Armando Dias Duarte
(Organizador)

ENGENHARIA CIVIL:

Demandas sustentáveis e tecnológicas e aspectos ambientais 2

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Engenharia civil: demandas sustentáveis e tecnológicas e aspectos ambientais 2

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APRESENTAÇÃO

A coleção de trabalhos intitulada "*Engenharia civil: Demandas sustentáveis e tecnológicas e aspectos ambientais 2*" é uma obra que tem como foco principal a discussão científica por intermédio de diversos trabalhos que compõe seus capítulos. O volume abordar**á** de forma categorizada e interdisciplinar, pesquisas cujos resultados possam auxiliar na tomada de decisão, tanto no campo acadêmico, quanto no profissional.

Os trabalhos desenvolvidos foram realizados em instituições de ensino, pesquisa e extensão localizadas no Brasil. Nos capítulos apresentados, são encontrados estudos de grande valia nas áreas de: materiais da construção civil, análise de estruturas por meio de métodos numéricos, recursos hídricos e gestão. A composição dos temas buscou a proposta de fundamentar o conhecimento de acadêmicos (as), mestres (as) e todos (as) aqueles (as) que de alguma forma se interessam pela área da Engenharia Civil, através de temáticas atuais com resoluções inovadoras, descritas nos capítulos da coleção. Sendo assim, a divulgação científica é apresentada com grande importância para o desenvolvimento de toda uma nação, portanto, fica evidenciada a responsabilidade de transmissão dos saberes através de plataformas consolidadas e confiáveis, como a Atena Editora, capaz de oferecer uma maior segurança para os (as) novos (as) pesquisadores (as) e os (as) que já atuam nas diferentes áreas de pesquisa, exporem e divulguem seus resultados obtidos.

Armando Dias Duarte

SUMÁRIO

CAPÍTULO 7

VALORIZATION OF SLATE WASTE TO PRODUCE MATERIALS CERAMICS AND COMPOSITES

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ABSTRACT: In slate extraction industries, mining and rock refining activities, up to the processing of products, generate a large quantity of tailings (~75% of the extracted rock). The block extraction for the production of slabs, floors and roofs generates a chip, dust or mud-shaped residue, composed mainly by water, lubricants and slate. This waste, which does not have a defined destination, accumulates in landfills, reservoirs and close to riverbeds, ensuing in technical, economic, environmental and social problems. Due to the physical and chemical properties of slate, the generated waste has great prospects for recovery and recycling in ceramic processing. This research showed four uses to slate waste and the properties of the products produced.
KEYWORDS: Slate waste, characterization, processing, new materials, civil construction.

1 I INTRODUCTION

Mining is an activity that over the years has proven to be of paramount importance for development of the regions involved, as well as for the whole country, both for generating the raw material used on a large scale in various segments of industry and commerce, as well as for generating a net of jobs in the region where it is practiced and further, thus boosting development of the economy in various scales.

However, mining companies often do not properly dispose of their waste, causing their activities to become increasingly harmful to the local ecosystem. The residue generated by the extraction of slate, for example, as well as its processing, can have several heavy impacts on the environment. Industries that process these rocks have as their main activity sawing and polishing them for the production of plates, generally used in the civil construction industry.

The system of extracting rock blocks to produce plates generates a significant amount of waste in the form of sludge, basically composed of water, lubricants and ground rock. This undestined waste accumulates in yards, landfills, reservoirs and streams, compromising the environment (Figure 1).

According to the Brazilian Association of the Ornamental Stone Industry (ABIROCHAS, 2021), until 2019, Brazil was the third largest exporter of slate products, losing this position to Turkey in 2021. Minas Gerais remains being the main producer state, accounting for about of 90% of its extraction.

In 2016, slate production in Minas Gerais totalled approximately 200,000 tons/year, distributed into sheets, tiles, billiard tops, tiles and other products, reaching a US$ 21 million exportation rate (MME, 2019).

