Revista ARACÊ
ISSN: 2358-2472

SUSTAINABLE REUSE OF MANGANESE TAILINGS: A REVIEW OF APPLICATIONS IN CIVIL CONSTRUCTION

REAPROVEITAMENTO SUSTENTÁVEL DE REJEITOS DE MANGANÊS: UMA REVISÃO SOBRE APLICAÇÕES NA CONSTRUÇÃO CIVIL

REAPROVECHAMIENTO SOSTENIBLE DE RESIDUOS DE MANGANESO: UNA REVISIÓN SOBRE APLICACIONES EN LA CONSTRUCCIÓN CIVIL

https://doi.org/10.56238/arev7n11-300

Submission date: 10/24/2025 **Publication Date:** 11/24/2025

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ABSTRACT

The present article provides a literature review on waste generated from manganese mining, with emphasis on its physicochemical characteristics and the possibilities of reuse as an alternative material in civil construction. Manganese mineral exploitation, historically relevant in Brazil especially in the regions of Serra do Navio (AP) and Carajás (PA) has produced large volumes of waste that mostly remain without proper disposal, representing a significant environmental liability. The studies analyzed show that these residues have a predominantly inert composition, with high Mn content and low levels of impurities, characteristics that make their use feasible as a partial substitute for natural aggregates in concrete, mortars, and ceramic materials. Reported results in the literature even indicate improvements in mechanical properties, such as increased compressive strength, when incorporated in controlled dosages. It is concluded that the reuse of manganese tailings presents high technical and environmental potential, aligning with the principles of sustainability and circular

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economy, although further studies on the durability and environmental safety of the produced materials are still needed.

Keywords: Manganese Tailings. Sustainability. Alternative Aggregates. Civil Construction. Circular Economy.

RESUMO
O presente artigo apresenta uma revisão bibliográfica sobre os rejeitos provenientes da mineração de manganês, com ênfase em suas características físico-químicas e nas possibilidades de reaproveitamento como material alternativo na construção civil. A exploração mineral do manganês, historicamente relevante no Brasil, especialmente nas regiões da Serra do Navio (AP) e Carajás (PA), gerou grandes volumes de rejeitos que, em grande parte, permanecem sem destinação adequada, representando um passivo ambiental significativo. Estudos analisados demonstram que esses resíduos possuem composição predominantemente inerte, com altos teores de Mn e baixos níveis de impurezas, características que possibilitam seu uso como substituto parcial de agregados naturais em concretos, argamassas e materiais cerâmicos. Resultados reportados na literatura indicam, inclusive, ganhos nas propriedades mecânicas, como aumento da resistência à compressão, quando incorporados em dosagens controladas. Conclui-se que o aproveitamento dos rejeitos de manganês apresenta elevado potencial técnico e ambiental, alinhando-se aos princípios da sustentabilidade e da economia circular, embora ainda sejam necessários estudos complementares sobre durabilidade e segurança ambiental dos materiais produzidos.

Palavras-chave: Rejeitos de Manganês. Sustentabilidade. Agregados Alternativos. Construção Civil. Economia Circular.

RESUMEN
El presente artículo presenta una revisión bibliográfica sobre los residuos provenientes de la minería de manganeso, con énfasis en sus características fisicoquímicas y en las posibilidades de reaprovechamiento como material alternativo en la construcción civil. La explotación minera del manganeso, históricamente relevante en Brasil especialmente en las regiones de Serra do Navio (AP) y Carajás (PA), ha generado grandes volúmenes de residuos que, en su mayoría, permanecen sin una disposición adecuada, representando un pasivo ambiental significativo. Los estudios analizados demuestran que estos residuos poseen una composición predominantemente inerte, con altos contenidos de Mn y bajos niveles de impurezas, características que permiten su uso como sustituto parcial de los agregados naturales en concretos, morteros y materiales cerámicos. Los resultados reportados en la literatura incluso indican mejoras en las propiedades mecánicas, como el aumento de la resistencia a la compresión, cuando se incorporan en dosificaciones controladas. Se concluye que el aprovechamiento de los residuos de manganeso presenta un alto potencial técnico y ambiental, alineándose con los principios de la sostenibilidad y de la economía circular, aunque aún son necesarios estudios complementarios sobre la durabilidad y la seguridad ambiental de los materiales producidos.

