Valorization of Marble Waste Powder as a Replacement for Limestone in Clinker Production: Technical, Environmental and Economic Evaluation

Luara Batalha Vieira 1,2, Vito Francioso 2,*, Bruna Bueno Mariani 1, Carlos Moro 3,*, Josiane Dantas Viana Barbosa 4, Larissa da Silva Paes Cardoso 1, Cleber Marcos Ribeiro Dias 5, and Mirian Velay-Lizancos 2,6

1 Department of Civil Construction, SENAI CIMATEC School of Technology, Salvador 41650-010, BA, Brazil; luara.batalha@fieb.org.br (L.B.V.)
2 Lyles School of Civil Engineering, Purdue University, West Lafayette, IN 47907, USA
3 Department of Engineering Technology, Texas State University, San Marcos, TX 78666, USA
4 Department of Materials, SENAI CIMATEC School of Technology, Salvador 41650-010, BA, Brazil
5 Department of Science and Materials Technologies, Federal University of Bahia, Salvador 40210-630, BA, Brazil
* Correspondence: vfrancio@purdue.edu

Abstract: This research combines technical, environmental, and economic aspects regarding the utilization of Bege Bahia marble waste (BB) in clinker production. Three different eco-friendly clinkers were produced, investigated, and compared with one that is commercially available. BB was used to replace 49.2%, 77%, and 80.3% of the limestone by total amount of clinker. Two clinkers were selected to produce cement pastes, and their impact on compressive strength at 28 days was examined. The results suggest that substituting limestone with BB does not adversely affect the compressive strength of cement paste. Moreover, employing 77% or 80.3% BB in clinker production does not significantly influence the alite and belite contents but slightly increases the tricalcium aluminate and ferrite phases while reducing the periclase content. A life cycle analysis was conducted to assess the effects of replacing limestone with marble waste. The results revealed a substantial decrease in abiotic depletion, leading to conservation of substantial natural resources. Consequently, the utilization of BB in clinker production makes a significant contribution to environmental preservation while providing an effective alternative to limestone. In addition, the resulting clinkers serve as useful repositories, providing a permanent and sustainable destination for waste that is currently deposited in landfills. Finally, the economic viability was also examined under various scenarios based on the distance between marble and cement plants. The results highlight the transport distance of marble waste as the primary determinant of economic feasibility in utilizing this residue as a limestone replacement.

Keywords: limestone; marble waste; clinker; cement; environmental assessment

1. Introduction

The use of waste from other industries is an increasingly studied subject in civil construction [1]. Research on the production of ceramic brick [2–5], cement [6–9], mortar [10–13], and concrete [14–18] has been conducted in the past few years. Among these wastes, marble residue is of great interest because of the amount generated during marble exploration [19].

The methods of mining marble are diverse and depend on the costs of acquisition, maintenance of machinery, available labor, and topography of the deposit [20]. Marble stones are chosen based on their aesthetics, which ends up influencing their value. As a result, acquisition prices are not standardized, even when evaluating materials extracted from the same deposit. The most influential factors causing aesthetic differences in ornamental stones are color, texture, and granulometry [21]. All of these parameters are
subjective and, due to market acceptance or lack thereof, the entire process of exploring ornamental stones generates a large amount of waste.

Around 70% of extracted marble block is rejected and currently considered waste material [22]. During the sawing of accepted marble blocks, powder is released due to friction between the marble and blades or wires. As the block is bathed with water throughout the process to cool the blade/wire, this mixture (i.e., stone powder, water, and waste material used for cutting) forms a sludge that is transported to a decantation site. Here, the water is reused in the sawing process and fine powder is left as final waste [4]. Therefore, 40% of the volume of the original marble block becomes waste, either in the form of powder or aggregate [23]. In Brazil, it is estimated that 1.5 million tons of marble powder and 1.0 million tons of aggregate residue are generated annually [23]. The sawing phase generates between 32 and 40 m$^3$ of sludge per day [4]. This sludge causes economic losses since a large part of this material is deposited on land without any type of later use [22]. Studies have been conducted in search of a proper destination for the residue because mining and cutting processes can result in a loss of up to 83% of raw material [19,23].

In Brazil, one of the marbles that stands out the most is Bege Bahia marble. This marble is found in Campo Formoso, Mirangaba, Umburanas, Jacobina, Juazeiro, Itaguaçu da Bahia, and Ourolândia (Bahia, Brazil), with the last city responsible for 90% of its exploitation [20,24]. The number of blocks of Bege Bahia marble wasted in the Ourolândia region reached more than 12 million tons in 2019, while the accumulated fine waste reached over 13 million tons in the same period [25]. Around 47 million tons of Bege Bahia marble per month are extracted in Ourolândia. Of this volume, almost 33 million tons (70%) become discarded blocks and 3500 tons become waste powder.

Previous studies have shown that aggregates produced from discarded marble blocks do not perform well in concrete production since their Los Angeles coefficients are almost twice the typical values of aggregates regularly used in construction [26,27]. In addition, numerous studies have explored the potential of waste marble powder as a sustainable supplementary cementitious material (SCM) in cement-based composites [28].

However, as shown in Figure 1, marble powder residue could be used as a raw material for cement production, replacing limestone [29–32]. Therefore, it could help decrease limestone extraction and consumption, lowering its impact on soil and topography [33].

Kirgiz [34] developed experimental research on clinker production using ultrafine marble and ceramic waste, replacing limestone and clay, respectively. The dosages of the raw meals were defined based on chemical parameters such as the alumina modulus (AM), silica modulus (SM), hydraulic modulus (HM), lime standard modulus (LS), and lime saturation factor modulus (LSF). The raw meals were produced with three waste dosages: 77% marble + 23% ceramic, 79% marble + 21% ceramic, and 81% marble + 19% ceramic. The best cement was produced with 77% marble waste, as it contained 54% calcium oxide. Nonetheless, all formulations achieved overall good performance. El-Alfi and Gado [35] used another method to define the dosages of raw meals when producing belitic cement using Egyptian marble residue as a limestone substitute. This calcium sulfoaluminate cement required a lower temperature of the kiln (close to 1250 °C) since its main phases, belite (C$_2$S) and hauyne (C$_4$A$_3$), were formed at temperatures below those necessary for the production of Portland cement, the main phase of which is alite (C$_3$S). Due to this temperature reduction, belitic calcium sulfoaluminate cement production released less CO$_2$. After characterizing the raw materials (marble, gypsum, and kaolin), the dosages of raw meals were determined using Bogue equations, a methodology that estimates the clinker phases after burning. Gypsum accounted for 20% of all mixtures, whereas marble waste accounted for 55%, 60%, or 65% of the mixtures. The raw meals were compacted in 5 × 5 cm cubes using 5% water and then dried at 100 °C. These pellets were burned at three different temperatures (1150 °C, 1200 °C, and 1250 °C) for 1 h, at a heating rate of 10 °C/min, and then ground. To produce cement pastes, a w/c ratio of 0.50 was considered. After physical and chemical analyses, the cement produced using clinker with 55% marble residue, 20% kaolin, and 25% gypsum showed the best burning capacity with the greatest
formation of belite at 1250 °C, as well as good mechanical properties, suggesting that it was the most viable for use.

