

Article

Dimension Stone Processing Sludge at Different Stages of Production: Insights for Waste Management

Mirna A. Neves ^{1,*} , Wenderson A. R. Nascimento ² and Adolf H. Horn ³ ¹ Department of Geology, Federal University of Espírito Santo (UFES), Alegre 29500-000, ES, Brazil² Agrochemical Graduate Program, Federal University of Espírito Santo (UFES), Alegre 29500-000, ES, Brazil; wendersonambiental@gmail.com³ Geosciences Institute, Federal University of Minas Gerais (UFMG), Belo Horizonte 31270-901, MG, Brazil; hahorn@gmail.com

* Correspondence: mirna.neves@ufes.br; Tel.: +55-028-999309050

Abstract: Brazil stands out as one of the main producers of dimension stones and, in order to maintain sustainable production, the principles of environmental sustainability have been increasingly desired. The importance of studying sludge from dimension stone processing is not only based on the economic and environmental burden that its waste disposal represents for the sector but also on the opportunity to use a material that can reduce the extraction of other mineral goods. This study aimed to describe the characteristics of this sludge at different stages of the processing to evaluate the differences between the material circulating in the production process and after dehydration, when it becomes a residue to be disposed of. Aluminum, iron, manganese, and barium concentrations were high in the liquid phase of the sludge, but they were reduced considerably in the solubilized extract. The hydrogen potential reduced, falling below the threshold of corrosivity, after the withdrawal of the liquid phase. Elements with concentrations higher than the maximum allowed value for inert wastes come from both the inputs used in the processing and the processed stone itself. Initiatives to segregate materials from different sources and investments for the creation of eco-products that can replace inputs, besides the use of wastes, should be encouraged to work towards sustainable production.



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Keywords: ornamental stones; abrasive slurry; classification of residues; ore processing waste

1. Introduction

Almost 70% of the global dimension stone production is from China, India, Turkey, Iran, and Brazil [1]. Brazilian exports of dimension stones in 2021 exceeded historical records, totaling USD 1.34 billion, with a positive variation of 35.5% compared with the previous years [2]. Espírito Santo, Minas Gerais, and Ceará are the main exporting states, and Espírito Santo and Minas Gerais are responsible for about 93% of sales. The stone sector in Espírito Santo accounts for 8.7% of formal jobs and 19.6% of businesses [3], and its main segment is dedicated to processing, that is, the transformation of rocky blocks into raw and polished slabs.

Among all the waste generated by this activity, dimension stone processing sludge (DSPS), whose management is regulated by the State Institute of Environment and Water Resources of Espírito Santo (IEMA) [4–6], has been gaining prominence. The composition of this material is of interest for the manufacture of various products, and the disposed volumes are significant. According to some authors [1], about 41% of the material taken to the processing plant is transformed into waste in Iran, which is one of the world's major

producers of dimension stones. In Brazil, the volume of waste accumulated in deposits in the region of Cachoeiro de Itapemirim, southern Espírito Santo, is estimated to be at least 3 million m³ by 2019, and the minimum growth predicted in the next two decades is 6 million m³ [7]. Although the Institute of Applied Economic Research (IPEA) [8] puts dimension stones on the list of the main Brazilian export mining products, the sector is not on the list of the largest mining waste producers. However, considering the local reality, limitations in waste management, and economic issues involved, further studies on the characteristics of these materials are necessary.

Many studies have already addressed the use of rock wastes as part of the raw material to produce ceramics [9–12], cement, concrete, and mortar [13–16], as well as bricks and blocks [17–19], besides evaluating it to correct the hydrogen potential (pH) [20–23] and for the mineral enrichment of soil [24–26]. However, significant fear and insecurity still surround environmental issues, since it involves industrial wastes whose characteristics, compositional variability, and source of potentially toxic components are unknown.

DSPS has different characteristics according to the stages of the production process [27], which gives it different classifications in terms of environmental hazards. While some authors classify wastes from the disposal of DSPDS as inert [28], others consider them non-inert due to the presence of various parameters above Brazilian thresholds [29]. In fact, this sludge is composed of a solid and a liquid phase, and significant differences between these parts are expected after drying, for example.

This study aimed to describe the characteristics of DSPS at different stages of the rock processing, both in compositional terms and considering the waste classification of the Brazilian Association of Technical Standards [30]. The research was conducted in the State of Espírito Santo, Southeast Region of Brazil, where the main Brazilian dimension stone production center is located. Samples of DSPS were divided into the liquid phase and solid phase to evaluate the differences between the sludge circulating in the production process and the waste from DSPS, which is dehydrated before disposal. The data were compared with the characteristics of processed stones and some of the inputs used, seeking to map possible sources of some elements that define the type of waste.

2. Materials and Methods

2.1. Sampling

Samples were collected in companies that use different types of rock processing: conventional looms plus plate polishing, diamond (or multi-wire) looms plus plate polishing, and only plate polishing. Figure 1 shows the location of the sludge collection points in the production line of the companies.

Samples of the blocks (fragments of rocks) that were being sawn at the time of the collection of DSPS were also collected, in addition to samples of the slurry that is temporarily stored in the sedimentation tanks. These tanks receive the effluent from the polishing stage and return the liquid phase to the processing system after decantation of the solid phase. In these tanks, samples of the supernatant liquid phase and samples of the particulate material decanted at the bottom of the tank were collected. Samples of the mixed sludge, which is driven by channels (conduits) to the filter press, where the material is dehydrated before disposal, were also collected.

