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Use of waste rock and iron ore tailings in road pavement infrastructure

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ABSTRACT
The increase in the generation of waste from mining activities has motivated reflections on sustainability in the face of the serious environmental and social problems caused by the disposal of such products in the environment. Currently, the culture of tailings disposal and waste rock from iron mining is based on the construction of tailings dams and storage in waste piles. These procedures are totally contrary to sustainable development on the part of mining enterprises, as they demand large areas of the environment for their existence, in addition to having no purpose and putting the lives of populations and biomes neighboring the mines at risk. At the same time, Brazil is still going through another problem, which consists of improving the current situation of the highways, in terms of quality and quantity of paved roads. This fact seriously compromises the country's internal economic development, since highways are the main means of cargo transport and represent great importance for investments in the industry sector in general. Therefore, the present work aimed to propose an alternative destination for iron mining waste through its use in layers of road pavements. The methodology was based on the physical and mechanical analysis of mixtures containing such residues in compaction, CBR and expansion tests, as well as the subsequent comparison of the results with the standards in force in the country, imposed by the National Department of Transport Infrastructure (DNIT). The results obtained were very satisfactory, reaching high CBR indices and expansions within the required limits.

Keywords: Iron Ore Tailings, Road Pavements, Infrastructure, Sustainability.

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INTRODUCTION

Mining is an activity that, although it is extremely necessary for human beings, can cause irreparable damage to the environment. In view of this, the search for sustainability while carrying out an activity of this size is fundamental. Currently, however, it has been difficult to reconcile these two pillars.

The constant generation of significant amounts of waste from mining activity implies great environmental and social impacts. Two of the biggest of these impacts are, without a doubt, the implementation of waste piles and the construction of tailings dams, since they require the deforestation of huge areas of the environment around the mine. In addition, the existence of tailings dams puts the lives of populations and biomes neighboring the mines at risk, since their rupture is a real risk.

Thus, it is expected that any study that aims to minimize the environmental and social problems caused by the activities of the sector will be of great importance for future generations.

Therefore, the present work proposes an alternative destination to waste rock and iron mining tailings through its use in the paving sub-layers (base, sub-base and subgrade reinforcement) in order to provide better quality and lower cost pavements.

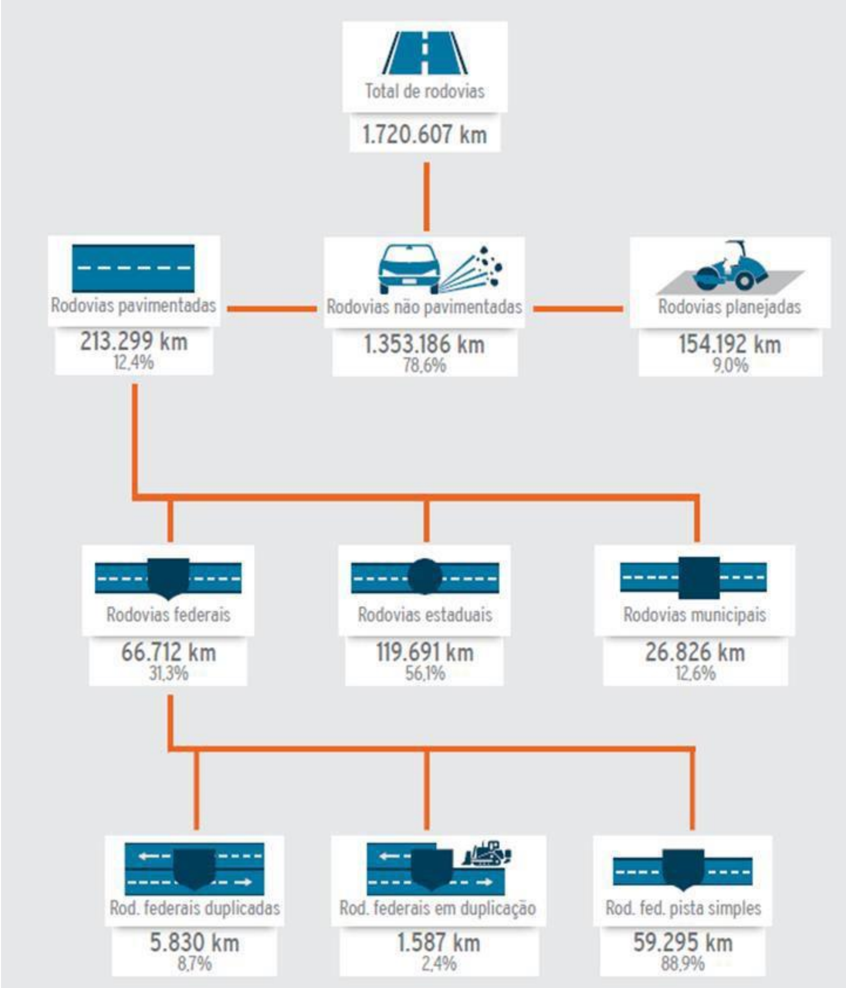
CONTEXTUALIZATION OF THE THEMES

Brief overview of the condition of Brazilian highways

One of the great challenges to be overcome by Brazil in the area of infrastructure is to improve the situation of the existing roads. The poor state of the highways causes hundreds of deaths each year and seriously limits the country's possibilities for economic growth (Silva, 2010).

The figure below illustrates, in numbers, how the highways are distributed across the country according to CNT data from the year 2015.

Figure 1.1 – Brazilian road network (Source: CNT Rodovias Survey, 2015).



In the quality ranking, only among South American countries, Brazil is in sixth place, behind Chile, Uruguay, Argentina, Bolivia and Peru. Federal investments in transportation infrastructure as a percentage of GDP have been falling systematically since the 1970s when it was 1.84%, rising to 0.29% in 2014. Between 2010 and 2014 alone, these public investments suffered a shrinkage of 30.27% (Gama, 2017).

In view of the conditions in which the national road network is, there is a need for initiatives and investments in this infrastructure sector that aim to build roads that provide better rolling conditions in terms of comfort, quality and safety.

In this context, the application of mining waste in the constitution of pavements can represent a viable alternative for the reduction of environmental liabilities caused by them, in addition to contributing immensely to the reduction of costs for the State regarding the consumption of conventional aggregates for this purpose by civil construction.

For the construction of durable highways, such as those in more developed countries, it is necessary to increase the strength of base layers, through the addition of cement or other binder, creating the soil-cement or soil-lime mixture, reducing water entry and improving resistance to applied loads (Gama, 2017).

To obtain high-quality soil-cement or soil-lime mixtures with a better cost-benefit ratio, the cement part can be replaced by pozzolan obtained through the processing of iron ore tailings. On local roads, the proper construction and compaction of a soil-cement base reasonably replaces the final paving with asphalt, providing the existence of "dirt roads" with high quality and durability and at a lower cost (Gama, 2017).

Initial considerations on iron ore waste and tailings

Mining can be understood as the process of extracting mineral products of economic value found in the Earth's crust in order to provide products to the population.