Figure 1. Marble powder waste generation (upper) and cement production (lower). Limestone in clinker production is replaced with marble powder waste.

Martínez-Martínez et al. [31] also used Bogue equations to determine the dosages of raw meals in their research. The objective was to evaluate the possibility of increasing the amount of belite in the clinker, in the same proportion as the alite present in the usual Portland cement, replacing limestone for marble residue or clay for ceramic residue. For this purpose, they considered rates of replacement of 2.5%, 5%, and 10% by weight of limestone or clay. The raw meals produced were compacted into spherical pellets, using the least amount of water possible, and then dried at 110 °C. Burning occurred at 1130 °C, 1160 °C, and 1190 °C for 40 min. The produced clinkers contained a higher proportion of belite, as desired, and the burning temperature of the pellets was reduced.

Nevertheless, despite the increased number of studies and patent registrations regarding the use of marble powder in clinker production since 2014, there are only 18 patent documents about this topic [19]. Most studies have focused on using marble waste to produce clinker or filler. However, there are no studies on the feasibility of utilizing Bege Bahia marble powder (BB) waste in clinker production. The present study differs from others already published due to the particular composition of BB, which contains mostly calcium oxide in its composition, allowing greater preservation of limestone, the main raw material for clinker. Therefore, BB waste was used for the first time in this study to replace part or all of the limestone in the production of clinker. Finally, this research also aims to evaluate the technical, environmental, and economic feasibilities of using BB waste as a partial or total limestone replacement to produce clinker and evaluate its behavior when used with limestone filler. This will help to find a sustainable alternative to using waste with an accumulated volume that tends to cause environmental impacts in the state of Bahia, Brazil, and in many other countries.
2. Materials and Methods

2.1. Raw Materials

Limestone, clay, marble waste, copper slag, and calcium sulfate were used in this study to produce all of the clinkers and cements. The marble waste powder used in this study was obtained from Reveste Bege—Revestimentos em Bege Bahia Ltda, located in Ourolândia (Bahia, Brazil). The Bege Bahia marble powder (BB) was initially stored in an open area, and it formed fine grains and agglomerates due to the humidity conditions. This raw and untreated waste was ground using a ball mill (model DL-MB, Lobomax) with porcelain balls and sieved through a #75 µm sieve.

A cement plant located in Campo Formoso (Bahia, Brazil) provided the limestone, clay, and calcium sulfate, all used to produce the clinkers and cement. Copper slag was added during clinker production to compensate for the low percentage of Fe₂O₃ in the clay.

Like the marble powder, the limestone was ground using a ball mill and sieved through #75 µm mesh. The clay, copper slag, and calcium sulfate already had reduced particle sizes, so they were ground using a disc mill (model MA-700, Marconi Equipments) before being sieved through a #75 µm sieve.

2.2. Raw Materials' Properties

All materials were dried in an electric oven (model 7513, JUNG, Blumenau, Brazil) at 100 °C, except for calcium sulfate, the drying temperature of which was 40 °C. Then, their physical, chemical, and mineralogical properties were evaluated.

- **Skeletal Density**
  The densities of the clay, copper slag, and calcium sulfate were determined using a helium pycnometer (model Ultrapyc 1200e, Quantachrome Instruments—Anton Paar, Graz, Austria). The samples were dried in an oven at 110 °C for 24 h, and between 3 and 4 g of material was used. Five repetitions were performed. The skeletal densities of the limestone and marble waste were determined as recommended by ASTM–C118 [36] using water as the liquid.

- **Specific surface area**
  The determination of the specific surface area was performed by adsorption of nitrogen/helium using an Autosorb BET Surface Analyzer (Quantachrome Instruments—Anton Paar, Graz, Austria). The samples were dried in an oven for 24 h at 60 °C. Measurements were repeated five times.

- **Chemical composition (XRF)**
  The XRF analyses were performed without the use of binder using an FRX 720 X-ray fluorescence spectrometer (Shimadzu, Kyoto, Japan). The compaction pressure was 5 T for 30 s and the pellets used were 15 mm height.

- **Mineralogical composition (XRD)**
  The XRD analyses of the raw materials were performed using an XRD-6000 (Shimadzu, Kyoto, Japan), with Cu Ka radiation at 40 kV/30 mA, goniometer speed of 2°/min, and step of 0.02°. For the XRD analysis of the clinkers, the Ultima IV (Rigaku) was used, respecting the same parameters applied in the other tests. Profex software (version 4.3.5) was employed to identify and quantify the phases using the Rietveld refinement.

2.3. Clinker Dosage

Chemical modules and Bogue equations were employed to determine the dosages of the clinkers' raw meals.

- **Clinker design with chemical modules**
  The main clinker oxides are CaO, SiO₂, Al₂O₃ and Fe₂O₃, which together compose between 94% and 97% of the total mass of clinker [37]. Excess or insufficiency of some of
those oxides causes adverse reactions that compromise the formation of clinker minerals and, consequently, the performance of the cement. For example, if the MgO content in clinker is above 2%, it can form periclase, which can cause destructive expansion through slow reactions with water. Similarly, excess SO$_3$, despite improving burnability at low temperatures, can also cause destructive expansion in addition to increased SO$_2$ emissions and the possibility of durability issues in concrete [37,38].