Palabras clave: Residuos de Manganeso. Sostenibilidad. Agregados Alternativos. Construcción Civil. Economía Circular.

Revista ARACÊ
ISSN: 2358-2472

1 INTRODUCTION

The production and consumption process adopted in the current economic development model largely disregards the limited capacity of natural resources. The more technological advances occur, the greater the demand for natural resources in other words, a larger amount of raw material is required for the production and supply of the wide range of consumer goods available to society.

Considering the metallurgical industry, manganese ore is one of the most important natural resources for Brazil, since the country has a considerable reserve of this mineral and participates directly in the production of metal alloys and steel. The steel industry consumes approximately 85% of global manganese production as pig iron or manganese-based alloys. The physicochemical characteristics of the ore allow it to be used as a desulfurizing and deoxidizing agent. The remaining 15% of manganese consumption is used in the production of batteries and as inputs for the chemical industry, with the purpose of producing fertilizers and animal feed (Ministry of Mines and Energy – MME, 2009).

The manganese tailings originating from the exploitation of Serra do Navio, in the state of Amapá which are the focus of this study—represent the first mining experience in the Amazon region, which began around 1957. At that time, following the end of World War II, the former Soviet Union, holder of the largest manganese deposits in the world, had suspended its exports, which made the exploration of this ore economically attractive due to its high market value.

In December 1997, ICOMI ended its operations, leaving behind a negative social and environmental legacy for the state of Amapá and the municipality of Santana, as noted by Facundes (2011). Currently, both at the ICOMI port in Santana and in the Serra do Navio mines, tons of manganese ore and waste remain awaiting their final Destination whether for processing and sale or for the appropriate disposal of the generated residues.

According to John (2008), the civil construction sector is responsible for consuming the largest volume of natural resources, with estimates ranging between 15% and 50% of extracted materials. Moreover, its products are major energy consumers. For these reasons, the development of alternative materials to meet the demands of this sector is of fundamental importance. In this context, Viveiros (2017) analyzed the feasibility of using manganese tailings as filler and fine aggregate in partial replacement of cement and concrete, respectively, demonstrating a viable alternative for the management of mining waste and a sustainable solution for civil construction.

2 METHODOLOGY

The present study is characterized as a narrative literature review, based on the analysis of scientific articles, dissertations, technical reports, and institutional documents addressing manganese mining tailings and their potential for reuse in civil construction. The search was carried out in databases such as Scielo, Scopus, and Google Scholar, using the descriptors "manganese tailings," "alternative aggregates," "sustainability," and "civil construction." Publications in Portuguese, English, and Spanish were selected without temporal restriction, prioritizing studies that presented physicochemical and experimental analyses of the residues.

After collection, the studies were organized and compared regarding the methodology used, composition of the tailings, and results obtained from the use of these materials in concrete, mortars, and ceramics. The qualitative analysis of the data made it possible to identify trends, potentialities, and technical limitations of manganese tailings reuse, as well as their environmental and economic feasibility, contributing to the discussion on the sustainable use of mineral resources and the promotion of a circular economy.

3 RESULT AND DISCUSSION

3.1 MANGANESE IN BRAZIL

The Brazilian territory is rich in various minerals, making the country one of the world's largest producers, alongside Russia, the United States, Canada, China, and Australia. This was made possible due to investments that fostered the growth of this activity over the past decades.

Manganese is the fourth most used metal in the world, occurring naturally as an ore and having a high global demand due to its essential applications in metal alloys, being used mainly in steel production, as well as in the manufacture of high-capacity batteries. Although nearly 90% of production is destined for the steel industry, its applications also include the manufacture of fertilizers, animal feed, and use in the automotive sector.

