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Geociências

Geomechanical properties of mixtures of iron ore tailings improved with Portland cement

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Abstract:

This study aimed to use iron ore tailings in the construction of road pavements and embankments. To this end, it was investigated the geomechanical properties of mixtures of two iron ore tailings, improved with cement, whose results are important to characterize the behavior of mixtures regarding the mechanical actions imposed to the structural layer of paved roads. The results indicated that the studied tailings and mixtures without addition of cement presented uniform particle size, and despite having a CBR value that allows their application in sub-base layers, there would be the risk of other situations that compromise the mechanical behavior. However, with the addition of 5% cement, these mixtures showed behavior compatible for use in sub-base layers and embankments.

Keywords: iron tailings, cement, geomechanical properties.

Introduction

The construction of road pavements and embankments are engineering works that require a significant amount of material having geomechanical behavior which fundamental parameters meet technical specifications of current regulations.

In fact, if natural soils, which fulfill the necessary requirements for a given function are scarce and often distant from the points of use becoming economically unviable, soil stabilization appears as a viable option, mainly in the which concerns the economic, technical and environmental aspects In this context, the

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use of alternative materials, such as mining tailings and other industrial waste, represents a technical and environmentally sound alternative possibility.

In order to continue studies already proposed in the literature and analyzing different mixtures of iron ore tailings improved with cement, this study investigated the influence of the different cement content on the mechanical resistance of these mixtures, for different curing times, through unconfined compression tests. It was also analyzed the bearing capacity of these mixtures, compared to their optimum compaction parameters through the CBR test.

Material and methods

Two types of iron ore tailings were provided by the company Vale S/A, from the Mine Alegria, in the municipality of Mariana, State of Minas Gerais. Tailings were sampled in the processing, and then called flotation tailing, which was generated by hydro cyclones in the separation of minerals by flotation, and magnetic concentration tailings, which was obtained from the fall cone for magnetic concentration tailings.

Each sample of iron ore tailing was geotechnically characterized by the following laboratory tests: (i) Atterberg limits, according to the testing methods ME 082 and ME 122 (*Departamento Nacional de Estradas de Rodagem* [Dner], 1994a), b) (ii) Unit weight of solids, according to the technique NBR 6508 (*Associação Brasileira de Normas Técnicas* [ABNT], 1984) and (iii) Sieve Analysis, according to testing method ME 051 (*Departamento Nacional de Estradas de Rodagem* [Dner], 1994c).

Table 1 shows the geotechnical characterization and classification of tailings according to the classification system of TRB (Transportation Research Board).

The Portland cement CP-II-E-32, manufactured by the Company of Paraíba Valley Cement, commercially known as Tupi, was used as a chemical stabilizer.

Also, the Compression Test under Normal Proctor energy was performed following the technical standard NBR 7182 (*Associação Brasileira de Normas Técnicas* [ABNT], 1986), for mixtures with different contents of iron ore tailings, obtaining the optimum compaction parameters that were used in the CBR (California Bearing Ratio) tests. The mixture with the best response in terms of mechanical strength obtained in this test was considered as the optimum mixture and then characterized with respect to the Unconfined Compression Strength, according to the technique NBR 12025 (*Associação Brasileira de Normas Técnicas* [ABNT], 2012a) by adding different cement content and using different curing times.

The mixture of iron ore tailings considered as optimal when improved with different cement contents was evaluated for its mechanical strength according to the CBR test and was geotechnically classified according to the MCT Methodology, following the guidance of the CLA 259 classification method (*Departamento Nacional de Estradas de Rodagem* [Dner], 1996). To this end, it was necessary to carry out the following tests: weight loss by immersion, according to the ME 256 test method (*Departamento Nacional de Estradas de Rodagem* [Dner], 1994d) and Mini-MCV compaction, according to the method ME 258 (*Departamento Nacional de Estradas de Rodagem* [Dner], 1994e).

Mixtures tested contained 10, 20, 30, 40, 50, 60, 70, 80 and 90% flotation tailings with 90, 80, 70, 60, 50, 40, 30, 20 and 10% magnetic concentration tailings, respectively, in relation to the dry unit weight percentage.