The lime saturation factor (LSF), silica modulus (SM), and alumina modulus (AM) were used to determine the raw material proportions, evaluating the mass percentages of oxides in the cement raw meals. Chemical modules were calculated using the following equations:

\[
LSF = \frac{100\text{CaO}}{2.8\text{SiO}_2 + 1.2\text{Al}_2\text{O}_3 + 0.65\text{Fe}_2\text{O}_3} \quad (1)
\]

\[
SM = \frac{\text{SiO}_2}{\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3} \quad (2)
\]

\[
AM = \frac{\text{Al}_2\text{O}_3}{\text{Fe}_2\text{O}_3} \quad (3)
\]

LSF indicates the proportion of free lime in the clinker and influences the contents of alite and belite (formed during burning). Clinker with a high LSF value requires a higher burning temperature and more energy during grinding due to its increased hardness. LSF values normally range between 92 and 98. An LSF value exceeding 102 indicates an increase in free lime content, which can negatively interfere with cement strength development [37–39].

SM relates the proportion of silicates and other components of the interstitial phase. A desirable SM value is between 2 and 3. Higher SM values attest to a reduction in the liquid phase content, making it difficult to burn the clinker, and therefore requiring a higher temperature [37–39].

AM refers to the ratio between aluminate and ferrite, which reduces the burning temperature and energy consumption in the clinker phases. It also indicates the viscosity of the liquid phase formed. AM values should be between 1 and 4, and increased values lead to greater cement reactivity in the early stages, reducing the setting time of the cement [37–39].

- Clinker design with Bogue equations

Another way of determining the dosages of cement raw meals is to use Bogue equations. Unlike the chemical modules, Bogue equations roughly calculate the amounts of the four main clinker phases. This method considers that clinker minerals are formed from the interaction of the four main oxides in the raw meal and excludes the participation of other components [40,41]. Table 1 lists the Bogue equations.

<table>
<thead>
<tr>
<th>Mineral Phases</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>C$_3$S (Alite)</td>
<td>$C_3S = 4.071\text{CaO} - 7.602\text{SiO}_2 - 1.430\text{Fe}_2\text{O}_3 - 6.719\text{Al}_2\text{O}_3$</td>
</tr>
<tr>
<td>C$_2$S (Belite)</td>
<td>$C_2S = 2.868\text{SiO}_2 - 0.754C_3A$</td>
</tr>
<tr>
<td>$C_3$A (Tricalcium aluminate)</td>
<td>$C_3A = 2.650\text{Al}_2\text{O}_3 - 1.692\text{Fe}_2\text{O}_3$</td>
</tr>
<tr>
<td>C$_4$AF (Ferrite)</td>
<td>$C_4AF = 3.043\text{Fe}_2\text{O}_3$</td>
</tr>
</tbody>
</table>

2.4. Clinker Production

Pellets of 1 cm in diameter were produced for each mixture, adding water until the proper consistency was obtained. The burning process sought to recreate the same process used by the cement industry, which uses preheaters to reach a temperature around 900 °C. Therefore, the pellets were gradually heated at a rate of 5 °C/min to a temperature of 900 °C, which was maintained for 30 min. Then, with the same heating rate, the temperature was raised to 1450 °C and kept constant for 15 min before firing was completed [40,42,43].
When burning was finished, the pots containing the clinkers were removed from the oven and stored at room temperature. The oven used was the Ultra Temperature oven (JUNG). After burning, the clinkers underwent XRD analysis.

2.5. Cement Paste Production

Three cement pastes were produced by mixing clinker, calcium sulfate, and limestone filler. Two of them were produced using previously produced clinkers and one cement paste was produced with a commercial clinker. A total of 4.47% gypsum was added, by mass, in the production of the cements, which guaranteed less than 4.5% SO$_3$ in the mixture. This amount of gypsum was close to that used by other researchers [42–44] and respected the recommendation of 3% to 6% calcium sulfate in cement [45]. The clinkers were ground using a hammer mill (model CT 12061, Servitech) and then mixed with gypsum (4.47%) and limestone filler (25%). The w/c ratio was 0.45 for the three cement pastes.

2.6. Compressive Strength of Cement Paste

One of the expected characteristics of cement is to reach a minimum compressive strength at 28 days. Given the unfeasibility of producing more clinker and the amount of material needed to make the samples, it was decided to use smaller molds. Four cylindrical samples were produced for each cement paste, 20 mm in diameter and 40 mm in height (adapted from the Brazilian Standard NBR 5739 [45] and maintaining a ratio of 2 between diameter and height [34]). The choice of diameter was due to the amount of material available and the commercial options for PVC pipes used as molds. Each sample was molded in two consecutive layers of cement paste, each receiving 15 blows. After the first 24 h, the samples underwent wet curing following NBR 5739 [45].

Isopropanol was used to stop hydration of the samples at 28 days, as recommended by [46,47] and performed by [48,49], as this is the least destructive solvent to the microstructure of cement paste [47]. Storage in isopropanol lasted 15 days, the time needed to release the equipment to carry out the compressive strength test. Before testing, samples were dried in the environment to minimize the effect of the solvent.

To assess the compressive strength at 28 days, the top and bottom surfaces of the samples were meticulously ground using P180 sandpaper, and their dimensions were measured using a caliper. A 4.5 mm layer of leather was interposed between the specimen and the press’s top surface to ensure a more uniform load distribution, as shown in Figure 2. An Insight 300 SL universal testing machine (MTS) equipped with a force capacity of 300 kN, speed control, and a 15 kN load cell was used for the tests. The loading rate was 1 mm/min. The compressive strength of the cement pastes was determined by calculating the average of the results obtained from four samples.

![Figure 2. Compressive strength test set-up.](image-url)

2.7. Life Cycle Assessment (LCA)

Life cycle assessment (LCA) methodology was employed to address marble waste utilization from an environmental perspective. The objective was to compare the clinker pro-
duction options using LCA methodology. Based on the international standards ISO 14040 and ISO 14044 [50,51], the LCA comprised four phases: (i) goal and scope definition, (ii) life cycle inventory, (iii) life cycle impact assessment, and (iv) interpretation of results. The functional unit (F.U.) selected for this study was 1 ton of clinker. Figure 3 shows the framework for the current assessment. Note that the sludge was generated from a process that classified it as waste; therefore, this assessment did not consider its environmental burden. In addition, transportation was not included because the cement plant and marble quarry were located nearby.

Figure 3. LCA framework for this study.

- **Goal and scope definition**

  The objective of this study was to evaluate the environmental impact of conventional clinker production compared with that of substituting limestone with marble sludge waste in clinker production. The aim was to identify a potential sustainable approach for utilizing this waste material while ensuring the performance of the final product (cement). A “cradle-to-gate” system boundary was adopted, encompassing the extraction and processing of raw materials as well as the production of clinker.

