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Challenges for the Destiny of Iron Mining Tailings in the Iron Quadrangle of Minas Gerais, Brazil

Desafios para a Destinação dos Rejeitos da Mineração de Ferro no Quadrilátero Ferrífero de Minas Gerais, Brasil

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Banded iron formations are exploited in the Iron Quadrangle of Minas Gerais, Brazil. To produce the iron ore concentrate these iron formations are processed by a physicochemical process. Huge amounts of tailings are generated and stored in dams. After two major collapses of dams in 2015 and 2019 with severe loss of lives and environmental impacts, the storage in new dams was prohibited. The storage of tailings in piles or exhausted open pits and their utilization as raw materials to produce several products are being considered. The huge amount of tailings and their characteristics, especially the fine granulometry, are the challenges that scientists and engineers must face to develop applications for them. Research and developments carried out to address the issue of these tailings in the region of the Iron Quadrangle are presented in this paper.

Keywords: Iron ore; tailings; storage; alkali activation; concrete.

1. Introduction

The Iron Quadrangle (“Quadrilátero Ferrífero” in Portuguese) is located between latitude 19-20°S and longitude 43-44°W in the Central Region of Minas Gerais State in Brazil. The iron ore deposits are Banded Iron Formations (BIF), locally known as “itabirite”. The iron ore bodies occur as discontinuous lenses of varied sizes and shapes within the itabirites. There are two main types of iron ores: high-grade ore (Fe > 64%), called hematite ore and intermediate-grade ore (52% < Fe < 64%), called itabiritic ore. The intermediate grade itabiritic ore is typically friable and generally grades to hard itabirite with low iron content. The itabirite can be silicious or dolomitic. The silicious itabiritic ore is currently exploited.¹

Figure 1 shows the typical morphology of a silicious itabiritic ore. The light bands are rich in quartz and the dark ones are rich in iron oxides. The run of mine is comminuted up to the point where the iron oxide particles are separated from the quartz ones. Before the flotation step, the fine particles ($\leq 70 \mu\text{m}$) are removed in a desliming step when the first kind of tailing is generated. Its a slime rich in iron oxides (40 to 50% iron oxide and 10 to 30% silica). In the flotation, chemical substances are added to the pulp to give hydrophilic characteristics (starch) to the iron oxide particles and hydrophobic characteristics (amines) to the quartz particles. Air is injected at the bottom of the pulp so that the quartz particles would attach to the air bubbles and collected at the top of the flotation cell (column), and the iron oxide particles are collected at the bottom. The collected material at the top is the sandy tailing, a kind of very fine

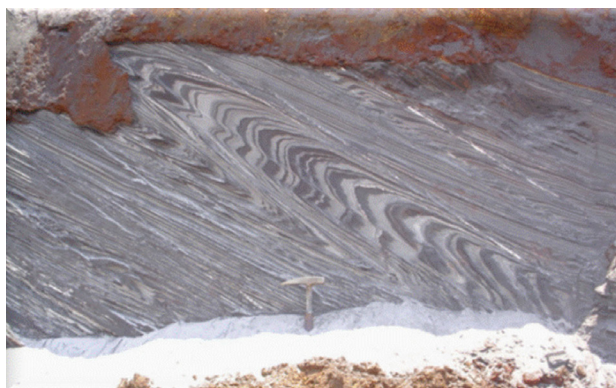


Figure 1. Typical silicious itabiritic ore (Courtesy of Samarco)

sand of quartz (5 to 10% iron oxide and 85 to 95% silica). Both the slime and the sandy tailings are considered inert and non-dangerous.^{2,3}

These tailings were stored in dams over many years. There were initiatives of using them as raw materials for the fabrication of paving blocks (the sandy tailing as a partial substitute for sand) and pigments (the slime as a substitute for iron oxide pigments). Dozens of other products have also been developed, but mostly only on a laboratory scale (adsorbents, catalysts, battery cathode, mesoporous silicates, magnetic iron oxide, synthesis of carbon nanotubes, and lithium silicate).^{3,4} The collapse of dams in Mariana in 2015 and Brumadinho in 2019 completely changed the scenario.⁵ The upstream construction of dams is not allowed anymore, and the mining companies are moving to store the tailings in piles or exhausted open pits. In addition to storage to replace dams, it is necessary to develop products that can use tailings in large enough quantities to reduce the need for storage.