Specimens were made with each of these mixtures, using the optimum compaction parameters under Normal Proctor energy, and tested for the California Bearing Index (ISC or CBR). The mixture with the highest mechanical bearing capacity in the CBR test was considered as the mixture of ore tailings with optimum contents.

For the mixture of iron ore tailings with optimum contents, specimens were molded with and without the addition of cement, under Normal and Intermediate Proctor energy, and subjected to Unconfined Compression Tests.

For the addition of cement in the mixture of iron ore tailings with optimum levels of compression under Normal and Intermediate energies, we adopted the percentages 3, 4 and 5% cement and curing periods of 3, 7, and 28 days in a humid chamber at 23 ± 2°C and relative humidity greater than 95%.

With results of the Unconfined Compression Tests, it was obtained the empirical curve of strength variation depending on the cement content, which was used to estimate the amount of cement needed to reach 2.1 MPa, minimal resistance required for the materials to be applied in the implementation of sub-base layers or soil-cement bases, according to the technical standard NBR 11798 (*Associação Brasileira de Normas Técnicas* [ABNT], 2012b).

The mixture called 60f-40c, when applied in the mechanical analysis test, with the addition of 5% CPII-E-32 cement, will hereinafter be called as 60f-40c+5% CPII-E-32.

From the optimum compaction parameters obtained under Normal and Intermediate Proctor energies for the 60f-40c mixture, specimens were produced at the optimum moisture content (W_{op}) and maximum dry unit weight (γ_{dmax}), by means of static compression, with average dimensions of 5 cm diameter and 10 cm height, which were used in the Unconfined Compression Tests.

Soil specimens were made in cylindrical molds with no lateral confinement, under Normal and Intermediate Proctor energies, for the CBR tests, using the 60f-40c mixture with and without the addition of cement. The cement added in the 60f-40c mixture occurred after homogenization obtained between the different tailings; the water was incorporated in the final stage of homogenization of the compounds.

TABLE 1.
Geotechnical characterization and classification of iron ore tailing samples.

Physical characterization		Sample	
		Flotation	Concentration
Sieving (% Passing) through Dner - ME 051	# 10 (2.0 mm)	100	100
	# 40 (0.425 mm)	96	65
	# 200 (0.075 mm)	49	10
Atterberg Limits	LP (%)	15	NP
	LL (%)	10	
	IP (%)	5	
Unit Weight of Solids	γ_s (kN m^{-3})	31.76	35.58
Classification	TRB	A-4(3)	A-3(0)
Clay	(% < 0.002 mm)	2	3
Silt	(0.002 < % ≤ 0.06 mm)	47	7
Sand	(0.006 ≤ % < 2.00 mm)	51	90

In the case of CBR tests with samples of the 60f-40c mixture with cement, before immersing the specimen in water for 96 hours for the expansion analysis, they were cured in a humid chamber for 7 days.

Results and discussion

The physical characterization of the mixture of iron ore tailings, called as 60f-40c mixture, composed of 60% iron ore tailings from the flotation process and 40% tailings from magnetic concentration, defined as optimal mixture, showed 100% passing the 2.0 mm sieve, 92.6% passing the 0.425 mm sieve and 40.8% passing the 0.075 mm sieve. The Atterberg limits, the plasticity index, indicated the mixture as NP (non-plastic) and it had a unit weight of 33 kN m^{-3} and 5 clay, 36 silt and 59% sand in its composition.

The particle size analysis showed that the mixture is a material with silt sandy texture, belonging to the group A-4, according to TRB classification system, and presenting a group index equal to 1. Also according to the TRB classification system and considering the 60f-40c mixture without the addition of cement, the group A-4 relates to silty soils with good to weak behavior for use in subgrade layers

With regard to the TRB classification system for the mixture, the percentage of cement, in relation to the dry unit weight of soil or alternative materials, necessary to obtain a stable soil-cement mixture with minimal mechanical strength in compliance with the technical requirements of structural projects for base layers of flexible pavements must initially be in the order of 7% according to the technical standard NBR 12253 (*Associação Brasileira de Normas Técnicas* [ABNT], 2012c).