After the peak of gold mining in the 18th century, manganese emerged as the main mineral substance in Brazil's export agenda at the end of the 19th century. Global steel production reached 28.3 Mt in 1900 and 60.3 Mt in 1910, which increasingly required meeting the growing demand.

In Serra do Navio, in the state of Amapá, about US$ 8 million were invested in mineral research between 1948 and 1951. In 1957, the Serra do Navio manganese mine (a

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partnership between ICOMI – Indústria e Comércio de Minérios S/A – and Bethlehem Steel) began production. By the late 1970s, the richest manganese ore had already been mined (with an initial reserve estimate of 10 Mt). In 1972, ICOMI began the pelletizing process, with an annual capacity of 250,000 tons, which became operational only in 1975, was halted in 1983, and permanently closed in 1985.

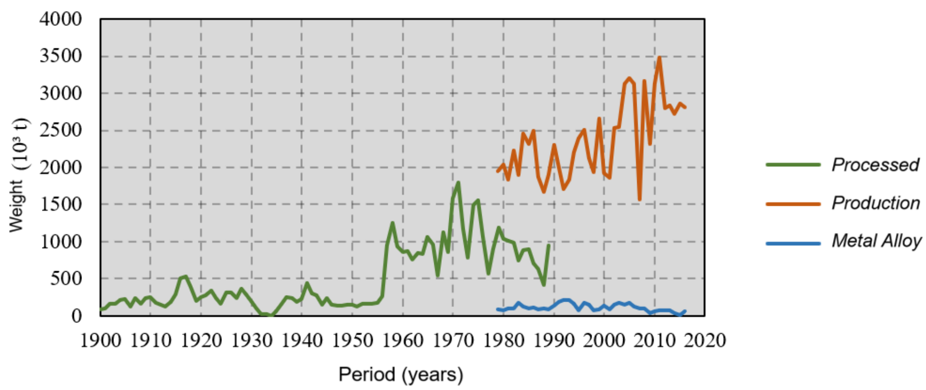
In 1988, after several modifications, the plant began sintering fine manganese ore. This operation was managed by Companhia Ferro Ligas do Amapá (CFA), created by CAEMI, ICOMI's parent company, in 1990, with an investment of US$ 22 million to produce ferromanganese alloys. In 1996, CFA prematurely ended its steel industry operations, citing the enterprise's unfeasibility due to the high cost of electricity and the decline in alloy prices on the global market.

After 40 years, in 1997, when ICOMI ended its operations in Serra do Navio, it was estimated that 33.2 million tons of manganese oxide had been produced and more than 123 million tons of overburden moved, with over 61 million tons of ore processed and more than 26 million tons of tailings generated. The production from the Serra do Navio mine, which began in 1957, significantly increased exports, with annual averages rising from 201,000 tons between 1900 and 1956 to 1.01 million tons between 1957 and 1971.

Figure 1 presents the historical data on manganese exports from 1900 to 1989. During the 1929 economic crisis, exports fell to 2,000 tons in 1934, showing recovery only from 1936 onward. In 1957, with the beginning of exports by ICOMI (Indústria e Comércio de Minérios S/A), Brazil became a major player in the global market. Figure 2 shows the manganese ore titles in Brazil.

Figure 1

Production of manganese ore, beneficiation, and metal alloys



Source: DNPM e http://memoria.bn.br/pdf/123021/per123021_1949_00161.pdf

Today, the largest manganese production takes place at the Azul Mine, owned by Vale, in Carajás (Parauapebas/PA). Next are Urucum Mineração, in Corumbá (MS), and Mineração Buritirama, in Marabá (PA). BMC (Espigão D'Oeste/RO) appears as the fourth national producer. Nogueira Duarte Mining and Tratex, both located in Minas Gerais, are smaller-scale producers.

In 2017, Vale produced 1.4 million tons of manganese ore at the Azul Mine, 673,000 tons at Urucum, 80,000 tons at the Morro da Mina Mine (MG), and 146,000 tons of ferroalloys.