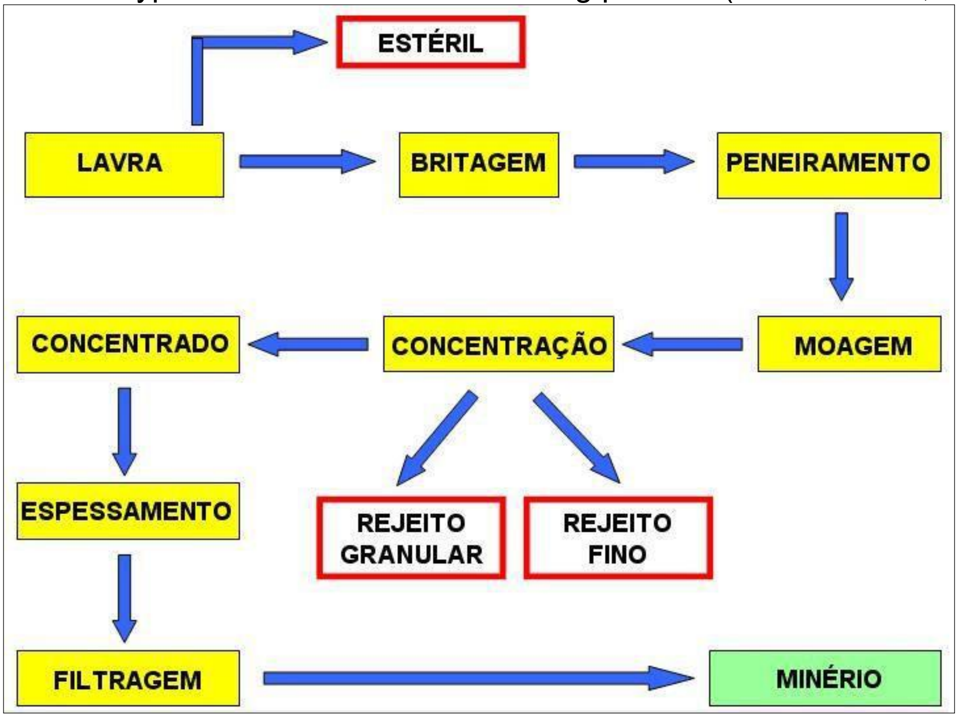
In Minas Gerais, immense reserves of iron ore are located in the region known as the Iron Quadrangle, which comprises an area of approximately 7000 km². In this region, numerous mining companies intensively exploit the mineral, resulting in significant volumes of waste, including waste and tailings (Pereira, 2005).

Waste rocks are rocks with no economic value, removed from rich rock during mining activities, where they are commonly deposited in the form of piles in green areas that are valuable to the environment. These rocks (e.g., metabasic and phyllite, in the case of iron mining) have phyllosilicates (clays) with pozzolanic properties (ability to react with hydrated lime in the presence of water to form compounds with cementitious properties).

Tailings, on the other hand, are co-products from the ore processing process, which are disposed of directly in the form of pulp or mud in large reservoirs known as tailings dams. During the iron ore concentration activities, in which the selective separation of minerals occurs, two types of waste can be generated called granular tailings, of a sandy nature, and fine tailings (mud), of clayey nature, both contain phyllosilicates, with pozzolanic and pigmenting properties.

Figure 1.2 shows in a simplified and illustrative way the typical flowchart of an iron mining process for a better understanding of the process.

Figure 1.2 – Typical scheme of the iron mining process (Source: Silva, 2010).



The intense exploration of deposits and the improvement of mining and processing techniques, over time, promote the use of ores with increasingly lower levels, consequently increasing the generation of waste and tailings, requiring larger areas for their deposition. The state of Minas Gerais is responsible for a considerable generation of mining tailings, which requires more and more investments in containment structures for its disposal.

Mining in urban areas produces environmental impacts that are inherent to the activity, generating discomfort for the local population and possible socio-environmental conflicts. The environmental implications involved in the iron mining process, the proximity to urban areas and the pressure of public opinion have made it difficult to license areas for the construction of new dams or the raising of existing dams, raising the need to investigate new methods for the reuse of tailings (Guimarães, 2011).

The enormous quantity and volume of waste and tailings from the mining and processing of iron ore, added to the lack of incentives and corporate strategies for its reuse, led to the use of structures for its storage, especially dams and piles, which generate high construction, maintenance and decommissioning costs for the miner, without any generation of economic or social return (Gama, 2017).

When these deposits become too bulky, they become, by themselves, unstable and subject to localized landslides. The constant rupture of the containment systems of these materials has caused considerable impact on the environment, such as the rupture of the Fundão Dam in Mariana/MG in November 2015 – one of the largest environmental accidents in the history of Brazil (Martins, 2017). On January 25, 2019, at 12:28 pm, the dam at the Córrego do Feijão Mine, owned by the mining company Vale, in Brumadinho, broke, causing the death of 272 people and spreading ore waste throughout the Paraopeba River basin. In 2023, the tragedy completes four years in the years 1969 and 2001 in São Sebastião das Águas Claras - MG, the rupture of an ore tailings containment dam, caused the death of workers and a serious environmental impact, which affected the entire basin of the municipality, compromised by the immense deposition of this ore tailings in the bed of its streams and streams. The accident silted up the Alegria Stream, one of the main watercourses in the region (Silva, 2017).

The transformation of waste rock, tailings and sludge generated by mining companies into raw material for products to be used in engineering works, promotes synergy between the mining sector and the civil construction park, optimizing the use of raw material, incorporating new markets and generating revenue for mining companies, reducing environmental risks and damages, transforming environmental liabilities and their costs into revenue, maximizing the use of exploited resources and creating new jobs (Gama, 2017).

An alternative for the disposal of waste generated in iron ore plants, with clayey characteristics, is the production of calcined pozzolanic material in a Flash calcination process. Previous studies by experts in the field have made it possible to develop this substance, which has already been used in countries such as France. This material has applications in the steel sector, as a binder for the production of pellets, and in the civil construction sector, and can be used in the paving of roads, among several other uses (Gama, 2016).

Brief considerations on pozzolanic materials

Pozzolanic materials are finely divided siliceous and clayey materials that, at room temperature and in the presence of water, combine with hydrated lime to form stable cementitious compounds (DNIT Paving Manual, 2006).

These materials can replace 10% to 40% of cement in concrete, improving its workability and reducing exudation, segregation, and hydration heat. The increase in impermeability and resistance to aggressive water of the concretes in which these materials are introduced recommend their use in large structures found in soils (aggressive conditions) (DNIT Paving Manual, 2006).

The most commonly used pozzolanic materials are: microsilica, fly ash, volcanic ash, heat-treated diatomaceous earths, raw shale or heat-treated clays (DNIT Paving Manual, 2006).

Flash calcination applied to iron mining tailings and waste rock

Flash calcination is a rapid heat treatment facility for pulverized materials. This technique makes it possible to transform certain products mineralogically or chemically. The heat treatment lasts no more than a few seconds and is designated as flash in case pulverized particles undergo a mineralogical transformation (Martins, 2017)

In the case of iron mining, calcination is ideal for the production of metakaolin, from kaolinite, a clay-mineral removed from the ore mine. This clay is associated with different minerals (phyllosilicates, quartz and iron oxides) in varying proportions according to the mineral deposit, kaolin.

Kaolin is a capping rock for several mineral reserves such as itabirite (source rock of iron ore) and limestone. It is formed by a group of hydrated aluminum silicates, mainly kaolinite (DNPM, 2018).

According to Gama (2016), the innovative process based on rapid calcination, applied to waste rock and dam sludge, develops important properties such as increasing the specific surface and increasing the pozzolanicity index (ability to react with $Ca(OH)_2$ in the presence of water) of the material, transforming it in an active binder. This binder is a high-strength binder, used in the treatment of soils, in base and sub-base for roads as well as addition to concrete, mortars and ceramic materials.

The use of waste and tailings in paving

In Brazil, there is still a lack of research and published studies that address the use of iron ore tailings in paving, compared to industrial waste (Silva, 2010). Pozzolanic material from tailings and mining waste can be applied to paving roads. This material is used starting from the base and sub-base and cold asphalt capping during the process in question. This measure presents itself as another viable and sustainable solution to the problem of the accumulation of mining waste in dams and dikes in power plants (Gama, 2016).

One drawback of roads built from clay, sand and silt (soils considered weak) is that they lose their resistance properties over time, as there is an increase in water concentration. Knowing that there is a variation in the concentration of water in these materials throughout the year, the durability of the road is compromised, making it more expensive to maintain. In this context, an advantage of the use of pozzolanic material in highway infrastructure is the fact that binders produced from the Flash calcination of mining waste and tailings, applied to the base and sub-base of the pavement considerably improve the properties of the soil, increasing its resistance and durability and reducing its susceptibility to water ingress.