The mixture composed of 60% flotation tailings and 40% magnetic concentration tailings, in relation to the dry unit weight of the mixture 03, has the higher bearing capacity (Table 2). However, this value of CBR (20.4%) is not significantly higher when compared with CBR values obtained for the mixtures 04, 05 and 06. All mixtures presented low expandability, less than 0.05%.

Table 2 shows the values of the optimum parameters of compaction and bearing capacity obtained by CBR tests of the mixtures analyzed as a function of different levels of iron ore tailings.

With respect to the particle size of mixtures in Table 2, it is seen that by increasing the levels of the flotation tailing, the mixture becomes finer as to the textural appearance and tend to have a higher optimal moisture value. This behavior is normally reported in the technical literature for compaction parameters similar to those found in this investigation.

Regarding the maximum apparent dry unit weight, it was expected lower values for granulometrically finer mixtures. However, the observed behavior was not consistent with the particle size characteristics, which can be explained by the little divergence in the real dry unit weight of solids of the different tailings, resulting therefore in a finer mixture. It can be included greater amounts of solids with fewer voids, obtaining higher apparent dry unit weights.

The increase in compaction energy is responsible for the increase in values of the maximum apparent dry unit weight and reduction in the optimum moisture values of the mixture. The optimum compaction parameters are consistent with the behavior usually found in the technical literature on Soil Mechanics for granular materials.

It was observed 20.4% CBR for the 60f-40c mixture without addition of cement and 43.7% CBR with the addition of cement at seven curing days under Normal energy. With the intermediate energy, CBR was 50%, without the use of cement and 174% when using 5% of cement, after seven curing days. These values meet the technical specifications for using the mixture in sub-base layers of flexible pavements, according to the Dnit Paving Manual (*Departamento Nacional de Infraestrutura de Transportes* [Dnit], 2006).

TABLE 2.
Optimum parameters of compaction and mechanical strength of the mixtures analyzed.

Content of iron ore tailing							
Energy	Mixture	Magnetic concentration tailing	Flotation tailing	γ_d(kN m^{-3})	w_{ot}(%)	CBR (%)	Exp.*
Normal	01	20%	80%	21.33	8.76	5.6	Less than 0.05%
	02	30%	70%	20.73	11.40	13.8	
	03	40%	60%	20.30	11.59	20.4	
	04	50%	50%	19.86	10.70	17.0	
	05	60%	40%	19.41	11.80	16.0	
	06	70%	30%	19.90	9.55	15.7	
	07	80%	20%	18.62	9.84	11.7	
	08	90%	10%	17.90	7.55	14.9	
Inter.**	01	40%	60%	21.09	9.05	50.0	

*CBR test expansion. **Intermediate compaction energy.

The addition of cement to this mixture had the purpose of improving its mechanical and hydraulic properties, as iron ore tailings exhibited a uniform particle size distribution, with a coefficient of non-uniformity (CU) ranging from five to six, according to the particle size characteristics previously mentioned.

The maximum apparent dry unit weight and optimum moisture content obtained with the use of normal energy, for mixtures with optimum levels of iron ore tailings were 20.3 kN m^{-3} and 11.6%, respectively. In turn, when using the intermediate energy, it was obtained 21.0 kN m^{-3} and 9.0%, respectively.

The mixture with optimum content of iron ore tailings contained 5% cement in the CBR test, because it concerns the improvement of engineering properties of this material, and among the cement levels used in this study, 5% is the percentage of cement with the highest mechanical strength; and because it is a viable quantity from the economic point of view. The addition of 5% cement represented an 114% increase in bearing capacity of this material, under Normal energy, and an increase of 248%, under Intermediate energy.

According to CBR values found for the mixture of iron ore tailings improved with cement, the use of Intermediate Proctor compaction energy and considering the technical criteria proposed by Dnit, this mixture could be applied as a base layer in road pavements, provided that it meets the other technical criteria proposed for this purpose, since it has CBR value greater than 80% and less than 0.5% expansion.

Table 3 lists the values of Unconfined Compression Tests (UC) for mixtures with optimal contents of iron ore tailings improved with cement at 3, 4, and 5% and subjected to curing in a humid chamber for 3, 7 and 28 days.