It is essential to develop products that can use a significant amount of tailings, in such a way as to reduce the amount that must continue to be stored. In the following, some products that have the potential to achieve this goal are considered.

2. Experimental Solutions under Development

Several universities and research and developments centres of the Iron Quadrangle are studying alternative destinations for the iron ore tailings, *e.g.*, the Federal University of Minas Gerais, Federal University of Ouro Preto, Federal Center for Technological Education of Minas Gerais, Nuclear Technology Development Center, Federal University of Viçosa, Federal University of São João Del Rei, Pontifical Catholic University of Minas Gerais, and the CIT SENAI (Innovation and Technology Center of the National Industry Service of the Industry Federation

of Minas Gerais State). Also, the iron mining companies have their development projects in most cases with the involvement of these research and development institutions.

2.1 Uses of the Sandy Tailing

Due to their composition, the sandy tailing are rich in quartz, can be considered very fine sand and can be used as fine aggregate in cementitious products using Portland cement. But there is a technical limit to this solution shown in Figure 2. According to the Brazilian norm for fine aggregate, the granulometry of the sandy tailing is outside the usable zone limits.^{2,6} It should be blended with natural or artificial sand routinely used by the concrete industry to achieve the usable zone limits. The experience on an industrial scale reveals that it is possible to use 20-30% of sandy tailing in the composition of the fine aggregate.

2.1.1. Alkali Activated Materials

Alkali activated materials (AAM) do not show this technical limit, so it is possible to obtain mortars using only the sandy tailing as fine aggregate with properties that may be better when compared to Portland cement mortars.^{7,8,9} AAM are binders, called geopolymers when the content of calcium is negligible, that are produced through the reaction of an alkali source with aluminosilicates. The most commonly used alkali sources are alkaline (sodium or potassium) hydroxides and/or silicates, while aluminosilicates may include a wide range of raw materials and wastes. Although there are records of the use of alkaline-activated cement by ancient civilizations, they have regained attention since the second half of the 20th century.¹⁰ What motivates this new interest is the lower emission of carbon dioxide in its production chain when compared to Portland cement and the possibility of using industrial wastes under the Circular Economy.¹¹

From the point of view of using iron mining tailings from the Iron Quadrangle, there is an additional interest

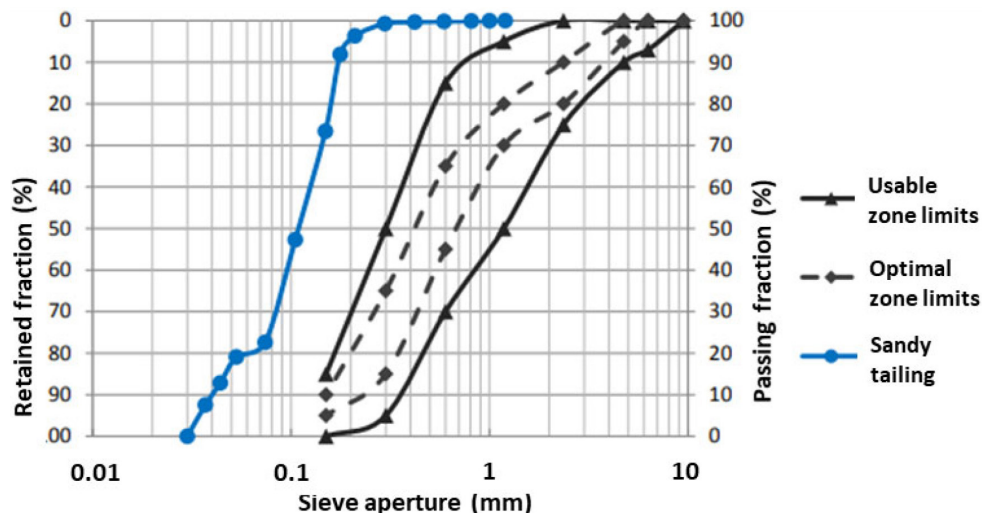


Figure 2. Size distribution of the particles of the sandy tailing. Adapted from Melo, V. A. R⁵

in these binders because mortars of good mechanical and chemical properties can be obtained using sandy tailings as fine aggregate. For example, compressive strengths above 40 MPa can easily be obtained in the first days of curing. Table 1 shows the raw materials that can be used to produce alkali-activated materials in the Iron Quadrangle.