In France, the use of special materials produced from waste rock and mining tailings as a construction material for the structuring of road pavements is already consolidated. It should be noted that, in the case of France, the technology is standardized, legalized and referenced by public and private organizations for use and use in the construction of pavements and access roads. Therefore, its migration to Brazil would only involve encouraging its use at the federal, state and municipal levels, since the materials and their applications are already standardized by ABNT and DNIT (Gama, 2017).

Initial considerations about pavements

According to the DNIT Paving Manual (2006), a highway pavement is a superstructure consisting of a system of layers of finite thickness, based on a semi-space theoretically considered as infinite – the infrastructure or foundation terrain, which is called subgrade. The layers are made up of materials of different strengths and deformabilities that are placed in contact, resulting in a high degree of complexity with regard to the calculation of stresses and strains acting on them, resulting from the loads imposed by traffic.

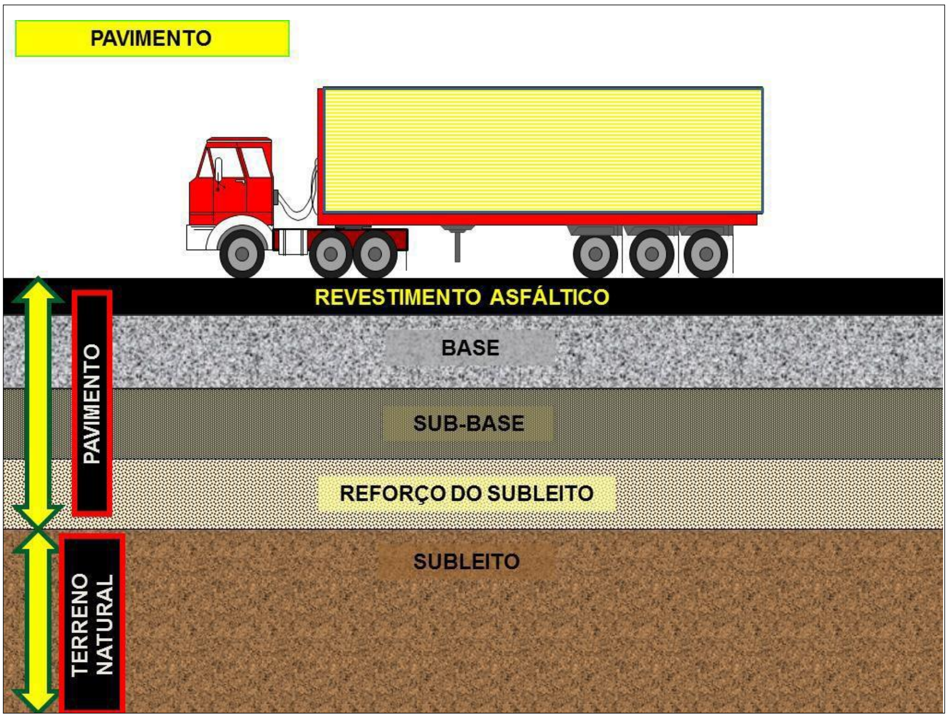
Classification of floors

In general, pavements can be classified as: flexible, rigid and semi-rigid (DNIT, 2006).

Flexible flooring

Flexible pavements are those made up of layers that do not work with traction. They are usually made up of thin bituminous coating on purely granular layers. The bearing capacity is a function of the load distribution characteristics by a system of overlapping layers, where the best quality layers are closer to the applied load. An example of a typical section can be seen in Figure 1.3 below.

Figure 1.3 – Typical structure of a flexible pavement (Silva, 2017).



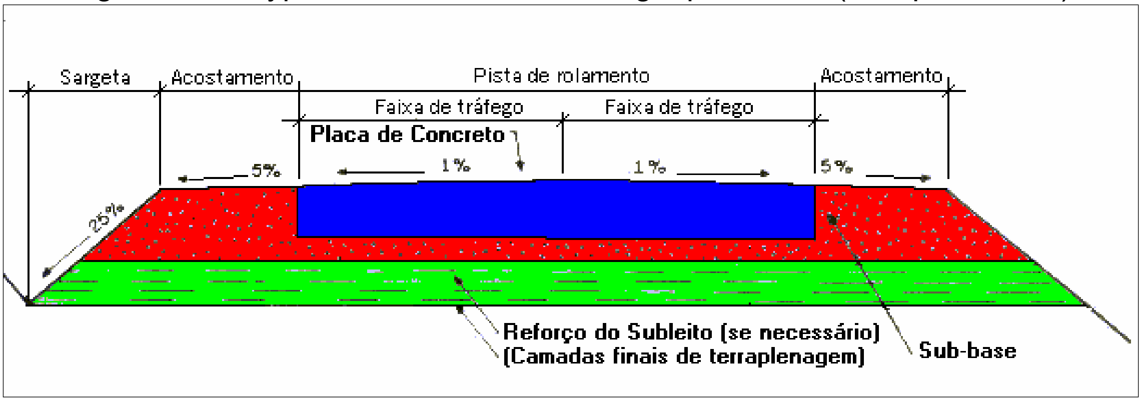
In traditional design, the geotechnical characteristics of the materials to be used are considered, and the definition of the thickness of the various layers depends on the

California Support Index (CBR) value and the minimum request for a standard axle (8.2 tons).

Rigid pavement

Rigid floors are made up of layers that work essentially with tension. Its design is based on the resistant properties of Portland cement concrete slabs, which are supported on a transition layer, the subbase. The determination of the thickness is achieved from the tensile strength of the concrete and considerations are made in relation to fatigue, reaction coefficient of the sub-grade and applied loads. They are poorly deformable with a longer service life. The design of the flexible pavement is commanded by the resistance of the subgrade and the rigid pavement by the resistance of the pavement itself (Marques, 2016). A characteristic section of this type can be seen in Figure 1.4.

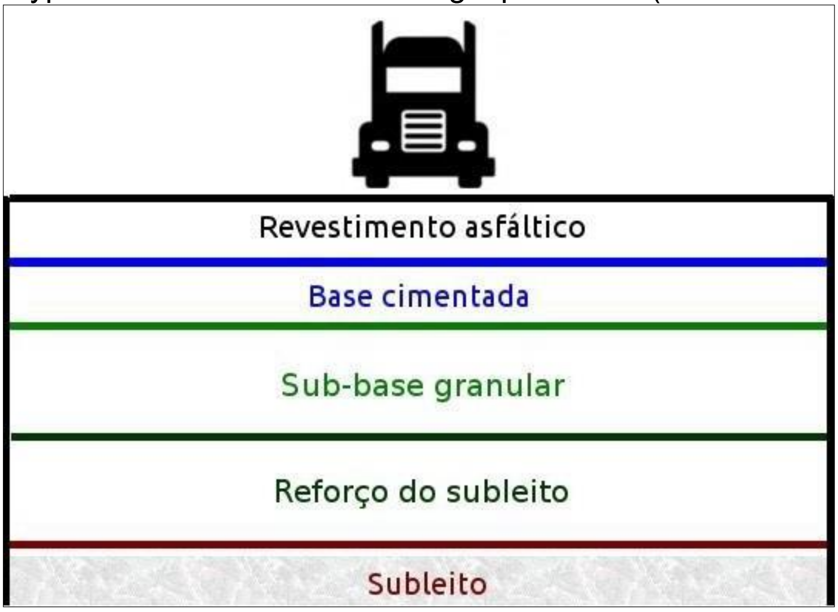
Figure 1.4 – Typical cross-section of a rigid pavement (Marques, 2016).



Semi-rigid pavement

A semi-rigid pavement is an intermediate situation between rigid and flexible pavements. This is the case of soil-cement, soil-lime, soil-bitumen mixtures, among others, which have reasonable tensile strength. When you have a cemented base under the bituminous coating, the floor is said to be semi-rigid. Asphalt concrete reinforced pavement on concrete slab is considered as composite pavement. Below, figure 1.5 illustrates a so-called semi-rigid pavement.

