Article

Quartz Mining Waste for Concrete Production: Environment and Public Health

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Abstract: Brazil, one of the largest ore producers in the world, holds 95% of the world's quartz reserves. The aim of this research is to enhance mitigation measures in quartz ore exploration common in the Serra do Espinhaço Meridional region through the specific study of a mining venture. The three (3) phases of the study were: (1) characterization of the project under study and evaluation of the impacts generated; (2) evaluation of the economic feasibility of using the waste as a coarse aggregate for concrete production; (3) evaluation of the technical feasibility of reusing this waste through analysis of compressive strength. The results of the study show potential negative impacts on occupational health from the piles of disposed waste, specifically silicosis, caused by silica dust dispersed in the air. In the economic analysis, a decrease of 49.05% was verified in coarse aggregate cost through the use of the residue. The compressive strength of the concrete was 26.80 MPa when quartz residue was used and 29.2 MPa when limestone was used. The quartz residue generated by the venture can be reused as aggregate for the production of concrete, generating improvements in environmental and health aspects.

Keywords: active silica; mineral exploration; occupational health; silicosis

Citation: de Carvalho, F.A.; Nobre, J.N.P.; Cambraia, R.P.; Silva, A.C.; Fabris, J.D.; dos Reis, A.B.; Prat, B.V. Quartz Mining Waste for Concrete Production: Environment and Public Health. *Sustainability* **2022**, *14*, 389. <https://doi.org/10.3390/su14010389>

Academic Editor:
Constantina Skanavis

Received: 23 November 2021

Accepted: 24 December 2021

Published: 30 December 2021

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1. Introduction

Brazil stands out among Latin American countries for the greatest inequality in income distribution [1,2]. This is reflected in the quality of life linked to the characteristics of the environment in which people live, especially housing [3,4]. The lack of investment in housing credits in Brazil has generated a housing deficit, which for 2011 was 5,409,210 units [5]. In 2015, estimates were proposed by the João Pinheiro Foundation (2015), based on data from the Pesquisa Nacional por Amostragem de Domicílios (National Household Sample Survey) (PNAD), this number rose to 6,355,743 units.

Building requires a labor force, which, when receiving earnings proportional to the services rendered, would then be able to acquire goods such as their own homes. This housing, if properly designed and implemented, would provide better living conditions for its occupants and society in general [6]. Such housing has variable construction costs depending on the proposed project, location of implementation, and materials used, which are usually conventional materials characterized as impactful and unsustainable [7]. One of the most commonly used materials in civil construction is concrete [8], which is usually

produced by mixing Portland cement (binder), aggregates (sand and gravel), water, and additives. According to the granulometry, aggregates can be identified as fine (sand) and coarse (gravel) [9]. Both are mostly classified as natural materials, that is, taken directly from nature. Limestone, granite, and quartz are mentioned among aggregates with mineralogical classifications [10].

To use such materials, it is necessary to intervene in the environments that contain them, and after the removal of the mineral mass from a certain area, this becomes characterized as a degraded area. Mining damage could be mitigated through the adoption of impact reduction measures [11], including the application of recovery plans for degraded areas. Another possible action aiming to reduce such impacts would be the search for minerals, classified as mining waste (tailings or sterile) that could be used as aggregates [12]. Thus, materials that are initially classified as waste, with characteristics harmful to the environment due to disposal and storage, would be treated as a material that can be used in relevant activities, leading to a sustainable measure.

These waste materials generally have a low commercial value [13], as they are not the main object of the mining project. Moreover, such materials are an inconvenience to the main activity, as large areas must be made available for temporary or permanent storage. Waste products need to be controlled to maintain the environment and prevent contact with workers, thereby preventing accidents and the spread of diseases [14]. Specifically, exposure to small particles can cause environmental problems and/or harm human health [15].

Thus, building housing at the lowest possible cost using mineral waste materials is a sustainable activity [16]. To achieve this objective, a preliminary study of the technical, economic, and environmental feasibility of the waste to be used is necessary [17]. The use of a product classified as waste will promote environmental benefits and better living conditions for its users, highlighting the possibility of reducing construction costs.

Brazil is one of the largest producers and exporters of minerals in the world [18]. Among other minerals, quartz stands out, with Brazil holding 95% of world reserves [19], with the largest explorations in the states of Pará and Minas Gerais, where, in Serra do Espinhaço Meridional (SdEM) there are many outcrops of this mineral [20]. Studies on the reuse of waste generated by quartz mining companies can serve as an example to reduce the negative impacts generated by its exploration.

On average, industries connected to mineral extraction and processing represented 2.33% of the value of Brazilian GDP between the years 2000 and 2017 [21]. One of the guidelines that should be strengthened in the Brazilian mining sector is the reuse of mining waste [22]. For example, in Gouveia-MG, there is a quartz mining venture with an annual production of approximately 420,000 tons/year, where the quantity of waste material that is commercialized is practically nil. To improve sustainability in this industry, it is important to promote the use of generated waste.

The general aim of this study is to relate the use of quartz mining residues in the SdEM to the promotion of occupational health and housing health. The contribution to occupational health relates to the mineral exploration environment. Housing health is implemented by proving the technical and economic feasibility of using mining waste as civil construction materials.

Based on the specific study of a mining venture located in the SdEM, this article demonstrates the benefits existing in the potential reuse of quartz mining waste. The study was divided into three (3) phases (1) profile of the mining venture and the mining waste generated; (2) analysis of the economic feasibility of the reuse of the waste; and (3) analysis of the technical feasibility.