Brazil holds 10% of the world's manganese reserves, behind only Ukraine (24%), South Africa (22%), and Australia (16%). Vale is the largest manganese producer in Brazil, accounting for about 70% of the national market. The Azul Mine, in Pará, is responsible for 80% of the country's production. The Brazilian mines of Azul, in Pará, and Urucum, in Mato Grosso do Sul, stand out for having high-grade ore at least 40% manganese content.

3.2 PUBLICATIONS ON TAILINGS

3.2.1 Faria et al. (2012)

Faria et al. (2012) proposed the chemical, physical, and mineralogical characterization of the granulated manganese product from the Azul Mine, which is the largest manganese ore producer in Latin America, with an annual production of 2.5 Mt. It is located in the central-western portion of the Carajás Mineral Province, within the Carajás National Forest, Municipality of Parauapebas, southeastern Pará State. A large portion of this manganese is used for the production of ferroalloys, while a smaller portion is destined for the chemical and battery industries. However, due to the frequent lack of knowledge about the aforementioned characteristics in alloy production, a significant amount of residues is generated.

A 50 kg sample of manganese waste was used. This sample was crushed in a jaw crusher until all the material was below 6.3 mm. The material was then quartered again, and 1 kg was subjected to another jaw-crushing process. The comminuted product was quartered again, and 500 g were sampled and sent to a closed-disk mill for pulverization. The pulverized material was divided into representative aliquots for chemical, physical, and mineralogical analyses.

Thus, the granulometric classification of the sample was carried out according to Figure 2.

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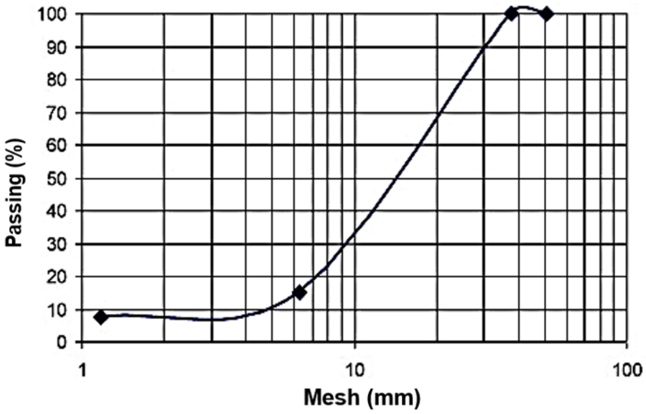
Figure 2

Particle size distribution curve of granulated manganese (FARIA, 2012)



Furthermore, according to Table 1, the samples were opened and treated in an aqueous solution of hydrochloric acid (1:1) to determine the contents of Mn, Fe, CaO, MgO, SiO_2, Al_2O_3, TiO_2, and P.

Table 1

Chemical composition of the material (FARIA et al., 2012)

Sample	Al_2O_3	CaO	Fe	MgO	Mn	P	TiO_2	SiO_2
Granulated (%)	5,22	0,12	3,59	0,18	47,68	0,097	0,24	3,16

It was identified that the ore is high-grade, as it contains more than 35% Mn, showing slightly acidic characteristics and limited fluidity in the slag generated during the alloy production process, due to a binary basicity of approximately 0.04. Additionally, the low phosphorus content indicates that the material is not significantly weakened by the presence of this element.

Moreover, X-ray diffractometry and semiquantitative analysis by reflected light optical microscopy were performed to identify the minerals present in the sample, as shown in Table 2, with their respective percentages relative to the total amount.

