system, leading it to states of saturation that can result in unscheduled equipment downtime. The author also reported the conditions that could cause salt deposits on the walls of the equipment's circulation ducts. In this parameter, the SCB demonstrated effectiveness, remaining within the expected operational range, presenting chlorine and sulfur values below 0.4%, which excluded any possibility of incidents related to fouling or sticking in the equipment's ducts.

As expected for a non-hazardous waste (classification: Class II), the main oxides identified in the sugarcane bagasse ash after burning are compatible with the materials used in cement production (CONAMA), as in Table 5.

Although ash does not generate energy, by using sugarcane bagasse to replace part of the fuel, it not only promotes energy efficiency by replacing petroleum coke, but also ensures the management of the resulting waste, in this particular case, up to 11.87% of ash was generated and incorporated into the product. Finding similar to one of the records by Huang *et al.* (2017), which states that ash with a low carbon content is preferable when used in the cement and concrete sectors.

Despite the generation of ash considered high for the production unit, 11.87%, when relating the chemical composition generated with the work carried out by Fazil, Kumar e Mahajani (2023), who studied the conversion of cellulose waste into energy, whose research evidenced that ash formed with a higher proportion of Ca, followed by Al, Si, Mg and Fe, can avoid agglomeration and the formation of scale during the process due to the high melting temperatures of the ash, which are between 1320 and 1420 °C. Information that helped in the understanding related to possible incrustations due to gluing on the equipment.

Table 4 - **Physical-chemical properties SCB**

Requested Test	Duplicate results	
Chlorine (%)	0.36	0.18
Sulfur (%)	0.16	0.20
Ash (%)	11.87	11.62
HHV (MJ kg-1)	16.93	17.28
Density (kg L-1)	0.09	0.08

Table 5 - **Main oxides present in SCB ash**

Oxides	% by mass
Na_2O	0.096
MgO	3.07
Al_2O_3	2.753
SiO_2	29.504
P_2O_5	6.474
SO_3	1.443
K_2O	16.94
CaO	28.337
TiO_2	0.418
MnO	0.309
Fe_2O_3	7.854
Co_3O_4	0.139
NiO	0.069
CuO	0.072
WO_3	1.385

The choice of a material as an alternative fuel involves physical-chemical characterizations, which provide initial criteria for decision making. The Heating Value is among the determining parameters for the use of an alternative fuel, the sugar cane bagasse analyzed presented 17.28 MJ kg^{-1}, a value compatible with the literature. Kusuma *et al.* (2022) pointed out criteria that he considered essential for the use of biomass as an alternative fuel, among which the energy requirement of the calciner must be greater than 8.0 MJ kg^{-1}, corroborating the value found in this research.

The density was measured because through it, the production unit can size the storage bays, control the feed flow to the burners and decide when it is necessary to mix the product with other denser waste.

Even with a HHV twice as large as the real need for the calciner, it was still not possible to completely replace the typical fuel used by the production unit. For this action, an amount of material that could be ten times greater due to the density (90kg.m^{-3}) compared to the coke density, which varied between 687 a 900kg.m^{-3} (Fernandes, 2019; Júnior; Coelho; Santos, 2022; Vega Mejía; Gallardo Brito; Cesin Granado, 2020).

Granulometry

The particle size of the SCB is presented in Table 6. This test correlates with the apparent density of the material and its residence time in the equipment.

The granulometric analysis revealed that the majority of the material has dimensions greater than 0.6 mm, representing approximately 82% of the total. The maximum dimension found was 19 mm, while the majority of particles were smaller than 12.5 mm and larger than 1.18 mm. These results point to a material with a wide contact surface, favoring efficiency in the combustion process. This suggests that the material has a shorter residence time in the equipment, which may contribute to improved efficiency in the thermal process.

Particle size analysis, combined with material density, provides information on logistical aspects of the SCB, such as transportation and storage. This information is essential for estimating the number of trucks needed for transportation and determining the ideal dimensions of the storage after receipt.

Thermal analysis

The Thermogravimetry curves (TG) and its derivative (DTG) referring to the SCB are shown in Figure 4.

