REVISTA MATÉRIA V.28 N.1
ISSN 1517-7076 articles e20220328, 2023

Amethyst quartz tailings in cement mortars production

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ABSTRACT

Brazil has immense potential in the production of quartz and its gem varieties, consequently generating huge amounts of waste. This research aims to utilize the amethyst quartz tailings from the Alto Bonito mine-Brazil accumulated for decades in waste dumps, through a specific study of cementitious mortar production, considering the mineralogical and chemical characterization; evaluation the use of tailings as a fine aggregate for mortar production; estimate the technical feasibility through mechanical tests and; characterize of specimens by SEM after breakage. The tailings are quartz associated with mica. Quartz is polycrystalline with medium to fine grain, being SiO_2 the main component. The comminuted tailings showed a very fine fineness modulus, affecting the formulations. With cement:tailings (1:3) traces the mechanical tests show 5.65 Mpa and 1.05 Mpa to compressive and flexural strength respectively, slightly below the reference. The fine-sized and metamorphic morphology of the tailings affects the mechanical strength of the mortar. The process adopted in the production of mortars with total replacement of the fine aggregate have a great impact contributing to the reduction of waste in dumps, minimizing the environmental impact of mining, in addition to benefiting the Amethyst Miners Cooperative.

Keywords: Amethyst Gem; Quartzite. Aggregate; Civil Construction.

1. INTRODUCTION

In mining, the most mined minerals are rocks and minerals that contain SiO_2, which, in addition to playing an important role in geological processes, are also important for various industrial applications, with quartz being the most important and abundant silica mineral in the crust terrestrial, occurring in igneous, metamorphic and sedimentary rocks. The quartz industry (mining and mining processing), in the broadest spectrum of varieties, produces residues and tailings, which require managing them and seeking alternatives for their treatment and reuse in new applications [1–4]. There are different recommendations for the use of waste in civil construction in different applications [5, 6]. These materials with different origin have varying quality and usually show fine particulate and chemical composition in SiO_2 as main component and Al_2O_3, Fe_2O_3 and TiO_2, as minor components. Clay, feldspar, mica, iron ore, etc. are the main minerals associated with quartz residues and their quality is due to the great difference in the quality of the raw ore and in the production technique and, sometimes being reprocessed [7, 8]. Residues and tailings are deposited on the ground, which causes occupation of spaces requiring constant maintenance and monitoring, otherwise they can cause potential environmental and ecological risks, such as air pollution and pollution of surface and underground water due to leaching of chemical elements [9–13].

Usually, quartz occurring in Brazil are registered as reserves of quartz sands and industrial quartzite, whose reserves exceed 1 billion tons. During the extraction and processing of quartzite, its tailings can reach 92% of the extracted material [14, 15]. About 70% of the production of natural sand in Brazil is obtained from river beds extraction [16] and the rest from other sources (floodplains, lake deposits, mantles of rock decomposition,

Corresponding Author: Oscar Jesus Choque Fernandez Received on 06/12/2022 Accepted on 13/01/2023

DOI: https://doi.org/10.1590/1517-7076-RMAT-2022-0328

pegmatites and decomposed sandstones). The exhaustion of areas close to large consumer markets and environmental restrictions have resulted in the displacement of miners to locations increasingly distant from large urban centers, which increases the final price of natural sand, which increases the cost of freight and, consequently, the price of the final product [17]. As a substitute for quartz sands, quartzites can be used as long as they have an adequate granulometry for their application in the civil construction industry [18]. Some relevant research that evaluated the use of quartzites, for example, as recycled aggregates in self-compacting concrete for environmental sustainability [19]; incorporation of fillers from marble and tile wastes in the composition of self-compacting concretes [20]; quartzite residues on concrete and mortars, analyzing mechanical behavior and reaction alkali-silica [21, 22]; verifying compactness and properties of the hardened state of mortars with quartzite residues [3] verifying its mechanical behavior and its durability when attacked by sodium sulfate [23], investigating the specific heat of cement-based composites and the factors influencing it coating mortars friable quartzite [24] as well as several studies that aim at the processing and application of quartzite tailings acting as a non-plastic material in mortar traces or even as a substitute for part of the silica in the production of these materials [25, 26], but few on amethyst quartz tailings used in civil construction.

Quartzites are rocks classified according to their geological origin as metamorphic rocks, whose mineralogical composition is constituted mainly by quartz minerals, also presenting feldspar (orthoclase or plagioclase), muscovite and biotite, depending on the type of quartzite present in the region [21, 27]. Quartzite mining and beneficiation companies have as main activities the extraction, cutting and sawing for production of ornamental rocks, which are used in coatings, countertops, lavatories, floors and in construction. During the processing and beneficiation of quartzite blocks, millions of tons of residues are created throughout the world every year [21]. These residues end up being improperly discarded, usually causing negative impacts to the environment. These residues are classified into two types: the first one is quartzite powder, resulting from the abrasion between the saw blade and the rock plates. The second type is the quartzite chunks (pieces of rocks resulting from the cutting of quartzite plates in commercial dimensions), which originates the quartzite sand, after going through the processes of crushing, grinding and sieving [23]. The material in this work falls into the second type, specifically from the ore sorting of amethyst gem.

