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STATE OF THE ART OF THE USE OF MINING TAILINGS IN ROAD PAVEMENTS

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Abstract: Mining activities in Brazil play an important social and economic role in the country. Allied to this fact, mining produces a large number of tailings, which disposal is an economic and environmental challenge for mining companies. Mining residues are studied as an alternative source of materials for several applications, and among them, for the construction of pavements. This work presents the development of research related to the use of mining tailings in pavements. Works related to iron ore, bauxite, copper, and tungsten tailings were found. The iron ore tailings presented a greater number of publications and, consequently, a greater scope of explored themes, when compared to the others. Mining tailings were studied in asphalt mixtures, cement mixtures for rigid pavements and interlocking pavement blocks, and mixtures to compose the base, subbase, and subgrade reinforcement layers.
Keywords: Mining tailings; iron ore; pavement; alternative materials.

INTRODUCTION

Brazil is one of the main ore producing countries in the world. In 2020, despite the pandemic, Brazil grew by 36.2% compared to 2019, reaching R$208.9 billion, which represents a 4.0% share of Brazilian GDP (IBRAM, 2020). The most prominent mineral substances in the Brazilian mining sector are iron, limestone, bauxite, phosphate, manganese, and niobium. Table 1 presents the benefited production of the main mineral substances extracted in Brazil and their respective position in the world ranking in the year 2020 (IBRAM, 2020).

Despite its economic importance, the mining activity causes a great environmental impact on its extraction site. Large volumes and masses of materials are extracted and moved, and the generation of waste depends on the location of the deposit about the surface, the concentration of the mineral substance stored in the matrix rock, and the ore extraction process (IPEA, 2012).

Substance	Production benefited 2020 (ton)	World ranking
Iron	387.995.292,03	2º
Limestone	128.844.807,51	
Bauxite	30.960.674,95	5º
Phosphate	8.720.124,40	6º
Manganese	3.697.370,05	3º
Niobium	3.354.842,13	1º
Zinc	445.979,04	10º
Nickel	293.579,75	4º
Gold	82.941,53	9º

Table 1 - World ranking and production benefited from the main mineral substances in Brazil.

Source: IBRAM, 2020.

The two main solid wastes generated by the extraction process are sterile and tailings. The sterile, also known as mining, are the materials generated by the extraction activities that are arranged in piles but have no economic value. Tailings are generated from the ore beneficiation process, which seeks to "purify" the ore, removing associated minerals without economic value, and increasing the quality or content of the final product (IPEA, 2012). Depending on the beneficiation process and the type of raw ore, the tailings generated can present different granulometric characteristics, from coarse materials to very fine granulometry bands (sludge), with significant variations in terms of geotechnical behavior.

In the management of ore tailings, recycling and reuse are strategies considered more appropriate than the simple disposal of tailings made in dikes or dams. An alternative to minimize the impacts associated with the disposal of tailings is its reuse in engineering works, such as road infrastructure works.

The pavement works are related to a great consumption of materials and, therefore, high financial cost. In addition, significant environmental impacts are caused for the extraction of natural aggregates used to compose the pavement layers (ANTT, 2018). The use of tailings in pavement works presents a new purpose for the tailings, generating a sustainable development, reducing the need for natural aggregates, and, possibly, reducing the costs for the construction of new pavements.

This work aims to present the current situation of research related to the use of different mining tailings in pavements, presenting test results obtained by different authors, and showing the technical feasibility of using mining tailings in pavements.

MINING TAILINGS

In Brazil, the mineral sector is considered very important for the country's economy, because, in addition to the production of 70 mineral substances, it generates many jobs. According to IBRAM (2020), in 2019, 190 thousand direct jobs and more than 2 million indirect jobs were created. Consequently, it generates tons of tailings.

Of the 70 mineral substances produced in Brazil, only 15 correspond to about 90% of the national gross production, also characterizing themselves as the most important generators of tailings and, in 15 years, they were responsible for the origin of about 4.86 billion tons of accumulated tailings, with the production of iron, gold, and phosphate representing 58% of the total generated (MORAES et al., 2017).

According to Moraes et al. (2017), each person consumes around 5.4 tons of inputs of mineral origin per year, reaching about 328 tons in 70 years of life, which would result in 3,000 tons of tailings per inhabitant. Considering the current Brazilian population of 213 million inhabitants, this implies a total of over 9 billion tons of waste generated annually!