In 2021, Brazilian production of ornamental and cladding stones totalled around 10.2 million tons, of which 0.5 million were slates, with 6.5% consumed domestically (ABIROCHAS, 2021). In the quarries of ornamental and cladding rocks, there happens a significant loss in mining stages. Although the exploration has registered a technological evolution in the extraction process, there are still accountings of large quantities of tailings deposited in the mines which, on average, reach significant values, up to the order of 60% of the total of the material extracted in the mining fronts.

Figure 1: Mining area with the presence of tailing piles.

Source: APL, 2006.

The main environmental problems caused by the production of slate are mainly linked to three factors: reduced rate of use in mining and processing, which is also seen in other slate producing centres worldwide; low value aggregation to the commercial products elaborated, which reduces the attractiveness of business investments; and not using the scrap material in mining and processing, for various industrial uses (FILHO CHIODI, et al, 2014).

The main focus of slate extraction and processing in Minas Gerais is the city of Papagaios (60% of the total production), with gray slates (mostly). The deposits are mined in the open, on slopes and in pits. The pits have a regular and normally flat floor due to the horizontal cleavage. 137 dump piles were registered, accumulating almost 100 million tons of mining and industrial tailings (FILHO CHIODI, et al, 2014).

The production of alternative materials, having as constituents the waste generated in the rock transformation industries, can reduce and even aim to eliminate pollution in the extraction areas, as well as to promoting the emergence of new careers, job opportunities and profits, essential to progress and development, locally, regionally and nationally. Many authors CATARINO et al. (2003); PALHARES et al. (2004); CAMBRONERO et al. (2005); PALHARES et al. (2012); FRÍAS et al. (2014), among others, have studied the production of industrial and commercial pieces with slate residue through traditional ceramic processes such as pressing, extrusion and bonding, in addition to the insertion of these residues in concrete and mortars.

The civil construction industry is the human activity with the greatest environmental impact. The sector is the biggest extractor of natural resources in the world, and biggest polluter. It is the largest consumer of natural raw materials (up to 50% of the total resources), involves processes with high energy consumption (of which, about 80% of the energy used in the execution of a structure is consumed in the production and transport of materials), generates pollution in almost all of its processes (from the extraction of raw materials to the production of inputs, such as cement and concrete), and even finished and being used, buildings cause numerous environmental impacts, there being data acknowledging that the volume of resources consumed in the maintenance of a building is practically equivalent to that consumed during its construction.

The present work aims to show results of alternatives for the use of waste from quarries and sawmills in various products/processing that can be used in civil construction and other applications. In addition, they can generate revenue for slate extracting companies and reduce the environmental impact caused by the disorderly deposition of these materials. The application and use of these products in the civil construction sector will contribute to reducing the discomfort caused by a sector known as one of today's society main foes and reduce the clay and sand extraction in world.

The slate residue used was generated in the extraction and processing site of the Micapel Slate company in Pompéu – Minas Gerais - Brazil. In previous work the author showed the characterization of slate powder in terms of morphology, crystallography, chemical, thermal and mineralogical analysis, to verify the minerals present in the rock.

2 I USE OF SLATE WASTE

2.1 Production of ceramic bricks via extrusion

The traditional ceramic industry is one of the most prominent in the recycling of industrial waste, due to its high production volume that allows the consumption of large amounts of waste and that, combined with the physicochemical characteristics of the raw materials ceramic and the particularities of ceramic processing, makes the ceramic industry one of the great options for recycling solid waste. Furthermore, it is one of the few industrial areas that can benefit from its production process by incorporating waste into its raw materials, such as saving high quality raw materials, which are increasingly scarce and expensive, the diversification of supply of raw materials, and the reduction of energy consumption and, consequently, reduction of costs, the growing volume of solid waste, which puts public health at risk, occupies space and degrades natural resources.