Figure 3 shows the contribution of the raw materials to the cost of geopolymer concrete compared with Portland cement.¹² It is three times more expensive and sodium silicate is responsible for about 80% of the cost. It is important to produce sodium silicate at a lower cost, as well as all raw materials. Sodium silicate can be produced by adding sodium hydroxide to the sandy tailing and heating the mixture. A fine powder of sodium silicate is obtained, that can be used to produce geopolymer.¹³ It is a low-grade sodium silicate but it is useful for civil construction. A dry mixture of metakaolin, sodium silicate and sandy tailing is made. To get the geopolymer, water should be added and mixed to form a paste, just like the common procedure for Portland cement, which is molded and hardened in a few hours. This is the so-called one-part procedure to produce geopolymer.¹⁴ The adjustment of the Si/Al in the geopolymer could also be made by adding amorphous silica, a residue available in a region close to the Iron Quadrangle. If the calcined overburden rich in kaolinite is employed, a binder and a mortar can be made using only materials available in the iron mining facilities.

The alkali-activated binders may be employed where Portland cement is used, both in civil construction as a binder and for piling of tailings.¹⁵ But the feasibility of alkaline-activated materials, including geopolymers, still needs to be proven on an industrial scale, for example, their long-term durability must be ensured, especially the role of

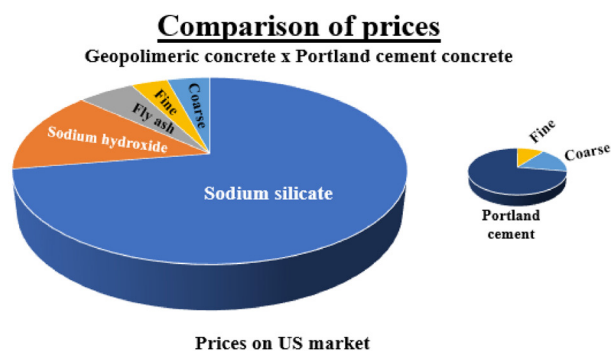


Figure 3. Comparison of prices between geopolymer concrete and Portland cement concrete. Adapted from Tempest *et al* (2015)¹²

efflorescence,¹⁶ and standards must be established, also the development of low-cost raw materials.

2.1.2. Silicon Products

The quartz of the BIF in the Iron Quadrangle is usually very pure if one looks at the crystal structure scale, with low aluminium contents and other elements.¹⁷ So, the sandy tailing may also be used as raw material to obtain other products, like high-grade amorphous silica, metallurgical grade silicon or Si-Fe alloy. The fine granulometry of the sandy tailing is a problem for its use as raw material in this process. But the pelletizing of the sandy tailing with coal or graphite may be considered to develop this process.

2.1.3. High Purity Silica and Silicon

Silicon and Fe/Si alloy are prepared by reduction of silicon dioxide with carbon and iron oxide in a submerged arc furnace at temperatures approaching 2200 °C.¹⁸ Instead of being introduced separately in the arc furnace, a pellet

Table 1. Raw material that can be considered to obtain alkali-activated materials and geopolymers in the region of the Iron Quadrangle

Raw material	Availability	Advantage/Disadvantage	Observation
Commercial kaolin	Commercial product	Technical purity/High price	Requires calcination
Kaolin	Tailing from sand extraction	Low price/Low purity	Requires calcination
Metakaolin	Commercial product	Technical purity/High price	Sometimes not adequate to obtain geopolymers with good properties
Blast furnace slags	Comercial product	Low price/Entire generation consumed by the Portland cement industry	Requires grinding
Serpentinite tailing	Little	Low price/Not commercial	Requires development
Recycled glass	Available	Low price/Generation consumed by the glass industry	Requires grinding
Overburden from iron ore extraction	Available	Low price/Low uniformity	Requires calcination and development
Residue from slate stone extraction	Available	Low price/Many uncertainties	Requires development
Amorphous silica from silicon production	Available	Low price/Low generation	Partial substitute for silicates
Sodium and potassium silicates	Available	Technical purity/High price	Requires careful handling
Sodium hydroxide	Available	Technical purity/Medium price	Large scale utilization by the iron ore minings requires careful handling
Potassium hydroxide	Available	Technical purity/High price	Substitute for sodium hydroxide and requires careful handling

of sandy tailing, carbon (coke or graphite) and iron oxide could be developed, so that both the sandy tailing and the iron oxide could be used, assuming that the development of such a pellet is feasible. This route is at TRL 1 and is waiting for development. Figure 4 shows an envisaged for the production of Si-Fe alloys with the sandy tailing, where the amorphous silica collected in the filter can be used for alkali activation. This process has the potential to manufacture high added value products from the sandy tailing using a significant amount of it.