2. Materials and Methods

The study was carried out in 3 phases (Figure 1). Initially, the characteristics and location of the SdEM were described, and the mining venture was characterized, with an emphasis on the potential negative impacts on occupational health due to the piling of waste. Subsequently, an assessment of the economic feasibility of using the waste as

an input in concrete production was carried out. This reuse can mitigate the project's negative impacts, reducing the waste disposal area and enabling the improvement of housing health by reducing construction costs. Finally, the technical feasibility of using the residue for concrete production was evaluated. The following equipment was used: (a) 12.1 MP cyber-shot digital camera, manufacturer-Sony; (b) digital hydraulic press for 100 T, manufacturer-SOLOCAP; (c) GPS 60CSX, manufacturer-GARMIN; (d) energy dispersive X-ray fluorescence spectrometer, model-EDX-720/800HS, manufacturer-Shimadzu.

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

2.1. Phase 1-Characterization of Quartz Mining in SdEM

A search was carried out on the State Secretariat for the Environment and Sustainable Development website. The technical report for the environmental feasibility analysis of the project was evaluated. The project was located in the municipality of Gouveia (State of Minas Gerais (MG)), under the responsibility of the Superintendência Regional de Meio Ambiente Jequitinhonha (Jequitinhonha Regional Environment Board) [23]. In addition, a search for similar studies in the literature was conducted using the following keywords: “healthy and sustainable housing”; “occupational health in mining”; “concrete and quartz”; and “concrete and phyllite.” This survey of preliminary information provided a basis for discussions on the negative impacts of the mining project and the positive impacts of the proposed material reuse.

To better characterize the mining venture, a survey of field data was carried out regarding mineral exploration and processing, in addition to the characteristics of the surrounding area, enabling conformity verification of the collected information. All visits to the mineral exploration, which included a walk around the area of direct intervention to characterize both the internal area and the surroundings, were recorded using a notebook and digital camera for the collection of georeferenced images of the environment and the collected materials.

Initially, the data generated in the field were imported to the TrackMaker® application to proceed with the treatment of pathways to generate information on the perimeter and area and later transferred to Google Earth®, where satellite imagery information was obtained on various dates, enabling comparison of the environmental characteristics on the dates made available by the program. The notes from the field surveys referred to exploration, processing, the destination of the main mineral product and tailings, as well as the value of the latter transferred to third parties and nearby cities for trade purposes.

In addition to the verification in documentary records, a walk was carried out around the area of direct intervention of the project to characterize both the internal part and the surroundings.

2.2. Phase 2-Assessment of the Economic Feasibility of Using the Waste as an Aggregate for Concrete Production

To confirm the lower cost of concrete production through the use of waste, the sales values of the material classified as waste were compared with the aggregate values of limestone gravel. The same company under study has a quartz mine in the municipality of Gouveia and a limestone mine in the municipality of Curvelo, both in Minas Gerais, southeast Brazil.

The following costs were analyzed: diesel fuel type, mineral transport truck model, fuel consumption per kilometer, and type of concrete dosage used in single-family homes. As the concrete production would take place in the city of Diamantina, this was the location used to define the distances for transporting materials. The origins of the materials were as follows: (a) waste: location of the mining venture (municipality of Gouveia) (b) limestone: the cities of Curvelo, Sete Lagoas, and Montes Claros. The distances covered were obtained using Google Earth[®] software (Versão 9.152.0.1). The value of the material at the point of mineral exploration and the value of the fuel used in transportation were used. With the data obtained, it was possible to calculate the following values:

- (a) Cost of transportation and material used as coarse aggregate for the production of concrete in the city of Diamantina-MG. The four (4) alternatives evaluated were: waste from the project located in Gouveia and the use of limestone purchased at three (3) different locations: Curvelo, Sete Lagoas, and Montes Claros.
- (b) Calculation in percentage cost reduction that 1 m³ of concrete from the use of waste would have. For this calculation, concrete with a compressive strength of 20 MPa was considered.

2.3. Phase 3-Evaluation of the Technical Feasibility of Using the Waste as an Aggregate for Concrete Production

The following steps were carried out: (a) characterization of the materials involved (fine and coarse aggregates, cement, water, and silica fume additive); (b) definition of the composition of mixtures, from dosage by the ABCP Method, for the production of 2 types of concrete; (c) production of waste and crushed concrete; (d) production of twelve (12) specimens from the 2 types of concrete produced; (e) curing by submerging the specimens in water; (f) execution of the axial rupture test using a hydraulic press to characterize the resistance to simple axial compression stress; (g) compilation and analysis of results, enabling comparison; and (e) Visual inspection of the specimen breakage.

The compositions of the produced concrete had the following denominations: BQSA—concrete with quartz gravel with a percentage of 5% silica fume in relation to the Portland cement mass; and BC—concrete with limestone gravel as a coarse aggregate. The specifications of the materials used were:

- (a) Portland cement CP IV 32 RS, with low hydration heat, from the manufacturer CAUÊ.
- (b) According to the specifications of NBR 7211 [24], the fine aggregates were sand of natural origin or resulting from the crushing of stable rocks, or a mixture of both, whose grains pass through a 4.8 mm mesh sieve and are retained in a 0.075 mm mesh sieve.
- (c) The coarse aggregates were gravel of limestone origin from a mining venture in the municipality of Curvelo, and quartz mining residue, from a mining venture located in the municipality of Gouveia. The first material was acquired from the construction materials retailer and the second directly from the mining area, where it was collected from the tailings piles.
- (d) Silica fume from the steel industry in the city of Pirapora was also included. This residue comes from the production of metallic iron and silicon alloys and is sold at

low cost to concrete manufacturers in the region (around R\$5.00 per ton). This silica originated from the quartz extracted to supply the steel industries, which at its source produces mineral residues that are being proposed as aggregates for incorporation in concrete. Thus, the proposal includes the use of residues from the origin of the mineral material and residue from the silicon metal alloy industry, enhancing the sustainability factor.