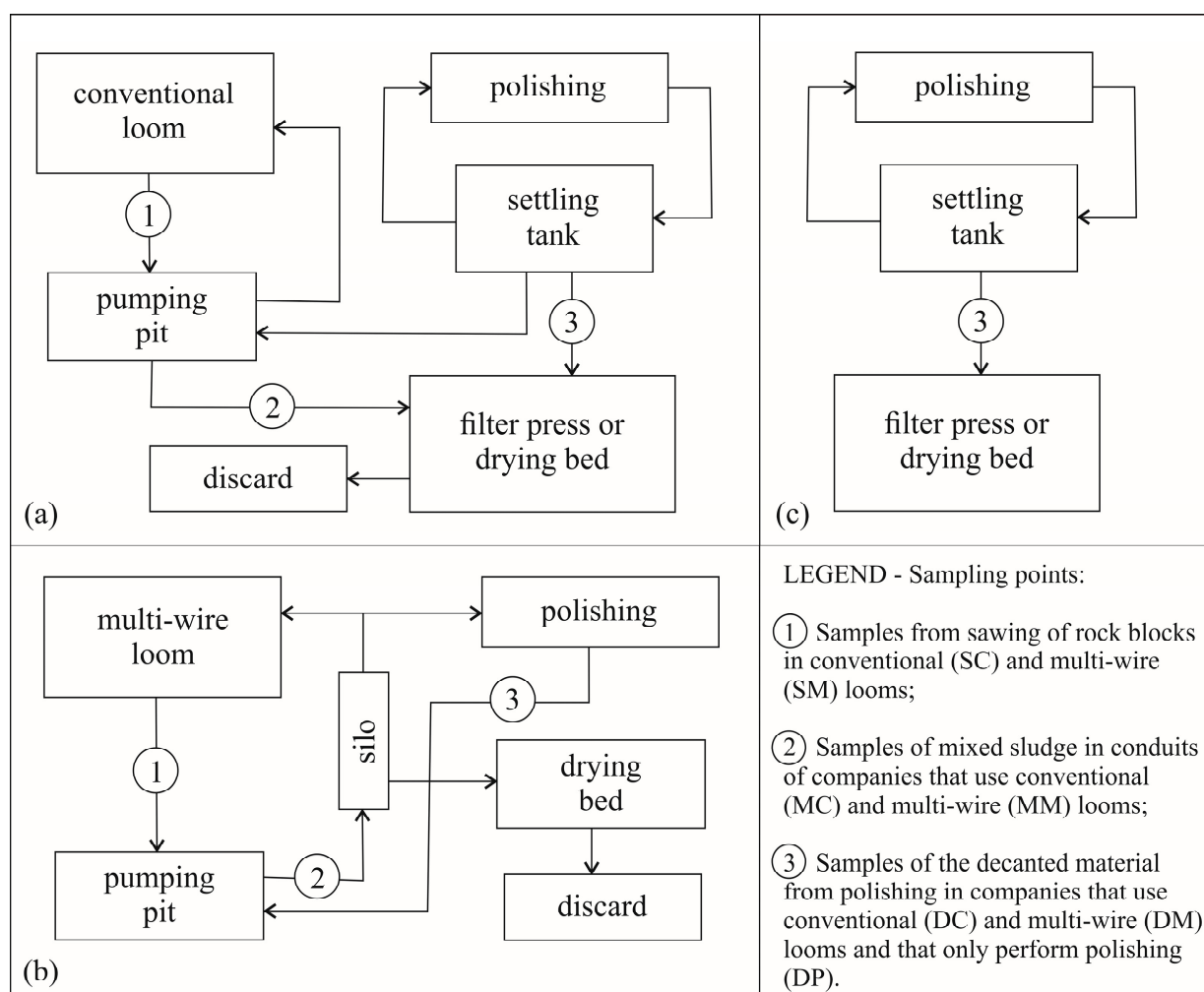


Figure 1. The locations of the sampling points in the processing system of dimension stones of companies that use (a) a conventional loom and polishing machine; (b) a multi-wire or diamond loom and polishing machine; (c) a polishing machine only (the acronyms in parentheses in the legend are used throughout the text).

In total, 80 samples of DSPS, 50 samples of traditionally processed stones from the region, and 5 samples of inputs used in the processing were collected. The samples of DSPS were stored in previously cleaned 2 l bottles made of resistant polyethylene with a wide mouth and screw cap and packed in a cooler with ice to ensure the preservation of their original characteristics. The samples were transported to the Laboratory of Applied Geology of the Department of Geology at the Federal University of Espírito Santo (UFES), where they were stored in a refrigerator under 4 °C until analysis. Stone and input samples were packed in resistant plastic bags until properly identified.

2.2. Separation of Liquid and Solid Phases and Determination of Water Content

Samples of DSPS in the liquid and solid phase were homogenized and then placed in a graduated cylinder of a known volume to rest. After the decantation of particles (24 h at rest, with the graduated cylinder capped to prevent the entry of external particles), the liquid and solid phases were obtained (Figure 2). The liquid phase was pipetted and stored in a previously cleaned resistant polyethylene container with a screw cap for pH measurement and metal analysis. The solid phase was kiln-dried at 42 °C for later analyses.

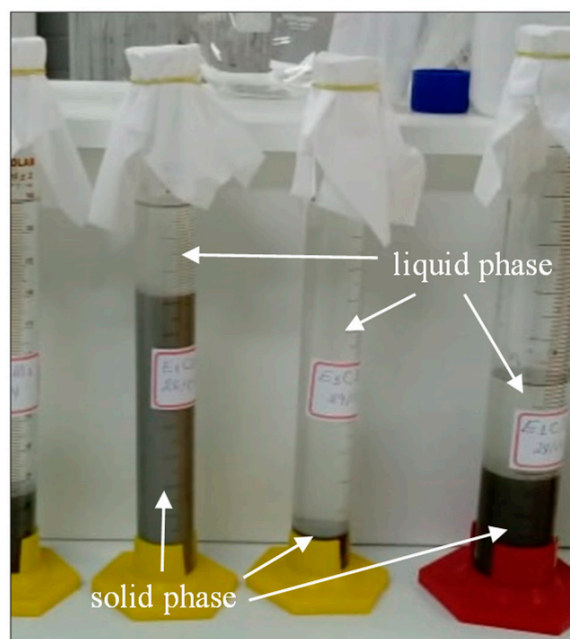


Figure 2. The separation of the liquid and solid phases of DSPS samples collected from companies.

2.3. Particle Size Analysis of the Solid Phase of DSPS

For the particle size analysis of the solid phase of DSPS, previously dried samples were wet-screened using a set of sieves with an opening of 18 to 270 mesh. The fraction that passed through the finest sieve (0.053 mm) was analyzed in a laser sedigraph at the Sedimentology Laboratory of the Department of Oceanography of UFES, where fractions of up to 0.00025 mm were dimensioned.

2.4. Analysis of the Chemical Composition of the Solid Phase of DSPS, Stones, and Inputs

The chemical compositions of the solid materials (the solid phase of DSPS, stones, and inputs) was evaluated by X-ray fluorescence (XRF) spectrometry. Previously dried samples were ground and mixed with reagents for the manufacture of fused pellets made of 1 g of sample, 9 g of lithium tetraborate, and 1.5 g of lithium carbonate. The mixtures were fused in a fusing machine for 17 min at about 1300 °C. The steel grit sample was prepared for chemical analysis by complexometric titration. Previously ground and dried samples were subjected to ultrapure HCl for 24 h, and the filtered extract was titrated using DCTA (1,2-cyclohexylendinitrile-tetraacetic acid monihydrate) to determine the iron content. To evaluate the loss on ignition (LOI), platinum crucibles (without samples) were taken to the muffle furnace at 1000 °C for 20 min. A total of 1000 ± 0.001 g of sample was weighed in each crucible. Samples were calcined in a muffle furnace at 950 ± 50 °C for at least 50 min until reaching a constant mass. Before each weighing, crucibles with and without samples were placed in a desiccator to reach room temperature without absorbing moisture from the environment.

2.5. Analysis of the Liquid Phase and the Solubilized Extract of the Solid Phase of DSPS and Rocks

The IEMA adopts the ABNT waste classification system as a valid regulation to evaluate the potential of environmental impacts of solid wastes. According to NBR 10,004/2004 [30], wastes can be classified as dangerous (type I) or non-dangerous (type II). Non-dangerous waste may also be non-inert (type II-A) or inert (type II-B). To identify dangerous and non-dangerous wastes, the leaching test is used according to NBR 10,005/2004 [31]. This test was not performed in this study, but considering the pH levels of the samples, their corrosivity was tested. A waste is considered corrosive and, therefore,

dangerous when, in the case of aqueous samples, its pH is less than or equal to 2.0 or greater than or equal to 12.5, or its mixture with water, in the proportion of 1:1 by weight, produces a solution with a pH less than 2.0 or greater than or equal to 12.5 [30]. Type II-A waste (non-inert) may have biodegradability, combustibility, or solubility in water. When type II-B waste (inert) enters into dynamic and static contact with distilled or deionized water at room temperature, according to NBR 10,006/2004 [32], none of its components are solubilized to concentrations higher than the water potability standards, except for the appearance, color, turbidity, hardness, and flavor. Waste classification as type II-A or II-B is evaluated by the solubilization test, in which the sample is mixed with deionized water and left at rest for seven days. Later, the mixture is filtered, and the extract is analyzed to measure the elements and/or substances that were solubilized in the liquid phase.