2.2. Uses of the slime

Since the slime is rich in iron oxides and given the need to use large amounts to avoid storage, its reprocessing should be considered to produce iron ore concentrate. Besides iron oxides, mainly hematite and goethite, the slime has quartz and clays. Goethite usually contains phosphor and thus should be kept at low levels in iron ore concentrates. The reprocessing and uses of slime based on processes that require its drying should be taken into account with caution, because it is generated with moisture contents around 40% by weight and can retain much of this humidity for a long time, making drying difficult on an industrial scale.

Drying is a common industrial process in many industrial segments. It is probably the oldest, the most common and the most diverse operation of chemical engineering. There are more than four hundred types of dryers available on the market. Hot air is the most commonly used drying means. On the other hand, drying competes with distillation as the industrial operation that most consumes energy due to the high latent heat of water vaporization and inherent

inefficiency of using hot air. The following points should be considered for the drying process: 1) mechanical dewatering is generally ten times cheaper than evaporation, which in turn is ten times cheaper than drying; 2) It is always necessary to analyze the drying system as a whole, not just the dryer; 3) The pre-drying (mechanical dewatering, etc.) and post-drying (cooling and de-agglomeration) should be considered in the overall drying strategy to save energy.²⁰ Above mentioned three recommendations define some main strategies for designing a drying system for slime. The stages of dewatering, evaporation and drying itself should be considered. Dewatering can reduce the moisture content from 40% to approximately 20%, while evaporation can reduce this content to approximately 10%, with drying reducing the moisture content to the desired level.

2.2.1. Reprocessing

There is a patent application related to a process for extraction of iron oxide from the slime of the iron ore concentration process, containing quartz as the main impurity.²¹ Alkaline fluxes for quartz are added to the slime in the presence of humidity, followed by the stages of air calcination, quenching, and leaching in acid solution. As a result, an ultrafine iron oxide concentrate is obtained in the hematite phase with adequate characteristics for incorporation into the feed pellet generally used to produce iron ore pellets. A moisture of 10-20% of the slime is required in this process. Figure 5 shows the microstructure obtained by Scanning Electron Microscopy/Energy Dispersive Spectroscopy (SEM/EDS) of the material obtained after quenching. There are regions rich in iron or silicon. Once goethite is transformed into hematite