The most serious thing is that, generally, the disposal is done in piles and dams, and the dams need to be planned, operated, and maintained correctly, otherwise they pose serious risks of failure. For this reason, the use of accumulated tailings, as well as the reduction of its generation, is essential for the mineral sector. The Mariana accident, on November 5, 2015, triggered the alert of several mining companies, which began to make public their actions to reduce water and energy consumption, and, consequently, the generation of tailings. For this, the search for the sustainable development of mining came to appear as an important goal of the various sectors that work in the area, where the generation of technologies has become fundamental. It was hoped that the tragedy would not repeat itself. However, on January 25, 2019, Brumadinho also suffered a tragic accident with the rupture of its dam. Could this have been avoided?

The search for technologies that result in the use of tailings efficiently could reduce the number of tailings disposed of in dams. According to Moraes et al. (2017), many studies using the tailings generated by mining have been carried out in Brazil and several countries around the world, and in the last 15 years, more than 500 articles involving mineral substances produced in Brazil have been identified. In 2017, the mining theme was the subject of research in 41 Science, Technology, and Innovation institutions spread across 17 Brazilian states, with emphasis on the State of Minas Gerais, one of the main producers of ores in the country. The number of research groups studying the mining topic was 68, and there were 25 lines of research directly related to the reuse of tailings (MORAES et al., 2017). The research approaches the application of tailings in several areas, such as in civil construction and, particularly, in road engineering, in pavement works, where the main tailings studied come from iron, bauxite, copper, and tungsten ores. It is worth mentioning the research developed by the main federal institutions of Minas Gerais, as well as such as research carried out in Rio de Janeiro, Rio Grande do Norte and in Paraiba.

IRON ORE TAILINGS

Among the mining tailings studied in this work, the tailings related to iron ore is the one with the most developed research. This fact is related to the large share of this mineral in the Brazilian economy and the high amount of mineral extracted annually (IBRAM, 2020). In 2020, Brazil was the second largest producer of iron ore in the world, with the value of production reaching 138.69 billion reais (BRASIL MINERAL, 2021). A search was performed for current data on iron ore tailings production, but no results were found. However, considering the values published by Moraes et al. (2017), where the number of iron ore tailings generated corresponded to 26.7% of its annual production, it can be concluded that more than 100 million tons are generated per year. In this work, the use of iron ore tailings in pavements was divided into 6 classes:

- Class I - Soil and tailings mixtures;
- Class II - Chemically stabilized mixtures;
- Class III - Granulometrically stabilized mixtures;
- Class IV - Concrete;
- Class V - Interlocked pavement;
- Class VI - Asphalt mixtures.

Class I, II, and III Mixtures

The mixtures belonging to classes I, II, and III were developed with the same purpose: to apply the tailings in structural layers of pavements, such as base layers, sub-base, and subgrade reinforcement (ANTT, 2018; DANTAS, 2015; GALHARDO, 2015; BASTOS, 2013; CAMPANHA, 2011; PEIXOTO, 2006; BARATI *et al.*, 2020; OLIVEIRA *et al.*, 2019; OJURI *et al.*, 2017; GRASSE *et al.*, 2019; SÁ *et al.*, 2019).

Class I can be subdivided into two subclasses: I-a) mixtures of iron ore tailings with granular soil, and, I-b) mixtures of iron ore tailings with lateritic soil. Class II is divided into 3 subclasses: class II-a, for cement-stabilized mixtures; class II-b, for lime stabilized mixtures; and class II-c for slag stabilized mixtures. Table 2 presents the characteristics of the mixtures studied and the appropriate proportions of the materials used.

The analyzes and tests covered included physical, chemical, and mineralogical, mechanical, and environmental characterizations. The physical characterizations approached granulometry, specific gravity, determination of Atterberg limits (liquidity limit - LL, plasticity limit - LP, and plasticity index - PI), and water absorption. Some results are presented in Table 3.

Chemical and mineralogical characterizations were performed using X-ray fluorescence and X-ray diffraction tests. These tests contribute to the identification of soil and tailings constituents, thus being able to explain the behavior of the samples evaluated. In general, the results of the characterization of iron ore tailings showed higher amounts of hematite (Fe_2O_3), quartz (SiO_2), kaolinite ($Al_2Si_2O_5(OH)_4$), gibbsite ($Al(OH)_3$), and magnetite (Fe_3O_4).