To obtain the solubilized extract, a 250 g aliquot (dry basis) of each sample (including the solid phase of DSPS and rock powder samples) was separated in a 1500 mL bottle, in which 1000 mL of ultrapure water was added. The mixture was stirred at a low speed for 5 min. The bottle was sealed with PVC film and a lid and left to rest for seven days at a controlled temperature of up to 25 °C. The supernatant solution was filtered in a filtration apparatus garnished with a 0.45 µm porosity filter membrane. The liquid obtained after filtration is the solubilized extract. Its potential hydrogen (pH) value was measured, and an aliquot was stored in a previously cleaned polyethylene bottle acidified with nitric acid (HNO₃) until the pH was lower than 2.

The pH value of the liquid phase samples of DSPS was also previously measured, and then, an aliquot was filtered in a 0.45 µm membrane and acidified with ultrapure HNO₃ until reaching a pH lower than 2. These samples, together with the solubilized extracts, were analyzed by inductively coupled plasma optical emission spectrometry (ICP-OES) to obtain the concentrations of aluminum (Al), barium (Ba), cadmium (Cd), calcium (Ca), cobalt (Co), copper (Cu), chromium (Cr), lead (Pb), iron (Fe), magnesium (Mg), manganese (Mn), nickel (Ni), titanium (Ti), and zinc (Zn). This analysis was performed at the Environmental Geochemistry Laboratory (NGqA) of the Professor Manoel Teixeira da Costa Research Center (CPMTC), Institute of Geosciences, Federal University of Minas Gerais (UFMG). The values obtained were compared with the limit values between inert and non-inert waste in the classification system of NBR 10,004/2004 [30].

The laboratory procedures involved the preparation of a “laboratory blank”, which was a sample of the same ultrapure water used in all laboratory processes and which was subjected to the same procedures as the samples under analysis. It would identify cross-contamination or contamination from any source outside the original sample.

A survey of DSPS classification reports was conducted, and IEMA and 145 classification data were also included in this study. These data show an overview and support part of the discussion presented at the end of this study.

3. Results

3.1. Characteristics of DSPS

The water content in DSPS is extremely variable (Figure 3a) and tends to be lower (up to about 60%) when using conventional looms. When using diamond or multi-wire looms, the water content is higher, reaching values close to 100%. The amount of particulate material greatly reduces when the processing system used is diamond looms, hindering the collection of samples in the solid phase for analysis. In this type of processing, instead of “sludge”, the more appropriate term for referring to the material would be “processing fluid”.

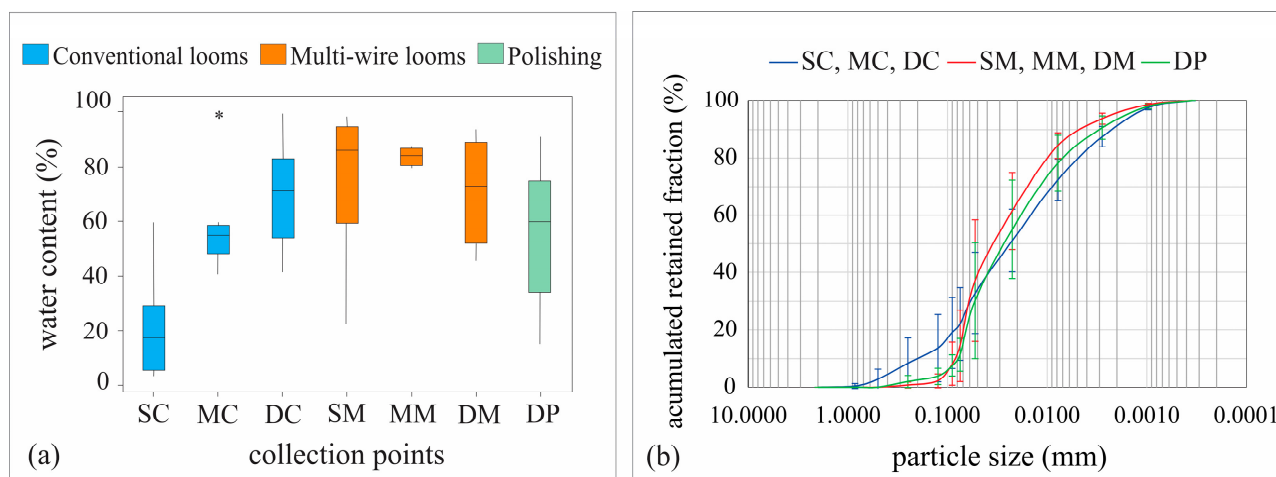


Figure 3. (a) The water contents (liquid phase) in samples of DSPS and (b) particle size of the solid phase (SC: sawing in a conventional loom; MC: conduit mixture from a conventional loom, DC: decantation tank of companies with a conventional loom; SM: sawing in a multi-wire loom; MM: conduit mixture in a multi-wire loom; DM: decanting tank of companies with a multi-wire loom; DP: decanting tank in a polishing company) (the asterisk means an outlier).

The grain size of the particulate material existing in sludge, or processing fluid, is very small, ranging from 1.0 to 0.00025 mm (Figure 3b), and about 70% of the particles are smaller than 0.05 mm. About 20% of the grains from samples collected in the conventional system (SC, MC, and DC) are 1.0 to 0.1 mm, while in other sets (SM, MM, DM, and DP), only 5% of the grains are in this range. This is due to the steel grit, which is part of the abrasive material used for sawing in the conventional system. In companies that use diamond looms, as well as those that perform the polishing, the particulate material tends to have a smaller grain size.

3.2. Chemical Composition of the Solid Phase of DSPS

The percentage of components existing in the solid phase of DSPS is very similar, regardless of the processing technique used (Figure 4). Si, Al, and Fe are the main elements, and they usually constitute more than 70% of the solid phase. Ca is also a relevant element in samples from multi-wire looms, and its provenance in these cases is associated with marble that is commonly sawn using this type of equipment. In conventional looms, the lime in the sawing pulp also provides Ca, along with the steel grit, which introduces Fe into the sludge.

The solid waste classification system of ABNT involves the analysis of the concentration of elements and substances in extracts obtained from solubilization and leaching tests. The liquid phase of DSPS is not this type of extract, but it is the liquid portion that separates from sludge, in a greater or lesser amount, when it is left at rest. The concentrations of elements in this liquid phase were measured to compare this solution with the liquid extracted from the solubilization of the components of the solid phase after sludge dehydration in the filter press or drying bed.