The Brazilian traditional ceramic sector is the main supplier of materials for masonry and roofing for residential and commercial use and the ceramics companies are distributed throughout all regions of Brazil. According to the Ministry of Mines and Energy in the Statistical yearbook MME (2014), the sector is made up of 9,071 companies, with annual revenues exceeding R$ 18 billion. Most of them are small companies, being a sector traditionally known for family management. The segment represents 4.8% of the civil construction industry and generates around 300 thousand direct jobs and 1.5 million indirect ones. Monthly, more than 4 billion sealing and structural blocks and 1.3 billion tiles are produced (ANICER, 2018).

Considering the average weight of a ceramic product (brick or tile) as 2Kg, and the incorporation of 30% of waste, it is possible to estimate the recovery of approximately 3 million tons of slate waste per month.

The ceramic bricks were produced in an extruder at Jacarandá Brick Enterprise, headquartered in Ribeirão das Neves – Minas Gerais - Brazil, in a traditional extruder for small-sized ceramic materials.

Pastes were produced from slate and clay powders, according to Table I. After the ceramic mass was formed, the pastes were molded in an extruder. Subsequently, the blocks were burned in a muffled furnace at a temperature gap of 900ºC to 1000ºC. Afterwards, the pieces were characterized in terms of mechanical and physical behaviour, according to NBR 15270-3 standards.

Designation	Clay	Slate
Formulation I	100	-
Formulation II	80	20
Formulation III	70	30

Table I: Designations for formulations (Palhares, et.al., 2012).

Table II presents the results obtained during the physical and mechanical characterization of the specimens worked at the temperature gaps between 900ºC and 1000ºC.

Formulation	Water Absorption (%)		Linear Retraction (%)		Mechanical Resistance (MPa)
	900˚C	1000˚C	900˚C	1000˚C	1000˚C
I (100%clay)	23,0	21,9	13,6	16,1	1,79
II (80%clay/20%slate)	19,9	18,9	8,4	9,6	2,53
III (70%clay/30%slate)	21,8	20,2	9,7	15,2	2,33

Table II: Physical and Mechanical Characterization of parts produced as a function of burning temperature. (Palhares, et.al., 2012).

In general, water absorption and shrinkage after burning have the same configuration for the temperatures under study. Higher amounts of slate in the ceramic mass led to a decrease in the levels of water absorption and shrinkage when related to the ceramic mass without the presence of residues.

By increasing the burning temperature, a glassy phase is formed, which is responsible for closing the pores, causing a decrease in the piece's water absorption. The absorption values presented are within the NBR 15270-3 standards specified for red ceramic (AA ≤ 22%).

The addition of slate (20%) decreased the linear shrinkage rate compared to the regular ceramic brick. It is suggested that these residues improve the pieces' permeability, improving the drying and burning processes. The same amount of slate increased the object's strength by 41%. Figure 2 shows the bricks in green state (before thermal treatment) (A) and after thermal treatment (B).

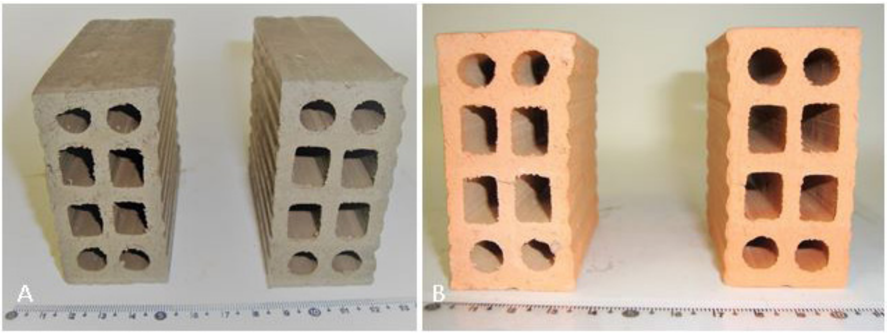

Figure 2: Bricks produced (A) before firing (B) after firing.