- (e) The mass mix for concrete cast with limestone, with the objective of meeting the f_{ck} of 20 MPa, was 1:1.71:2.61:0.54, referring, respectively, to the proportion of cement for sand, gravel, and water. The mass mix defined for the concretes to be produced from the residue was presented as 1:1.81:2.40:0.54, also with the objective of meeting the f_{ck} at 20 MPa. The traces were calculated thus that the amount of cement per m^3 of concrete was the same for both types of concrete (Table 1). According to the class specification as per NBR 8953 [25], the concrete used in this study is of C20 type (20 MPa) from Group 1.

Table 1. Concrete mix design.

	Quantity per Cubic Meter of Concrete-BC	Quantity per Cubic Meter of Concrete-BQSA
Cement	409.13 kg	409.13 kg
Sand	699.61 kg	740.52 kg
Water	220.93 kg	220.93 kg
Limestone from Curvelo	1067.82 kg	-
Quartz from Gouveia	-	981.90 kg
Active Silica	-	20.46 kg

The tests were conducted at the following laboratories: that of the Programa de Mestrado Profissional em Saúde Sociedade e Ambiente (Professional Master's Program in Health, Society and Environment) at UFVJM, JK Campus (physical analysis, concrete production, and specimens); that of the Integrado de Pesquisa Multiusuário dos Vales do Jequitinhonha e Mucuri (Jequitinhonha and Mucuri Valleys Multiuser Research Institute) at UFVJM-LIPEMVALE (chemical composition analysis of aggregates); that of the Curso de Edificações e Engenharia Civil (Buildings and Civil Engineering Course) at IFNMG, Pirapora Campus (physical analysis of aggregates); and that of the Concreteira Pirapora private company, in the city of Pirapora (simple axial compression rupture test—press). A press with a load capacity of 100 t (tons) was adopted. This hydraulic press was equipped with an electronic device that displays information on the maximum load (breaking load) applied, with an accuracy of 100th of a ton.

3. Results and Discussion

3.1. Quartz Mining Characterization

3.1.1. General Characteristics of SdEM

According to Pougy et al. [26], the SdEM is part of the subdivision of the Espinhaço Range that is geographically positioned between the Quadrilátero Ferrífero (Iron Quadrangle) and the south of the state of Bahia, extending for approximately 1000 km (Figure 2). Given its environmental characteristics and its importance, the SdEM was recognized by UNESCO in 2005 as a “Terrestrial Biosphere Reserve” [27]. It corresponds to the divisor of the hydrographic basins of the São Francisco, Jequitinhonha, and Doce Rivers (Figure 2). The altitudes of this mountain range are between 1000 and 2000 m above sea level.

Figure 2. Delimitation of the Serra do Espinhaço Meridional and its federal hydrographic basins. Plano de Ação Nacional para a conservação da flora ameaçada de extinção da Serra do Espinhaço Meridional (National Action Plan for the Conservation of the Endangered Flora of the Serra do Espinhaço Meridional)–2015, p. 22 [28].

The relief of the SdEM is mountainous and steep [27], with outcrops of metarenitic rocks of the Espinhaço Supergroup being frequent, interspersed with phyllites and basic rocks. Lithologic Neosols and Quartzarenic Neosols predominate among the soils. The predominant biome is the Cerrado, with a predominance of rural phytophysognomies (Campo Rupestre (rupestrian grasslands), Campo Limpo (grasslands), and Campo Cerrado (Cerrado fields)), with endemism of species from the Orchidaceae, Bromeliaceae, Xyridaceae, and Velloziaceae families and fauna. According to Koppen’s classification, the climate is identified as Cwb (mesothermal), with an average temperature of 18.7 °C, with cold, dry winters, and mild, humid summers with an average annual rainfall of 1300 mm [27].

3.1.2. General Characteristics of Quartz Mineral and Phyllitic Rock

According to the Ministério de Minas e Energia (Ministry of Mines and Energy) [28], quartz crystals can be obtained naturally, directly from deposits, or industrially, through hydrothermal growth. Natural quartz exploration takes place rudimentarily in open pit or underground mines, with little technology. In a global analysis, the main producers are Brazil, Switzerland, Japan, and South Africa, with emphasis on Brazil.

Composed of silicon dioxide (SiO_2), quartz is mainly used by the optical, electronic, instrumentation, abrasive, ceramic, and metallurgical industries, depending on its quality [29]. SiO_2 appears naturally in polymorphous forms of quartz, tridymite, and cristobalite with a melting point at a temperature of 1713 °C. The main crystalline varieties of quartz are hyaline quartz or rock crystal, and milky, smoky, purple (amethyst), black (morion), or green (prásio) quartz [28].