Figure 1.5 – Typical cross-section of semi-rigid pavement (Source: ecivilnet.com).



The latter is the category of flooring that best suits the purpose of this work (semi-rigid pavements), as it accepts alternative materials in its composition.

Nomenclature of floor layers

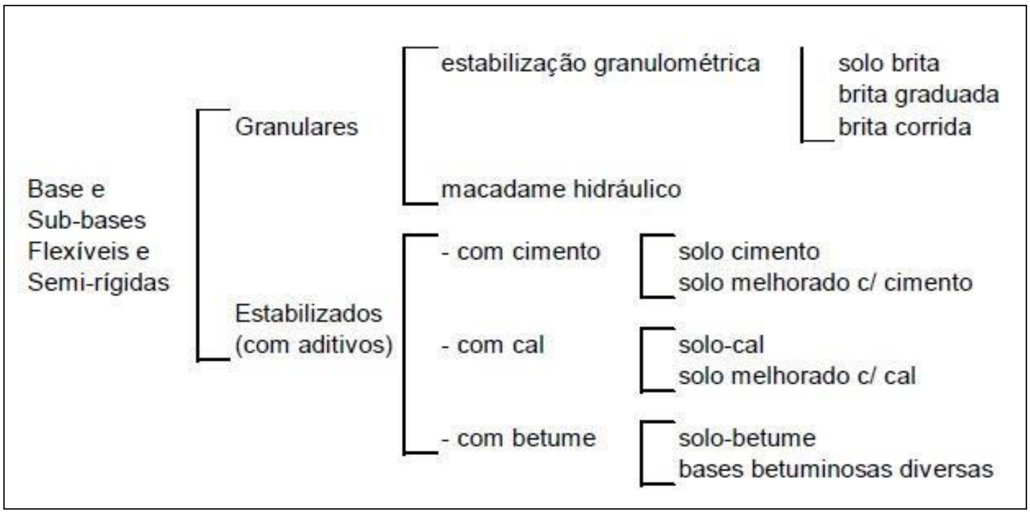
According to DNIT (2006), the main constituent layers of the pavement structure and the characteristics of the materials used in the execution are:

- Coating: layer of the surface, impermeable, which receives the direct action of vehicle traffic and is intended to improve it, in terms of safety, comfort and resistance to wear and tear.
- Base: Layer intended to resist and distribute the forces arising from traffic and on which the coating is built.
- Sub-base: Layer directly below the base. It can be used to regulate the thickness of the base.
- Subgrade reinforcement: It is the layer of constant thickness transversely and variable longitudinally, according to the pavement dimension, being part of the and which, due to technical and economic circumstances, will be carried out on the regularized subgrade. It serves to improve the qualities of the subgrade and regularize the thickness of the subbase.
- Regularization of the subgrade (leveling): It is the operation aimed at shaping the bed, transversely and longitudinally. It may or may not exist, depending on the conditions of the bed. It includes cuts or fillings up to 20 cm thick.
- Subgrade: It is the foundation ground where the pavement is built.

Classification of flexible and semi-rigid bases and subbases

According to DNIT (2006), the bases and sub-bases can be grouped according to the scheme below:

Figure 1.6 – Classification scheme of bases and sub-bases (DNIT Paving Manual, 2006).



In view of the exposed scheme, it is perceived that the addition of lime to a material is a technique used to promote the stabilization of the resulting soil, which is in accordance with the purpose of this work

Soil stabilization

According to Vargas (1997), stabilizing a soil is to use a process in order to obtain greater resistance to load stresses, climatic actions and wear. This technique is used when there is no material with adequate competence or when large distances between the deposit and the work make the transportation costs high to be used in pavement layers, foundation reinforcements or slope stability.

From the road point of view, to stabilize a soil is to subject it to treatments with or without the presence of additives, so that the pavement layers: subgrade, sub-base and base, are able to withstand the imposed traffic conditions - without considerable displacements - resisting wear and weather without degradation (Baptista, 1976).

All stabilization involves the study of soils, and it is necessary to characterize these materials and their properties. Therefore, the use of materials in appropriate proportions, together with the mastery of stabilization techniques is of fundamental importance in road construction, directly impacting the cost of the work and consequently the schedule.

According to Oliveira (2010), the soil stabilization process aims to improve the geotechnical characteristics to support the projected work, that is, to increase the gain in strength and stability in soil properties, and presents the following definitions:

- Stabilized soil: when there is a significant gain in resistance with the use of the additive;
- Improved soil: when the addition seeks to improve other properties (reduced plasticity and expansion and contraction), without a significant gain in strength.

Thus, it can be said that the main methods of soil stabilization are mechanical, granulometric and chemical.

OBJECTIVES AND RELEVANCE

GENERAL OBJECTIVE

The general objective of this work is to propose an alternative destination for tailings and waste materials from iron mining through its use in the infrastructure of road pavements (base, sub-base and subgrade reinforcement) in order to provide better quality and lower cost pavements, given the problems currently caused for the disposal and deposition of these materials in the environment and the current poor conditions of the country's roads.

SPECIFIC OBJECTIVE

Verify the physical and mechanical behavior of mixtures containing tailings and iron mining waste, in the appropriate proportions, through compaction, CBR, and expansion tests.

DEVELOPMENT

SAMPLE CHARACTERIZATION

The material used in this study was donated by Mineração Samarco, as well as the mineralogical characterization and granulometric distribution of the tailings used.

The informed constitution of the material was as follows:

- 85% sandy iron ore tailings
- 15% Metakflex (binding material consisting of 60% calcined metabasic rock from waste rock removed from iron ore mining + 40% hydrated lime)

In terms of mass, the sample proportion was:

- 35 kg: total mass of the sample
- 29.75 kg: Rejeit arena
- 3.15 kg: metabasic
- 2.1 kg: hydrated lime $Ca(OH)_2$

Mineralogical characterization of sandy tailings

The minerals that constitute the portion of tailings used are shown in table 3.1 below:

Table 3.1 – Mineralogical characterization of the sample.

Sample – Sandy tailings	
Mineral	%
Caulinita	9,1
Mica	-
Rutile	-
Goethite	17,5
Feldspar	-
Hematite	9,3

Magnetite	-
Gibbsite	-
Quartz	50,7
Talc	13,4

Source: Provided by Professor Evandro Moraes da Gama

Density Data:

- Bulk density: 1.20 g/cm³
- Actual density: 2.89 g/cm³

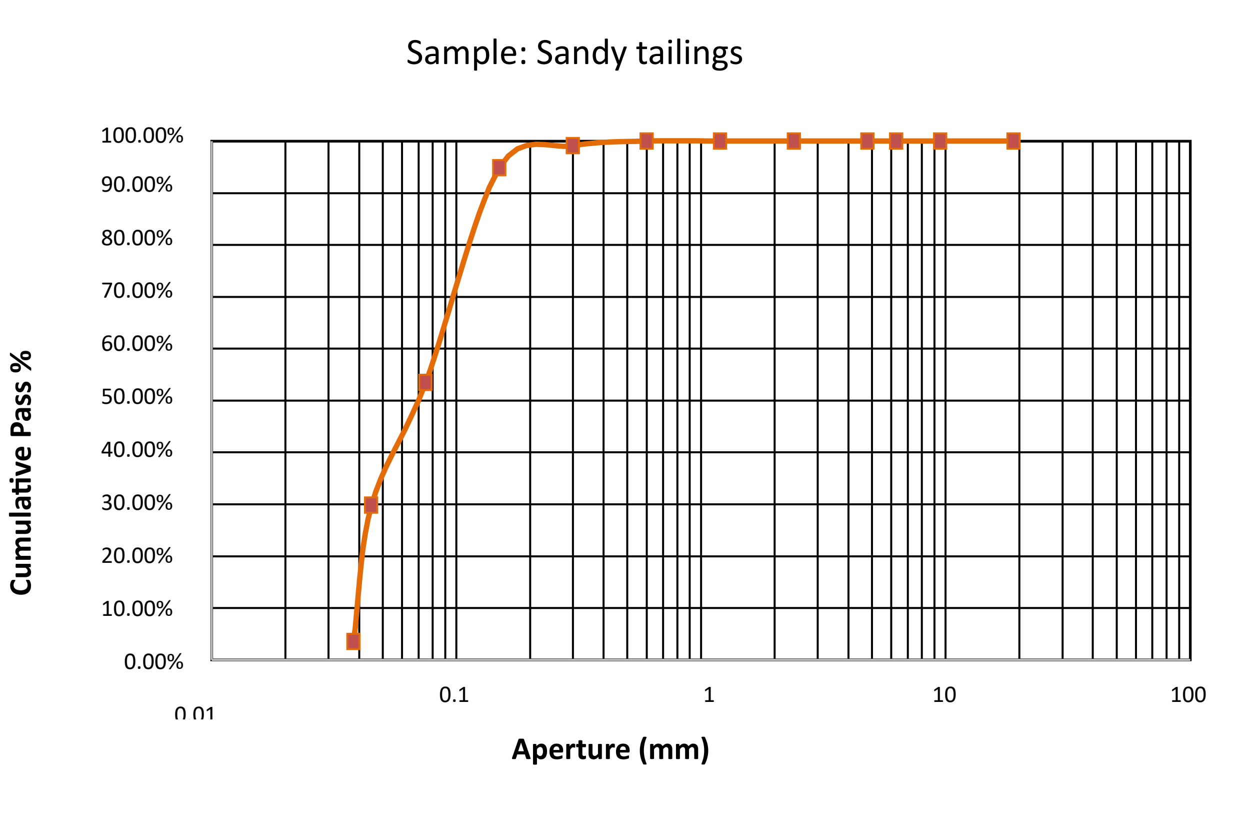
Table 3.2 – Granulometry of the tailings.

Particle Size Analysis Sandy tailings				
Sieve (mm)	Mass (g)	% retained	% cumulative withdrawal	Cumulative pass-through %
19	0	0,00%	0,00%	100,00%
9,5	0	0,00%	0,00%	100,00%
6,3	0	0,00%	0,00%	100,00%
4,8	0	0,00%	0,00%	100,00%
2,4	0	0,00%	0,00%	100,00%
1,2	0	0,00%	0,00%	100,00%
0,6	0	0,00%	0,00%	100,00%
0,3	0,880	0,89%	0,89%	99,11%
0,15	4,160	4,22%	5,11%	94,89%
0,075	40,840	41,39%	46,50%	53,50%
0,045	23,400	23,72%	70,22%	29,78%
0,038	25,890	26,24%	96,46%	3,54%
< 0.038	3,490	3,54%	100,00%	0,00%
Total	98,660	100,00%	-	-

Source: Provided by Professor Evandro Moraes da Gama.

The respective particle size curve of the sandy tailings is shown in the graph below:

Graph 3. 1 - Granulometric curve of the sandy tailings (Source: Provided by Professor Evandro Moraes da Gama).



SAMPLE PREPARATION

First, the material was dried in an oven for 24 hours so that the studies could begin with the material at its minimum possible moisture. Figure 3.1 below represents the material in its "natural" state.

Figure 3.1 – Material in nature.

All the tests performed in this work were carried out at the Laboratory of Geotechnics and Transport of the School of Engineering of UFMG.

SOIL COMPACTION

According to the DNIT Paving Manual (2006), compaction is the operation that results in the increase of the apparent specific mass of a soil by the application of pressure, impact or vibration, which causes the constituent particles of the material to come into more intimate contact, by expelling air. By reducing the percentage of air voids, it is also possible to reduce the tendency for the moisture content of the pavement materials to vary during the service life.

After this process, the contact area of the solid particles increases, also increasing the resistance of the soil and reducing its deformability. In addition, compacted soil obviously becomes denser, which makes it difficult for water to pass through its interior, that is, it becomes less permeable.

On a laboratory scale, a mass of moist soil is taken in a cylinder and, applying a certain number n of blows through the height drop H, from a socket of weight P, results, after compaction, a certain volume V. The objective of the process is to obtain a compaction curve from which the optimal moisture content and the value of its maximum dry bulk density are identified. In other words, optimal moisture is the humidity at which the material will present the highest value for its dry bulk density.

Compaction Energy is the effort applied in the process. The process is repeated for different samples with different moisture contents, assuming that the optimal moisture for the material is among the moisture contents used.

According to DNIT (2006), the compaction energy for the base and sub-base materials of pavements should be modified energy, in which the small cylinder and the large socket are used in the compaction of 5 layers of soil, applying 27 blows to each layer, according to the NBR 7182 standard.

Compaction test

For the compaction test, 5 samples of 2.0 kg each were weighed, and different amounts of water were added to each sample in order to assume moisture contents of 11%, 13%, 15%, 17% and 20%.

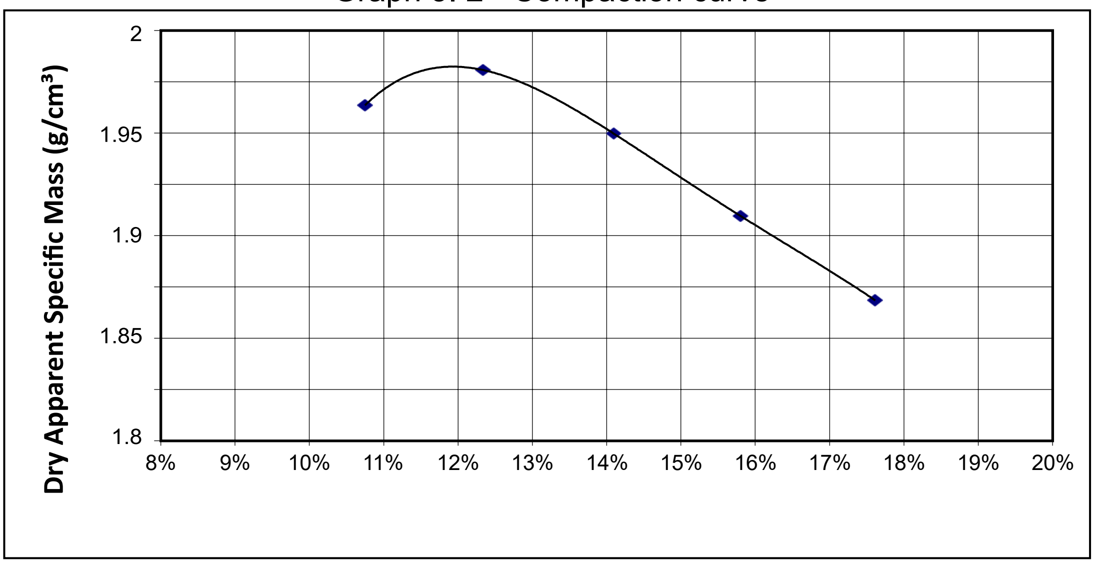
Each sample was well homogenized in a metal tray, turning it continuously as the amount of water necessary to reach the humidity in question was added. After homogenization, the material was separated into 5 apparently equal portions, corresponding to each compaction layer, as shown in the following figure.

Figure 3.2 – Separation of the sample into five portions.

The material was then compacted in the cylindrical mold, in five layers, receiving 27 strokes in each layer, evenly distributed over the surface of each layer. After compacting each mixture, the complementary cylinder was removed and the material was scraped to the exact height of the mold with the help of a beveled ruler. Once this was done, the mass of the set (mold + moist soil) was weighed and the weight of the mold was subtracted, in order to obtain the weight of the moist soil. Subsequently, small triplicate samples were taken from the moist soil and placed in the greenhouse for 24 hours, to determine the real moisture of each mixture.

Moisture content values of 10.7%, 12.3%, 14.1%, 15.8% and 17.3% and apparent dry density (g/cm³) of 1.93, 1.96, 1.90, 1.82 and 1.74 were obtained, respectively. From these levels, a compaction curve was drawn as shown in the graph below.