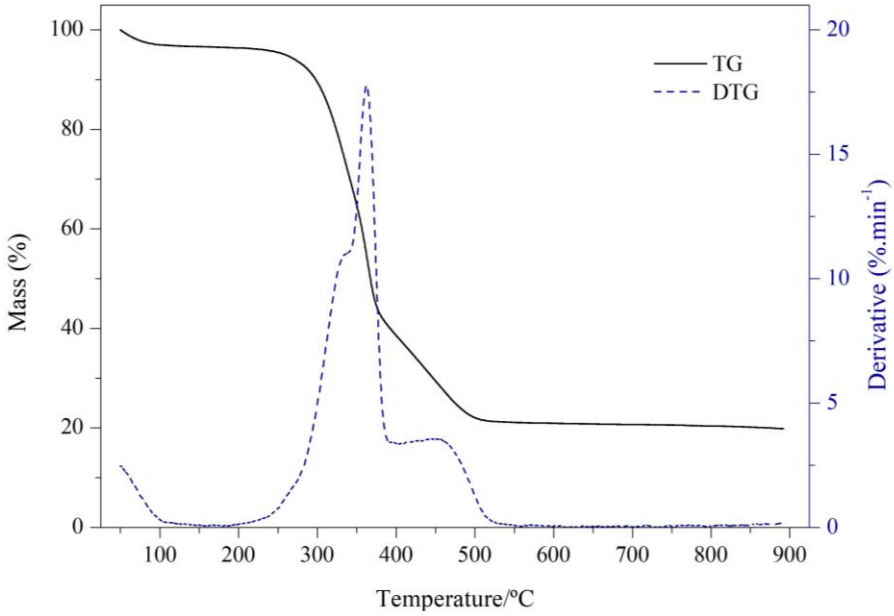
The thermal behavior of SCB in natura is intrinsically linked to the composition of its three main fractions cellulose, hemicellulose and lignin, which degrade in different temperature ranges (Díez *et al*., 2020; Nurazzi *et al*., 2021). Essentially, three distinct stages were observed in the TG/DTG curves, varying according to the previous treatment given to the material.

Initially, the first mass variations associated with moisture loss were observed, occurring from room temperature to approximately 65 °C.

Table 6 - **Granulometry of SCB**

Sieve diameter (mm)	retained mass (g)	Retained %	Accumulated %
19	23.39	2%	2%
12.5	90.64	9%	11%
9.5	38.01	4%	15%
6.3	102.34	10%	25%
4.75	236.84	24%	49%
2.36	24.85	2%	52%
1.18	135.97	14%	65%
0.6	166.67	17%	82%
0.3	103.80	10%	92%
0.15	54.09	5%	98%
0.075	19.01	2%	100%
Collection Pan	3.27	0%	100%

Figure 4 **- TG and DTG curves of sugarcane bagasse**



The second event detected occurs in the temperature range between 200 °C and 370 °C and is linked to the thermal degradation of hemicellulose, cellulose and, partially, lignin, corroborating previous observations documented by other researchers (Marques *et al*., 2022; Ponte *et al*., 2019).

Finally, the degradation of lignin stands out more significantly due to its more complex structure, presenting a more extensive range of decomposition, which extends from 200 °C to the region of the maximum peak of the analysis (Suárez *et al*., 2019).

The residual mass at the end of the third event consists of two distinct parts: a portion still susceptible to combustion and a portion of ash, predominantly composed of inorganics resulting from decomposition reactions. This fraction represented 19.7% of the total residue, showing similarities with data found in the literature (Gonçalves *et al.,* 2023; Grotto *et al*., 2021; Mulinari *et al*., 2009; Nunes *et al*., 2020; Ponte *et al.,* 2019).

The sample's final degradation temperature occurred at around 570 °C, indicating significant compatibility with the fuel used in pre-calciners. This property was beneficial to promote rapid burning of the material, since the pre-calciner operates at temperatures around 900 °C.