- **Life cycle inventory (LCI)**

  During this phase, the collection of data involved gathering information on energy and materials processing, which serve as inputs, as well as emissions and waste data, which act as outputs. To ensure the reliability and consistency of the data, all of the necessary information was obtained from the Ecoinvent3.2 database [52] within openLCA software (version 1.11, GreenDelta, Berlin, Germany).

- **Life cycle impact assessment (LCIA)**

  The LCIA phase evaluated the environmental impact based on the results from the LCI. In this study, the “Tool for the Reduction and Assessment of Chemical and other Environmental Impacts” (TRACI) [53] (mid-point approach) methodology was employed. The following impact categories were considered for the analysis: (i) global warming potential (GWP), (ii) ozone depletion potential (ODP), (iii) eutrophication potential (EP), (iv) acidification potential (AP), (v) smog formation (S), (vi) respiratory effects (RE), and (vii) energy consumption (EC). Ecotoxicity was excluded from this analysis because there is no evidence of ecotoxicity by the main compounds of cement clinker [54,55].
to assess the relative contribution of each input and output to the impact categories, characterization factors from the U.S. Environmental Protection Agency (EPA) database were utilized. Finally, an extra category was added to those suggested by TRACI: abiotic depletion potential (ADP). This category plays a crucial role in the environmental assessment of secondhand products. In fact, the ADP quantifies the consumption of raw materials.

- **Interpretation of results**

After the LCIA phase, two approaches were employed to analyze and compare the results. First, the impact categories were examined to assess the effect of substituting limestone with marble waste in clinker production on the TRACI single impact categories. Second, normalized values were utilized to convert the results of each impact category into a common unit. Normalization factors (NFs) derived from Ryberg et al. [56] were applied to achieve this conversion. However, the abiotic depletion potential category was not included in this analysis since no NFs are available in the literature. The LCA results were compared using commercial clinker (CLIN-COM) as the reference.

### 3. Results and Discussion

#### 3.1. Characterization of Raw Materials

Table 2 displays the chemical and mineralogical compositions and physical properties of the raw materials. BB had a high lime oxide (CaO) content, greater than that of the limestone it would replace. This indicated excellent substitutive potential since it is one of clinker’s main constituents. Other researchers also worked with marble residue composed mainly of CaO. However, its percentage was not as significant in any of these studies, except when another Bege Bahia marble was used [29–32,34,35,57].

<table>
<thead>
<tr>
<th>Composition</th>
<th>BB (%)</th>
<th>Limestone (%)</th>
<th>Clay (%)</th>
<th>Copper Slag (%)</th>
<th>Calcium Sulfate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>52.99</td>
<td>46.76</td>
<td>0.38</td>
<td>3.10</td>
<td>33.96</td>
</tr>
<tr>
<td>SiO₂</td>
<td>2.98</td>
<td>10.81</td>
<td>47.81</td>
<td>25.07</td>
<td>2.92</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>0.4</td>
<td>3.29</td>
<td>33.57</td>
<td>6.55</td>
<td>1.03</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>0.17</td>
<td>1.22</td>
<td>2.32</td>
<td>55.58</td>
<td>0.58</td>
</tr>
<tr>
<td>MgO</td>
<td>2.02</td>
<td>2.02</td>
<td>1.16</td>
<td>1.23</td>
<td>0.00</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.08</td>
<td>0.99</td>
<td>3.83</td>
<td>0.65</td>
<td>0.21</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.0</td>
<td>0.17</td>
<td>0.2</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>SO₃</td>
<td>0.19</td>
<td>0.33</td>
<td>0.07</td>
<td>2.96</td>
<td>38.42</td>
</tr>
<tr>
<td>Others</td>
<td>0.02</td>
<td>0.0</td>
<td>0.2</td>
<td>4.76</td>
<td>1.91</td>
</tr>
<tr>
<td>Loss of Ignition (LOI)</td>
<td>44.14</td>
<td>34.11</td>
<td>10.46</td>
<td>0.1</td>
<td>20.98</td>
</tr>
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</table>

**Physical properties**

<table>
<thead>
<tr>
<th>Property</th>
<th>BB</th>
<th>Limestone</th>
<th>Clay</th>
<th>Copper Slag</th>
<th>Calcium Sulfate</th>
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<tbody>
<tr>
<td>Skeletal Density (g/cm³)</td>
<td>2.69</td>
<td>2.71</td>
<td>2.73</td>
<td>4.00</td>
<td>2.45</td>
</tr>
<tr>
<td>Specific surface area (BET) (m²/g)</td>
<td>5.47</td>
<td>5.35</td>
<td>14.95</td>
<td>1.77</td>
<td>15.09</td>
</tr>
</tbody>
</table>

**Mineralogical composition (m%)**

<table>
<thead>
<tr>
<th>Mineral</th>
<th>BB</th>
<th>Limestone</th>
<th>Clay</th>
<th>Copper Slag</th>
<th>Calcium Sulfate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anhydrite (CaSO₄)</td>
<td>91.02</td>
<td>85.88</td>
<td>73.67</td>
<td>100 *</td>
<td>93.70</td>
</tr>
<tr>
<td>Bassanite (CaSO₄·0.5H₂O)</td>
<td>4.04</td>
<td>4.04</td>
<td>4.04</td>
<td>4.04</td>
<td>4.04</td>
</tr>
<tr>
<td>Calcite (CaCO₃)</td>
<td>4.04</td>
<td>4.04</td>
<td>4.04</td>
<td>4.04</td>
<td>4.04</td>
</tr>
<tr>
<td>Kaolinite (Al₂Si₂O₅(OH)₄)</td>
<td>6.5</td>
<td>5.37</td>
<td>5.37</td>
<td>5.37</td>
<td>5.37</td>
</tr>
<tr>
<td>Dolomite [CaMg(CO₃)₂]</td>
<td>6.5</td>
<td>5.37</td>
<td>5.37</td>
<td>5.37</td>
<td>5.37</td>
</tr>
<tr>
<td>Fayalite (Fe₂SiO₄)</td>
<td>100 *</td>
<td>100 *</td>
<td>100 *</td>
<td>100 *</td>
<td>100 *</td>
</tr>
<tr>
<td>Gypsum (CaSO₄·H₂O)</td>
<td>100 *</td>
<td>100 *</td>
<td>100 *</td>
<td>100 *</td>
<td>100 *</td>
</tr>
<tr>
<td>Illite/Muscovite</td>
<td>100 *</td>
<td>100 *</td>
<td>100 *</td>
<td>100 *</td>
<td>100 *</td>
</tr>
<tr>
<td>(K₃H₅O)(Al₃Mg₁₂Fe₂)(Si,Al₄O₁₀)[(OH)₄·H₂O]</td>
<td>11.75</td>
<td>11.75</td>
<td>11.75</td>
<td>11.75</td>
<td>11.75</td>
</tr>
<tr>
<td>Microcline (K₃Al₅O₈)</td>
<td>7.04</td>
<td>7.04</td>
<td>7.04</td>
<td>7.04</td>
<td>7.04</td>
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<tr>
<td>Quartz (SiO₂)</td>
<td>1.42</td>
<td>1.42</td>
<td>1.42</td>
<td>1.42</td>
<td>1.42</td>
</tr>
</tbody>
</table>