1.1. Description of the study area and material

Brazil is a country with immense potential in the production of quartz and its gem varieties, with around 95% of world reserves, equivalent to 78 million tons. The state of Pará holds the largest reserves in the country (64%), followed by Minas Gerais, Santa Catarina, Bahia and Goiás [28–30]. The deposits of Marabá (Alto Bonito) and Pau D'Arco both in Pará, Jacobina, in Bahia and those in Rio Grande do Sul stand out for their production volume and crystal quality [31]. The amethyst mines of Alto Bonito, also known as Garimpo das Pedras or Garimpo do Alto Bonito, are part of the Serra dos Carajás context [31–33]. In Alto Bonito, amethyst occurs in two types of deposit: primary with faults and fractures of quartzites filled whit amethyst veins; secondary as detrital material with disaggregated amethysts and transported in the lower parts of the area [33, 34]. Amethyst is exploited in cavities that today reach up to 150 meters, opened along ravines on the side of a hill. The geodes where amethyst crystallizes are usually oval, elongated or not, with sizes from a few centimeters with small crystals, to metric to decametric, where crystals can reach 0.5 m in length, with 10 to 15 cm in diameter. The amethyst mining in Alto Bonito is carried out in a rudimentary way, extracting fragments of crystals for cutting or well used as ornamental pieces. In the beginning, mining was carried out manually, with pickaxes, diggers and shovels, today it is done inside galleries or open pit, through the combination of artisanal explosives and of rubble removal as well as manually and by machine. The material extracted from the bottom of the mine is transported to a sorting site (sheds) and hammered (chipped with small iron hammers to remove impurities). The amethyst exploitation process is extremely impressive, there is a huge waste of raw material, observed both in the old mine conduits, where it is possible to find a large amount of amethyst still stuck in the walls, and in the surroundings near the entrance, where fragments of kaolinite, with or without amethyst crystals, are abandoned; to the sheds where there are piles of chipping remains or even quartz crystals of different sizes, fragmented or not, discarded from the chipping processes or obtaining the raw material [35].

The amethyst quartz tailings from Alto Bonito are dumped in so-called feldspar waste dumps accumulated in nature without a specific destination. The mined material is destined for the gem industry, and low quality materials are rejected, accumulating in large piles, which cause physical and environmental risks, at the same time, there is a growing demand for fine aggregates, with an increase in sand mining for use in civil construction and showing considerable exploitation, as well as increasing prices, which affects the growth of construction industries [6]. Although the waste from Alto Bonito has no use and its commercial value has not been quantified, it is in the interest of miners to make use of this material. This material is inconvenient for the exploitation activity and needs to be controlled to maintain the environment and avoid contact with miners, thus avoiding accidents and the spread of diseases. Therefore, using this material as an alternative material, as a sustainable activity, becomes necessary.

The aim of this work is to experimentally study the use of amethyst quartz tailings in total substitution of fine aggregates in the production of mortars for floor laying, an aggregate that can lead to minimizing the use of natural aggregates. To evaluate this material, as it is considered feldspathic, it was necessary to carry out characterization studies. From an economic and technological point of view, the use of this industrial mineral can prove to be an interesting alternative for the use of tailings by the construction industry, in the development of materials that meet technical standards, improving their properties and not posing risks to the environment. The use of a product classified as waste will promote economic benefits and better living conditions for miners.

2. MATERIAL AND METHODS

The methodology chosen to carry out this work followed as shown in Figure 1. Initially with the collection of material in the mine, followed by characterization of the material, mortar formulations, mechanical tests and microstructural tests.

2.1. Materials of mortars

Amethyst quartz tailings were obtained from the Alto Bonito mine in collaboration with the Amethyst Miners Cooperative of Marabá, Pará, Brazil. The tailings are disposed on the surface (Figure 2a) where the amethyst quartz tailings reach decametric sizes, whitish aggregates to colored crystals, translating into material that can be used as aggregates of excellent quality in civil construction. Five batches of samples were sampled and collected in the tailings deposit, they were cataloged as Amethyst Quartz Tailings-RQA (RQA-1, RQA-2 (Figure 2b), RQA-3, RQA-4 and RQA-5) totaling approximately 200kg and extracted aliquots for technological characterization using different analysis techniques.

Cement CP II-32F was used as binder. The fine aggregate of mortars was natural sand, it is basically composed of silica. To guarantee the desired quality of the experimental mortars and the tests, the sand was dried

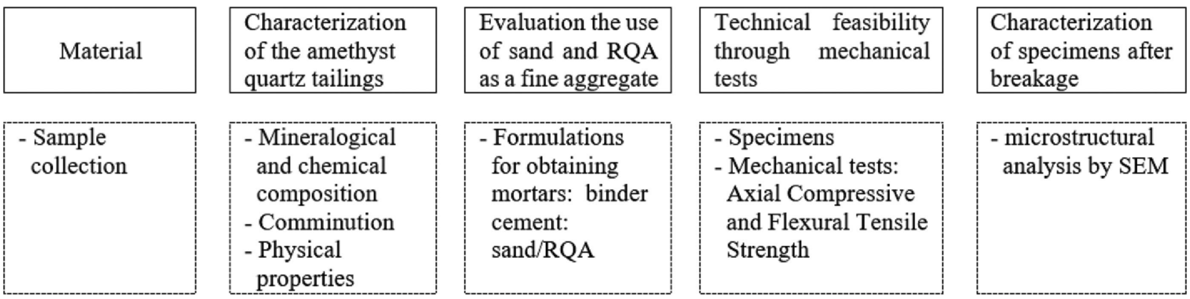

Figure 1: Flowchart indicating the methodology followed in this study.