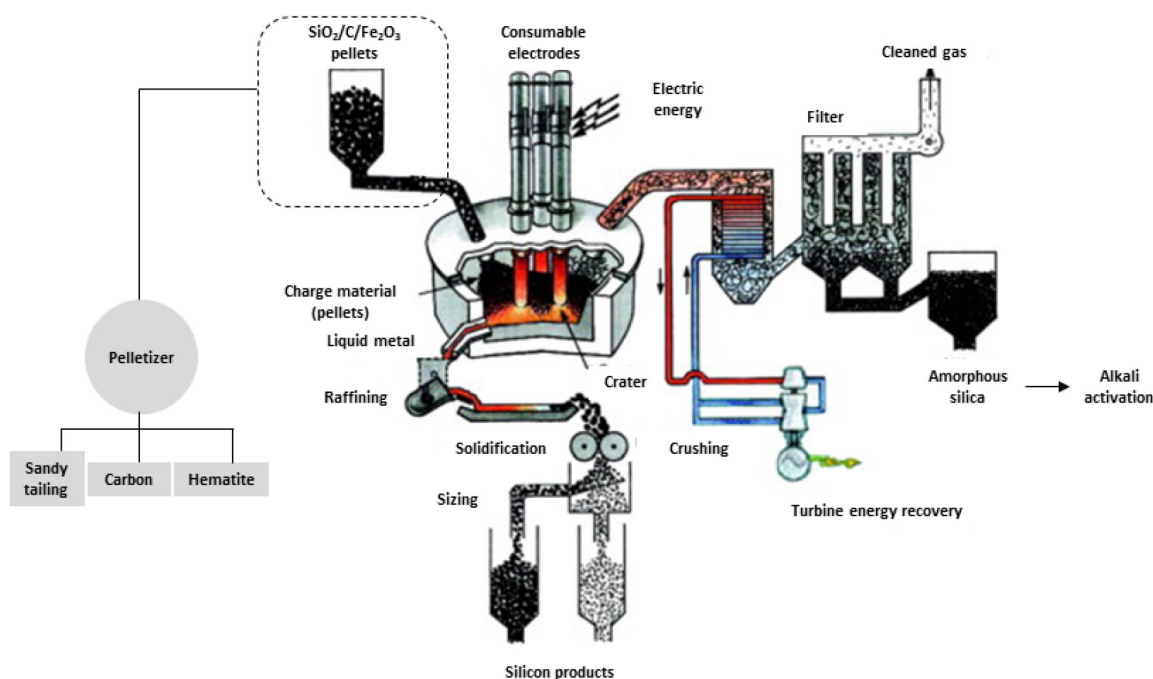


Figure 4. Schematic drawing for the production of Si-Fe alloys using sandy tailing as raw material. The amorphous silica collected in the filter could be used for alkali activation. Adapted from Takla *et al.* (2013).¹⁹

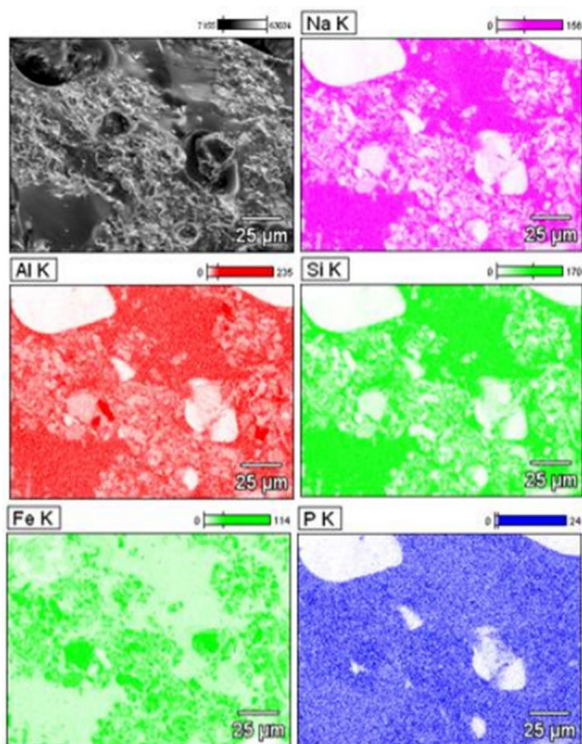


Figure 5. SEM/EDS image after quenching where it is possible to observe the separation between the vitreous phases and iron-rich phases

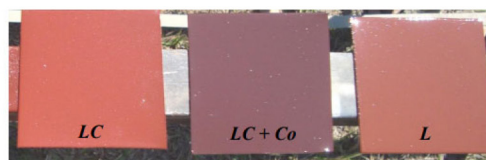
by the calcination, the phosphor is partially captured by the vitreous phases, as well as the remaining content of clays. This process is at TRL 2 and is also waiting for development.

2.2.2. Pigments

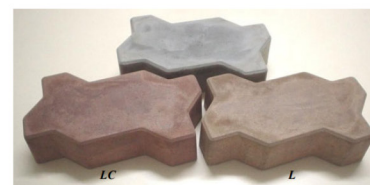
The use of the slime as pigment or mineral filler for plastics, paving, and other products should also be considered. The dried slime composition is approximately 38 wt% hematite, 38 wt% goethites, 09 wt% quartz and 15 wt% clays (kaolinite and muscovite).³ A fraction of the slime particles is greater than 25 μm and can be separated by sieving. It is very similar to sandy tailing, composed of quartz and hematite. The remaining part can be used as pigment for paints, concrete or plastic wood, brown in its natural color or red if calcined (Figure 6). Although the pigment is a product with high added value, the amount



(a)



(b)



(c)

Figure 6. (a) Public square bench made of plastic wood pigmented with the slime (Courtesy of Samarco); (b) Boards painted with an ink pigmented with the slime (LC: calcined slime, LC+Co: calcined slime with cobalt, L: slime); (c) Paving blocks pigmented with the slime compared with one not pigmented³

consumed by the market would be very low compared to the slime generation by mining companies.