* Predominant crystalline phase compared to others.
BB had a low content of magnesium oxide (MgO). The recommendation is not to exceed 4% MgO in limestone [14] due to the possibility of periclase formation and unwanted expansion of the cement. In BB and limestone, levels below the recommended values were obtained, but they were higher than those available in the literature [29–32,34,35].

Clay had a low content of ferric oxide (Fe$_2$O$_3$), which differed from what commonly occurs [44]. The Fe$_2$O$_3$ content is usually significant in clay and responsible for the reddish color of this material. Considering the importance of Fe$_2$O$_3$ for the formation of the clinker phases, copper slag was used because it had a higher Fe$_2$O$_3$ content.

Due to decarbonation, BB and limestone presented high LOI values of 41.44% and 34.11%, respectively. The loss of ignition value of BB was also close to the data found for other marble residues [5,16,18,22,58].

In limestone, the calcite (CaCO$_3$), quartz (SiO$_2$), and dolomite [CaMg(CO$_3$)$_2$] phases were identified at levels of 85.57%, 5.53%, and 8.9%, respectively, which was consistent with the chemical composition. BB presented the same phases, proving the similarity of the chemical and mineralogical compositions of these materials, as shown in Figure 4. However, BB proved to be an even greater source of calcium, since it contained 91.92% calcite and 6.5% dolomite, which was expected after the results obtained with XRF. These results suggested that there would be no decrease in CO$_2$ emissions from the decarbonation of BB during clinker production when used as a substitute for limestone.

![X-ray diffraction patterns of raw materials.](image)

Figure 4. X-ray diffraction patterns of raw materials.

The clay had kaolinite (Al$_2$Si$_2$O$_5$(OH)$_4$), illite/muscovite (K$_4$H$_2$O)(Al,Mg,Fe)$_2$(Si,Al)$_4$O$_{10}$[(OH)$_2$,H$_2$O])//Muscovite (KAl$_2$O$_{10}$(OH,F)$_2$), quartz (SiO$_2$), and microcline (K(AlSi$_3$O$_8$)) at levels
of 73.67%, 11.75%, 7.55%, and 7.04%, respectively. The copper slag had mostly fayalite (Fe$_2$SiO$_4$) as the predominant phase. It was possible to perceive with the quantification of the phases that clay and copper slag were the biggest sources of silica; however, as indicated by the XRF results, the biggest source of iron was copper slag, through the mineral fayalite, and the biggest source of aluminum was clay.

In calcium sulfate, gypsum (CaSO$_4$.H$_2$O), bassanite (CaSO$_4$.0.5H$_2$O), anhydrite (CaSO$_4$), and quartz (SiO$_2$) were identified. Although the latter is not a typical mineral of calcium sulfate, there are records of the existence of contaminants such as quartz in the deposits of this material [59].

Regarding the specific surface area, the data obtained for BB and limestone were very similar, indicating that BB had the required reactivity for the burning process. However, the BB specific surface area was higher than that of limestone probably because of agglomeration of the residue.

The skeletal densities of BB and limestone were also similar, close to the theoretical density of calcite, 2.72 g/cm$^3$ [60] and to data in the literature [30,35,57].

3.2. Definition of Cement Raw Meals

Three different meals were designed for this study, BB49-L35, BB77-L03, and BB80-L00, with the first part of the name indicating the use of Bege Bahia marble powder waste and the amount in the meal, and the second part of the name representing the use of limestone and its percentage. Considering that the cement industry uses an LSF value higher than that suggested in the literature, SM and AM were verified for LSF values between 98 and 105. However, the higher the LSF value, the lower the amount of belite, which could affect cement strength at later stages. Thus, the LSF value was established as 98, as suggested in the literature [40,42].

For the BB80-L00 meal, we assumed an LSF value of 98 and an AM value of 1.63. In this meal, BB replaced all of the limestone. For BB49-L35, the LSF value was also 98, and the AM value was 1.63. However, we assumed that the meal should contain at least 40% BB, and the combined amount of limestone and BB should be the same as if the meal consisted solely of limestone.

For the BB77-L03 meal, the LSF value was 98. However, as clay had a low amount of Fe$_2$O$_3$ and copper slag was used in all meals to compensate for it, the AM value was assumed to be 1.4, as recommended when slag is used as a corrective material [61]. Nevertheless, this was not applied to all meals because it affected the SM value.

Table 3 displays the compositions of the cement raw meals. The compositions of the clinker phases, estimated stoichiometrically from chemical analyses in terms of oxides, were calculated using the Bogue potential method. As the BB content increased by up to 77%, we observed an increase in the estimated levels of silicates (alite and belite), attributed to the rise in CaO content (as shown in Table 2). Conversely, there was an increase in the estimated concentration of C4AF due to BB’s lower ratio of Al$_2$O$_3$ to Fe$_2$O$_3$ compared to limestone and clay. The introduction of this residue into the raw material resulted in a reduction in the alumina modulus.

Table 3. Cement raw meal composition, values for LSF, SM, and AM, and estimated mineralogical composition.