According to the Departamento Nacional de Produção Minerária (National Department for Mineral Production) (DNPM) [30], among the various regions of Brazil, the quartz mineral (Figure 3) can be found in between phyllite-type enclosing rocks (phyllite), which can be found in SdEM regions, near the sources of the Pardo Pequeno and Paraúna rivers.

Figure 3. Quartz mineral commercialized by a company located in the municipality of Gouveia—MG. Photograph taken on 9 February 2018. Quartz gravel with dimensions close to 5 cm (five centimeters) and milky in color.

According to Chaves and Dussim [20,31] and Knauer and Schrank [32], phyllite is a rock of low added value, with different colors from white to pink, and mainly composed of aluminum (Al) and silicon (Si), which is easily pulverized, providing a very fine powder. It is adopted in ceramics, cement, paint, and animal feed industries as a feed composition. Phyllite is composed of small-sized phyllosilicates (muscovite, sericite, kaolinite) and quartz.

3.1.3. Quartz Mineral Exploration Activity-Characterization Regarding the Environment, Services, and Products

The studied area is located in the following central coordinates (DATUM WGS84): 18°33'25" S and 43°54'52" W, with an average altitude of 1260 m (Figure 4).

Figure 4. Partial view of the quartz mining area. Photograph taken on 9 February 2018. In the foreground, there is typical native vegetation of the Cerrado in the vicinity of the project; in the middle, on the right, the mineral processing area; and in the background, the topographical characteristics of the surroundings inserted in the SdEM.

Mining takes place in the open and consists of exploration and processing activities. There are also services that support the main activity, such as internal access, mineral transport, workshop, office, and structures to meet the demands of employees. The project is located at the midpoint of the route between the cities of Curvelo and Diamantina, being exactly 64 km away from the latter.

The main destination for this mineral is the ferrosilicon, ferro-manganese-silicon, and aluminum-silicon metal alloy industries located in the municipalities of Pirapora and Várzea da Palma (MG). The products destined for these metallurgical industries are crushed quartz rock material with dimensions ranging from 1.5 inches to 3 inches.

According to descriptions in the Sole Opinion of the Superintendência Regional de Meio Ambiente e Desenvolvimento Sustentável (Regional Superintendency for the Environment and Sustainable Development) [23], the project has an annual mineral extraction forecast of 420,000 tons. Only 21.43% of the extracted mineral is actually converted into a final product to be commercialized to metallurgical companies, and the remainder is characterized as sterile (50%) and tailings (28.57%) (Figure 5). These values are an average analysis of the available mineral material, which may vary according to the exploration position in the pit, considering the inhomogeneity of the material.

Figure 5. Flowchart of the destinations of materials from quartz mineral exploration.

The mining venture covers an area of approximately 328,000 m² (32.8 ha), with a perimeter of 3,760 m (Figure 6). It is subdivided into areas of extraction, waste deposits, and mineral processing tailings, the latter two occupying approximately 44% of the area.

The project's mineral exploration process began with open-pit extraction, in the form of benches, through mechanical excavation by excavators/loaders and transport of the material by dump trucks to the processing plant. At certain points in the exploration area, it is necessary to detonate explosives to blast the rock. Considering the positioning of the rock object of exploration within the mineral mass, it is necessary to strip the mineral deposit. This initial process produces the material classified as sterile.

Figure 6. Satellite image from June 2021 covering the development area. Map elaborated in QGIS software (Version 3.22.2) with background from satellite images (June 2021) provided by Google Earth® plugin. Adapted image including points of interest and delimitation of the project's current intervention area, calculated at approximately 32.8 ha.

The quartz deposits are embedded in phyllitic rock and require processing at a plant, where they undergo primary particle size classification to separate the fine material (phyllite and small quartz residues) from the larger rocks. The larger material is directed to a primary jaw-type crusher equipped with a classifying sieve that initially separates all material below 0.0381 m, which is classified as tailings. This material is directed to the tailings piles located near the processing plant.

According to project records, a very small portion of this waste is sold at R\$25.00/m³ (25 reais per cubic meter) or R\$15.92/t (15 reais and 92 cents per ton). This material is generally used as an area covering or for compounding pavement layers. Limestone gravel is sold for R\$48.16/m³ or R\$28.00/t.

Material larger than 0.0381 m and smaller than 0.0762 m is directed to the second classification sieve, which is equipped with a hydraulic pressure system that cleans the material, removing as much fine material as possible (Figure 7), this then being added to the tailings pile. The material of interest is then directed to the conveyor belts for collection by employees, who manually remove phyllite and quartz fragments that show a darker color. The final material also undergoes a second visual classification in terms of size, leading to the bundling of certain grains.

Figure 7. Partial view of the quartz processing plant under study. Photograph taken on 9 February 2018. From left to right, crusher, silos, conveyor belts, wet vibrating sieve in the background, and settling basin for reuse of water in the foreground.

3.1.4. Impacts Arising from the Mining Venture on the Physical, Biotic, and Anthropic Environments, Considering the Occupational Health of Mine Workers

The positive and negative impacts are, respectively, enhanced and mitigated or offset by a proposal presented by the company or requested by the competent environmental agency [23]. It is mitigation proposals that determine the carrying out of studies to develop the use of materials classified as mining waste that stands out. Impacts on local vegetation and those related to the anthropic environment are emphasized, especially those related to the impact of air transport of parts of fine particulate material from the tailings piles in the vicinity of the processing plant and those related to changes in the landscape (Figures 8 and 9).