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Table 2

Photomicrograph obtained with a reflected light microscope (FARIA, 2012)

	Identified Mineral			
Sample	Predominant (> 40%)	Major (< 20%)	Minor (< 10%)	Trace (< 3%)
Granulated product from Azul	Cryptomelane [KMn_8O_{16}]	Todorokite [$(NaCaK)_2Mn_6O_{12} \cdot 4.5(H_2O)$] Pyrolusite [$MnO_2$]	Gibbsite [$Al(OH)_3$]	Spessartine [$Mn_3Al_2(SiO_4)_3$] Magnetite [Fe_3O_4] N-sutita $Mn(O, OH)_2$

Thus, the high Mn content in the ore can be justified by the predominance of cryptomelane and the presence of pyrolusite, while the occurrence of gibbsite and spessartine accounts for the significant Al_2O_3 content.

Using the alcohol pycnometer, helium micropyc-nometer, and nitrogen adsorption technique, the properties summarized in Tables 3 and 4 were observed.

Table 3

Total porosity and apparent densities measured using the alcohol pycnometer and helium micropyc-nometer (FARIA, 2012)

Granulated Product	Alcohol	Helium	Porosity
Density (g/cm³)	3,55	3,98	10,9%

Table 4

Parameters defined by the BET technique for the granulated product

Sample	**Specific surface** (m²/g)	Total volume (cm³/g) (0,3-300 nm)	Maximum pore size (Ã)	Average pore diameter (Ã)	Micropore volume (cm³/g) (0,3-2 nm)	Micropore area (m²/g)
Azul	11,26	29,4	1307	104,40	5,00	14,15

In this way, the ore presents a high apparent density due to the predominance of cryptomelane, a high-density oxide (4.35 g/cm³). The results also confirm the small average

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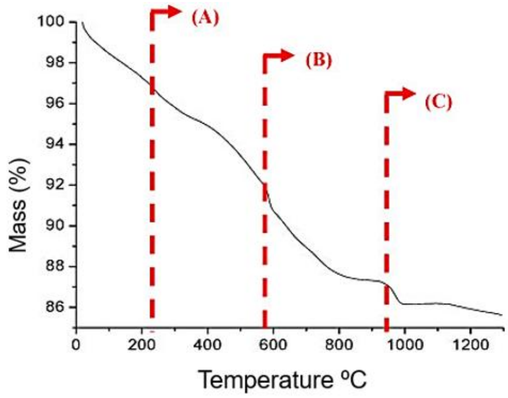
pore size (10.4 nm), and this pore distribution combined with the high specific surface area may be good indicators regarding the reducibility of the Azul Granulated Product.

After these characterizations, a thermogravimetric analysis was also carried out using a thermobalance, where the temperature was raised from room temperature up to 1300°C at a constant rate of 5°C/min. The mass loss of the material was obtained and is shown in the following graph:

Figure 3

Mass loss profile by thermogravimetric test (FARIA et al., 2012)



The first pronounced mass loss, which begins at around 300 °C, is associated with the onset of the thermal decomposition of hydrated mineral phases mainly todorokite and nsutite (A). Near 600 °C, the decomposition of some oxides begins, specifically the transformation of MnO_2 into Mn_2O_3 (B). The mineral phases cryptomelane and pyrolusite start decomposing and are completely consumed at temperatures close to 850 °C. In this temperature range, the greatest mass loss is observed, confirming cryptomelane as the predominant mineral phase.

Thus, based on the tests carried out on the sample from the Azul Granulated Product, this material can be classified as a hydrated oxidized ore, with cryptomelane [KMn_8O_{16}] as its main mineral constituent.

3.2.2 Reis et al. (2010)

According to Reis et al. (2010), manganese is a material extensively mined in Brazil for use in ferroalloys, being an important element in steel alloys, as it helps refine grain structure, increases mechanical strength, and improves hardenability and ductility of steel.