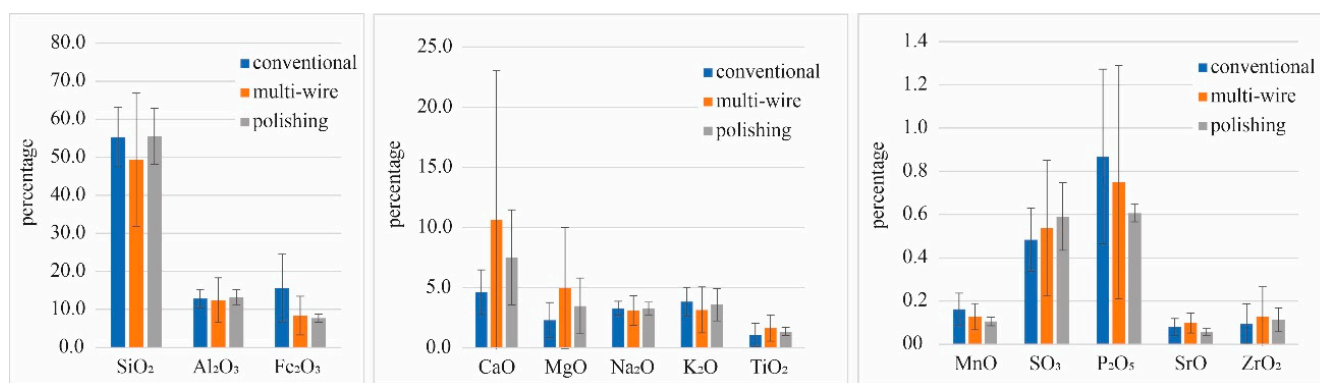


Figure 4. The chemical composition of the solid phase of DSPS collected in companies using conventional looms ($n = 48$) and multi-wire looms ($n = 19$), and companies that only perform polishing ($n = 8$) (n = number of samples in each group).

Table 1 shows data on the samples of the liquid phase of DSPS and the solubilized extract of the solid phase. In all cases studied, Al has values higher than what is allowed for inert waste according to NBR 10,004/2004 [30]. However, the values are considerably higher in the liquid phase compared with the solubilized extract. Fe, Mn, and Ba exhibit the same behavior. The regulation for Ti, Ca, and Mg does not establish a limit value, but their concentrations are always higher in the liquid phase of DSPS compared with the solubilized extract. The elements Cd, Co, Cr, Cu, Ni, Pb, and Zn were also analyzed, but the values were below the detection limit of the equipment.

The pH values of the liquid phase of DSPS vary considerably between samples at different stages of production (Figure 5a). Samples from sawing in a conventional loom (SC) and the channel mixture of a conventional loom (MC) have values higher than 12.5, which is the threshold from which waste is considered corrosive, that is, dangerous from an environmental perspective. On the other hand, the pH values of the solubilized extract of the solid phase (Figure 5b) are lower compared with the liquid phase, especially the samples from conventional looms (sawing and mixture). The corrosivity test (Figure 5c) showed no value as higher than the maximum limit allowed, indicating that this waste is non-dangerous regarding this parameter.

Table 1. The concentrations of elements in (a) the liquid phase of DSPS and (b) the solubilized extract of the solid phase of DSPS. T-Inert: thresholds for inert waste, according to NBR 10,004/2004 [30]; n : number of samples.

(a) Liquid Phase of DSPS (mg L^{-1})								
Elements		Al	Fe	Mn	Ba	Ti	Ca	Mg
T-Inert		0.2	0.3	0.1	0.7	(null)	(null)	(null)
Conventional ($n = 46$)	mean	2.64	1.57	0.05	0.18	0.03	47.41	28.22
	median	0.56	0.18	0.01	0.13	0.00	25.98	11.13
	stand.dev.	4.74	4.24	0.13	0.22	0.09	64.18	48.53
	minimum	0.00	0.00	0.00	0.00	0.00	1.01	0.01
	maximum	20.71	23.81	0.79	1.13	0.47	366.30	266.80
multi-wire ($n = 34$)	mean	1.43	0.67	0.15	0.12	0.05	65.69	37.99
	median	0.14	0.04	0.07	0.10	0.00	23.86	16.86
	stand.dev.	3.91	1.83	0.27	0.09	0.16	110.31	32.35
	minimum	0.00	0.00	0.00	0.00	0.00	0.00	9.23
	maximum	18.54	9.19	1.34	0.40	0.81	477.00	105.30

Table 1. Cont.

Polishing (n = 20)	mean	0.47	0.36	0.09	0.17	0.03	16.78	47.31
	median	0.13	0.02	0.09	0.12	0.00	16.41	12.12
	stand.dev.	0.98	0.89	0.07	0.15	0.09	6.03	74.25
	minimum	0.00	0.00	0.01	0.00	0.00	8.13	6.92
	maximum	4.42	3.86	0.22	0.48	0.41	23.17	208.10
(b) Solubilized extract of the solid phase of DSPS (mg L ⁻¹)								
Elements		Al	Fe	Mn	Ba	Ti	Ca	Mg
T-Inert		0.2	0.3	0.1	0.7	(null)	(null)	(null)
Conventional (n = 42)	mean	0.30	0.07	0.00	0.01	0.04	6.81	1.27
	median	0.07	0.00	0.00	0.00	0.02	4.25	0.15
	stand.dev.	0.69	0.14	0.00	0.01	0.04	7.16	2.05
	minimum	0.00	0.00	0.00	0.00	0.02	0.72	0.01
	maximum	4.31	0.57	0.01	0.03	0.09	32.53	7.42
multi-wire (n = 26)	mean	0.40	0.15	0.03	0.05	0.01	34.20	5.71
	median	0.14	0.04	0.01	0.04	0.00	17.48	4.32
	stand.dev.	0.63	0.23	0.07	0.04	0.02	80.84	3.95
	minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.25
	maximum	2.41	0.84	0.27	0.17	0.06	426.00	15.19
Polishing (n = 10)	mean	0.55	0.35	0.01	0.04	0.04	13.32	9.72
	median	0.12	0.21	0.01	0.03	0.03	10.93	12.33
	stand.dev.	0.67	0.45	0.01	0.02	0.05	9.30	5.14
	minimum	0.00	0.00	0.00	0.00	0.00	6.04	2.18
	maximum	1.74	1.50	0.03	0.08	0.12	35.85	15.17