Figure 2: Amethyst quartz tailings from the Alto Bonito mine. a) Disposal of amethyst quartz tailings in the mine, b) amethyst quartz fragments.

in an oven. The granulometry [36], the modulus of fineness and characteristic diameter were determined. The tailings (RQA) was used as substitute of natural sand material to the mortar. The water used in the preparation of the mortars was provided by the concessionaire. The specific and unitary masses of the sand materials and tailings RQA used in mortars [37, 38] were also determined.

2.2. Experimental method

Characterization of the amethyst quartz tailings

- Mineralogical and chemical characterization of the amethyst quartz tailings (RQA). Thin section petrographic analysis was carried out to identify mineralogical phases and textural features in thin sections of RQA samples. They made it possible to evaluate the use of the tailings for use as gravel and sand for civil construction. However, it also made it possible to evaluate the type of rock called feldspathic. Mineralogical composition was determined by X-ray diffraction (XRD), being the patterns collected in the D2PHASER of Bruker, copper tube, steps of 0.02° and interval 2θ of 5° to 65°. The results were analyzed in the X'PertHighScore program version 3.0e. Chemical composition was determinate by X-ray fluorescence (XRF) using the S2 RANGER of Bruker, with Pd tube. Pressed pellets were used for analysis.
- Comminution. To obtain the required size as fine aggregates used in mortars, initially the blocks coming from the mine were fragmented with sledgehammers until reaching the size of feed to the crusher, approximately 10 cm. A jaw crusher with a minimum discharge of 8 mm and a maximum of 20 mm was used, which determines the grain size to be used in grinding. For grinding a ball mill was used, with parameters of ball:sample ratio (10:1) and constant rotational speed (65 rpm), only the grinding time was considered as variable. Following the considerations of the petrographic analyses, with medium to fine granulation and the quartz hardness being 7 on the Mohs scale, the RQA was initially considered as a hard material, thus using an estimated time of 30 minutes. Longer times fragment the material into very fine grain sizes, therefore, 30 minutes is used as the initial time for the preparation of the traces.
- Physical characterization of the amethyst quartz tailings (RQA). The granulometric analyzes of the RQA tailings and of the natural sand aggregate were carried out, which allowed the determination and assessment of the grain sizes characteristics. Therefore, the fineness modulus was calculated, as well as the specific mass and the unit mass, of the RQA tailings only [36, 39]. It is worth mentioning that there are no technical standards predefined by standards for verification of analyzes for tailings.

Evaluation the use of sand and RQA as a fine aggregate

Preparation and manufacturing of mortars. The formulations for obtaining mortars were defined by analyzing the results of granulometric distribution, that is, similar and/or within the limits of the reference curves, as well as their fineness modulus. The formulations were performed (Table 1) as proportions for mixing materials in the manufacture of mortars are typically 1:3 (binder cement:sand) as reference CRE and 1:3 (binder cement:RQA) as substitution of sand with tailing. The mortars were produced using a Slitrsz 5L vertical shaft mechanical mixer.

Technical feasibility through mechanical tests

Specimens and mechanical tests. In order to perform the Axial Compressive Strength tests, cylindrical dimensions of 50 × 100mm specimen of mortars [40] were molded in stainless steel and for Flexural Tensile Strength tests, prismatic shapes in the dimensions of 40 × 40 × 160mm were used [41] both specimens were broken in an AROTEC WDW-10OEIII universal machine and compared with specific reference mortar. The objective of the comparison between the reference mortar and mortar with tailings is to evaluate the materials strength used in the manufacture of mortars with the incorporation of the tailings. The tests were carried out after 28 days of curing in humid chambers at 23°C.

Table 1: Raw materials used in mortar traces with natural sand and RQA tailings.

RAW MATERIAL	TRACE (g) 1:3 CRE REFERENCE	TRACE (g) 1:3 RQA SUBSTITUTION
Cement	624	624
Sand	1872	–
RQA tailings	–	1872
Water	400	400

Characterization of specimens after breakage

Microstructural analysis. To identify the surface micromorphology of specimens broked by Axial Compressive Strength and Tensile Strength tests were used a Scanning Electron Microscopy (SEM) of TESCAN VEGA 3 LMU and MICRO-ANALYSIS SYSTEM (EDS). Samples were extracted from fragments of cylindrical and prismatic specimens subjected to mechanical tests.

3. RESULT AND DISCUSSIONS

3.1. Mineralogical characterization of tailings and raw materials

The tailings fragments are white colored rocks (milky), due to the abundance of quartz, with light pinkish to lilac tones, medium or fine-grained, and rarely coarse of centimeter crystals of amethyst quartz (Figure 2). They present discreet foliation and banding. These are rocks of the metamorphic class, whose precursors are sedimentary rocks rich in quartz, such as pure sandstones (Figure 3).