Figure 8. Tailings pile characteristic of the surroundings of the mining area under study. Photograph taken on 9 February 2018. Typical ground vegetation native to the Cerrado environment in the foreground and tailings pile in the background with larger grain size processed material on the lower part of the slope. There is surface furrowing along the pile with material movement by rainwater.

Figure 9. Quartz processing tailings pile from the study area. Photograph taken on 9 February 2018. Tailings pile composed of quartz and phyllite with larger quartz dimensions at the bottom of the slope and smaller ones at the top. Occurrence of slope surface furrowing due to material movement by rainwater. Arrangement of a Garmim GPS 60 CSX satellite signal manual navigation device to compare dimensions, highlighting grains with dimensions close to 3 cm in diameter.

If phyllite powder (material with smaller granulometry) does not undergo constant humidification of its surface or is not covered by mesh to prevent its transport by wind, it tends to be suspended in the atmosphere and can be absorbed, through breathing, by mine employees.

Annex II of Federal Decree 3048, which regulates Social Security [33], classifies Free Silica (SiO_2) as pathogenic, as it is related to the following occupational diseases: Malignant neoplasm of the bronchi and lung; Cor Pulmonale (Pulmonary Heart Disease); Obstructive Asthma; Chronic bronchitis; Chronic Obstructive Bronchitis; Silicosis; Pneumoconiosis associated with Tuberculosis; Tuberculosis; and Caplan's Syndrome.

Silicosis is the most recurrent pathogeny and is classified as an incurable disease caused by the accumulation of dust containing silica in the lungs. This accumulation of silica causes the lungs to harden, making it difficult to breathe, and can lead to death. The manifestation of this pathology will depend on the amount of material breathed in with the presence of silica, as well as the length of exposure time [34]. For instance, there is a report of this type of disease occurring in the province of Cádiz (Spain), where cutting activity in natural and artificial ornamental rocks takes place with a lack of investment in health prevention [34].

The Fundacentro manual [35] also presents appropriate ways to prevent the disease, such as: change of raw material; process or operation change; humidification; ventilation; enclosure; isolation; cleaning; general maintenance; signage and labeling; environmental monitoring; breath protection; personal cleanliness; medical exams; limitation of exposure; and training time.

When visiting the mining activities under study, it was observed that some of the items specified above had been adopted, such as the humidification of the material during processing, humidification of internal accesses, and the use of personal protection equipment, such as partial face masks. The impossibility of adopting measures such as enclosure, isolation, and change of raw material was also observed, considering that it is an economic activity conducted outdoors. Moreover, the main objective of the operation is the extraction of material with the mineral principle of silica (SiO_2), which should be present in the material in a greater proportion. There is, however, the possibility for greater investment in the change of process or operation with the aim of reducing the material exposed to the intervention of natural winds.

Considering that the manifestation of silicosis is related to the concentration of silica and the length of exposure time, it is understood that any intervention that promotes their reduction would improve the quality of worker health. Thus, it is understood that if an adequate final destination were given to part of the materials with the presence of silica classified as removable waste, it would meet the objective of preventing problems related to occupational health.

3.2. Evaluation of the Economic Feasibility of Using the Waste as an Aggregate for the Production of Concrete

3.2.1. Literature's Review of Uses of Quartz Mining's Waste as Aggregate for Concrete Production

It is feasible to use these residues for the production of civil construction materials such as concrete and mortar [36]. Phyllite can also be used as a fertilizer, as animal feed, in the ceramics industry, and in cement production due to the presence of aluminum oxide (Al_2O_3) [37]. Quartz has a favorable history for its use in concrete. This material deposited along rivers (quartz pebbles mixed with washed sand) has been used in concrete for the production of works of art (bridges—road-rail crossings) and their supporting structures (foundations, pillars, and beams) [38]. There is also the possibility of transforming quartz through size reduction for use as a fine aggregate (sand) or as an additive for the production of high-performance concrete (CAD) [39–41]. Once the material has been characterized for use as an input in concrete and mortar, through the performance of laboratory tests, it may then be classified as an aggregate or additive.

Aggregates are construction materials that occupy significant volumes in buildings and other infrastructure works and that can be presented as low cost, especially those classified as large [38]. Concretes with Portland cement added to their composition rely on water, additives (sporadically in the conventional and usual way), fine aggregate (sand), and coarse aggregate. Coarse aggregates generally occupy 31% of the volume or 50% of the mass of all concrete. The structural elements (foundations, grade beams, columns, beams, and slabs) of a conventional building are generally made of concrete (typical Portland cement binder). Therefore, a significant volume of construction materials requires coarse aggregates, which may be of different mineral compositions, including limestone, dolomite, granite, and quartz [38].

For example, in the 41.87 m² popular housing project evaluated by Ferreira [5], the consumption of hydraulic concrete was 6.16 m³. Adopting a specific mass of 2.4 t/m³ for concrete, we would have the corresponding mass of 14.77 t (tons). Considering that gravel occupies around 50% of the concrete volume, on average, we would have approximately 7.46 t of gravel in this total mass. This would be the consumption of gravel in social housing projects. In addition to the use of this aggregate for this type of project, it can be applied to any type of work in which concrete needs to be produced.

The final destination of the material initially classified as waste and now as an aggregate for concrete and mortar will enhance mitigation measures reducing the negative impacts generated in the mining project. The residue will be removed from the disposal environment to compose a mass that will provide its agglutination, thus preventing the possibility of affecting human respiratory tracts. At the same time, wind transport of the material will be avoided, reducing its impact on rural environments. Thus, it is a proposition with sustainable characteristics.