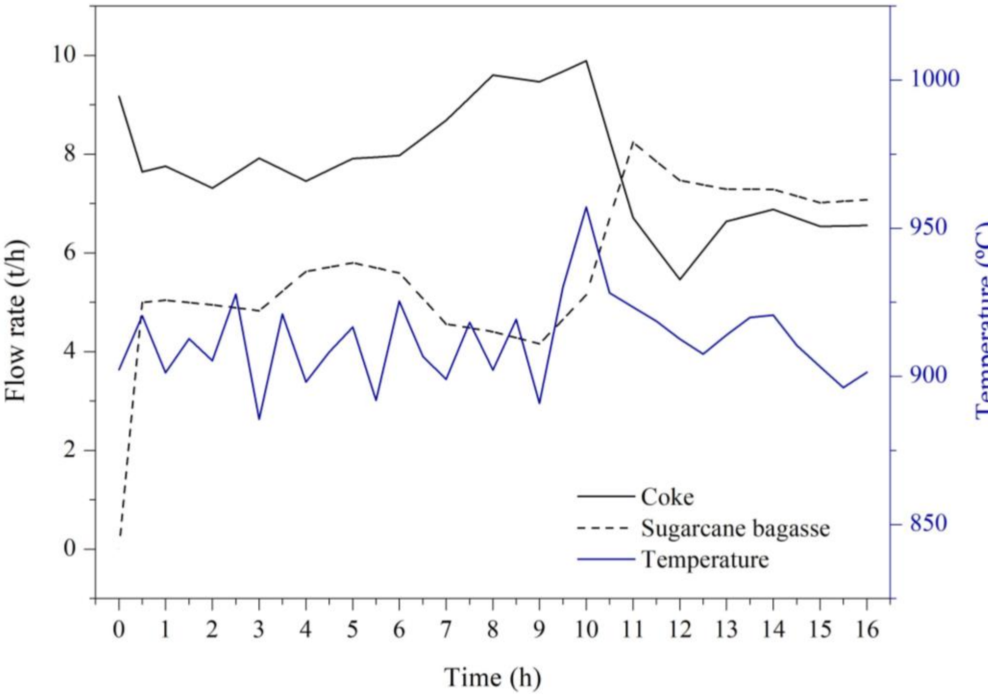
Industrial tests

During the entire process, the fuel supply was constantly monitored, using a total of 98 tons of SCB, as illustrated in Figure 5.

Only during 4 hours of the process did coke consumption exceed the average established after the start of SCB feeding. In the twelfth hour of the test, it was observed that the coke flow rate approached half of the initial value, indicating a significant influence of the introduction of sugarcane bagasse into the system. This data provides valuable insights into the behavior of the fuel supply system during testing, highlighting the influence of BCA on coke consumption.

Despite the additional consumption observed between the seventh and tenth hour of the test, resulting from a mismatch in the fuel supply, which was not identified in the graph representing the pre-calciner exit temperature, it is important to to mention that the fuel supply curves fuels were inverted in the final stage of the experiment, just after the tenth hour. This scenario contributed to an even more significant increase in the savings generated by the solution, pointing a success story in the implementation of the practice of replacing fuel for generating thermal energy. This inversion of the curves show the importance of continuous monitoring and adequate adjustment of the process, highlighting the effectiveness and optimization potential of this strategy to reduce costs.

Figure 5 - **Flow rate and temperature in the pre-calciner**



Even considering the cost reduction generated by the partial replacement of coke with bagasse, it is still not feasible to increase the rate of this replacement. This is due to the high volume of bagasse that would be necessary for this exchange, which could require a logistics and storage infrastructure that has not yet been mapped. Additionally, additional controls would need to be implemented to monitor and regulate the temperature of the equipment during the process.

During the analyzed period, the petroleum coke feed flow was reduced from 9.2 tons per hour to 7.0 tons per hour, while the average temperature at the pre-calciner exit remained at around 912 °C. This temperature is located in the typical operating range of modern pre-calciners, between 840 and 900 °C, and is capable of initiating limestone calcination reactions. As noted by Kline e Kline (2017), these reactions begin around 600 °C and involve the thermal decomposition of limestone ($CaCO_3$) to produce calcium oxide (CaO).