The RQA tailings correspond to metamorphic silicic acid rocks classified as quartzite with sericite and mylonitic quartzite, with polycrystalline granoblastic textures of fine to medium granulation consisting mainly of quartz (approximately 98%) and sericite (2%). In Figure 3a, quartz grains have indented contacts and strong undulating extinction, but some grains have triple point (polygonal) contacts. Elongated quartz grains with strong undulating extinction are related to deformation. Fine sericite lamellae are preferentially oriented, defining an incipient deformation, and in these cases, the granulation is finer. In Figure 3b, amethyst veins, with pure quartz, such as porphyroblasts, are common. The rock is formed by large quartz crystals, very deformed, with strong undulating extinction. This deformation is reflected in the crystal boundaries or in zones inside the grains, segmenting them into bands, where smaller grain aggregates with triple point contacts are found, indicating superimposed metamorphism effects. In rare portions of the thin section, the host rock of the vein is registered, showing a pure quartzite (<1% sericite), fine-grained. In Figures 3c and 3d, banded granoblastic quartz texture alternated whit sericite matches to mylonitic quartzite type, presenting fine or medium granulation, anisotropic structure with alternating millimeter beds rich in sericite and bands rich in quartz. Larger quartz crystals stand out in lenticular or porphyroclast forms with strong undulating extinction and others strongly elongated and recrystallized, related to shear deformation. In the mica-rich bands, the fine lamellae are associated with fine quartz grains, where foliation develops by the preferential orientation of sericite lamellaes, which are found around the quartz bands. Sometimes mica has a fish-like shape due to shear deformation. In the micaceous bands, foliation is evident, with a preferential orientation of sericite lamellae. When quartz is present in these micacean bands, the quartz size is small.

The mineralogical composition of five tailings samples show quartz as the main phase and muscovite occurs in smaller proportions (Figure 4). The chemical composition shows higher amounts of SiO_2:90% (Table 2), in addition to minor amounts of Al_2O_3, Fe_2O_3 and K_2O. The Al_2O_3 and Fe_2O_3 contents correspond to muscovite phase occurring in the tailings.

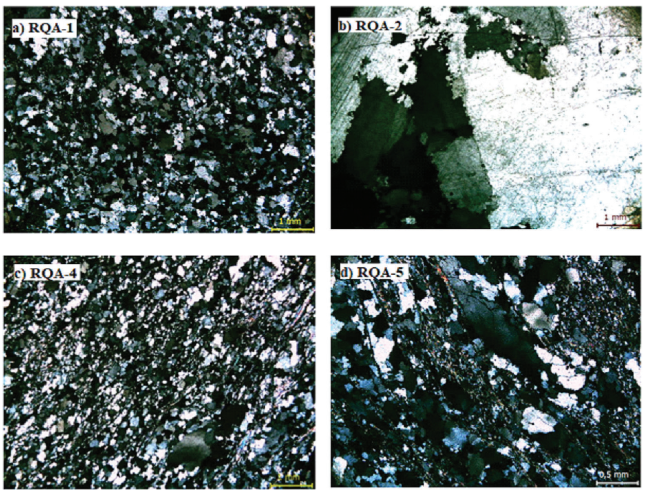

Figure 3: Thin-section microphotographs of RQA tailings: a) Polycrystalline granoblastic quartz texture with sericite (white mica); b) Amethyst vein formed by large quartz crystals; c) Banded granoblastic quartz texture alternated whit sericite; d) Mylonitic quartzite of granoblastic texture. Crossed-polarised images.

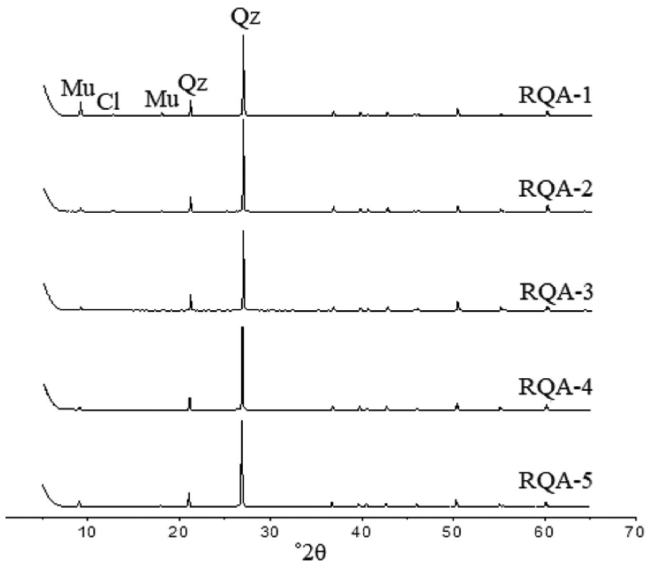

Figure 4: Difractograms of amethyst quartz tailings.

Table 2: Chemical composition of amethyst quartz tailings.

COMPONENT	RQA-1	RQA-2	RQA-3	RQA-4	RQA-5	RQA AVERAGE
SiO_2	89.9	91.0	92.8	88.2	87.0	89.78
Fe_2O_3	1.22	2.23	1.06	0.68	1.10	1.30
TiO_2	0.10	0.12		0.19	0.16	0.12
Al_2O_3	6.14	4.59	4.22	8.94	8.62	6.50
MgO	0.57	0.52	0.59		0.57	0.45
Cr_2O_5		0.32				0.06
Cl	0.12	0.10				0.10
P_2O_5				0.12		0.02
K_2O	1.72	0.98	0.96	1.55	2.27	1.50
	100.00	100.00	100.00	100.00	100.00	100.00

Amethyst quartz tailings are quartzite rock constituted by quartz, more than 98%, and is possible to corroborate that this material correspond to quartz formed in different geological events, such as amethyst from hydrothermal veins and metamorphic quartzites, as determined by other works [33, 34].