2.2 Production of ceramic pieces via slip casting

Slip casting is an old procedure that is widely applied in the production of ceramic pieces because it is considered a low-cost and simple process, in addition to the advantages of producing pieces of complex shapes, with thin and uniform walls. It is described as the consolidation of ceramic particles from a colloidal suspension, through the removal of the liquid part, by an absorbent mould, usually plaster.

The slip casting process is mainly used in Brazil for the production of sanitary ware and tableware. According to the Ministry of Mines and Energy, in 2014, Brazil has 18 manufacturing units, distributed in 8 states. The production is around 235 pieces/employee/month or 2,800 pieces/employee/year. The most automated and productive Brazilian units reach a productivity of 300 pieces/employee/month, in the same range production than leading international companies. The minimum productivity in the country is in the range of 180 parts/employee/month, related to some older and less automated units.

According to Ceramic World Review, in 2014, the Brazilian production of sanitary ware was 24 million pieces, corresponding to a turnover of around R$ 2 billion, which places Brazil as the world's second largest producer country.

Based on annual production of 24 million large pieces and considering pieces with average weight of 13 kg, an estimated consumption of mineral raw materials (mainly clays and feldspars) is around 320,000 tons per year. Using slate waste this consumption can be reduced to more than half because the slip casting process can absorb up to 70% of the residue.

Slate powder suspensions in distilled water were produced with constant solids percentage (approximately 70% w/v) and dispersant (ammonium polyacrylate) also constant (1.5% v/v). The ammonium polyacrylate used was the Liosperse 51, supplied by Miracema-Nuodex.

Plaster moulds were made using plaster / water (P/W) ratios of 70. The plaster was first added to the water, mixed for one minute and poured into plastic matrix moulds, in order to form the plaster moulds. After hardening the mould, it was removed and dried at room temperature for 15 days before use and characterization tests.

Mechanical rupture tests were performed according to procedures recommended by standard NBR 15270-1 (adapted) for ceramic slate pieces. The adaptation may be justified because the slate pieces can be framed in the group of traditional red ceramic materials. The tests were performed at room temperature, on the Autograph AG-X SHIMADZU universal mechanical testing machine.

In the heat-treated samples, new phases such as gehlenite, mullite and spinels were identified. The presence of these minerals was already expected due to the incidence of calcite in the raw material (PALHARES, et al. (2006). Gehelenite is formed through reactions of calcium oxide with Si and Al from the decomposition of clay (JORDAN et al., 2001). Figure 3 shows the pieces obtained by bonding, after heat treatment.

The compression tests performed disclosed a high strength for the pieces when compared to other common ceramics. The values are between 1.9 and 4.3 MPa.

Figure 3: Pieces produced after heat treatment.

Source: Palhares, et al. 2012.

2.3 Production of concrete with slate waste

To produce the concrete samples with slate residues (Figure 4), the composite cement CP II-E-32 was employed, being that it is already commonly applied in structural and conventional concrete, for pieces such as slabs, beams, pillars, foundations and in mortars in general.

The composition adopted was 1:2:3, where 1 is equivalent to the cement fraction, 2 to fine aggregates and 3 to coarse aggregates, by mass. The water/cement ratio used was 0.55. In addition to the slate dust, fine and coarse washed sand were used as fine aggregates, with maximum granulometries of 4.8 and 5.53 mm, respectively, and gravel gneiss n°0, as the coarse aggregate.