The mechanical characterizations comprised tests of compaction, California bearing ratio (CBR), expansion, and modulus of resilience. For class II and class III, the characterization was performed through unconfined compressive strength tests. These tests are essential to understand

Class I-a		Class I-b		Class II-a	Class II-b	Class II-c	Class III	
% waste	% granular soil	% waste	% lateritic soil	% cement	% lime	% slag	% waste	% slag
0%	100%	0%	100%	1%	1%	1%	30%	70%
15%	85%	10%	90%	2%	2%	2%	50%	50%
25%	75%	20%	80%	3%	4%	-	70%	30%
40%	60%	30%	70%	4%	5%	-		
50%	50%	40%	60%	5%	6%	5%		
100%	0%	50%	50%	10%	10%	10%		
				15%				

Table 2 - Compositions of the mixtures studied - Classes I, II, and III.

Source: ANTT (2018); DANTAS (2015); GALHARDO (2015); BASTOS (2013); CAMPANHA (2011); PEIXOTO (2006); BARATI *et al.* (2020); OLIVEIRA *et al.* (2019); OJURI *et al.* (2017); GRASSE *et al.* (2019); SÁ *et al.* (2019).

Materials	Grain Specific gravity (g/cm^3)	Atterberg Limits (%)		
		LL	LP	PI
Waste	2.664 - 3.996	Non-liquid	Not plastic	Not plastic
Lateritic soil	2.653 - 3.018	43	29	14
Residual soil	2.510 - 2.556	40	Not plastic	Not plastic
Soil-tailing mixtures	2.625 - 3.213	Non-liquid	Not plastic	Not plastic

Table 3 - Results of material characterization tests.

Source: ANTT (2018); DANTAS (2015); GALHARDO (2015); BASTOS (2013); CAMPANHA (2011); PEIXOTO (2006); BARATI *et al.* (2020); OLIVEIRA *et al.* (2019); OJURI *et al.* (2017); GRASSE *et al.* (2019); SÁ *et al.* (2019).

Mixture	California Bearing Ratio - CBR (%)			Expansion (%)
	Normal Energy	Intermediary Energy	Modified Energy	
Waste	5.6 - 23.5	19.4 - 50.0	37.2 - 53.0	<0.40
Lateritic soil	-	-	53.7	0.00
Lateritic soil	-	1.4 - 16.5	25.0	0.12 - 6.10
Mixture with lateritic soil	-	46.5	44.2 - 90.8	0.00
Mixture with residual soil	-	14.7 - 30.5	23.7 - 57.7	0.04 - 3.90
Mixture with cement	-	45.0 - 180.0	-	<0.30
Mixture with lime	-	38.0 - 32.0	-	<0.32
Mixture with lime	-	80.0 - 115.0	-	-
Mixture with slag (chemically)	-	28.0 - 47.0	-	<0.36
Mixture with slag (granulometrically)	-	52.0 - 85.0	-	<0.11

Table 4 - Results of CBR and expansion tests.

Source: ANTT (2018); DANTAS (2015); GALHARDO (2015); BASTOS (2013); CAMPANHA (2011); PEIXOTO (2006); BARATI *et al.* (2020); OLIVEIRA *et al.* (2019); OJURI *et al.* (2017); GRASSE *et al.* (2019).

the structural behavior of materials (mixture of tailings with soil) in the pavement and to assist in the design by the designers. The test results are presented in Tables 4 and 5. In addition, the durability of the mixtures was evaluated through the weight loss by wetting and drying, and the results are presented in Table 6.

From the results presented in tables 4 to 6, it is possible to conclude that the application of pure tailings and mixtures of slag and tailings, granulometrically stabilized, is unfeasible due to the 100% mass loss in the durability tests (BASTOS, 2013). The CBR tests showed interesting values, especially for tailings and cement mixtures, in which the CBR values ranged from 45% to 180% (BASTOS, 2013), and for tailings and lime, with CBR values ranging from 80% to 115 % (GRASSE et al., 2019). These results present values greater than the minimum, of 30%, established by DNIT (DNIT, 2005; DNIT, 2010), for mixtures of improved soil with cement and lime soil for sub-base layers. For use as a base layer, only a few materials met the recommended minimum CBR ≥ 80% (DNIT, 2010), such as soil-lime-tailings. The expansion tests were also satisfactory and met the recommendations required for the use of the mixture as a base layer (maximum expansion of 0.5%) and sub-base (maximum expansion of 1%).