The granulometric tests show well-differentiated particle size distribution curves (Figure 5) between natural sand and RQA tailings aggregates, the first is on the border of the optimum zone while the second with a fine fraction (<0.5mm) below the usable zone. The tailings show finer fractions than the sand. The RQA tailings granulometric distribution curve shows homogeneity while masses accumulated in the particle sizes from 6.3mm to 0.5mm, with 5% cumulative retained for coarse fractions, that is 95% fine passing, this demonstrates that 30 minutes of grinding produces greater fragmentation of the RQA tailings, thus producing a higher fine fraction. This fact is also manifested in the fineness modulus of the RQA tailings, which corresponds to 0.67, considered very fine because the standard suggests it to be <1.71. It can be seen (Figure 5), that the RQA sample can be characterized as a small aggregate, since its values are in line with what the norm exposes.

Grinding studies of less than 30 minutes are required, as well as optimization of grinding parameters: Ball to Powder weight Ratio (BPR), time milling process, and rotational speed (rpm) to avoid unnecessary energy expenditure, since the particle size reduction with the decrease in grinding time can optimize the suitable grain size for the production of mortars.

The specific masses of the RQA tailings and sand natural are 2.65 g/cm^3 to both aggregates. No specific standardization references were found for RQA tailings characterization. However, the results obtained in the

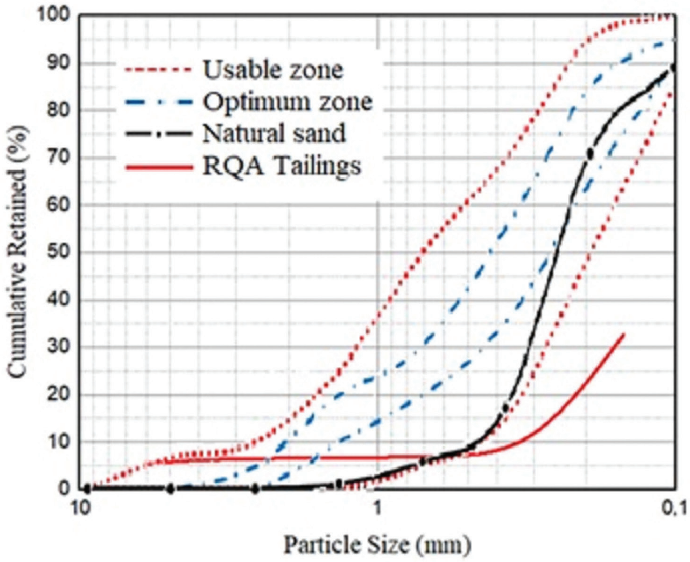

Figure 5: Particle size distribution of natural sand and RQA tailings aggregates.

research, for comparison purposes, are in agreement with the information obtained in the literature, for quartzite materials where the specific mass for the most recurrent comparison varies from 2.6 g/cm^3 to 2.7 g/cm^3. The results of the experiments show that these data are similar in relation to sand. That is, if a certain composite had to replace a sand aggregate with RQA tailings in mass, the RQA volume should be similar. These values are relevant for the calculation of mortar dosage materials [42].

3.2. Use of amethyst quartz tailings in mortars

The petrographic tests carried out on the tailings showed quartzites with amethyst quartz crystals whit quartz as the predominant phase, making it viable to use it as a natural substitute for pebble and sand for civil construction. The mineralogical composition as well as physical and chemical properties has a critical influence on the mortals. Amounts quartz (98%) whit higher SiO_2 (90%) in the RQA tailings may change the hydration kinetics of pastes, as the specific area of this phases affects hydration. In the metamorphic rocks were not identified feldspars or amorphous material, which could favor the production of mortar as long as the material has high reactive pozzolanic activity. The crystalline phases of quartz have small reactivity when purchased with amorphous material whose reactivity is higher [43]. The heat of hydration of materials produced with pozzolans depends on several factors, such as chemical and mineralogical composition, morphology, and fineness. Studies of mortars as quartzites suggest that this material has no pozzolanic activity [21]. In fact, the fragments collected in the so-called feldspathic banks do not correspond to feldspathic waste, they are quartzite rocks.

Quartz in tailings (RQA) occurring in fines sizes (6.3mm a 0.5mm) with alternating banding and foliation of quartz and mica, has higher structural distortion, it is implies the more extended defects possible, such as stacking faults and dislocations in material structure. However, the quartzite have silica in high crystalline form (Figure 4) with a high chemical stability together with pozzolanic cement can developed mortars has a high resistance [21].

The constituent minerals and chemical composition of quartzites suggest that they may be directly influencing their grindability. Quartzite is identified in the field as a quartz-rich rock (exclusive vein quartz) that is exceptionally hard and, when broken by a rock hammer, fractures irregularly through both grains and cement (where present) to form an irregular or conchoidal fracture surface. Quartzite is differentiated from quartzose sandstone (arenite), which is softer and fractures around individual grains [25]. However, the banded and foliated typology of quartzite (major quartz) RQA tailings gives different results of energy requirement, having lower resistance to the comminution process, with energy requirement values close to friable ores.