Graph 3. 2 - Compaction curve



The results obtained were optimum moisture content of 12% and maximum dry bulk density of 1.965 g/cm³.

California Support Index (ISC) or CBR (California Bearing Ratio) Assay

The CBR test consists of determining the relationship between the pressure required to produce the penetration of a piston in a specimen and the pressure required to produce the same penetration in a standardized gravel. The result is expressed as a percentage.

According to the DNIT Paving Manual (2006), the requirements for the materials of the base, sub-base and reinforcement layers of the subgrade of pavements, in relation to the CBR values are:

- Base: CBR ≥ 60%
- Sub-base: CBR ≥ 20%
- Subgrade reinforcement: CBR ≥ 2%

Procedures

From the result obtained in the compaction test for the optimal moisture of the material (12%), 5 samples were prepared for the CBR test with this same moisture to give more credibility to the study through the comparison of the five results.

The compaction energy used was again the modified energy, as required by DNIT, however, this time in the large cylinder and large socket, sizes indicated for CBR tests, as well as the addition of a standardized spacer disc at the base of the mold.

Again, each sample was well homogenized in a metal tray by continuously turning it over as the amount of water necessary to reach the determined optimal humidity (12%) was added. After homogenization, the material was again separated into 5 apparently equal portions, corresponding to each compaction layer. Each layer received 55 hits (modified energy), evenly distributed over each layer.

After compacting each specimen, the complementary cylinder was removed and the material was scraped to the exact height of the mold with the aid of a beveled ruler. Once this was done, the cylinder was inverted, the spacer disc was removed from the base and a perforated plate with an expansion rod was placed in the space left by the spacer disc and, on top of it, two overload discs totaling 4540±20 g.

After this procedure, the specimens were submitted to complete immersion in a tank with water to analyze their expansion in relation to the initial height of the specimen (height of the cylindrical mold). An extensometer was attached to the rod of each perforated plate to read the expansion of the soil. Expansion readings were taken every 24 hours for 4 days.

Also according to the DNIT Paving Manual (2006), the requirements for the materials of the base, sub-base and reinforcement layers of the subgrade of pavements, in relation to the expansion values are:

- Base: Expansion ≤ 0.5
- Sub-Base: Expansion ≤ 1
- Subgrade reinforcement: Expansion ≤ 1

The results obtained are shown in the table below:

Table 3.3 – Results of expansion of the specimens.

Specimen	1	2	3	4	5
Strain gauge reading (mm) after 1 day	0,60	0,38	0,65	0,61	0,41
Strain gauge reading (mm) after 2 days	0,55	0,45	0,56	0,55	0,50
Strain gauge reading (mm) after 3 days	0,44	0,47	0,51	0,54	0,55
Strain gauge reading (mm) after 4 days	0,44	0,50	0,51	0,54	0,55
Expansion (%)	0,384	0,436	0,445	0,471	0,479

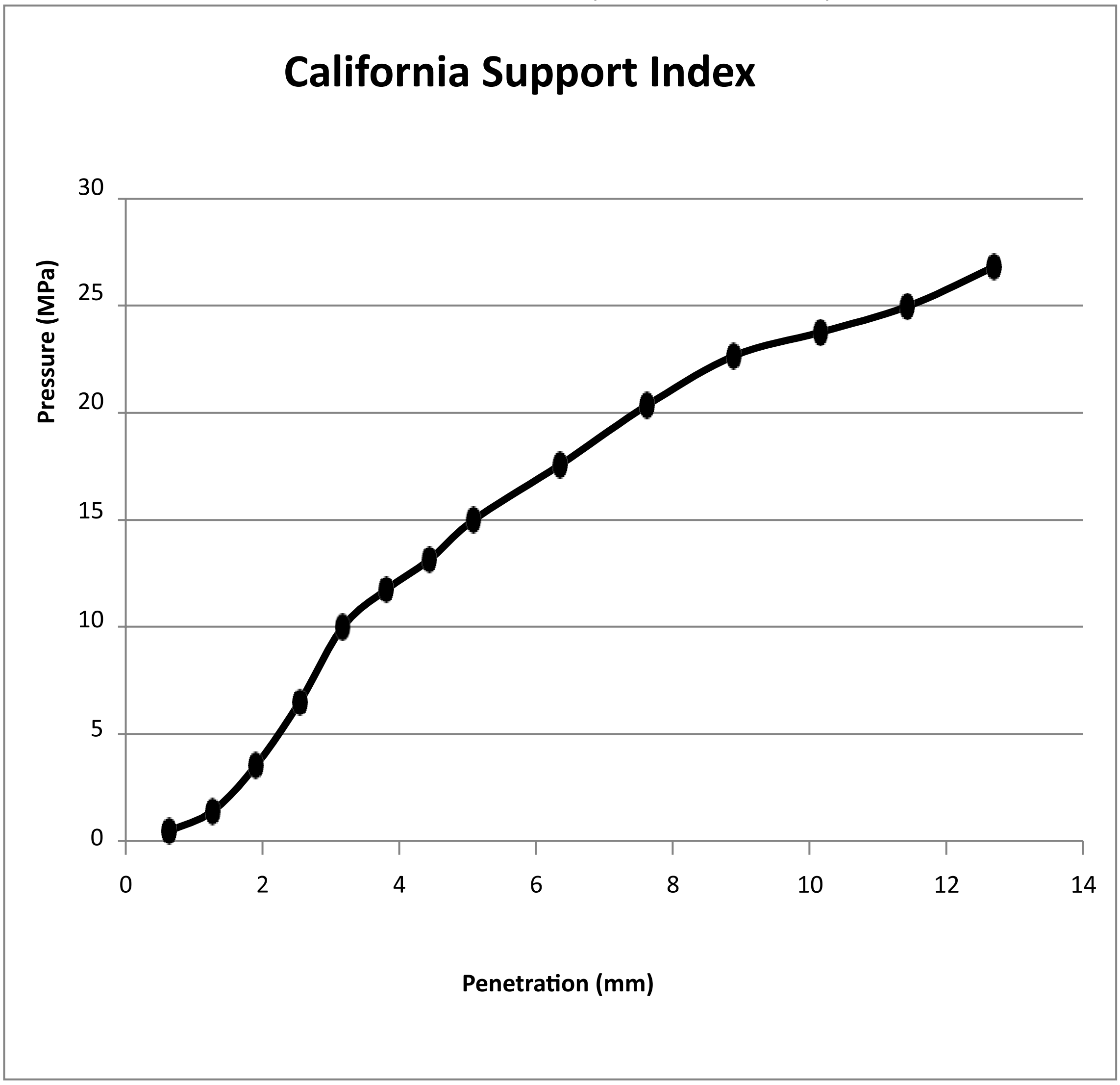
After the immersion period, the specimen was removed from the tank and left on the bench for the water to drain. The assembly was then prepared for penetration as shown in Figure 3.3.

Figure 3.3 – Electric press.

Specimen penetration occurs at a constant speed of 0.05 in/min (or 1.27 mm/min). Every 0.5 min, the strain gauge of the press ring was read (mm). Each reading considered is a function of a piston penetration into the specimen and a specified time. From these readings, it is possible to determine the load (N) and pressure (MPa) exerted by the press.

A pressure curve (MPa) was then constructed as a function of penetration (mm) for each specimen, which can be seen below in the respective graphs and, subsequently, the respective tables were assembled with the data used to calculate the CBR of each specimen.

Specimen 1
Graph 3. 3 - Pressure versus penetration curve (Test specimen 1)



The reading points corresponding to 2.54 mm (0.1 in) and 5.08 mm (0.2 in) penetration provide the pressure values to determine the CBR index, which is calculated by dividing the calculated pressure by the standard pressure and multiplying the value by 100. The CBR index is the highest of the values obtained in the penetrations of 2.54

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mm and 5.08 mm:

$$CBR = \frac{Pressão\ calculada}{Pressão\ padrão} \times 100$$

Table 3.4 – California Support Index (Test Body 1).