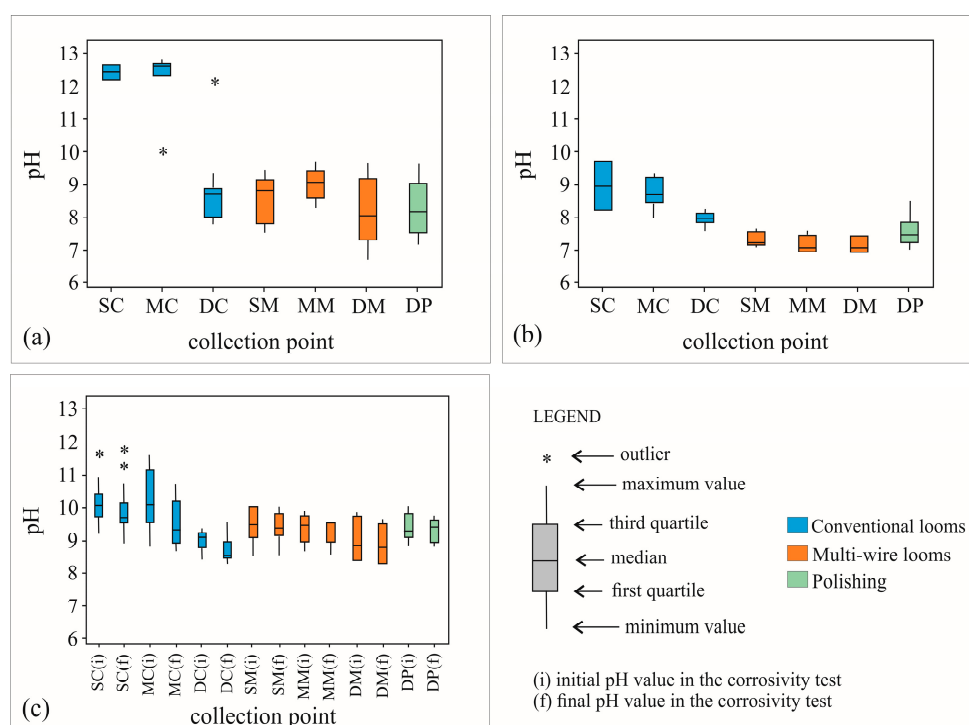


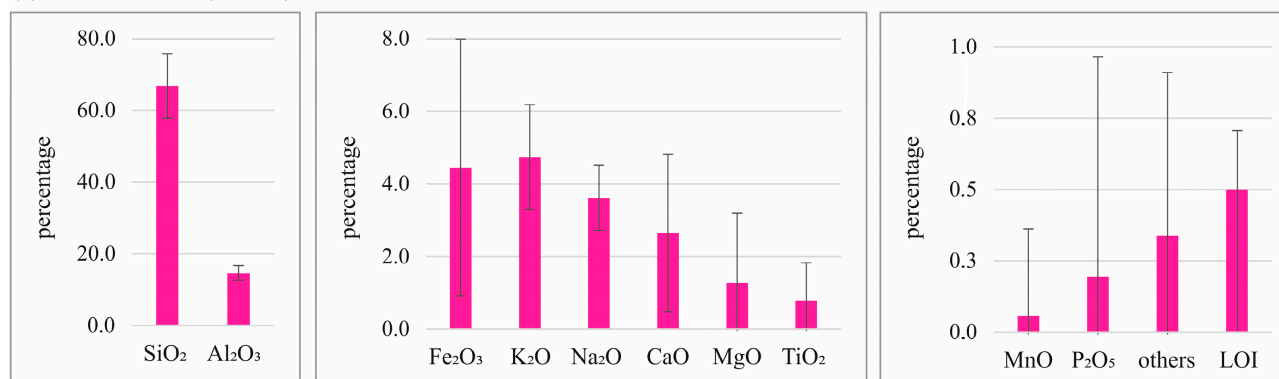
Figure 5. pH values measured in (a) the liquid phase, (b) the solubilized extract of the solid phase, and (c) the corrosivity test of the sample groups of DSPS (SC: sawing in a conventional loom; MC: channel mixture in a conventional loom, DC: decantation tank of companies with a conventional loom; SM: sawing in a multi-wire loom; MM: channel mixture in a multi-wire loom; DM: decanting tank of companies with a multi-wire loom; DP: decanting tank in a polishing company).

3.3. Chemical Characteristics of Processed Stones

In the commercial sector, silicate rocks are generally called “granite”. However, according to geological nomenclature, these rocks involve various lithotypes, including granite itself, granodiorite, diorite, gabbro, and gneiss, among others. Their common characteristic is the predominance of quartz and the various types of silicate in their composition. On the other hand, carbonate rocks consist of marble. This name is commonly used in both the commercial and scientific sectors. The waste analyzed in this study came from the processing of both silicate and carbonate rocks.

The main chemical composition of silicate rocks (Figure 6a) includes Si and Al and secondarily Fe, K, Na, Ca, Mg, and Ti. Ti, Mn, P, and LOI accounted for less than 1%. “Other” elements include Sr, Zr, and Ba. The main components of carbonate rocks (Figure 6b) were Ca, Mg, Si, and the radical carbonate (CO_3^{-2}), which is evaluated as the LOI in this type of analysis. The percentage of the other components is very low (less than 0.5%), which substantially differentiates the two large lithological groups studied.

(a) silicate rocks (n = 52)



(b) carbonate rocks (n = 5)

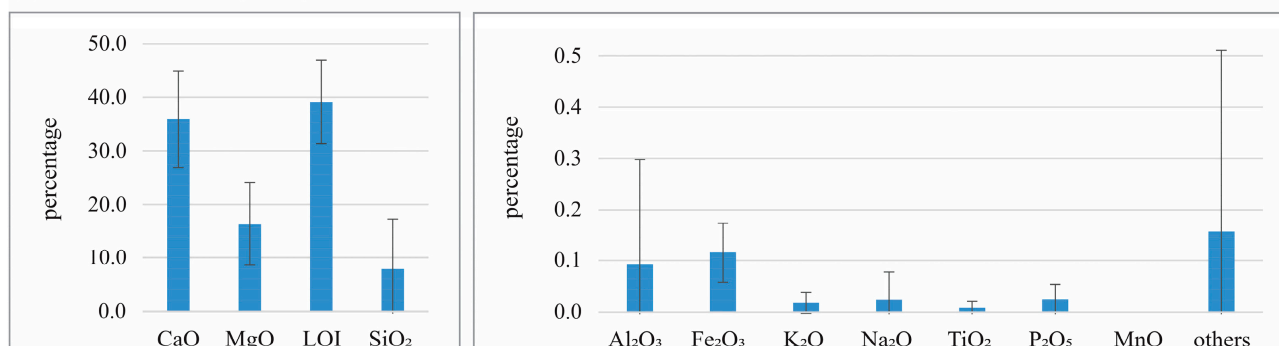


Figure 6. The chemical compositions of the processed rocks, which have a (a) silicate composition (referred to as “granite” in the commercial sector, as mentioned before) or (b) carbonate composition (marbles) (n: number of samples).

Table 2 shows the concentration of chemical elements in the solubilized extract obtained from the powder of the rocks that were sampled during the collection of DSPS and milled in our laboratory. The values for both Al and Fe were higher than the thresholds for inert waste, showing that these elements are also released by the processed rocks.

Table 2. The concentrations (values in mg L^{−1}) of elements extracted from the solubilization test of the powder of dimension stones (powdered rocks). T-Inert: thresholds for inert waste according to NBR 10,004/2004 [30]; n: number of samples.

Elements	Al	Fe	Mn	Ba	Ti	Ca	Mg
T-Inert	0.2	0.3	0.1	0.7	(null)	(null)	(null)
mean	0.73	0.57	0.01	0.03	0.05	20.55	3.06
median	0.22	0.00	0.00	0.01	0.00	23.34	1.79
stand.dev.	1.33	2.06	0.03	0.06	0.22	9.68	3.21
minimum	0.00	0.00	0.00	0.00	0.00	3.45	0.22
maximum	5.40	9.26	0.12	0.19	0.98	30.30	12.61

3.4. Main Inputs Used in the Processing of Rocks

Fe is the main component of the inputs used in the sawing of blocks in conventional looms (Figure 7a), as it constitutes the steel grit and blades, which are materials that wear out and become part of the DSPS. Regarding the main inorganic components of the abrasive materials used in the polishing of slabs (Figure 7b), the conventional type mainly includes Si and Mg, while the type referred to as “luster” has more than 50% of Al, almost 40% of resinoid, and almost 20% of Na. The analysis performed (XRF) did not identify organic components, but they were quantified by the LOI.