Although comminution operations are expensive, increasing the production costs of RQA tailings, due to the initial investments in equipment, energy consumption and maintenance during the operation, the option of applying RQA tailings in civil construction may become viable, as the material has mineralogical, physical and chemical characteristics that favor its fragmentation. A sieving step must be submitted so that the material is used in the production of the mortar.

3.3. Mechanical test

Mortar catalogued reference specimen (CRE), with the presence of exclusively sand aggregate, was used as a reference for comparison with mortar made with amethyst quartz tailings (RQA) (Figures 6a and 6b).

Axial Compressive Strength. When the specimens were subjected to the compression-rupture test the CRE and RQA specimens present strengths of the 6.68 MPa and 5.65 Mpa, respectively, both above 5.5 MPa (Figure 6a). The compressive strength of RQA mortars was very close to that CRE, with only a 1.03 MPa difference, on average, or 15% minor. The results indicates that for breakages performed after 28 days of cure, RQA mortars presented similar efficiencies to CRE. As for the structural blocks, according to classification P5:5.5-9.0 MPa [39], the compressive strength should be higher than 3.0 MPa, therefore, all test pieces showed compressive strength above the accepted limit, which is sufficient for its viability of use thus being quite satisfactory.

Flexural Tensile Strength. The results of this type of test show approximate data between the CRE and the RQA, with 1.28 Mpa and 1.05 Mpa respectively (Figure 6b). The results show a difference of 0.23 Mpa (18%) between CRE and RQA These results are satisfactory at both specimens, corroborating with the results found in the compression strength and then those suggested by the standard [41] type R2:1.0-2.00 Mpa.

In results of Axial Compressive Strength and Flexural Tensile Strength tests, no significant differences were observed between RQA tailings and sand natural specimens. However, this difference can be attributed to two main factors: firstly, due to its mineralogical composition, quartzite as banded aggregates (foliated) in RQA tailings has relatively low (hardness) toughness and resistance to mechanic tests caused cracking of the aggregate. The second factor is low compaction of the internal structure of quartzite has been incorporated. This leads to a significant decrease in internal stresses [22, 44].

Most of the technological qualities and properties of RQA tailings mentioned above depend on the granulometry observed in RQA tailings by SEM, too. Amethyst quartz crystals with grain sizes of 65μm have simple relationships with those of fine size (Figure 6c). By XRD, the intensity peaks of quartz in the RQA tailings are strong, without mineralogical variations in the structure. In other words, major crystallinity leads to major strength, but the fine grain size shows a major specific surface area that can affect the rate of hydration [21] during solidification with cement, because the hydration reaction occurs at the interface with water. This fact is due to the stability shown by the aggregates from the quartzite residues. These aggregates have silica in crystalline form, with a high chemical stability, and the cement has pozzolan in its constitution, thus, the developed mortars has a mechanical resistance as the reference sand. Clearly, grain size also is an important factor [45]. Mechanical tests results indicate that the high percentages of fines generated in the comminution do not prevent to obtain mortars of good resistance, although they are slightly smaller than the reference ones.

3.4. Characteristics of mortars after the breakage by SEM

The mortar samples disrupted by Axial Compressive Strength tests (Figures 7a, 7b, 7c) show a matrix cohesive to loose of amethyst quartz aggregates and cement, with a substantial amount of external and internal pore spaces throughout the structure of the specimen, this allowed a disruption of microfragments in the compression test (Figure 7a). The aggregation of particles of varying size with cementitious products (as acicular crystals), shows cohesiveness (Figure 7b), but fractures occur along the boundaries of the particles with the cement adsorbed, as well as along the fine particles (Figure 7c) as micro-cracks. The microstructure of the CRE reference sample (Figures 7d, 7e, 7f), shows a much more cohesive matrix, is dense with smaller pores than the RQA specimen (Figure 7d), also showing microfragments, as well as ruptures at the sand grain boundaries (Figure 7e). Acicular

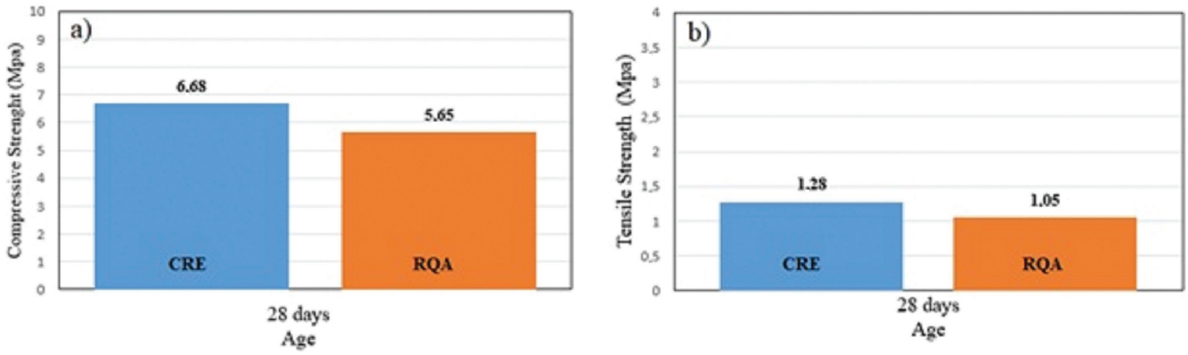

Figure 6: a) Axial compressive strength of natural sand CRE and tailings RQA mortars b) Flexural tensile strength of the natural sand CRE and tailings RQA mortars. Trace 1:3.