Analyzing the compressive strength of soil cement (BASTOS, 2013; BARATI et al., 2020; OLIVEIRA et al., 2019; SÁ et al., 2019), the mixtures with 5% of cement showed lower strengths than those recommended by the DNIT (2005) for minimum strength at 7 days which must be between 1.4 and 2.1 MPa so that the mixture can be used as a sub-base layer and above 2.1 MPa to be used as a base layer. The mixtures with 10% and 15% of cement were shown to be suitable for use as a base layer for pavements.

Finally, the environmental characterizations consisted of verifying the iron ore tailings according to the following standards: NBR 10004/04 - Solid Waste - Classification, NBR 10005/04 - Procedure for obtaining a leached extract from solid waste, and NBR 10006/ 04 - Procedure for obtaining a solubilized extract from solid waste. Based on the results found, Peixoto et al. (2006) and Bastos (2013) classified the tailings as class II A material - non-hazardous and non-inert. However, Galhardo (2015) classified the material as class II B - non-hazardous and inert. Ojuri et al. (2017) performed heavy metal leaching tests to determine the concentrations of these metals in soil contamination. The limits considered are determined by the United States Environmental Protection Agency (US EPA, 2002). The metals analyzed were nickel, copper, lead, zinc, chromium, and barium. The mixtures did not meet the chromium and barium leaching specifications.

Class IV and V mixtures

Studies related to the production of concrete for pavement (class IV) and the production of interlocking blocks for pavement (class V) aimed to use iron ore waste as a possible material to replace natural sand, in the production of concrete. In the case of class IV, concrete can be used in base layers and surface of rigid pavements, while for class V it can be used only in surface layers. Table 7 8 present the proportions of materials studied for the production of concrete (class IV) and interlocked flooring (class V).

The tests performed for classes IV and V are different from the tests for classes I, II, and III, given the differences in the material and its purposes. Compression and bending tests were carried out for mechanical characterization and aspects of durability, water absorption,

Mixture	Resistance (MPa)
Waste	0
5% cement	1.07 - 1.44
10% cement	4.00 - 5.65
15% cement	6.50
2% lime	0.62
4% lime	1.01
6% lime	1.43
10% lime	0.79
10% slag (granulometrically)	0
50% slag (granulometrically)	0.24
70% slag (granulometrically)	0.30

Table 5 - Results of unconfined compressive strength tests - Wet chamber curing - 7 days.

Source: ANTT (2018); DANTAS (2015); GALHARDO (2015); BASTOS (2013); CAMPANHA (2011); PEIXOTO (2006); BARATI *et al.* (2020); OLIVEIRA *et al.* (2019); GRASSE *et al.* (2019); SÁ *et al.* (2019).

Mixture	Weight loss
Waste	100%
5% cement	20% - 24%
10% lime	29%
Slag (granulometrically)	100%

Table 6 - Results of wetting and drying durability tests.

Source: BASTOS (2013); CAMPANHA (2011); PEIXOTO (2006).

Class IV		Class V			
% of waste	% of sand	% of waste	% of sand	% stone dust	% of gravel 0
5%	95%	10%	90%	-	-
10%	90%	20%	80%	-	-
20%	80%	50%	50%	-	-
40%	60%	50%	25%	25%	-
50%	50%	75%	25%	-	-
60%	40%	75%	-	25%	-
80%	20%	75%	75%	-	25%
100%	0%	80%	20%	-	-
		90%	10%	-	-
		100%	-	-	-

Table 7 - Material proportions - Class IV.

Source: PEIXOTO *et al.* (2006); CHE *et al.* (2019), COSTA (2009), SANT'ANA FILHO (2013), GUERRA (2014), KUMAR (2014); PANDITHARADHYA *et al.* (2017).

and shrinkage were evaluated. Some of the results are shown in Tables 8 and 9.