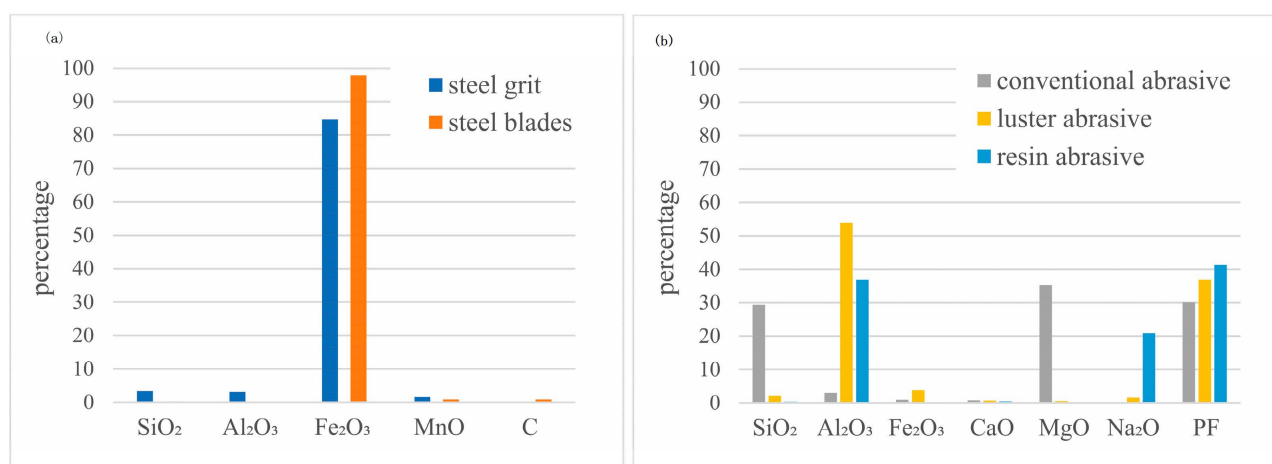


Figure 7. The chemical composition of (a) the steel grit and blades used in the sawing of blocks in conventional looms and (b) selected abrasive materials used in the polishing of slabs.

4. Discussion

This study presents the characterization and classification of the DSPS and the fluid circulating in the production system, as well as its comparison with the solubilized extract of processed rocks and the composition of the main materials used. The results show that the non-inert nature (according to ABNT) of the waste generated by discarding the DSPS is associated with both the processed stones and inputs used in the processing.

Some authors [27] showed that a direct correlation exists between the chemical composition of the solid phase of DSPS and sawn rocks, except for some components found in the sludge of conventional looms, such as Fe, as their contents can increase by more than 400% compared with rocks that are sawn with conventional sludge. Mn, Ti, and P also increase, probably because, along with Fe, these elements exist in the steel grit and blades. However, according to the present study, certain types of stones also provide Fe, while Ca and Mg can also come from both rocks (usually marble) and inputs (such as the lime used in the sawing process and magnesian abrasive used in the polishing of slabs).

Al and Na, besides being provided by silicate minerals that constitute the rocks, also come from the abrasive materials that are used in the polishing of slabs. Coagulants used in the decantation tank of particulate materials, a process that occurs after polishing, may be another source of Al. Unlike Al from silicate minerals, Al from coagulants exists in soluble substances, such as AlCl_3 and $\text{Al}_2(\text{SO}_4)_3$. Similarly, Fe can come from FeCl_3 , which is also used as a coagulant to accelerate the decanting of the solid phase of the polishing effluent. As companies usually perform water recirculation in the processing system, the liquid phase of sludge and processing fluids is full of various soluble components of inputs, as well as minerals, which are comminuted and solubilized. The small particle size of the solid phase of sludge shows the increase in the surface area of mineral particles, which can facilitate the release of chemical elements to the liquid phase. It can accelerate in cases in which the pH becomes corrosive (higher than 12.5) as a consequence of the introduction of lime into the sludge of the conventional sawing system. At the end of the process, the sludge and fluids of the sawing and polishing stages are usually mixed and all elements, and substances become effluents of the processing, which are dehydrated before disposal.

The dehydration of DSPS before disposal is extremely important to reduce the potential for environmental damage, since some components of the inputs may be toxic to living organisms [29,33], especially those that are used in the polishing of slabs. The analysis of the liquid phase that separated from the solid phase of sludge, as presented here, shows that DSPS is different from the dehydrated waste or the waste with reduced water contents. The IEMA Normative Instruction 12/23 [5] defines the licensing procedures for the processing of dimension stones and requires a reduction in the moisture content of sludge to a maximum of 30% before disposal. Corroborating the requirements of the managing body, the presented data show that removing the liquid content of sludge tends to make the waste from DSPS different from the original sludge, considerably reducing possible environmental risks.

The high pH measured in the liquid phase of DSPS tends to mitigate after dehydration by pressing. The collection of circulating sludge, when its liquid and solid phases coexist, can lead to the classification of waste as dangerous as a function of corrosivity. Previous studies have already thoroughly discussed the issue of the pH of waste from DSPS and showed that the pH values tend to mitigate over time [34]. However, the results of this study highlight the need to measure the pH in the solubilized extract and/or by the corrosivity test, according to NBR 10,004/2004, and never directly in the pasty sludge. Moreover, the sampling of waste from DSPS for classification should be performed after the material is subjected to the filter press or bed-drying.

In Brazil, following ABNT standards, studies have classified waste from DSPS as non-dangerous and non-inert [35,36] according to the IEMA Normative Instruction 11/16 [3], as has the state environmental management body itself. However, due to the compositional variability of the rocks, technologies, and inputs used, inert waste can also be produced, in line with previous work [28] and in accordance with the data presented here, as well as data obtained in the survey of reports provided by IEMA (Table 3).

Considering that the types of stones demanded by the market vary over time and depend more on trends related to visual aspects than on the composition of the product, suggesting the selection of types of rocks with predetermined compositions to avoid the production of non-inert waste is not feasible. On the other hand, investing in the creation of ecologically sustainable inputs can be an important action aimed to produce predominantly inert waste or waste with a low environmental risk. Moreover, the use of multi-wire looms should be encouraged, because this process produces a considerably lower volume of waste to be disposed, besides its other advantages, such as greater possibilities of using the waste in products of higher added value [7].

Table 3. Percentage of samples of DSPS classified as inert and non-inert by analyzing the solubilized extract obtained according to NBR 10,006/2004 [32] (data source: state environmental agency database and this study) (n: number of samples).