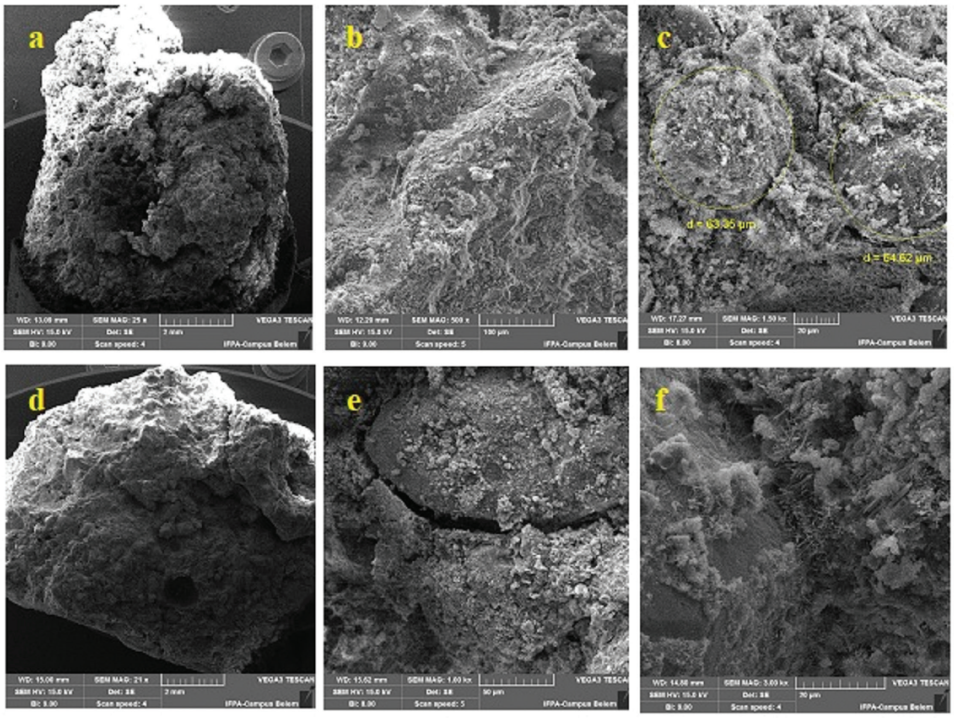

Figure 7: Microstructure SEM images of the mortar samples breakage of the Axial Compressive Strength: a) RQA fragments; b) RQA mortar sample with adherence; c) breakage sample of mortar sample with cement crystals; d) Reference fragments; e) CRE mortar sample with adherence; f) breakage of CRE mortar sample.

crystals that cement the sand aggregate were pulled from the sand boundaries (Figure 7f) forming an interfacial transition zone (ITZ). In this case, these microstructural differences show that the reference CRE has a greater bond between cement and sand particles than with RQA, showing a denser matrix with few pores and stiffness, which gave rise to greater compressive strength.

SEM micrographs for the samples RQA tailings (Figures 8a, 8b, 8c) and reference CRE (Figures 8d, 8e, 8f), for Flexural Tensile Strength displayed microstructural features similar to that observed in Figure 7. Acicular cement crystals are observed with aging and the mortars became more complex on the 28th day of aging (Figure 8c and Figure 8f). However, because of strength bending the RQA shows clean surfaces at the bonding/connection interface generated between the tailings aggregates and the cement, as well as at the pores, causing shrinkage (Figures 8a, 8b). Compared with CRE reference the bond between sand aggregate and cement is markedly improved, with pullout at the cement crystal-particle interface (Figures 8d, 8e). As well as the decrease in the amount of pore spaces with a decrease in the sand grain sizes justify the increase in tensile strength and stiffness compared with similar cases containing RQA tailings.

The microstructure exposed on the surface of the ruptured specimens (Figures 7 and 8), shows that the specimens using RQA tailings have less adhesion to the cement than the reference, due the foliated and alternating banding of quartz in the metamorphic rock, whether medium or fine-grained, may be influencing to a greater extent the limits of weak bonds of quartz bands, associated with a preferential orientation of muscovite [21], susceptible to breaking mainly with mechanical stresses of compression and flexion. The decrease in mechanical strength can be attributed to the finer and more irregular [46] particles of the RQA tailings that filled in and created a less compact mortar structure, especially in the ITZ zone when compared to the pseudo-spherical particles of natural sand aggregates. Another fact is that the porous structure of the RQA, making it less dense than the CRE, affects the mechanical strength being relatively lower than the reference ones [3, 46, 47]. In this study porosity was determined on the 28th day, perhaps samples can lower the porosity with curing time [46]. The irregular features of the fine-sized and metamorphic particles allowed the formation of small sized and irregular-shaped bubbles [48] in the RQA tailings mortar, in comparison with the pseudospherical natural sand particles that formed middle sized bubbles in the CRE reference mortar, contributed to the difference of the mechanical resistance, because the rupture in the contours of the particles with different shapes, will allow the degradation of mechanical properties. The presence of micro-cracks, especially in the interfacial transition zone (ITZ) between and cement-crystal [49] and particle in the aggregate of RQA tailing has noticeable impacts on the total pore volume [50]. Even so, the results showed good mechanical strengths.