Penetration (mm)	Pressure (MPa)		CBR (%)	CBR adopted (%)
	Calculated	Pattern		
2,54	6,4726	6,90	93,81	144,73
5,08	14,9796	10,35	144,73	

Specimen 2

Graph 3. 4 - Pressure versus penetration curve (Test specimen 2)

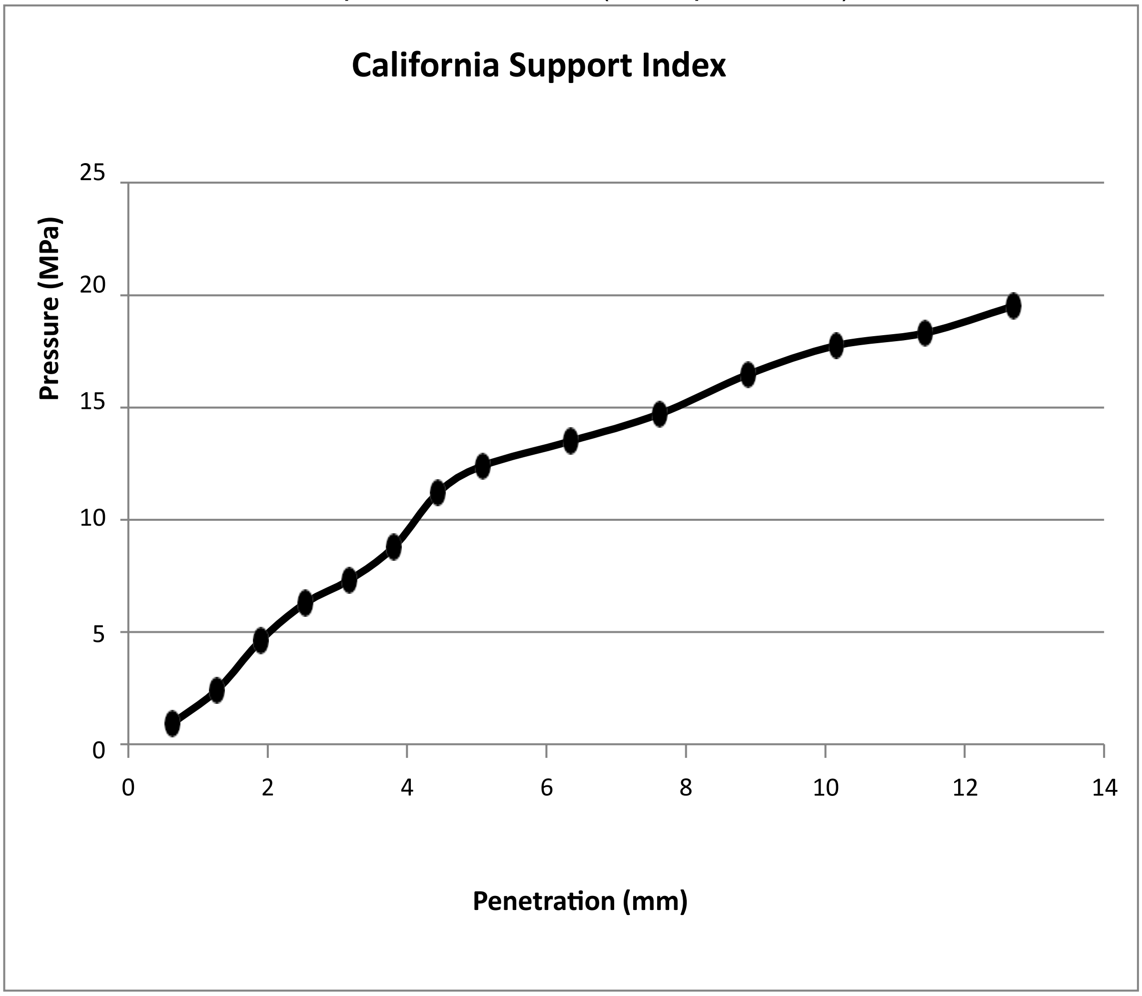

Table 3.5 – California Support Index (Test Body 2).

Penetration (mm)	Pressure (MPa)		CBR (%)	CBR adopted (%)
	Calculated	Pattern		
2,54	6,2877	6,90	91,13	
5,08	12,3905	10,35	119,71	119,71

Specimen 3

Graph 3. 5 - Pressure versus penetration curve (Test specimen 3)

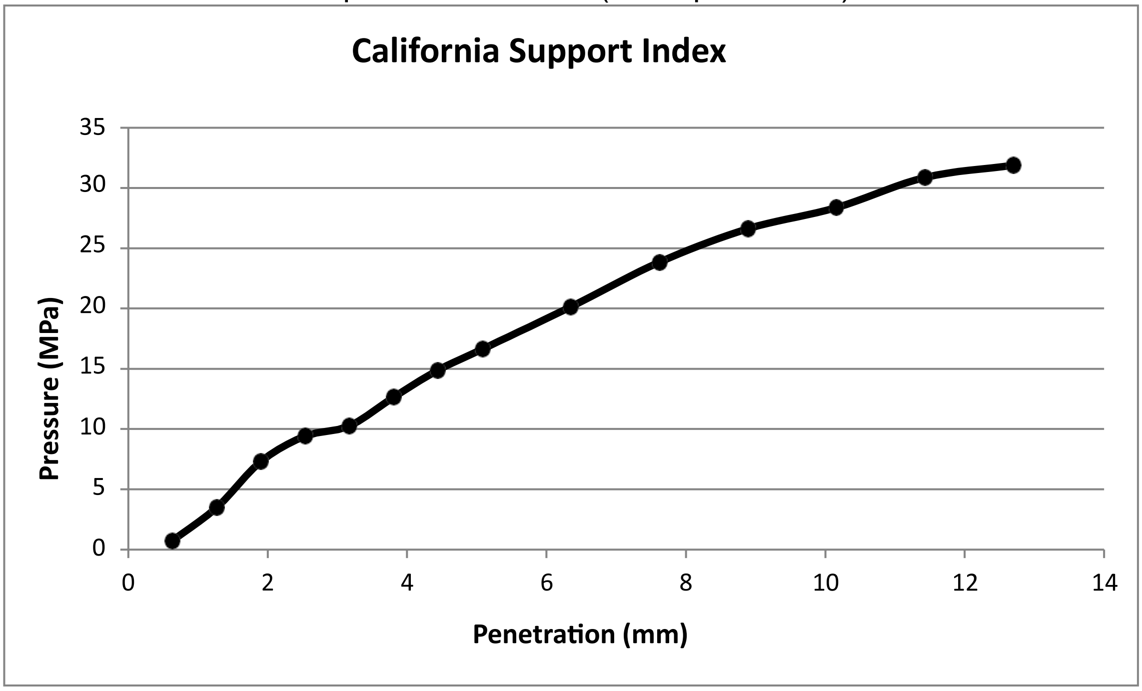

Table 3.6 – California Support Index (Test Body 3).