Origin of the Sample	Type	
	Non-Inert	Inert
conventional loom + polishing machine (n = 120)	51%	49%
conventional loom + multi-wire loom + polishing machine (n = 40)	45%	55%
multi-wire loom + polishing machine (n = 49)	43%	57%
polishing machine (n = 14)	50%	50%
TOTAL (n = 223)	48%	52%

Elements that usually prevent waste from being classified as inert (Al, Fe, and Mn) have a geochemical behavior of low mobility in the natural environment [37] and, thus, tend to constitute insoluble minerals or adhere to solid particles. However, under particular environmental conditions, these elements may be mobilized in the environment, which explains their presence in the list of parameters of technical standards and legal regulations. Moreover, the source of these components is not only rocks, but inputs, which often consist of highly soluble compounds.

The separation of effluents from sawing and polishing is another initiative that should be encouraged, aiming at the safe management of the waste from DSPS and other processing fluids. Considering that about 90% of the waste from DSPS comes from the sawing stage, future studies should address the segregation and differentiated treatment of the solid phase produced in the polishing, aiming at waste management. This would also contribute to eliminating mistrust regarding the safe use of sawing waste as a raw material in other production processes, as several studies suggest. The composition of waste from DSPS, especially that produced from sawing using diamond or multi-wire looms, consists essentially of milled rocks with extremely small particle sizes. Its potential to serve as a raw material in several production processes is great, especially when grinding or comminuting materials with compositions that are similar to the Al, K, Na, Ca, and Mg silicates, besides Ca and Mg carbonates, is necessary.

5. Conclusions

The characterization of the sludge circulating in the processing of dimension stones showed that the percentage of water content of the DSPS in the sawing of blocks in conventional looms is 60% and close to 100% in diamond or multi-wire looms. Therefore, in the latter two, the term processing “fluid” is used instead of “sludge”. Processing fluids and sludge must be distinguished from the waste that is produced after the removal of excess water, and it must be performed before taking the waste to industrial landfills or using it as a raw material in other industrial processes.

The effluents of the processing of dimension stones should be evaluated using the ABNT classification system based on samples collected after being subjected to the filter press or drying bed; however, they should not be collected in the system of circulation of sludge or fluids of the company. This is because the liquid phase of sludge has several components in high concentrations, which make it different from materials that are to be transported and stored in waste deposits.

The differences between sludge and fluids circulating in the production process of dimension stones and the waste produced are significant regarding their potential environmental impacts. In this study, the Al, Fe, and Mn contents in the solubilized extract of the solid phase of DSPS were higher than the thresholds established for inert waste by NBR 10,004; therefore, they are classified as non-inert materials. However, the concentrations

of these elements were higher in the liquid phase of DSPS, in which the Ba content was also higher than the threshold, showing the importance of dehydrating this material before transport and storage in deposits or landfills, in accordance with IEMA Normative Instruction 11/2016. Similarly, the pH reached levels of hazard in the liquid phase of DSPS, but it was below this threshold in both the solubilized extract of the solid phase and the corrosivity test recommended by ABNT.

Therefore, the removal of the liquid phase of the produced waste is essential to reduce environmental risks during disposal. Dehydration using a filter press should be prioritized, aiming at the effective removal of the liquid phase and not only air-drying, since in this case, part of the components that were previously in solution may precipitate.

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References

1. Jalalian, M.H.; Bagherpour, R.; Khoshouei, M. Wastes production in dimension stones industry: Resources, factors, and solutions to reduce them. *Environ. Earth Sci.* **2021**, *80*, 560–573. [CrossRef]
2. Associação Brasileira da Indústria de Rochas Ornamentais—ABIROCHAS. Balanço das exportações e importações brasileiras de materiais rochosos naturais e artificiais de ornamentação e revestimento em 2021. *Informe* **2022**, *1*, 2–17. Available online: https://abirochas.com.br/wp-content/uploads/2022/03/Informe-01_2022-Exportacoes-2021.pdf (accessed on 6 November 2023).
3. Instituto de Desenvolvimento Industrial do Espírito Santo/Federação das Indústrias do Espírito Santo IDEIES/FINDES. *Análise de Competitividade do Setor das Indústrias de Rochas Ornamentais do Estado do Espírito Santo*; FINDES: Vitória, Brazil, 2020. Available online: <https://inovacaoedesarrollo.es.gov.br/> (accessed on 30 November 2023).
4. Espírito Santo. *Secretaria de Estado do Meio Ambiente e Recursos Hídricos. Instituto Estadual de Meio Ambiente e Recursos Hídricos. Instrução Normativa nº 11 de 11 de outubro de 2016*; Diário Oficial dos Poderes do Estado: Vitória, Brazil, 2016. Available online: <https://iema.es.gov.br/legislacao> (accessed on 20 March 2024).
5. Espírito Santo. *Secretaria de Estado do Meio Ambiente e Recursos Hídricos. Instituto Estadual de Meio Ambiente e Recursos Hídricos. Instrução Normativa nº 13-N de 22 de agosto de 2023*; Diário Oficial dos Poderes do Estado: Vitória, Brazil, 2023. Available online: <https://iema.es.gov.br/legislacao> (accessed on 20 March 2024).
6. Espírito Santo. *Secretaria de Estado do Meio Ambiente e Recursos Hídricos. Instituto Estadual de Meio Ambiente e Recursos Hídricos. Instrução Normativa nº 12-N de 22 de agosto de 2023*; Diário Oficial dos Poderes do Estado: Vitória, Brazil, 2023. Available online: <https://iema.es.gov.br/legislacao> (accessed on 20 March 2024).
7. Moreira, B.C.; Neves, M.A.; Pinheiro, M.M.; Nascimento, W.A.R.; Barbosa, J.L.B.; Horn, A.H. Depósitos de resíduos de rochas ornamentais: Composição, dimensionamento e possíveis usos no setor de construção civil. *Geociências* **2021**, *40*, 525–538. [CrossRef]
8. Silva, A.P.M.; Viana, J.P.; Cavalcante, A.L.B. Diagnóstico dos Resíduos Sólidos da Atividade de Mineração de Substâncias Não Energéticas. In *Instituto de Pesquisa Econômica Aplicada—IPEA: Brasília, Brazil*; 2012. Available online: <http://repositorio.ipea.gov.br/> (accessed on 6 November 2023).