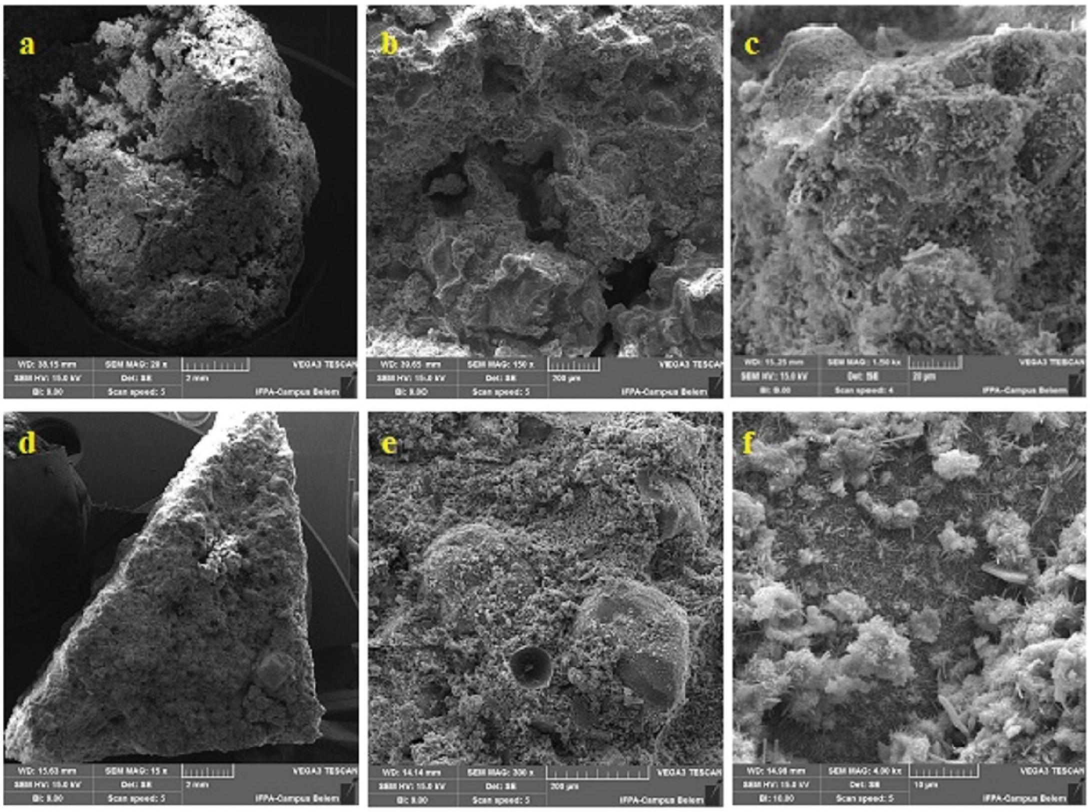

Figure 8: Microstructure SEM images of the mortar samples breakage of the Flexural Tensile Strength: a) RQA fragments; b) RQA mortar sample with adherence; c) breakage sample of mortar sample with cement crystals; d) Reference fragments; e) CRE mortar sample with adherence; f) breakage sample of CRE mortar sample.

4. CONCLUSIONS

Amethyst gem tailings consists mainly of quartz associated with micacean phyllosilicates, whit SiO_2 is the main chemical component of the tailings (90%), ruling out that they are feldspathic wastes. The tailings rocks are milky and due to the abundance of quartz are medium or fine-grained, and rarely coarse. The fragment rocks whit discreet foliation and banding correspond to metamorphic class, whose origin are quartz-rich sedimentary rocks, such as quartz sandstones.

The grain size of the tailings obtained in comminution is affected by the mineralogical characteristics of the rock, grain size and foliation, with a tendency to produce larger fine grain size during extensive fragmentation, which would affect the grindability of the rock. The tailings have fineness modulus considered very fine, which affects the strength of the mortars produced.

Mechanical tests of compressive and flexural strength of tailings have values slightly lower than the reference ones, not being very significant, showing that it is potentially favorable to replace natural sand by RQA tailings, at 28 days of curing, for a trace 1:3. The strength of a material is affected by the grain size and metamorphic morphology forming porous structure of the specimen. The strength is a function of particle size, therefore comminution cannot be neglected, and should be considered for industrial scale production.

From an environmental point of view, the use of mining tailings of amethyst gem can be used as an alternative aggregate in mortars and can contribute to reducing the amount of material destined for mining waste dumps, consequently mitigating the negative environmental impact. From an economic and technological point of view, the use of this waste can be an interesting alternative for the use of waste by the construction industry, in the development of mortars that meet technical standards. From a social point of view, it can contribute to the economic use of this waste, contributing to sustainable local development, aiming to improve the lives of the actors involved in this activity.

5. ACKNOWLEDGMENTS

To the Miners Cooperative in Marabá (Pará-Brazil), for the collection of tailings samples.

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