Penetration (mm)	Pressure (MPa)		CBR (%)	CBR adopted (%)
	Calculated	Pattern		
2,54	9,4316	6,90	136,69	
5,08	16,6440	10,35	160,81	160,81

Specimen 4

Graph 3. 6 - Pressure versus penetration curve (Test Body 4)

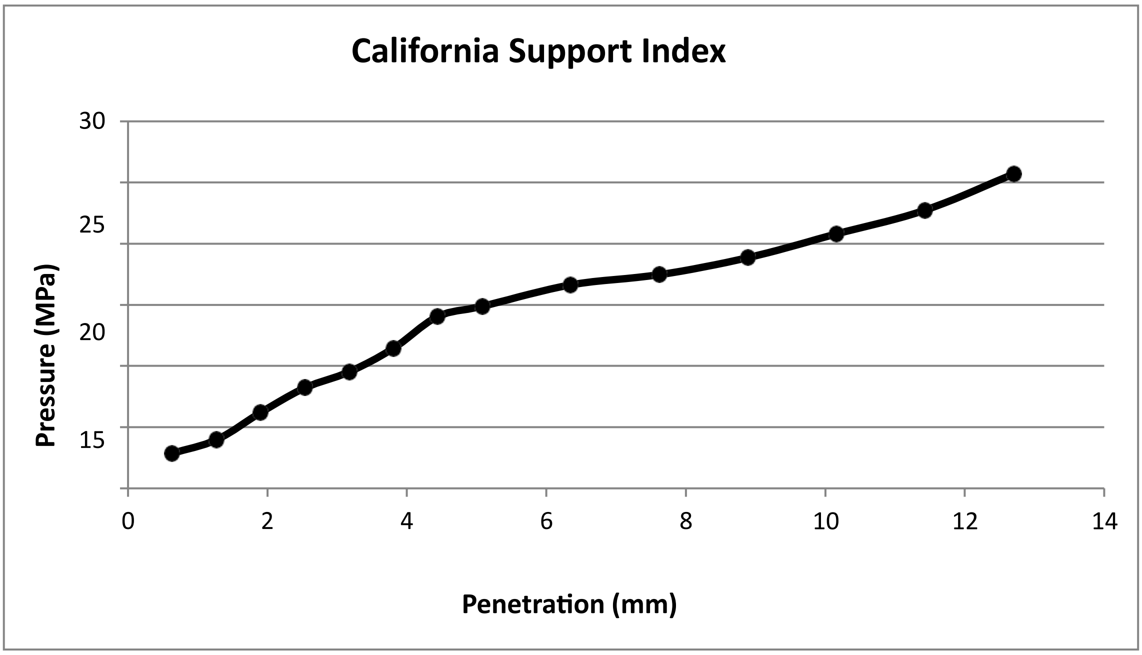

Table 3.7 – California Support Index (Test Body 4).

Penetration (mm)	Pressure (MPa)		CBR (%)	CBR adopted (%)
	Calculated	Pattern		
2,54	8,2295	6,90	119,27	
5,08	14,8871	10,35	143,84	143,84

Specimen 5

Graph 3. 7 - Pressure versus penetration curve (Test specimen 5)

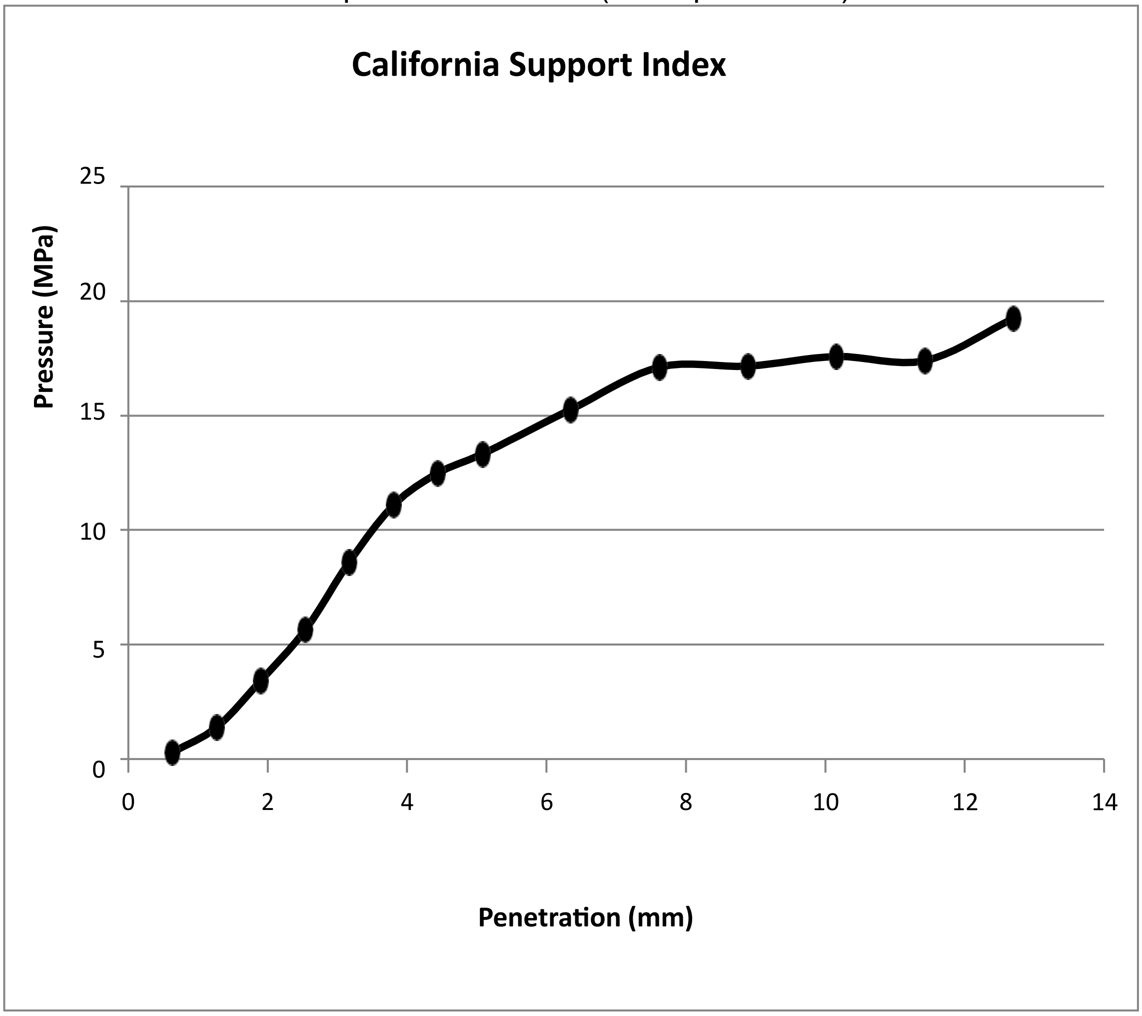

Table 3.8 – California Support Index (Test Body 5)

Penetration (mm)	Pressure (MPa)		CBR (%)	CBR adopted (%)
	Calculated	Pattern		
2,54	5,6404	6,90	81,74	128,65
5,08	13,3152	10,35	128,65	

Note: In addition to the CBR and expansion values for the materials that make up the paving layers, DNIT also makes some requirements regarding the Atterberg Limits (or

Consistency Limits), which are the Liquidity Limit (LL) and the Plasticity Limit (LP).

- Liquidity limit: it is the state in which the soil has a water content that, above this value, the soil behaves as a liquid.
- Plasticity limit: it is the state in which the soil has a water content that, above this value, the soil behaves as a liquid.
- The standard of the Brazilian Association of Technical Standards (ABNT) that regulates tests for LL and LP is NBR-6457, where it is specified that the material for carrying out such tests must have a granulometry greater than 0.42 mm. However, the material used in this work has a much lower particle size (between 0.038mm and 0.075mm basically), as shown in the particle size distribution provided earlier in the text. In view of this, it was not possible to carry out such tests.
- This fact, however, does not compromise the use of the material for the paving purposes in question in the work, in view of the studies cited in the text. In addition, the tests carried out (Compaction, CBR and Expansion) prove that the material has sufficient mechanical strength, as the results meet the requirements of DNIT.

CONCLUSION

In view of the results obtained in the tests and comparing them with the requirements of the National Department of Transport Infrastructure (DNIT), the use of tailings and waste iron ore in the civil construction industry as raw material in the road paving process can be considered as a good alternative for the disposal of such waste. The material has a great demand, with a projection of growth, in addition to very interested raw material suppliers. In addition, the use of such material encourages sustainable practices in the mining sector, reducing the environmental and social liabilities caused by the current way of depositing these wastes in the environment (tailings dams and waste piles), as well as providing quality pavements at lower costs than pavements built with conventional aggregates.

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