<table>
<thead>
<tr>
<th>Cement raw meal composition (%)</th>
<th>BB49-L35</th>
<th>BB77-L03</th>
<th>BB80-L00</th>
</tr>
</thead>
<tbody>
<tr>
<td>BB</td>
<td>49.20</td>
<td>77.00</td>
<td>80.30</td>
</tr>
<tr>
<td>Limestone</td>
<td>35.60</td>
<td>03.50</td>
<td>00.00</td>
</tr>
<tr>
<td>Clay</td>
<td>10.70</td>
<td>13.50</td>
<td>14.50</td>
</tr>
<tr>
<td>Slag</td>
<td>4.40</td>
<td>6.00</td>
<td>5.20</td>
</tr>
</tbody>
</table>
### Table 3. Cont.

<table>
<thead>
<tr>
<th></th>
<th>BB49-L35</th>
<th>BB77-L03</th>
<th>BB80-L00</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Values for LSF, SM, and AM</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lime Saturation Factor (LSF)</td>
<td>98.00</td>
<td>98.00</td>
<td>98.00</td>
</tr>
<tr>
<td>Silica Modulus (SM)</td>
<td>1.35</td>
<td>1.13</td>
<td>1.16</td>
</tr>
<tr>
<td>Alumina Modulus (AM)</td>
<td>1.63</td>
<td>1.40</td>
<td>1.63</td>
</tr>
<tr>
<td><strong>Potential mineralogical composition (Bogue) (m%)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alite (C₃S)</td>
<td>54.57</td>
<td>57.11</td>
<td>51.02</td>
</tr>
<tr>
<td>Belite (C₂S)</td>
<td>10.09</td>
<td>10.21</td>
<td>11.41</td>
</tr>
<tr>
<td>Tricalcium aluminate (C₃A)</td>
<td>13.50</td>
<td>12.90</td>
<td>15.01</td>
</tr>
<tr>
<td>Ferrite (C₄AF)</td>
<td>15.63</td>
<td>19.44</td>
<td>17.38</td>
</tr>
<tr>
<td>Lime (CaO)</td>
<td>0.67</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>Periclase (MgO)</td>
<td>4.17</td>
<td>4.96</td>
<td>2.05</td>
</tr>
</tbody>
</table>

3.3. Mineralogical Composition of Clinkers

Figure 5 and Table 4 display the X-ray diffraction patterns and mineralogical compositions of the produced clinkers. BB77-L03 and BB80-L00 had 63.92% and 64.34% alite, respectively, respecting the recommendations that this phase should represent 50% to 70% of the clinker [37,38]. They also had the closest amounts of alite to the industrial clinker, CLIN-COM.

![X-ray diffraction patterns of clinkers.](image)

Table 4. Mineralogical composition of clinkers, obtained by XRD.

<table>
<thead>
<tr>
<th></th>
<th>CLIN-COM</th>
<th>BB49-L35</th>
<th>BB77-L03</th>
<th>BB80-L00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alite (C₃S)</td>
<td>69.14</td>
<td>44.10</td>
<td>63.92</td>
<td>64.34</td>
</tr>
<tr>
<td>Belite (C₂S)</td>
<td>10.83</td>
<td>31.70</td>
<td>12.45</td>
<td>11.46</td>
</tr>
<tr>
<td>Tricalcium aluminate (C₃A)</td>
<td>1.41</td>
<td>4.69</td>
<td>3.42</td>
<td>3.78</td>
</tr>
<tr>
<td>Ferrite (C₄AF)</td>
<td>13.78</td>
<td>14.46</td>
<td>18.07</td>
<td>17.67</td>
</tr>
<tr>
<td>Lime (CaO)</td>
<td>0.67</td>
<td>0.11</td>
<td>0.11</td>
<td>0.26</td>
</tr>
<tr>
<td>Periclase (MgO)</td>
<td>4.17</td>
<td>4.96</td>
<td>2.05</td>
<td>2.52</td>
</tr>
</tbody>
</table>

The small amount of aluminate was justified because a low AM value was used (Table 3), which is the chemical module that relates the amount of aluminate itself with that
of ferrite. However, despite the low values adopted for AM, the percentage of aluminate was higher than for the clinker supplied by the industry.

Regarding ferrite, its amount varied little between the clinkers. BB77-L03 had the highest percentage due to the low values of AM and SM (Table 3), followed by BB80-L00. These values were higher than the maximum limit of 15% ferrite indicated in the literature [37,38].

All clinkers had periclase contents between 2.05% and 4.96%, with none respecting the recommendation of 2% [62]. However, all clinkers met the Brazilian standards requirements that the MgO content in cement should be lower than 6.5% [63]. All clinkers also exhibited a lime (CaO) content of less than 1%, aligning with the recommended 2% limit as mentioned in [62].

A reduction in the formation of periclase and an increase in the formation of free lime was also observed as the BB content in meals increased.

BB80-L00 (80.30% BB and 0% limestone) and BB77-L03 (77.0% BB and 3.5% limestone) presented the highest percentages of alite, smaller amounts of periclase and free lime, and the most similarity to the industrial clinker. Therefore, they were chosen to produce cement pastes. These designed cements are presented in Table 5.

### Table 5. Designed cements.

<table>
<thead>
<tr>
<th>Notation</th>
<th>Type of Clinker</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLIN-COM-LF</td>
<td>Commercial clinker</td>
</tr>
<tr>
<td>BB77-L03-LF</td>
<td>Produced with limestone (3.5%), BB (77%), clay, and copper slag</td>
</tr>
<tr>
<td>BB80-L00-LF</td>
<td>Produced with BB (80%), clay, and copper slag</td>
</tr>
<tr>
<td>LF = Limestone Filler</td>
<td></td>
</tr>
</tbody>
</table>

#### 3.4. Chemical and Physical Properties of Cement Pastes

Table 6 displays the chemical compositions and skeletal densities of the manufactured cements. All cements complied with the Brazilian standards recommendation of having less than 6.5% MgO and a loss on ignition lower than 12.5% [63]. The results obtained for skeletal density were very similar; however, they were a little lower than the usual value.