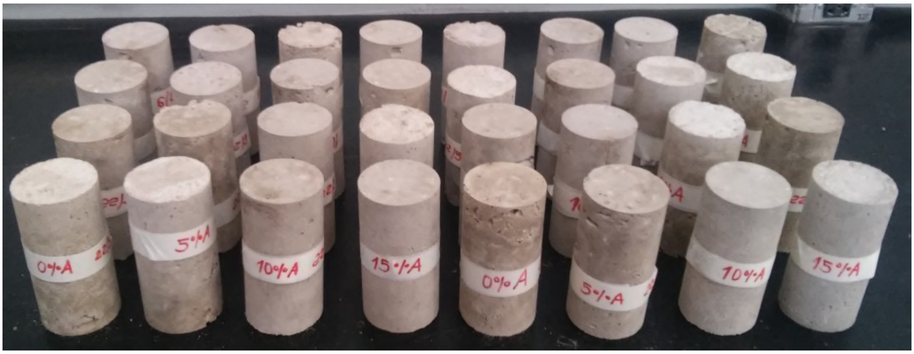

Figure 4: Specimens of reference concrete and with slate residue.

In addition to the reference concrete (without the addition of slate powder) specimens were produced with 5, 10 and 15% of slate powder instead of sand, by mass. For each percentage of slate and for each age of rupture, 4 cylindrical specimens of 50 mm in diameter and 100 mm in height were made, totalling 48 specimens. The production of specimens was referenced by NBR 5738.

To study the influence of slate on mechanical properties, the axial compressive strength of specimens at 3, 7 and 28 days of age was determined in a DL-30000 Emic universal testing machine. The water absorption by the concrete was evaluated through the immersion method, according to the NBR 9778.

It was observed that all concretes produced with slate presented, for all ages and all levels of substitution, higher compressive strengths when compared to the reference concrete (Figure 5). This result ensues the direct benefit of incorporating this technique to the regular industrial practice, justified by the use of residues in relation to the improved mechanical performance of the concrete. The specimen with 15% of slate residue presented resistance 38% greater than that of the reference concrete, for an example.

This gain in resistance indicates the occurrence of pozzolanic activity and the occurrence of the filler effect since the powder used as aggregate had a low granulometry. In other research about concrete made with slate waste were obtained similar results (OTI, et al. 2010). The particle size of the powder was sufficient to promote pore refinement and greater densification of the concrete.

The water absorption tests by immersion presented a tendency of absorbed water mass decrease with the increase of the substitute aggregate content, however, all the absorption levels are very close, being able to consider an average absorption of 7%, allowing their use as structural blocks according to the NBR 6136.

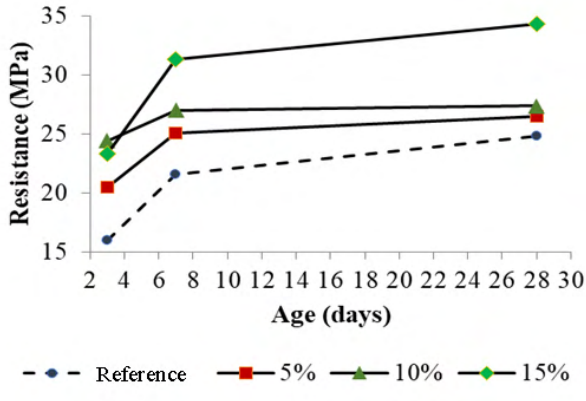

Figure 5: Evolution of axial compressive strength with age (Palhares and Da Silva, 2015).

2.4 Production of a slate/resin composite – Artificial Stone

According to Brazilian Association of the Ornamental Stone Industry [22], Brazil imported about 49.9 thousand tons of artificial stone materials in the period between January and September of 2020, totalling US$ 28.3 million in expenses. Of it, the major amount came from China, summing 46.4 thousand tons (ABIROCHAS, 2020).

The price per m^2 of artificial stone materials found in Brazil varies according to their size, aesthetics, region and brand. In general, the average price per m^2 of this product ranges from R$400.00 - R$3,000.00. Aglostone®, for example, has a cost of around R$500.00/$m^2$ while the price of Silestone® ranges from R$800.00 to R$1,300.00/m^2 (SILVA, 2017).

Due to the high prices attributed to artificial stones and the growing demand for these materials in Brazil, several studies, such as RIBEIRO et al. (2015,2017), SILVA et al. (2017), DEMARTINI (2017), among others, have been carried out in order to develop routes and means of producing these stones in the national territory.