2.3. Other developments

Table 2 shows recent developments registered at the Brazilian National Institute of Industrial Property related to the use or reprocessing of iron ore tailings. All of them deserve consideration by mining companies, universities, and research centers to study the technical, industrial, or economic feasibility.

One interesting development is related to the production of lithium orthosilicate, Li_4SiO_4 , a material considered for CO_2 sequestration from industrial processes and release for storage or industrial use. The cost of its production is the main problem for industrial applications.²² The sandy tailing can be used to produce Li_4SiO_4 , contributing to the cost reduction.²³

3. Results

3.1 Startups

Startups are important players in the scale-up of technologies using tailings from iron ore concentrate production. There are some initiatives underway in the Iron Quadrangle.

“The MinerALL Challenge”, launched by Samarco in 2018, was directly related to two commitments. One of them is the use of tailings from the processing of iron ore. The other, in turn, is related to economic diversification, which includes attracting business from tailings for economic diversification in the cities of Ouro Preto and Mariana in Minas Gerais, Brazil. In general terms, it proposed to model businesses and scale-up solutions capable of directing the use of tailings in a sustainable way to other markets. Thus, the Challenge aimed to build a bridge between technologies and the market through university entrepreneurship. There were 414 entries and 17 teams – each one based on a technology – that went through stages of immersion, business modelling and pre-scaling of solutions. A corporate accelerator brought the methodology that contributes

Table 2. Patens filed at the Brazilian National Institute of Industrial Property related to the use of iron ore tailings in the last five years

Number	Filing date	Title	IPC	Status
BR1020210112344	10/06/2021	System for fragmentation and separation of crystalline and mineralogical phases using a pendulum mill system coupled with a customized separator and dynamic separator devices.	B03B1/04	Under analysis
BR1020210099658	21/05/2021	Artificial and sustainable green quartz is produced from raw material constituted of waste, tailings and overburden originating from mining and steel and metallurgical industries.	C04B18/02	Under analysis
BR1020200261029	18/12/2020	Recovery processes are derived from mining products.	H05B6/64	Under analysis
BR1020200122045	17/06/2020	Geopolymer is produced from an innovative processing route and has raw materials waste, tailings and overburden originating from the mining and steel industry.	C04B12/00	Under analysis
BR1020200091964A2	08/05/2020	Iron mining tailings recycling process.	C01G49/06	Under analysis
BR1020190259094A2	06/12/2019	Iron ore tailings enriched with carbon nanotubes for application in cement matrices.	C01B32/16	Under analysis
BR1020190252766A2	29/11/2019	Iron ore concentrate and pellet manufacturing process with the addition of the tailings generated in the desliming step.	C22B1/14	Under analysis
BR1020190227249B1	30/10/2019	Artificial aggregate production process from mining tailings, artificial aggregate, concrete composition, and use.	C04B18/30	Patent issued in 16/06/2020
BR1020190107120B1	24/05/2019	Disposal process in piles of tailings from the iron ore treatment process.	B03D1/08	Patent issued in 04/02/2020
BR1020190095920B1	10/05/2019	Iron ore briquette production process including mining tailings	C22B1/243	Patent issued in 28/07/2020

to business planning – the survey of environmental and social impacts, the validation of market pains and the definition of the MVP (minimum viable product) and the project concept, among other milestones. In all, there were more than 35 activities, including mentoring, training, and evaluation boards. Of the original 17 teams, 13 presented their projects on the pre-acceleration phase Demoday. Of these, six were chosen to proceed to the acceleration and pre-scaling phase and four presented their pitches focused on solutions developed from inert and non-hazardous tailings, belonging to category II B, whether mud or sandy tailings. Two startups from The MinerALL Challenge are on the market. The Ecomud is using the slime for paving vicinal roads. This startup developed a solution that presents great control of dust and swamps, reduction in holes and durability by using a special binder. GEECO develops solutions using geopolymers with mining tailings.