### Table 6. Chemical oxide composition and skeletal density of cements used in this study.

<table>
<thead>
<tr>
<th></th>
<th>CLIN-COM-LF</th>
<th>BB77-L03-LF</th>
<th>BB80-L00-LF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chemical composition (%)</strong></td>
<td>Obtained</td>
<td>Expected</td>
<td>Obtained</td>
</tr>
<tr>
<td>CaO</td>
<td>56.35</td>
<td>54.87</td>
<td>57.42</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>18.04</td>
<td>18.22</td>
<td>15.18</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>3.84</td>
<td>8.50</td>
<td>2.83</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>2.62</td>
<td>5.40</td>
<td>6.90</td>
</tr>
<tr>
<td>MgO</td>
<td>3.17</td>
<td>2.75</td>
<td>0.86</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>1.25</td>
<td>0.73</td>
<td>4.29</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>0.19</td>
<td>0.18</td>
<td>0.81</td>
</tr>
<tr>
<td>SO$_3$</td>
<td>3.31</td>
<td>2.45</td>
<td>1.92</td>
</tr>
<tr>
<td>Others</td>
<td>0.59</td>
<td>0.62</td>
<td>0.09</td>
</tr>
<tr>
<td><strong>Loss on Ignition (LOI)</strong></td>
<td>11.26</td>
<td>9.14</td>
<td>9.71</td>
</tr>
<tr>
<td><strong>Physical property</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skeletal Density (g/cm$^3$)</td>
<td>2.58</td>
<td>2.67</td>
<td>-</td>
</tr>
</tbody>
</table>

#### 3.5. Compressive Strength of Cement Pastes

The average compressive strength results of the cement pastes at 28 days are shown in Figure 6. Based on the average and standard deviation of the different cement pastes, the coefficients of variation (COVs) were 7% for CLIN-COM-LF, 5% for BB77-L03-LF, and
14% for BB80-L00-LF. The compressive strength at 3 and 7 days was not verified due to insufficient amounts of the laboratory-produced clinkers.

![Compressive Strength of Cement Pastes](image)

**Figure 6.** Compressive strength of cement pastes.

After 28 days, all cement pastes exhibited a compressive strength greater than 25 MPa. The BB80-L00-LF and BB77-L03-LF cement pastes had higher peaks of alite (Figure 5), the mineral responsible for strength at early stages. However, at 28 days, only BB80-L00-LF showed strength higher than 30 MPa. The greater presence of alite in this cement could explain this effect. The presence of BB appeared to have positively influenced the formation of alite. The greater the percentage of BB in the raw meal, the greater the amount of alite in the clinker. This may have been due to the high CaO content in the marble waste, which is an element that promotes the formation of tricalcium silicate. As a result, cement pastes with higher amounts of alite exhibited higher compressive strength values.

Although research indicates that the use of limestone filler results in an increase in compressive strength and a decrease in the percentage of portlandite in cement [64], these effects could not be verified in the present study since the percentage of added carbonate material was fixed at 25% in all cements. It is also important to emphasize that the method used to determine the strengths of all cement pastes was adapted in this research, which may have resulted in greater variability in the results.

### 4. Environmental Assessment of Clinkers

Figure 7 illustrates the life cycle assessment (LCA) outcomes for the three types of clinker investigated in this study: CLIN-COM, BB77-L03, and BB80-L00. The results clearly indicated that limestone had the most significant influence on all impact categories. This was primarily due to the larger quantity of limestone used compared to other clinker components. The contribution of clinker production did not change, regardless of the amount of limestone replaced by marble sludge; therefore, it is not depicted in the graphs.

As expected, incorporating marble sludge waste to replace limestone content led to a reduction in the environmental impact of the clinkers analyzed. This reduction was observed across all impact categories, with the most substantial decreases observed in EC (energy consumption) and AD (abiotic depletion). EC measures the energy needed for raw material extraction in quarries, while AD reflects the depletion of non-renewable resources and associated environmental impacts. Therefore, reducing limestone usage for clinker production positively affected these categories. Comparing the values for the reference commercial clinker (CLIN-COM) with those for BB77-L03 and BB80-L00 clinkers, EC was reduced by 81% and 84%, respectively, while AD was reduced by 77% and 80%, respectively.
This was primarily due to the larger quantity of limestone used compared to other clinker amounts of limestone replaced by marble sludge; therefore, it is not depicted in the graphs.

Figure 7. Environmental impact of the studied clinkers: (a) global warming potential, (b) ozone depletion potential, (c) eutrophication potential, (d) acidification potential, (e) smog formation, (f) respiratory effects, (g) energy consumption, and (h) abiotic depletion potential.

A significant reduction was also observed in the EP (eutrophication potential), S (smog formation), RE (respiratory effect), and AP (acidification potential) impact categories.
BB77-L03 and BB80-L00 clinkers demonstrated reductions of 71%, 70%, 70%, and 61%, and 75%, 75%, 75%, and 66% for EP, S, RE, and AP, respectively. These reductions are particularly important due to the adverse effects associated with these impact categories on the environment [65].

EP measures the discharge of nutritional elements, whether natural or artificial, into bodies of water. Such compounds contribute to oxygen depletion in aquatic systems, thus impairing water quality. Contaminated water can pose threats to public health and biodiversity, necessitating ongoing monitoring. The S impact category focuses on air pollution resulting from the reaction between sunlight and emissions released during the combustion of fossil fuels during raw material production. This process promotes the formation of various chemicals, including ozone and peroxides, leading to increased concentrations of ground-level ozone. The RE impact category considers the potential consequences that respiratory effects can have on human health and wellbeing. The AP impact category is associated with the combustion of fossil fuels, which generates nitrous and sulfide oxides that can leach into the environment in the presence of oxygen and water. This leaching process poses risks to surrounding ecosystems.

Finally, reductions were also observed in the global warming potential (GWP) and ozone depletion potential (ODP). GWP measures the release of greenhouse gases into the atmosphere, including carbon dioxide (CO$_2$), methane (CH$_4$), and nitrous oxides (N$_2$O), based on their impact relative to CO$_2$ over a 100-year period. On the other hand, ODP refers to the thinning of the stratospheric ozone layer caused by anthropogenic pollutants, such as halocarbons. This thinning leads to a decrease in ozone density, resulting in increased exposure of human skin to UV light and higher risk of melanoma. For BB77-L03, reductions of approximately 53% and 36% were achieved in GWP and ODP, respectively. Similarly, BB80-L00 demonstrated reductions of 32% and 75% in GWP and ODP, respectively. These reductions highlight the significant environmental benefits attained through the utilization of marble sludge waste in clinker production.

### 5. Economic Viability

The number of studies on the circular economy is large in civil construction [66]; however, few companies in the sector apply circular strategies in their processes [67], and only internal processes are involved when it occurs. Therefore, there is little collaboration between companies, which is far from the real concept of the circular economy [68].