On the strength of unconfined compressed specimens compacted with the mixture containing the optimum levels of iron ore tailings (60f-40c mixture), when added 5% of cement in the dry unit weight of the material and cured for 7 days in a humid chamber, it was observed that it was not possible to reach the minimum strength, 2.1 MPa, required to meet the technical specifications for cement content aimed at soil stabilization, as explained in NBR 12253 (ABNT 2012c).

As to the results of Unconfined Compression Tests regarding the Normal and Intermediate energies, there was no increase in the mechanical strength for the mixture without addition of cement, which can be confirmed, since the ultimate shear stress for the different energies has not changed, with the value of 0.03 MPa.

Nevertheless, for Intermediate Proctor compaction energy, the increase in mechanical strength was higher than with Normal Proctor compaction energy, reaching increases of 47.2, 17.1 and 48.41% for the curing periods of 3, 7 and 28 days, respectively, for the content of cement of 5% in relation to the dry unit weight of the mixture. The values obtained for the compressive strengths represent the average of three specimens and the standard deviation was below 10% in the cases studied.

Figure 1 illustrates the fitting curve between strength variation after 7 curing days according to different contents of cement by a quadratic regression.

The equation fitted allows inferring that for a cement content of approximately 8.5%, in relation to the dry unit weight of this material, it is possible to achieve an ultimate shear stress with a value of 2.15 MPa and an estimated error of 0.04MPa.

Table 4 presents the geotechnical classification parameters according to the methodology MCT (Miniature, Compacted, Tropical).

According to Table 4, the weight loss by immersion reduced from 379% in the 60f-40c mixture sample, in its natural state, to 37% in the 60f-40c + 5% CPII-E-32 mixture, in relation to its dry unit weight significantly reducing its erodibility.

Weight losses exceeding 100% found for the mixture of iron ore tailings without the addition of cement are justified by the fact that the calculations of weight loss relate to extruded soil mass, in other words, it is related to the specimen mass protruding 1.0 cm (outside the mini-MCV compression cylinder).

As for geotechnical classification, according to the methodology MCT, the mixture 60f-40c in its natural state was classified as belonging to the group NA; the soils of this group are usually the sands, silts, and mixtures of sands and silts, having no fine cohesive clay, i.e., it is a non-laterite silty sand. Soils of this group, even when properly compressed, can be relatively permeable, little cohesive and slightly contractile when dried. These characteristics are not desirable for pavement bases, although presenting medium-high bearing capacity.

TABLE 3.
Results of Unconfined Compression Tests for mixtures of iron ore tailings improved or not with cement.

Intermediate energy – UC (MPa)								
Curing (days)	Mean				Standard deviation (n-1)			
	Cement contente							
	0%	3%	4%	5%	0%	3%	4%	5%
0	0.03	-	-	-	0.01	-	-	-
3	-	0.26	0.38	0.53	-	0.02	0.04	0.04
7	-	0.40	0.68	0.89	-	0.01	0.03	0.04
28	-	0.69	1.31	1.87	-	0.02	0.10	0.05
Normal energy – UC (MPa)								
Curing (days)	Mean				Standard deviation (n-1)			
	Cement contente							
	0%	3%	4%	5%	0%	3%	4%	5%
0	0.03	-	-	-	0.00	-	-	-
3	-	0.18	0.34	0.36	-	0.03	0.04	0.08
7	-	0.35	0.62	0.76	-	0.05	0.05	0.06
28	-	0.46	0.72	1.26	-	0.06	0.08	0.09

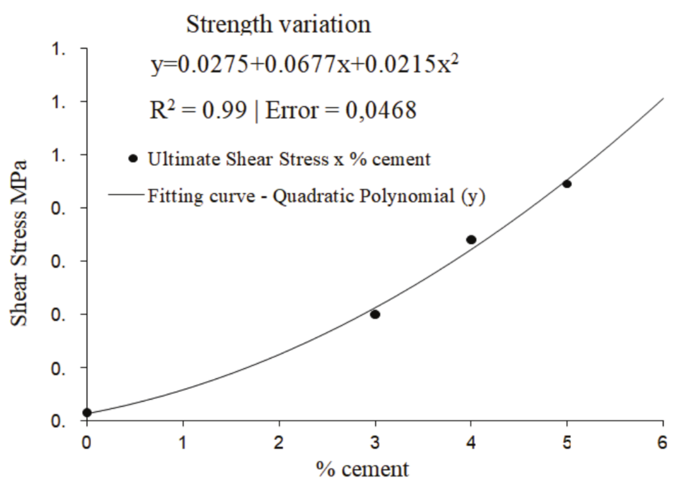

FIGURE 1.
Equation for mechanical strength.