Escalab is a technology scaling center and business modelling, conceived from a partnership between the Federal University of Minas Gerais, INCT Midas and CIT SENAI. INCT Midas, a National Institute for Science Technology, is a national network of researchers in the field of chemistry engaged in solving industrial problems through technological innovation. The startups Ecomud and GEECO are being accelerated by Escalab.^{24,25}

The Mining Hub is another interesting initiative that brings together the mining sector, with several participating

mining companies, suppliers, and startups. The objectives are to increase interaction and collaboration between actors in the mining chain, share knowledge and seek joint solutions to common challenges. Among its programs, the Mining Hub has the M-Start, which aims to encourage solutions to challenges in the mining sector, in contact with applied innovation initiatives (startups and technology-based companies). The challenges are brought by the participating mining companies, with those with the highest number of votes having greater chances of being part of the M-Start program. Mining companies can sponsor startups, helping them to have the necessary conditions to develop their solutions. This program is organized around the following themes: social development; operational efficiency; alternative energy sources; water management; waste and tailings management; and security (operational health and safety). Laminatus is a startup founded in the scope of the Mining Hub. It is dedicated to the use of mining tailings in civil construction.

JASMMIN is another startup that also works with alkali-activated materials. It was born at the Federal Center for Technological Education of Minas Gerais (CEFET-MG) with a team of highly skilled professors and professionals.

3.2. Solutions at industrial scale

The mining companies are also acquiring important

achievements for scale-up of using the iron ore tailings in other production chains:

- Samarco has produced paving blocks with sandy tailing and paved streets in some cities about its facilities. It also supplied the dried slime as pigment for the production of plastic wood. Unfortunately, the progress of these initiatives was interrupted by the collapse of the Fundão dam.
- Vale has inaugurated in partnership with CEFET-MG a pilot plant for products for civil construction that uses mining tailings as the principal raw material in 2020. The unit is installed at Mina do Pico, in the municipality of Itabirito (MG). Around 30,000 tons of tailings annually should be transformed into 3.8 million pre-molded products of wide application in the civil construction industry, such as floor interlocking, structural concrete blocks, sealing blocks, concrete plates, shackles, and sealing blocks, among others.
- Vale and CDTN – Nuclear Technology Developing Center have a collaboration aimed at developing geopolymers using tailings from iron ore exploitation.
- After seven years of research, since 2021, Vale has been supplying sand from the tailings for the civil construction industry. An investment of around R\$50 million was necessary for adjustments in the iron ore operations. The sand according to the legislation and is an efficient alternative for use in cement, precast concrete, interlocking blocks, and paving, among others.
- Gerdau launched in 2019 in Ouro Branco, Minas Gerais, the first house built with tailing from its mining operation. The technology was developed in partnership with the Department of Mining Engineering at the Federal University of Minas Gerais (UFMG), enabling the production of blocks, mortar, and drainage flooring, among other construction products with iron ore tailings.

3.3. Legislation

On January 15, 2020, the state of Minas Gerais enacted law number 23,575, which reduces to 0% (zero per cent) the tax burden on internal operations with cement or concrete works in which tailings are used or ore waste. This is an important incentive to make products made from mining tailings competitive, especially iron mining.

4. Conclusions

The main challenges involving the management of tailings generated by the exploitation of iron ore in the Iron Quadrangle of Minas Gerais, Brazil are related to 1) the huge amount of tailings generated; 2) the fine granulometry of the tailings; 3) the development of products that can use large amounts of tailings; 4) new storage strategies to replace dams. Several initiatives are underway in the Iron

Quadrangle to address the issue of these tailings, with achievements at the industrial scale in some cases.

Civil construction has the potential to use a significant fraction of these tailings, especially the sandy tailing. However, there is a technical limit to producing Portland cement artefacts, due to the fine granulometry. Alkali activated materials including geopolymers do not show this limit, but their feasibility on an industrial scale and long-term durability are yet to be proven. Also, low-cost raw materials and standards for their fabrication should be developed. They can be produced with raw materials available in the iron mines and be employed as a binder for dry stacking of tailings. The sandy tailing has also the potential to be employed as raw material for the fabrication of silicon products.

The best solution for using the slime is its reprocessing due to its high content of iron oxides. But there are other solutions for using it as raw material for paving roads, pigments, and other high-tech applications, although the market for these products cannot consume the slime in the scale of its generation.

Besides the research and development of technologies to use the tailings as raw materials for several products, initiatives to develop business for these products should be and are being carried out, involving startups or developments by the mining companies, as well as the implementation of policies to incentive the use of tailings.

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