To evaluate the project's direct costs, the replacement of 1.46 tons per hour of coke during the first six hours of the test resulted in savings of R$ 10,750.36 in the consumption of this fuel. During the same period, the inclusion of sugarcane bagasse generated an additional R$ 3,600.00. The difference in these data indicates a reduction of R$ 7150.36, demonstrating the potential of this approach. This context demonstrates the viability of replacing coke with sugarcane bagasse, evidencing its potential both in financial terms and in the promotion of sustainable practices.

The chemical analysis of the cement produced T0 (reference fuel) and T1 (coprocessing with SCB) are in Table 7.

The compressive strength was recorded in Table 8, where a comparison is made with the values prescribed by the standard (ABNT, 2018b). Furthermore, the chemical results found were correlated with the values determined by the standard and are recorded in Table 8.

As the only variable factor in this day's production was the alternative fuel used to replace coke, the possibility of chemical variation would be an oscillation in temperature, which was not noticed, for this reason, divergences in the formulation of the coke produced were not expected, and consequently the cement, which can be proven in Table 9.

Among the results observed in Table 9, perhaps Ignition loss (IL) and CO_2 could be considered the most critical, because a variation indicating an increase in these parameters would be directly related to possible inefficiency in the limestone decarbonization stage, however, this was not noticed, indicating the effectiveness of the replacement.

Table 7 - **Chemistry of the compounds present in the cement produced dring the research**

XRF		
Compounds	**CPII F 40 Sample T0**	**CPII F 40 Sample T1**
SiO_2	17.36	17.00
Al_2O_3	4.47	4.22
Fe_2O_3	2.59	2.22
CaO	59.88	61.18
MgO	5.87	3.47
Na_2O	0.10	0.38
K_2O	0.91	0.93
SO_3	3.36	4.11
Mn_2O_3	0.11	0.07
P_2O_5	-	0.14
TiO_2	0.21	0.18
ZnO	-	0.03
Cr_2O_3	0.00	0.01
SrO	-	0.18
PF	5.63	5.12

Table 8 - **Physical and mechanical requirements**

Tests	**Fineness (%)**		**Specific Surface**	**Consis-tency**	**Setting Time (min)**		**Expan-sion**	**Compressive strength (MPa)**			
	#200	**#400**	**(cm2/g)**	**Paste (%)**	**IS**	**FS**	**(mm)**	**1 Day**	**3 Day**	**7 Day**	**28 Day**
Standard Limits	≤ 10	-	-	-	≥ 60	≤ 600	≤ 5,0	-	≥ 15	≥ 25	≥40
T0	0.02	1.27	5113	30.00	199	255	--	22.4	34.7	39.4	47.2
T1	0.10	0.56	5310	30.30	175	225	--	24.8	35.8	40.5	49.1

Table 9 - **Chemical requirements**

Tests	**IL (%) NBR 17086-6 (ABNT, 2023)**	**MgO (%) NBR 17086-3 (ABNT, 2023b)**	**SO_3 (%) NBR 17086-5 (ABNT, 2023c)**	**IR (%) NBR 17086-4 (ABNT, 2023d)**	**CO_2 (%) NBR 17086-8 (ABNT, 2023e)**
Standard Limits	≤ 8.5	-	≤ 4.5	≤ 5.0	≤ 7.5
T0	5.63	5.87	3.36	1.36	4.51
T1	5.12	3.47	4.11	2.39	4.51

Conclusion

The SCB can be a viable alternative to replace petroleum coke by up to 17% as a fuel used in pre-calciners.

The use of up to 8 tons per hour of SCB to replace up to 3 tons per hour of petroleum coke in the monitored equipment proved to be technically viable.

This replacement had no impact on design or process control calculations, mainly due to the low variation in the pre-calciner exit temperature.

The chemical composition of SCB is similar to the composition of the main raw materials used in the production of clinker, being mainly composed of: silica, calcium, potassium, iron and aluminum.

An additional advantage associated with using bagasse as an alternative fuel is that all the ash generated in the process is incorporated into the cement produced. This completely eliminates the need for waste management expenses.

The results of SCB's energy coprocessing reveal a series of challenges, such as humidity management, logistics and the degree of compaction (density), which require attention and improvement to enable a more intensive and efficient use of these resources. It is essential that appropriate strategies and technologies are developed to overcome these limitations and enhance the environmental and economic benefits of this energy alternative.

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