From the results presented in Tables 8 and 9, it can be seen that the increase in the replacement of natural aggregate by iron ore tailings tends to reduce the compressive and flexural strengths. For the use of concrete slabs as a base and surface of rigid pavements, it is recommended that the flexural tensile strength be 4.5 MPa (DNIT, 2005). It can be seen that the concrete mixture with 10% replacement of natural aggregate by iron ore tailings met this recommendation and was the mixture with the highest compressive strength. In the case of interlocking blocks, Peixoto (2006) found that the blocks with the highest amount of iron ore tailings had lower water absorption, indicating increased durability. However, the high amount of iron ore tailings in the mixture also provided greater abrasion loss, with mixtures between 10% and 50% of tailings showing the best results between water absorption and abrasion.

The works also included physical, chemical, mineralogical, and environmental characterizations of mining tailings. The results for the physical, chemical and mineralogical characterizations were similar to those previously presented for classes I, II, and III. For the environmental classification, Guerra (2014) characterized the tailings as a class II A material - non-hazardous and non-inert. Costa (2009) classified the tailings as class II B - non-hazardous and inert.

Class VI mixtures

Iron ore tailings were also evaluated as an alternative material to compose asphalt mixtures for surface flexible pavements (SILVA, 2017; ARÊDES, 2016; APAZA et al., 2016; MOURÃO et al, 2016). The studies included the addition of waste in asphalt binders and also in asphalt mixtures. To evaluate the binders, the following tests were performed: penetration, softening point, viscosity, and ductility. The tests carried out to evaluate the asphalt mixtures were: modulus of resilience, fatigue, uniaxial repeated loading, tensile strength by diametral compression, and induced moisture loss. Some results of the tests performed are discussed below.

When added to the asphalt binder, the penetration values decreased with increasing tailings content, while the softening point increased with tailings incorporation. This shows that the addition of iron ore tailings to asphalt binders increases their consistency. The ductility tests confirm this result, where values lower than the minimum limits for pure asphalt can be observed, indicating that the material becomes less ductile before its rupture. In addition, when analyzed at the same temperature, it can be seen that there was an increase in viscosity with the use of the tailings, and, therefore, the machining and compaction temperatures must be higher. In the case of asphalt mixtures, the tensile strength by diametral compression was higher in mixtures containing iron ore tailings.

BAUXITE WASTE

Bauxite is the third most produced mineral by volume in Brazil, with about 32 million tons per year (IBRAM, 2015). For aluminum production to be economically viable, bauxite must have at least 30% of usable aluminum oxide (Al_2O_3). From the purification of bauxite, aluminum oxides (alumina) are produced, and from these, metallic aluminum is produced. It takes 5 to 7 tons of bauxite to produce 2 tons of alumina (aluminum oxide), which converts into 1 ton of aluminum (ABAL, 2017). It is estimated that there are around 600 million tons of bauxite waste in the world (ZHANG et al. 2021).

Mixture	Resistance (MPa)
Concrete C30 5%	55.0
Concrete C30 10%	63.0
Concrete C30 20%	49.3
Concrete C30 40%	50.3
Concrete C30 50%	52.0
Concrete C30 60%	41.6
Concrete C30 80%	41.1
Concrete C30 100%	33.8
Interlocked pavement 10% - 80%	34.8 - 62.4
Interlocked pavement - addition 5% - 25%	24.0 - 35.2

Table 8 - Unconfined compressive strength tests results - 28 days.

Source: PEIXOTO *et al.* (2006); CHE *et al.* (2019), PANDITHARADHYA *et al.* (2017), COSTA (2009), SANT'ANA FILHO (2013), GUERRA (2014), KUMAR (2014).

Mixture	Resistance (MPa)
Concrete C30 5%	4.0
Concrete C30 10%	4.5
Concrete C30 20%	3.7
Concrete C30 40%	3.5
Concrete C30 50%	3.9
Concrete C30 60%	2.8
Concrete C30 80%	2.0
Concrete C30 100%	1.4

Table 9 - Simple flexural test results - 28 days.

Source: PEIXOTO *et al.* (2006); CHE *et al.* (2019), PANDITHARADHYA *et al.* (2017).

The incorporation of bauxite tailings was studied in 5 ways:

- soil-tailing mixtures, with 60% soil and 40% tailings (KEHAGIA, 2008);
- mixtures of tailings stabilized with 4% fly ash (KEHAGIA, 2008);
- mortars with tailings, instead of cement, in the levels of 5%, 10%, 15%, 20%, and 25% (DODOO-ARHIN et al., 2017);
- pure tailings, as a subgrade layer for pavements (DAS et al., 2015);
- use of tailings as coarse aggregate, and in stabilized mixtures with other industrial tailings. In Western Australia, bauxite deposits have high amounts of quartz, which generates large fractions for the tailings (JITSANGIAM and NIKRAZ, 2012).