Studies show that the use of waste as a resource is one of the most-used circular processes in civil construction, as it is the easiest to adopt. It requires low technological investment and few regulations and stakeholders [67]. The use of BB in clinker production fits exactly into this category. Thus, in addition to technical analysis, economic analysis is key to understanding its feasibility and convincing stakeholders to adopt this waste. Money greatly impacts the civil construction industry because decisions on the application of circular strategies are taken based on the possibility of cost reduction. In addition, there is a market tendency towards reduced costs and high profits [69].

It is noteworthy to consider that the implementation of supplementary charges associated with waste disposal within the environment can exert a notable influence on the economic viability of waste material utilization initiatives. This regulatory approach is currently in effect within the European Union, among other regions, where it has successfully stimulated waste-generating entities to actively seek sustainable methods for waste utilization [70,71]. The prospective enactment of analogous regulations in Brazil holds the potential to exert a substantial impact on the financial feasibility and attractiveness of waste material utilization endeavors in the country.

The economic analysis in this study was adapted from Duran et al. and focused on the use of waste from civil construction [69]. It considered four topics for evaluation: (i) the decision of where to dispose the residue, (ii) imposition of taxes, (iii) use of subsidies, and (iv) the decision of which material to use (whether natural or waste). The first three topics did not apply to this research because BB is already disposed of in the exploration sites.
of Bege Bahia marble and the imposition of taxes and use of subsidies depend on public policies on the use of raw materials and landfills.

Therefore, (iv) was the only factor analyzed because BB can only be used if its cost is lower than that of limestone. The decision on which material to use can be summarized by Equation (4):

\[
P_L + T_L > E_{MP} + P_{MP} + T_{MP}
\]  

(4)

where:

- \(P_L\): price, per ton, of the newly extracted limestone.
- \(T_L\): price, per ton, of transport of limestone.
- \(E_{MP}\): extra costs, per ton, due to the use of the residue.
- \(P_{MP}\): price, per ton, of marble powder waste.
- \(T_{MP}\): transport, per ton, of marble powder waste.

Cement production plants are built close to, or even adjacent to, limestone deposits. Because of this, it can be assumed that the cost of transporting the limestone is irrelevant when compared to the cost of extracting the limestone, which is carried out by the cement plant itself. As BB and limestone are very similar, no extra costs were considered due to the use of BB [69].

Therefore, Equation (4) became:

\[
P_L > P_{MP} + T_{MP}
\]  

(5)

From Equation (5), it was clear that using marble waste as a substitute for limestone would only be economically viable if the sum of its acquisition value and transport was lower than the cost of limestone extraction. When considering a fixed value, per km, for \(T_{MP}\) and \(P_L\), both based on usual market values, the distance between the cement factory and quarry and the \(P_{MP}\) will be the preponderant factors. Two case studies were identified: the USA and Brazil. Figure 8a shows different scenarios depending on the \(P_{MP}\) value and distance between factories. From the data presented, it was possible to infer that when \(P_{MP} = P_L\), there was no economic viability in replacing limestone with marble waste. However, if \(P_{MP} = 0\), the distance between factories could be up to 82.2 km, making the use of marble waste an economically viable possibility. This result was corroborated in Figure 8b, which identified the maximum mileage for when \(P_{MP}\) varied between zero and \(P_L\). It showed that a higher acquisition cost of marble waste required a shorter distance between factories.

![Figure 8. Cont.](image-url)
A similar result was observed in Brazil, as shown in Figure 9a,b; however, as the cost of transporting materials was lower than in the USA, the maximum distance to be covered could be up to 176.5 km for $P_{MP} = 0$. In the case of the residue used in this research, the closest cement factory to the quarry was 174 km away, which implied that 1 ton of marble waste could be sold for up to $0.25 for it to replace limestone and be economically viable.

One proposal to encourage the use of the marble waste is to build cement factories in the same location as marble exploration. However, it would be necessary to evaluate the costs related to the acquisition of other inputs for the manufacture of cement, such as clay and additions.
Figure 9. Relationship between marble waste acquisition cost and distance between cement factory and quarry in Brazil (a) and maximum value (b).

6. Conclusions

The results of this study demonstrate that clinkers produced with Bege Bahia (BB) waste, obtained from the exploration of ornamental stones readily available in Ourolândia, Brazil, exhibit promising performance characteristics. Nevertheless, further research is imperative to confirm the technical feasibility, which could pave the way for an environmentally sustainable disposal solution for this waste. Cement pastes derived from laboratory-developed clinkers also exhibited favorable attributes for cement production.

X-ray diffraction (XRD) analysis confirmed the formation of all main phases (alite, belite, aluminate, and ferrite) in the clinkers. The presence of BB waste, as a substitute for limestone, did not significantly impact the amounts of alite and belite but led to an increase in aluminate and ferrite phases while reducing the periclase content.

An increase in compressive strength was observed with higher BB content in cement pastes made with clinkers produced in the laboratory. However, it is worth noting that the adapted method used to evaluate compressive strength may have influenced the results. Future research should delve into the hydration behavior of cement pastes containing BB and consider the influence of various filler types.

The environmental assessment of clinkers revealed substantial reductions across all impact categories when marble sludge waste was employed as a limestone substitute. Notable reductions were observed in energy consumption (EC) and abiotic depletion (AD), with reductions of up to 84% and 80%, respectively. These findings highlight the significant environmental advantages offered by the incorporation of marble sludge waste in clinker production, indicating its potential as a sustainable option for the cement industry.

Lastly, the results demonstrated that the cost difference associated with BB utilization depends on factors such as pricing agreements with ornamental stone companies for waste (not in course of action) and transportation distances. In the specific case of the companies who supplied materials for this research, the cost for transporting BB between plants (174 km) could be an economic issue depending on their commercial arrangements.

In conclusion, these findings emphasize the urgent need for continued exploration of policies and incentives that promote circular economy principles on a global scale, particularly in regions where such regulations are yet to be implemented.
Author Contributions: L.B.V.: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Validation; Visualization; Roles/ Writing—original draft; Writing—review & editing; V.F.: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Visualization; Writing—original draft; Writing—review & editing; B.B.M.: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Visualization; C.M.: Validation; Visualization; Writing—review & editing; L.d.S.P.C.: Conceptualization; Formal analysis; Methodology; Project administration; Resources; Supervision; Validation; Writing—review & editing; M.V.-L.: Conceptualization; Formal analysis; Methodology; Project administration; Resources; Supervision; Validation; Visualization; Writing—review & editing. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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