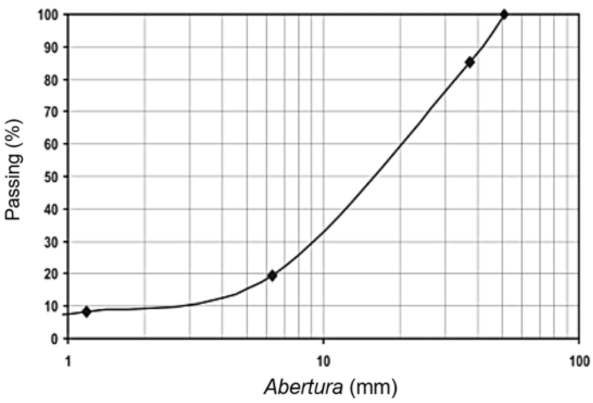
However, in most cases, during metallurgical furnace operations for manganese alloys, the physical and metallurgical properties of manganese ore are not well known, and the material is used based solely on its chemical and granulometric properties. Thus, the study conducted by the authors aimed to characterize a type of manganese ore produced in Carajás, in southeastern Pará State.

In this way, one ton of ore was homogenized and quartered until 50 kg were obtained, which were crushed to produce samples below 50 mm. The sample was then homogenized and quartered again and subjected to comminution in a disk mill to obtain the global sample for the characterization stages. Particle size tests were carried out using the ASTM sieve series with openings ranging from 50 mm to 0.045 mm, along with titration and ICP–OES (Inductively Coupled Plasma Optical Emission Spectrometry) to determine the content of elements in the sample. Additional tests were conducted in a muffle furnace to monitor mass loss under uncontrolled atmosphere conditions at 490 °C, 600 °C, and 1000 °C, each lasting four hours. Subsequently, the sample was characterized using X-ray diffraction to identify the mineral phases present.

From the tests performed, the granulometric classification shown in Figure 4 was obtained:

Figure 4

Particle size distribution of the sample (REIS et al., 2010)



Furthermore, based on Table 5, the chemical analysis of the sample was performed.

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Table 5

Chemical analysis of the sample (REIS et al., 2010)

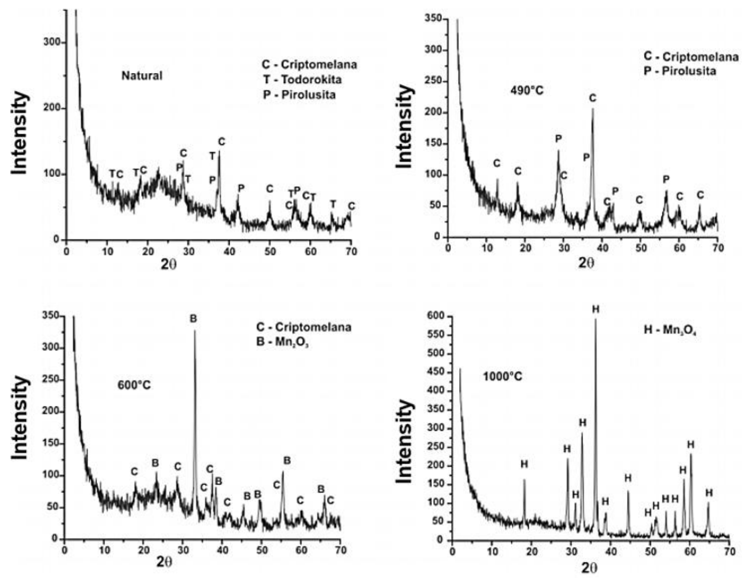
Manganese Ore	Mn (%)	Fe (%)	P (%)	SiO_2 (%)	Al_2O_3 (%)	BaO (%)	CaO (%)	MgO (%)
Sample	52,63	3,13	0,17	1,92	2,65	0,35	0,11	0,097

The manganese content is considered high since, according to commercial specifications from Brazilian ferroalloy producers, a content around 35% is acceptable. The phosphorus content was below the maximum level of 0.25% established by alloy manufacturers. Meanwhile, the silica content (1.92%) is considered low, as the usual commercial chemical specifications indicate values above 5%. The chemical analysis also showed that the Mn/Fe ratio was much higher than commonly used, suggesting that this ore could be blended with other manganese ore types for use in ferroalloy furnaces.