Composites with resin (orthophthalic and epoxy) and slate were prepared with additions of 10, 30, 50 and 70% slate. The samples were poured into rectangular moulds and left to rest for 24 hours. Then, they were removed for characterization of physical and mechanical properties.

Figure 6 shows the artificial slate stone after demoulding and cutting. Artificial stone has properties that allow its cutting, polishing and colour change, by adding other reagents and/or pigments.

The stretching test was performed on a Shimadzu Autograph AG-X 10kN universal testing machine. The test was a three-point bending at a 2 mm/min speed.

The hardness of the materials was determined using a Shimadzu Model HMV 2T microhardness tester. 10 tests were carried out for each sample, with a load of 200gf and load application time of 15s, in order to generally evaluate the samples' structures.

For porosity, bulk density and water absorption measurement, the ASTM C373-88 standard (though adapted) was used.

Values of mechanical compressive strength of up to 78MPa were obtained for the artificial stone, showing that it can be used for floors and coatings in civil construction. Natural rock has a strength of approximately 336MPa. The water absorption values were in all samples less than 1%. The values obtained for flexural strength ranged from 3MPa to 11MPa and Vickers Hardness (HV) from 18 to 33 (HV).

Table III shows the values obtained for the physical properties of the artificial stone as a function of the slate percentage.

Formulations	Apparent porosity (%)	Water absorption (%)	Density (g/cm^3)
10	1,01 ± 0,24	0,74 ± 0	1.43 ± 0
30	1,09 ± 0.27	0,95 ± 0	1.46 ± 0,01
50	1,07 ± 0.23	0,63 ± 0,01	1.69 ± 0,01
70	1,04 ± 0.22	0,62 ± 0	1.84 ± 0,04

Table III: Porosity, water absorption and density for each formulation.

The results indicate that the slate increase causes a density increase of the composite, tending towards values closer to the natural stone's density, ~2.7g/cm^3. The lower density favours transportation and its application, however, it reduces the resistance.

Nowadays, the search for diversity in materials for finishing environments and spaces recently built or renovated, has shown a significant growth in Brazil due to the demands of customers in the areas of decoration and design. These demands have been generating an increase in the consumption of artificial stone materials in Brazil, leading it to qualify as a major importer of these materials.

It is extremely important to advance this technology in Brazil and increase the production of artificial stone, as it will allow for a reduction in imports from China and the reuse of ornamental stone waste such as slate.

It is believed that the artificial stone materials produced can compete with those already on the market, mainly for quality and lower cost.

The use of alternative materials (waste and orthophthalic resin) led to savings of around 71% in relation to the amount spent if standard raw material (natural rock and epoxy resin) was used (PALHARES and LUCENA, 2021).

Figure 6: Samples of artificial stone products.

3 I FINAL COMMENTS

The works developed by the author since 2000 have shown that the use of slate residues can help reducing existing environmental issues in Minas Gerais and world, reducing pollution in the extraction areas.

Accounting for the potential of the state of Minas Gerais on the slate sector, many benefits would come forth through the use of waste to generate jobs, as well as collaborating to reduce the extraction of other natural resources such as sand and gravel, air pollution, water and landscape in general.

It is understood that the transfer of technology (know-how) from the laboratory to the industry involves a series of tests and problems that must be solved. However, other issues must be considered for applications to be developed on a large scale, such as: lack of investment in waste recovery, large number of small companies operating, awareness that waste has the potential to be transformed into raw materials for other sectors, to name a few.

Another barrier in the Brazilian market within the civil construction industry is the use of waste for production processes. The lack of technical knowledge of managers and business owners makes it inviable to use waste that often has a highly added value and composition similar to the raw materials used, which can lead to the development of products with equal or superior quality to those found in the current market.

The author has been studying other applications of slate waste such as the production of porous ceramic filters, light aggregates for concrete, application in autoclaved cellular concrete, abrasive, among others.

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