9. Kim, Y.; Park, H. A value-added synthetic process utilizing mining wastes and industrial byproducts for wear-resistant glass ceramics. *ACS Sustain. Chem. Eng.* **2020**, *8*, 2196–2204. [\[CrossRef\]](#)
10. Menezes, R.R.; Ferreira, H.S.; Neves, G.A.; Lira, H.L.L.; Ferreira, H.C. Use of granite sawing wastes in the production of ceramic bricks and tiles. *J. Eur. Ceram. Soc.* **2005**, *25*, 1149–1158. [\[CrossRef\]](#)
11. Silva, K.R.; Campos, L.F.A.; Santana, L.N. Use of experimental design to evaluate the effect of the incorporation of quartzite residues in ceramic mass for porcelain tile production. *Mat. Res.* **2019**, *22*, e20180388. [\[CrossRef\]](#)
12. Taguchi, S.P.; Santos, J.C.; Gomes, T.M.; Cunha, N.A. Avaliação das propriedades tecnológicas de cerâmica vermelha incorporada com resíduo de rocha ornamental proveniente do tear de fio diamantado. *Cerâmica* **2014**, *60*, 291–296. [\[CrossRef\]](#)
13. Al-Zboon, K.; Al-Zou'by, J. Recycling of stone cutting slurry in concrete mixes. *J. Mater. Cycles Waste Manag.* **2015**, *17*, 324–335. [\[CrossRef\]](#)
14. Azevedo, A.R.G.; Marvila, M.T.; Barroso, L.S.; Zanelato, E.B.; Alexandre, J.; Xavier, G.C.; Monteiro, S.N. Effect of granite residue incorporation on the behavior of mortars. *Materials* **2019**, *12*, 1449. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Buyuksagis, I.S.; Uygungoglu, T.; Tatar, E. Investigation on the usage of waste marble powder in cement bases adhesive mortar. *Constr. Build. Mater.* **2017**, *154*, 734–742. [\[CrossRef\]](#)
16. Ghorbani, S.; Taju, I.; Tavakkolizadeh, M.; Davodi, A.; Brito, J. Improving corrosion resistance of steel rebars in concrete with marble and granite waste dust as partial cement replacement. *Constr. Build. Mater.* **2018**, *185*, 110–119. [\[CrossRef\]](#)
17. Barros, M.M.; Oliveira, M.F.L.; Ribeiro, R.C.C.; Bastos, D.C.; Oliveira, M.G. Ecological bricks from dimension stone waste and polyester resin. *Constr. Build. Mater.* **2020**, *232*, 117–252. [\[CrossRef\]](#)
18. Eliche-Quesada, D.; Corpas-Iglesias, F.A.; Pérez-Villarejo, L.; Iglesias-Godino, F.J. Recycling of sawdust, spent earth from oil filtration, compost and marble residues for brick manufacturing. *Constr. Build. Mater.* **2012**, *34*, 275–284. [\[CrossRef\]](#)
19. França, B.R.; Azevedo, A.R.G.; Monteiro, S.N.; Filho, F.C.G.; Marvila, M.T.; Alexandre, J.; Zanelato, E.B. Durability of Soil-Cement Blocks with the Incorporation of Limestone Residues from the Processing of Marble. *Mat. Res.* **2018**, *21*, e20171118. [\[CrossRef\]](#)
20. Pérez-Sirvent, C.; García-Lorenzo, M.L.; Martínez-Sánchez, M.J.; Navarro, M.C.; Marimón, J.; Bech, J. Metal-contaminated soil remediation by using sludges of the marble industry: Toxicological evaluation. *Environ. Int.* **2007**, *33*, 502–504. [\[CrossRef\]](#) [\[PubMed\]](#)
21. Raymundo, V.; Neves, M.A.; Cardoso, M.S.N.; Bregonci, I.S.; Lima, J.S.S.; Fonseca, A.B. Resíduos de serragem de mármore como corretivo da acidez de solo. *Rev. Bras. Eng. Agríc. Ambient.* **2013**, *17*, 47–53. [\[CrossRef\]](#)
22. Tozsín, G.; Öztas, T.; Arol, A.I.; Kalkan, E. Changes in the chemical composition of an acidic soil treated with marble quarry and marble cutting wastes. *Chemosphere* **2015**, *138*, 664–667. [\[CrossRef\]](#)
23. Cazotti, M.M.; Costa, L.M.; Cecon, P.R. Biogenic, sedimentary, and metamorphic limestone: A comparative characterization of soil amendments. *Rev. Ceres* **2019**, *66*, 63–71. [\[CrossRef\]](#)
24. Silva, M.T.B.; Hermo, B.S.; García-Rodeja, E.; Freire, N.V. Reutilization of granite powder as an amendment and fertilizer for acid soils. *Chemosphere* **2005**, *61*, 993–1002. [\[CrossRef\]](#)
25. Theodoro, S.H.; Leonardos, O.H. The use of rocks to improve family agriculture in Brazil. *An. Acad. Bras. Ciênc.* **2006**, *78*, 721–730. [\[CrossRef\]](#)
26. Duarte, E.B.; Nascimento, A.P.S.; Gandine, S.M.S.; Carvalho, J.R.; Burak, D.L.; Neves, M.A. Liberação de potássio e sódio a partir de resíduos do beneficiamento de rochas ornamentais. *Pesqui. Geociênc* **2021**, *48*, e101373. [\[CrossRef\]](#)
27. Neves, M.A.; Prado, A.C.A.; Marques, R.A.; Fonseca, A.B.; Machado, M.E.S. Lama de beneficiamento de rochas ornamentais processadas no Espírito Santo: Composição e aproveitamento. *Geociências* **2021**, *40*, 123–136. [\[CrossRef\]](#)
28. Neves, M.A.; Raymundo, V. Depósitos de resíduos finos do beneficiamento de rochas ornamentais e qualidade do aquífero freático. *Eng. Sanit. Ambient.* **2022**, *27*, 257–267. [\[CrossRef\]](#)
29. Aguiar, L.L.; Tonon, C.B.; Nunes, E.K.; Braga, A.C.A.; Neves, M.A.; David, J.A.O. Mutagenetic potential of fine waste from dimension stone industry. *Ecotoxicol. Environ. Saf.* **2016**, *125*, 116–120. [\[CrossRef\]](#) [\[PubMed\]](#)
30. Associação Brasileira de Normas Técnicas—ABNT. NBR 10.004: Resíduos Sólidos—Classificação; ABNT: Rio de Janeiro, Brazil, 2004.
31. Associação Brasileira de Normas Técnicas—ABNT. NBR 10.005: Procedimento para Obtenção de Extrato Lixiviado de Resíduos Sólidos; ABNT: Rio de Janeiro, Brazil, 2004.
32. Associação Brasileira de Normas Técnicas—ABNT. NBR 10.006: Procedimento para Obtenção de Extrato Solubilizado de Resíduos Sólidos; ABNT: Rio de Janeiro, Brazil, 2004.
33. Venturoti, G.P.; Boldrini-França, J.; Kiffer, W.P.; Francisco, A.P.; Gomes, A.S.; Gomes, L.C. Toxic effects of ornamental stone processing waste effluents on *Geophagus brasiliensis* (Teleostei: Cichlidae). *Environ. Toxicol. Pharmacol.* **2019**, *72*, 103268. [\[CrossRef\]](#)
34. Neves, M.A.; Nadai, C.P.; Fonseca, A.B.; Prado, A.C.A.; Giannotti, J.D.G.; Raymundo, V. pH e umidade dos resíduos finos de beneficiamento de rochas ornamentais. *Rev. Esc. Minas* **2013**, *66*, 239–244. [\[CrossRef\]](#)
35. Manhães, J.V.T.; Holanda, J.N.F. Caracterização e classificação de resíduo sólido ‘pó de rocha granítica’ gerado na indústria de rochas ornamentais. *Quím. Nova* **2008**, *31*, 105–122. [\[CrossRef\]](#)

36. Braga, F.S.; Buzzi, D.C.; Couto, M.C.L.; Lange, L.C. Caracterização ambiental de lamas de beneficiamento de rochas ornamentais. *Eng. Sanit. Ambient.* **2010**, *15*, 237–244. [[CrossRef](#)]
37. Kabata-Pendias, A. *Trace Elements in Soils and Plants*; Taylor & Francis: New York, NY, USA, 2011.

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