The phase characterization test presented in Figure 5 was conducted using X-ray diffraction (XRD) on the sample subjected to different temperatures, yielding the following diffractograms:

Figure 5

X-ray diffraction of the natural and heat-treated sample (REIS et al., 2010)



In the room-temperature sample, the minerals cryptomelane, todorokite, and pyrolusite were identified. When the sample was heated to 490 °C, the diffractogram no longer showed peaks corresponding to hydrated phases such as todorokite and goethite, as the structural water was released at this temperature, leaving cryptomelane and pyrolusite as the main constituents.

At 600 °C, the absence of the pyrolusite (MnO_2) intensity peaks indicates that pyrolusite decomposes into Mn_2O_3 at this temperature, becoming the predominant mineral phase. The diffractogram of the sample treated at 1000 °C shows the diffraction pattern of Mn_3O_4, a result associated with the decomposition of residual cryptomelane and Mn_2O_3 into Mn_3O_4, which becomes the dominant mineral in the sample.

Thus, this type of manganese ore can be classified as a hydrated oxide, since at around 600 °C the thermal decomposition of the oxides cryptomelane and pyrolusite occurs, and near 950 °C, the transformation of Mn_2O_3 into Mn_3O_4 begins. At normal temperatures, the sample shows the presence of manganese oxides cryptomelane, todorokite, and pyrolusite. Additionally, the collected ore has most of its particle sizes within the specifications for the composition of granulated products, and the alkali content values are within acceptable limits. However, the Mn/Fe ratio (16.8) is high for direct use in the manufacture of manganese alloys.

3.2.3 Salguero et al. (2013)

The waste from manganese ore mining operations, which were extensively exploited in Spain in the past and left several deposits of this material, can represent a significant potential source of aggregate for the construction industry. Therefore, the authors aimed to identify suitable and low-cost aggregates for the market, exploring the possibility of transforming mining waste into a usable product.

The study sought to determine the mechanical properties of a new mixture composed of manganese residue and compare them with those of conventional concrete in terms of compressive strength and deformation, assessing the feasibility of using this material as a partial replacement for fine aggregate in concrete.

Samples of manganese waste were collected from the Santiago Mine in Calañas, where 30 kg were taken from five different locations to preserve mineralogical diversity. The samples were successively crushed first in a jaw crusher down to 32/16 mm, then in a ball mill. Before complete grinding, grains of different sizes were separated for shape analysis.

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After grinding, two granulometric fractions (<2 mm and <63 μm) were selected for chemical and mineralogical characterization. The mineralogical analysis included powder X-ray diffraction (XRD) and scanning electron microscopy (SEM). The remaining residues were used as fine aggregate in concrete preparation. Three concrete samples were made: one conventional mix and two with 20% replacement of natural fine aggregate by Mn residue one using the <4 mm fraction and another with <63 μm to compare results and evaluate the material's feasibility.

After the curing period, compressive strength tests were performed using an automated load-control machine with a capacity of up to 3000 kN, and deformations were measured with an electronic sensor. The chemical composition of the sample showed the main constituents to be Si, Al, and Ca, as shown in Table 6 below:

Table 6

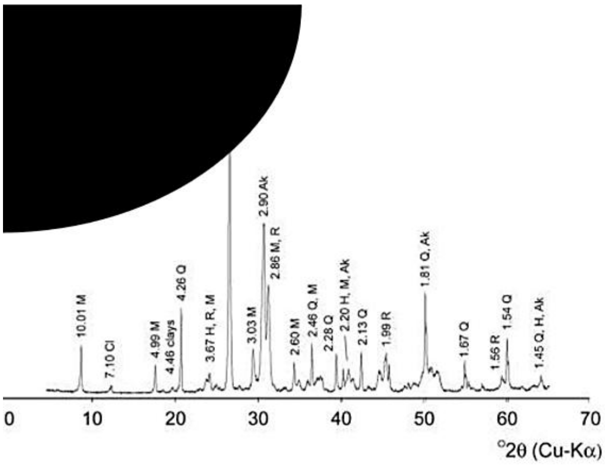
Chemical composition of manganese residue (SALGUERO et al., 2013)