TABLE 4.
Soil classification parameters according to the methodology MCT for samples of the mixture 60f-40c in its natural state and with the addition of cement.

Classification MCT		
Parameters	Sample	
	60f-40c+5%CPII-E-32	60f-40c
Coefficient c'	0.28	0.33
Coefficient d'	21.00	18.00
Coefficient e'	1.10	1.70
Weight loss by immersion (Pi)	37.00	379.00
Mini-MCV	10.00	10.00
Classification MCT	LA	NA

In this way, the mixture of iron ore tailings, called 60f-40c has low resistance to erodibility, with a high percentage of weight loss by immersion, which can be explained by the uniform particle size distribution and low cohesion, which is of the order of 19 kPa. The cement added to this mixture allowed to reduce the weight loss when immersed in water, representing an improvement in its mechanical and hydraulic properties, with positive interference with its geotechnical classification.

The mixture 60f-40c + 5% CPII-E-32 was classified as belonging to the group LA, which includes mainly sand with few laterite fines, and mixtures, such as sand silt laterite, which makes it applicable to various pavement layers including the base layer.

The laterization of tropical soils gives rise to a natural cementation caused by oxides and hydroxides of iron and aluminum. In the case of the mixture, the cementing developed by adding cement induced an artificial laterization.

This can be explain because, according Nogami and Villibor (1995) the index c' which correlates the granulometry of the material indicates for two mixtures a non-plastic sandy texture, since its values are less than 1.0 (c' < 1.0). In order to the coefficient d', it is verified one value below and another one above 20, being that value above are indicative of possibly lateritic soil. Also, according to Nogami and Villibor (1995), the index e' was designed to evaluate lateritic of non-lateritic behavior of soils and found that lateritic behavior manifests when the result of the analytical formulation of e' is less than 1.15, that occurs when d' >20 and Pi < 100, therefore, cement addition reduce the Pi value to below 100 and increased the d' value up to 20 performing the 'artificial laterization' mentioned above.

Conclusion

The studied mixture of iron ore tailings composed of 60 flotation tailings and 40% magnetic concentration tailings did not present mechanical behavior compatible for use in flexible pavement base layers and geotechnical embankments, even with CBR values above the minimum threshold recommended. This material lacks stability (Oliveira, 2013), as it is a mixture classified as A-4(1), with uniform particle size, and high weight loss by immersion, in addition to the total mass loss in the durability test above 10%, maximum acceptable value for this type of material, according to the NBR 12253 (ABNT, 2012c).

The addition of 5% cement improved the mechanical and hydraulic properties, leading to a medium bearing capacity, determined by CBR, to about 140%, and the Unconfined Compression Strength to about 0.89 MPa. Following the methodology MCT, the classification of the mixture was LA, and in agreement with the proposals of this classification, this mixture can be applied with good results in the various pavement layers (Nogami & Villibor, 1995).

About 8.5% of cement was estimated as the percentage required to reach a compressive strength of the order of 2.15 MPa, which would qualify this mixture for use in the base layer.

The estimation by quadratic regression must be taken as an initial parameter for determining the contents in this mixture aiming its application in flexible pavement base layers. Evidently, such a mixture has to be evaluated experimentally to determine the actual ultimate shear stress in simple compression tests and in view of particle size characteristics of tailings, which can result in high volumetric shrinkages with the inevitable presence of fissures and cracks.

Finally, it is concluded that 60f-40c + 5% CPII-E-32 mixture provides prospects of environmental nature gains, by creating alternative uses for tailings whose disposal causes severe impacts to the environment.

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