Physical, chemical, mineralogical, and mechanical characterizations were carried out for the bauxite tailings and the mixtures studied (KEHAGIA, 2008; DAS et al., 2015; DODOO-ARHIN et. al., 2017). The tests performed were: specific gravity, Atterberg limits, granulometry, modulus of elasticity, compaction, and CBR. Some results are presented in Tables 10 and 11.

Mixture	Specific gravity (g/cm³)	Atterberg Limits (%)		
		LL	LP	IP
Waste	3.33 – 3.95	25 - 37	18 - 33	4 - 7

Table 10 - Results of bauxite tailings characterization tests.

Source: KEHAGIA (2008); DODOO-ARHIN *et al.* (2017); DAS *et al.* (2015).

Mixtures	Normal energy
Waste	27
Soil - Waste (60% - 40%)	34
Waste - 4% fly ash	19

Table 11 - CBR test results (%).

Source: KEHAGIA (2008); DAS *et al.* (2015).

For the chemical and mineralogical characterization tests, X-ray fluorescence and X-ray diffraction spectrometry analyzes were performed. The results showed higher concentrations for hematite (Fe_2O_3), alumina (Al_2O_3), lime (CaO), quartz (SiO_2), sodium oxide (Na_2O), and titanium oxide (TiO_2).

The verification of the technical feasibility of using bauxite tailings in pavements requires further studies, necessary to validate the results obtained so far and to verify the technical feasibility of the use of this material. The CBR tests were performed with the energy of the Proctor Normal (energy lower than that recommended by DNIT) and showed values close to, and even higher (in the case of soil-tailings mixture), for the use of these mixtures as a subsurface layer. base. CBR tests with intermediate energy, expansion, compression, flexural and durability tests are necessary to evaluate the behavior of these mixtures.

COPPER ORE TAILING

Copper occupies the eighth position in the annual production, in volume, of mineral goods in Brazil, with 219,000 tons per year (IBRAM, 2015).

Copper tailings were studied in 2 combinations:

- soil-tailings mixture, for pavement base and sub-base layers (SOUSA, 2017);
- in addition to asphalt mixture, for surface layers (KATO, 2016).

For the soil-tailings mixture, a lateritic soil was used, with proportions of 50% soil and 50% tailings, and 70% soil and 30% tailings. In this study, physical, chemical and mineralogical, environmental, and mechanical characterizations of the tailings and mixtures were carried out (SOUSA, 2017; KATO, 2016). For the physical characterization, tests of granulometry, Atterberg limits, and the specific gravity of the grains were carried out

(Table 12). The mechanical tests consisted of compression tests, California bearing ratio (CBR), expansion, and modulus of resilience. Some of the results presented are summarized in Table 13.

Mineralogical characterization was performed through X-ray diffraction and scanning electron microscopy tests. X-ray diffraction indicated the presence, in the copper ore tailings, of the following compounds: aluminum and magnesium silicate hydroxide; quartz; potassium aluminum sulfite; double iron-molybdenum hydroxide; magnesium silicate hydroxide.

Research related to the use of copper ore in pavements also lacks studies. It is possible to notice that the increase in the use of tailings in soil-tailings mixtures reduces the liquidity limit, and the optimal moisture content and increases the dry apparent specific weight. However, there is a large decrease in the value of CBR and an increase in expansion. For the mixture of 70% soil and 30% tailings, the result of the CBR and expansion test suits the mixture as a sub-base layer.

The performance of other tests, such as compression, flexural, and durability, and new mixtures, such as cement, asphalt, and granular mixtures, using copper ore tailings, are necessary to enrich the research and understand the behavior of the material and its technical feasibility. as an alternative material for use in paving.

TUNGSTEN ORE TAILINGS (SCHEELITE)

Scheelite is one of the main ores extracted to obtain tungsten. Although the Brazilian exploration of tungsten is not very expressive, worldwide, for regional purposes, the reuse of tungsten ore tailings in the pavement can bring many environmental and economic benefits. The main Brazilian tungsten deposits are located in the state of Rio Grande do Norte (DNPM, 2016).