Regarding the environment, the proposed use of waste from quartz exploitation tends to positively contradict current, linearly organized production and market methodologies contrasting the natural characteristics of our habitat, which is part of a finite environment [7]. This proposition also opposes the proposal that conventional materials are generally those from industries that put products requiring a chain of consumption on the market, seeking the lowest possible cost. The introduction of quartz tailings into concrete pieces minimizes degradation arising from the mineral exploration of conventional aggregates.

Analyzing the geological map available on the DNPM website [30], which includes the SdEM, especially the map partially delimited by the municipality of Diamantina and its surrounding region, it appears that it does not have an appropriate area for the exploitation of large aggregates of limestone origin (usually adopted in civil works). The closest exploration areas for this type of limestone aggregate are located in the municipalities of Curvelo (128 km), Sete Lagoas (226 km), and Montes Claros (226 km), which have an average transport distance greater than that identified between the city of Diamantina and the mineral exploration area under study, which is 64 km. It is verified, therefore, that the transport distance of the material under study is shorter from its place of origin to the municipalities of Datas, Diamantina, and Gouveia, when compared to the distance from the municipalities where limestone is purchased (Curvelo, Sete Lagoas, and Montes Claros). Given that concrete production would take place in Diamantina, this means there is a greater cost involved in the transport of limestone material in relation to the residue.

It should be clarified that transport is part of the cost of any material, and as such, operators and drivers, transport equipment and vehicles, vehicle maintenance, and fuel are required. By adopting the transport of materials, there is the possibility of cumulative and even synergistic impacts. For example, there are socioeconomic impacts arising from the occurrence of accidents with cargo vehicles on highways due to increased traffic to meet the demand for materials. It is understood that reduced transport distance tends to reduce the possibility of accidents [42,43].

3.2.2. Cost Evaluation of Concrete Produced with Quartz Waste as Coarse Aggregate

The concrete was produced in the city of Diamantina. Diamantina is the capital of the upper Jequitinhonha region in the state of Minas Gerais (Brazil). The existing limestone mines are more than 128 km away from the city. Considering that the mine under study is only 64 km from Diamantina, the use of mining waste for concrete production in this urban center could be advantageous both environmentally and economically. Figure 10 shows the location of the city and the limestone and quartz mines. The limestone sources of large aggregates were in the cities of Curvelo, Sete Lagoas, and Montes Claros, while the quartz was sourced in the rural area of Gouveia. The truck transporting the material from the source to the place of use was a Mercedes-Benz Axor 2036, with a cost of 3.46 R\$/km (reais per kilometer) [44]. It was considered that the truck would start from the city of Diamantina, would transport a volume of 18.6 m³ of aggregate, and that driver expenses and vehicle depreciation were taken into account. Table 2 shows the comparison between the costs of waste aggregates and limestone aggregates.

Figure 10. Location and main paved road access to the cities mentioned in the study. Map generated from QGIS software (Version 3.22.2).

Table 2. Coarse aggregate cost comparison for concrete—Parameters referring to the prices of material and fuel for transport. Table prepared by the author with data from sources according to citations.

Consumption Center	Aggregate Origin	Transport Distance (km)	Aggregate Cost (R\$/18.6 m ³)	Shipping Cost (R\$)	Total Cost (R\$)	Cost per Aggregate m ³ (R\$/m ³)
Diamantina	Gouveia rural	128	465.00	442.63	907.63	48.80
Diamantina	Curvelo	256	896.00	885.26	1781.26	95.77
Diamantina	Sete Lagoas	452	896.00	1563.03	2459.03	132.21
Diamantina	Montes Claros	452	896.00	1563.03	2459.03	132.21

It is observed that, given the possibility of adopting quartz waste as coarse aggregate, its cost per cubic meter, considering only material and fuel values, is much lower than other sources supplying limestone. The cost reduction provided by the waste would be at least 49.05%. This would mean a reduction in the final cost of building social housing and/or any other construction that uses concrete.

For price composition, the following hypotheses were considered: the cost of cement and sand extracted from the price reference system for construction inputs, provided by Caixa Econômica Federal in the state of Minas Gerais for the month of September 2021; the cost of water provided by the Minas Gerais sanitation company, a water supplier in the municipality of Diamantina-MG, for monthly consumption of 10 to 20 m³; apparent density of sand of 1500 kg/m³ and of gravel of 1700 kg/m³; and for the cost of gravel, the values in Table 2 were used. The price of 1 m³ of concrete was compared in the case of using gravel from the city of Curvelo versus the use of the waste being evaluated in this study. The price comparison is detailed, respectively, in Tables 3 and 4. It can be observed that the potential use of waste as a coarse aggregate would reduce the cost of inputs of 1 m³ of concrete from 345.12 reais to 319.01. This is a reduction of 8.52%.

Table 3. Cost of inputs of 1 m³ of concrete using coarse aggregate from Curvelo.

	Quantity per Cubic Meter of Concrete	Unit Price	Input Cost
Cement	409.13 kg	0.62 reais/kg	253.66
Sand	0.466 m ³	74.17 reais/m ³	34.56
Water	0.221 m ³	4.43 reais/m ³	0.98
Limestone from Curvelo	0.628 m ³	95.77 reais/m ³	60.14
		Total cost	349.35 reais

Table 4. Cost of inputs of 1 m³ of concrete using the residue of the mining company under study as coarse aggregate.