Oxides and elements (%)																
SiO_2	Al_2O_3	Na_2O	MgO	K_2O	CaO	P_2O_5	TiO_2	MnO	Y_2O	S	Cl	Zn	Rb	Sn	Zr	Ba
36,1	6,6	0,1	3,2	1,6	12,4	0,1	0,05	15,7	0,01	0,05	0,02	0,02	0,02	0,03	0,02	0,1

The XRD results indicate that the Mn residue is mainly composed of quartz and mica, with smaller amounts of the carbonates rhodochrosite and ankerite, as shown in Figure 7.

Figure 7

X-ray diffraction (SALGUERO et al., 2013)



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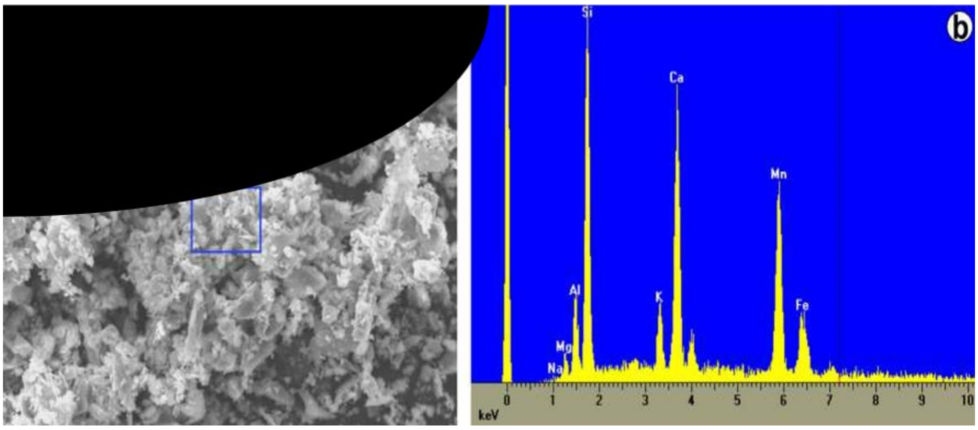
ISSN: 2358-2472

Confirming these findings, the elemental composition obtained by EDS shows a predominance of Si, Al, Ca, and Mn phases, as represented in Figure 8.

Figure 8

X-ray spectrometry (SALGUERO et al., 2013)



Regarding the compressive strength tests, the data showed that the concrete with 20% substitution of natural fine aggregate by Mn residue achieved greater strength than conventional concrete, reaching up to 56.44 Mpa an increase of nearly 40% suggesting that this mixture may even be more reliable than conventional concrete.

From this, it can be concluded that these manganese residues, which currently have no economic value and represent an environmental concern, can be used as fine aggregate in concrete production. Since the residues are non-reactive and have an adequate chemical composition to be mixed with cement, their use resulted in nearly 40% higher compressive strength compared to conventional concrete.

4 CONCLUSION

The literature review on manganese tailings shows that this material, traditionally regarded as an environmental liability of mining, exhibits physicochemical and mineralogical characteristics that qualify it as a potential alternative input for civil construction. Several studies indicate that manganese tailings have high Mn content, low reactivity, and a predominantly inert composition, allowing their use as a partial substitute for fine and coarse aggregates in concrete and mortar, as well as in ceramic and cementitious materials.

The analyzed works suggest that the controlled incorporation of these tailings can help reduce the environmental impacts associated with tailings dam disposal while simultaneously

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promoting economic and performance benefits in construction materials, in line with the principles of sustainability and circular economy. In some cases, improvements in mechanical Properties especially compressive strength were also observed, reinforcing the technical feasibility of reuse.

Despite the progress achieved, further studies are still needed to expand knowledge on durability aspects, compositional variability, and environmental behavior of manganese tailings, focusing on their large-scale application. Thus, consolidating the sustainable use of these materials represents not only a promising alternative for mitigating the impacts of mining but also a technological innovation strategy for the civil construction sector.

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