The scheelite tailings have been studied in two ways:

- replacing the fine aggregate in the production of concrete (BATISTA et. al., 2018);
- in mixtures of soil tailings and cement tailings (LINHARES and SILVA, 2014).

Physical, mineralogical, and mechanical characterizations were carried out

Mixture	Specific gravity (g/cm³)	Atterberg Limits (%)		
		LL	LP	IP
Waste	2.895	Not Plastic	Not Plastic	Not Plastic
Soil-waste (50% - 50%)	2.755	24.2	9.1	15.1
Soil-waste (70% - 30%)	2.660	16.5	3.1	13.4

Table 12 - Results of characterization tests of mixtures with copper ore tailings.

Source: SOUSA (2017); KATO (2016).

Mixture	Intermediary Energy	Expansion (%)
Soil-waste (50% - 50%)	21.8	0.75
Soil-waste (70% - 30%)	51.9	0.28

Table 13 - CBR test results (%).

Source: SOUSA (2017).

for the scheelite tailings. The physical characterization included granulometric analysis, determination of Atterberg Limits, and specific gravity. Some of the results are shown in Table 14.

Mineralogical characterization indicated the presence of, mainly, Cal (CaO), Quartz (SiO2), Hematite (Fe_2O_3), and Alumina (Al_2O_3). The mechanical tests included compaction tests and California bearing ratio (CBR) for the soil-tailings and cement-tailings mixtures. For the concrete with tailings, tests of unconfined compressive strength, flexural tensile, and diametral compression tensile tests were carried out. The results are presented in Tables 15 and 16.

The scheelite tailings had the highest CBR value, even using lower compaction energy. Complementary studies are necessary, but the pure tailings have the potential for application as a subgrade reinforcement and as a subbase layer. The mixture of tailings with 1.0% of cement showed a significant improvement in the CBR, pointing to another mixing alternative.

For concrete, the replacement of natural aggregate with scheelite waste tends to reduce its strengths. None of the samples analyzed in flexural traction reached the recommended value of 4.5 MPa (DNIT, 2005). Other dosages can be evaluated to achieve the desired strength.

Mixture	Specific gravity (g/cm³)	Atterberg Limits (%)		
		LL	LP	IP
Waste	3.15	Not Plastic	Not Plastic	Not Plastic

Table 14 - Results of characterization tests of mixtures with scheelite tailings.

Source: BATISTA *et al.* (2018); LINHARES and SILVA (2014).

Mixture	Normal Energy
Waste	45.5
Soil-waste (60% - 40%)	28.4
Waste-cement (99% - 1%)	62.1

Table 15 - CBR test results (%).

Source: LINHARES and SILVA (2014).

Mixture	Unconfined Compressive Strength (MPa)	Diametral compression tensile (MPa)	Flexural tensile (MPa)
Conventional concrete	29.3	3.2	4.2
10% waste (in replacement)	27.2	2.7	3.5
20% waste (in replacement)	24.1	2.6	3.3
30% waste (in replacement)	28.6	2.5	3.2

Table 16 - Results of concrete strength tests.

Source: BATISTA *et al.* (2018).

FINAL CONSIDERATIONS

The use of mining tailings in pavements has wide applicability and, therefore, a wide field of study, encompassing asphalt mixtures, cement mixtures, interlocked pavements, and granular mixtures to compose sub-base base layers and subgrade reinforcement. The research related to iron ore tailings was found to be in a more advanced state, covering a greater number of possible uses and also a greater number of tests performed. In this way, it allows a better understanding of the behavior and performance of the mixtures with the incorporation of the tailings. Bauxite, copper ore, and tungsten tailings have the potential for application but require further studies.

It is also worth mentioning that the distance between the place of extraction of ores, or the place where they are processed, and the place of application of the tailings can influence transport costs, as well as the state of the material (liquid or solid), affecting the feasibility of using the tailings. Another important observation is that there may be significant differences in the properties of these tailings depending on the extraction site, so these properties must be studied before their application. The values presented in this article serve as indicators for future studies.

The use of mining tailings in pavement works can reduce material consumption, promote a new destination for tailings, reduce environmental impacts and reduce work costs. Thus, the study of the use of this alternative material is interesting and necessary to promote sustainable development in the country.

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