	Quantity per Cubic Meter of Concrete	Unit Price	Input Cost
Cement	409.13 kg	0.62 reais/kg	253.66
Sand	0.494 m ³	74.17 reais/m ³	36.64
Water	0.221 m ³	4.43 reais/m ³	0.98
Quartz from Gouveia	0.578 m ³	48.80 reais/m ³	28.21
Active Silica	20.46 kg	0.005 reais/kg	0.1
		Total cost	319.59 reais

3.3. Evaluation of the Technical Feasibility of Using the Waste as a Coarse Aggregate for Concrete Production

To evaluate the technical feasibility of using the waste as coarse aggregate for concrete production, twelve (12) specimens were made, half with the waste as coarse aggregate and half with limestone. The predicted strength of concrete was 20 MPa. Table 5 presents the unit mass, specific mass, and water absorption of the coarse aggregates tested. It can be verified that the specific masses of the larger materials were similar. The difference between the water absorption of the quartz and limestone gravel can also be observed in Table 5, the limestone being much higher.

Table 5. Physical characterization of tested concrete components.

Tested Materials	Unit Mass (t/m ³)	Specific Mass (t/m ³)	Water Absorption (%)
Limestone gravel	1718	2778	4
Quartz gravel	1574	2652	0.37

The X-Ray fluorescence results (Table 6) demonstrate that the elements Si, S, and Al stand out in the quartz samples, with other elements being detected with a percentage below 0.49%. Si contents were above 89% in the three samples. The elements Si, Al, K, and Fe stand out in the phyllite. Considering that it is a non-destructive analysis and that for quartz, the sample inserted in the equipment was presented in gravel dimension, close to 19 mm, the X-rays beam position may have identified a point in one of the samples that presented the highest sulfur concentration. However, the quartz percentage remained very close to 90%. The phyllite was analyzed in powder which enabled greater sample homogenization.

Table 6. Quali quantitative composition of quartz and phyllite tailings elements.

Element Symbol	Sample-Value in %			
	Quartz 01	Quartz 02	Quartz 03	Phyllo Powder
Al	Nd	2.93	3.64	33.23
As	Nd	nd	0.09	nd
Ba	Nd	nd	nd	0.42
S	10.48	nd	nd	nd
Sr	Nd	nd	0.02	0.009
Fe	0.03	0.05	0.05	6.52
Ir	Nd	nd	0.03	nd
Y	Nd	nd	nd	0.01
Mn	Nd	nd	nd	0.03
Nb	Nd	nd	0.01	nd
Pt	0.09	nd	nd	nd
K	0.07	0.10	0.49	13.10
Ag	0.05	0.03	nd	nd
Rb	Nd	nd	nd	0.023
Si	89.24	96.88	95.70	45.72
Ti	Nd	nd	nd	0.86
Th	0.014	nd	nd	nd
Tm	0.036	nd	nd	nd
W	Nd	nd	0.032	nd
Zr	Nd	nd	nd	0.07
Overall sum:	100	100	100	100
Sum below 1%	0.28	0.18	0.7	1.42

“nd”—not detected.

It was found that the crushed stone composed of quartz from the mining residue, presented as Grade B in the Los Angeles abrasion test, with a percentage of 45%, which was lower than that specified by NBR 7211 [24] for the characteristics of the materials to be adopted in concrete. This result is presented as positive because it represents the loss of the aggregates’ original size through efforts on them, whereby the smaller, the better. The said test was not performed for gravel of limestone origin; however, it was verified in the literature that it presents around 41.9% [45].

Adopting the ABCP dosage methodology and starting from the conception of concrete production, classified as class C20 structural, it was possible to define the mass traces for dry aggregates of 1:1.71:2.61:0.54 (cement: sand: gravel: water-limestone gravel) and 1:1.81:2.40:0.54 (cement: sand: gravel: water-quartz gravel) with the addition of silica fume cement at 5% by weight. The same cement consumption per m³ of concrete of 409.13 Kg was adopted to reduce interference from changing the traits.

Concrete classified as BC, with the presence of exclusively limestone gravel, was used as a reference for comparison with BQSA concrete made with quartz gravel waste. When the specimens were subjected to the compression-rupture test, as provided for both in Neville (1997) [38] and in NBR 6118 [46], all of the specimens presented strengths above 20 MPa. Low standard deviation values were observed for these results, indicating good conditions for carrying out laboratory tests, especially regarding the homogenization of the concrete and the molding of the specimens. The results described in Tables 7 and 8 are presented as means for each set of specimens molded from the same concrete. The compressive strength of concrete with quartz gravel and the addition of silica fume was very close to that of limestone, with only a 2.32 Mpa difference, on average. The two types of concrete comply with the technical specifications regarding compressive strength for C20 class concrete. Table 9 indicates that for breakages performed after 28 days of cure, BC concrete presented similar efficiencies to BQSA. The present study’s cement efficiency values for the concretes have similar magnitudes to Aiman et al.’s Work [47]: 0.097 and 0.114 fc28/Kg cement.

Table 7. Compressive strength of specimens at 7 days of cure.

Trace Composition	fc28 (MPa)					
	Minimum	Maximum	Mean	Average	Variance	Standard Deviation
BQSA	13,966	16,089	15,056	15,149	0.724	0.851
BC	18,205	21,395	20,102	20,301	1273	1128

Table 8. Compressive strength of specimens at 28 days of cure.

Trace Composition	fc28 (MPa)					
	Minimum	Maximum	Mean	Average	Variance	Standard Deviation
BQSA	25,736	28,420	26,795	26,690	1118	1058
BC	28,022	29,735	29,116	29,215	0.337	0.580

Table 9. Concrete characterization quotients on the 28th day of cure. Identification of average specific masses, cement consumption per m³ of concrete, average compressive strength, and efficiencies in relation to cp cement consumption on the 28th day of cure.

Parameters	BQSA	BC
Average specific mass	2322	2373
Kg cem/m ³ concrete	407.410	407.410
fc28 Mpa	26.794	29.116
Efficiency Kg cem/fc28	15.205	13.993
Efficiency fc28/Kg cem	0.066	0.072

Breakage of the specimens exposed, their insides (Figure 11) making it possible to verify that the specimens with the least breakage of coarse aggregates were those composed of limestone gravel. This raises the hypothesis that the residue used as coarse aggregate could be used for concrete with compressive strength specifications of up to 30 MPa. If it is necessary to use this type of waste for the production of concrete with strengths greater than 30 MPa, more research should be carried out. If it were necessary to perform a deeper analysis of aggregate adherence with respect to the cement paste, microscopic analyses of the concrete could have been performed. To carry out such an analysis, the slides of extracted concrete should have parallel directions to the direction of load application in the compressive strength test [48,49].

cp with quartz crushed—BQSA

cp with limestone—BC

Figure 11. Characteristics of specimens after the disruption.

4. Conclusions

A mining venture that generates residues that could be introduced to the production of concrete was identified. This residue can be used as a coarse aggregate in concrete and has a 47.2% lower cost compared to conventionally aggregates.

When material is classified as mineral waste from quartz exploration, if kept in the area of the mining project, it tends to generate negative impacts. Among these, the impact related to occupational health was emphasized since the residue contains silica (SiO_2), which can cause the pathology known as silicosis when in direct contact with the human respiratory tract.

Thus, it was found that the proposed adoption of such waste to produce aggregates for civil construction meets the demand for the construction of low-cost housing. Furthermore, it reduces negative impacts, including the minimization of dust dispersion in open environments. This minimization is due to the mass reduction of the risk component, thereby generating positive impacts through the appropriate final destination of the waste.

In addition to environmental and occupational health benefits, the use of quartz mining waste for the production of concrete reduces the cost per m^3 of concrete by 7.57%. Thus, there is the economic feasibility of using this aggregate for concrete production.

The concrete produced from coarse aggregates from the quartz mining tailings under study have characteristics similar to those of concrete produced with limestone gravel. It meets the simple axial compressive strength specifications of NBR 8953 [25] and NBR 6118 [46] for the strength class of concrete, defined for this study as C20 (minimum load capacity of 20 Mpa).

The main parameters of the concrete were described in the technical feasibility analysis. The compressive strength test of the produced concrete and the Los Angeles abrasion test performed on the waste is considered the main parameters to demonstrate whether the use of the waste is technically viable or not. However, it should be emphasized that in future studies, more specific complementary parameters could be evaluated, such as flexural and tensile strengths, microscopic analysis of the produced concrete, analysis of the alkali-silica reactions, and other aggregated analysis (Micro Deval, Flakiness index, surface cleanliness). Another important aspect is that if it were necessary to use concrete with compressive strength above 30 MPa, further research should be carried out.

The reuse of quartz ore waste is an example of how this type of waste could be reused in other mining projects similar to the one shown in the present study, which is very common in SdEM. The results fit into the exercise of interdisciplinary professional practices that transform procedures, being presented across disciplinary boundaries of occupational and housing health, the environment, the economy, and construction materials, with the development of tools for anticipating health problems. This research corroborates the objectives of the National Health Research Agenda [50], which includes the theme of quality of health at work in activities that promote environmental change. It is also part of health promotion through the development of materials that enable the production of housing at low cost.

Author Contributions: Principal investigator: F.A.d.C.; conceptualization: F.A.d.C., B.V.P.; methodology: F.A.d.C., R.P.C., B.V.P.; formal analysis, F.A.d.C., B.V.P.; resources, F.A.d.C., B.V.P.; data curation, J.D.F.; writing—original draft preparation, B.V.P., J.N.P.N.; writing—review and editing, R.P.C., A.C.S., J.D.F., A.B.d.R.; supervision, J.N.P.N., B.V.P. All authors have read and agreed to the published version of the manuscript.

Funding: The authors thank the Provost Office for Graduate Studies and, more specifically, the Graduate Program in Health, Society and Environment (SaSA) at the Federal University of the Jequitinhonha and Mucuri Valleys in Diamantina, Minas Gerais, Brazil. The Brazilian Coordination for the Improvement of Higher Education Personnel (CAPES) granted studentships to the graduate students co-authoring this scientific research. JDF is indebted to the Brazilian National Council for the Scientific and Technological Development (CNPq), for providing the research grant # 304958/2017-4.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

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

Abbreviations

CAPES	Coordenação de Aperfeiçoamento de Pessoal de Nível Superior-Brasil.
CNPq	Conselho Nacional de Desenvolvimento Científico e Tecnológico (Brazilian National Council for the Scientific and Technological Development).
DNPM	Departamento Nacional de Produção Mineral (National Department for Mineral Production).
MG	State of Minas Gerais.
PNAD	Pesquisa Nacional por Amostragem de Domicílios (National Household Sample Survey).
SdEM	Serra do Espinhaço Meridional.

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