MCT CLASSIFICATION FOR COMPACTED MIXTURES OF SOIL-STEEL SLAG-FLY ASH FOR APPLICATION IN FOREST ROADS[1]

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ABSTRACT – This work aimed to evaluate the potential application of a stabilizer derived from the intimate mixture of powder electric arc furnace oxidizing slag and fly ash, aiming at the improvement of soil engineering properties for enforcement purposes on forest roads. This evaluation was undertaken by means of an experimental program of laboratory tests to classify soils and mixtures of these with the proposed stabilizer according to the MCT (Miniature, Compacted, Tropical) methodology. The proportions of waste mixtures were 10% and 20% of the total dry mass of soil-waste combinations and percentages of ground steel slag were 75%, 87.5% and 100% relative to total dry mass of waste mixtures. It was shown the potential to technically enable the use of steel waste in the composition of forest roads, emphasizing the relevance of the proposal in meeting the need of steel companies to confer a sustainable destination for the waste and the need of forest companies to meet, with low-cost materials, the significant demands of their unpaved road network.

Keywords: Soil stabilization; Steel waste; Forest transportation.

CLASSIFICAÇÃO MCT DE MISTURAS DE SOLO-ESCÓRIA DE ACIARIA-CINZA VOLANTE COMPACTADAS VISANDO A APLICAÇÃO EM ESTRADAS FLORESTAIS

RESUMO – Este trabalho visou avaliar o potencial de aplicação técnica de um estabilizante resultante da mistura íntima de pó de escória oxidante de aciaria elétrica moída e cinza volante, visando à melhoria das propriedades de engenharia de solos para fins de aplicação em estradas florestais. Essa avaliação foi empreendida por meio de um programa experimental de ensaios laboratoriais destinados a classificar os solos e as misturas destes com o estabilizante proposto segundo a metodologia MCT (Miniatura, Compactado, Tropical). As proporções das misturas dos resíduos foram de 10% e 20% da massa seca total das combinações solo-resíduos, e as porcentagens de escória de aciaria moída foram de 75%, 87,5% e 100% em relação à massa seca total das misturas dos resíduos. Para as particularidades da pesquisa e por meio da classificação MCT, foi possível demonstrar o potencial de viabilizar tecnicamente o aproveitamento de resíduos siderúrgicos na composição das vias de tráfego florestais, realçando a relevância da proposta no atendimento à necessidade de empresas siderúrgicas de conferirem uma destinação sustentável de seus resíduos e à necessidade das empresas florestais de suprirem, com materiais de baixo custo, as significativas demandas de sua malha viária não pavimentada.

Palavras-chave: Estabilização de solos; Resíduos siderúrgicos; Transporte florestal.

1. INTRODUCTION

Forest roads are the most important access roads to forests, serving to facilitate the traffic of manpower and production facilities for the implementation, protection, collection and transportation of forest products (MACHADO, 1989). According to Oliveira et al. (2013), the forest transportation corresponds to all wood movement from the stands where are the forests or the edges of roads to the courtyards of companies, and despite the shortcomings of the routes on which runs this mode of transport, they are responsible for connection between the producing communities and the large paved roads or between forest companies and the wood processing industries.

Lopes et al. (2002) highlight that the road sector is of great importance in the forest enterprise, since the road-transportation binomial costs significantly affect the final value of the timber. These authors also point out that the increased requirements related to the requests of these roads have as causes the increased volume of high-tonnage vehicle traffic, increase in transportation distances on poor quality roads, the need for trafficability all year and the need for roads with longer life.

Emmert et al. (2010) claim that the existence of a sufficient bearing capacity to support high loads imposed by truck traffic and an efficient drainage system are minimum requirements for the rolling surface of forest roads, emphasizing that, in most cases, the low quality in construction has prevailed in the execution thereof.

These technical concerns have, consequently, encouraged the development of research aimed at improving the hydraulic (drainage and resistance to erodibility) and mechanical (load bearing capacity) performance of forest roads, among which may be mentioned those involving stabilization of soils that comprise the structures of these traffic routes (MACHADO et al., 2003; SANT´ANNA et al., 2003a,b; TRINDADE et al., 2005a,b,2006; VELTEN et al., 2006; MACHADO et al., 2006; PEREIRA et al., 2006a,b,c, 2007; ALMEIDA et al., 2010; MACHADO; PORTUGAL, 2012).

In this context, it is important that these studies involve the possibility of using industrial waste, considering the fact that there is a growing demand for aggregate for use in road works and that the lack of traditional aggregates, combined with the demands and environmental restrictions imposed in the construction of these routes, make it imperative the development of careful investigation of alternative materials, seeking more economical technical solutions, with satisfactory performance and that minimize the negative impacts to the environment (ROHDE et al., 2003).

Concurrent with the lack of aggregates for road works, it is noteworthy that large quantities of waste are generated by steel industries, despite the undeniable benefits brought by the same to global society. The production of co-products and waste is very significant in the steel production process, since, for each ton of crude steel produced, more than 600 kg of these materials are generated (INSTITUTO AÇO BRASIL, 2015).

Among the steel waste, steel slag has particular technological characteristics that have enabled its use in road works (LIMA et al., 2000). Recent studies have pointed to the possibility of mobilizing the good mechanical and hydraulic properties of slag when combined with fly ash ((PARREIRA et al., 2014; MARTINS et al., 2014), a pozzolanic material that, according to Núñez (2007), has little or no ability to cementation, however, in finely divided form and in the presence of moisture, chemically reacts with alkaline and alkaline earth hydroxides present in the slag, at room temperature, forming or assisting the formation of compounds with cementing properties.

Therefore and considering the great potential for use of these materials in large-scale applications, such as applications in forest roads, it is justified the development of a research study to evaluate the technical viability of the use of industrial waste *powder electric arc furnace oxidizing slag* and *fly ash*, within the context of application as a stabilizer agent of soils that can be used in these routes, thus opening a field of interest for forest roads in the areas of operation of steel companies. This evaluation was undertaken by means of experimental laboratory tests to classify soils and mixtures of these with the proposed stabilizer according to MCT (Miniature, Compacted, Tropical) methodology for classification of tropical soils aimed at road engineering works.

2. MATERIAL AND METHODS

2.1. Material

Soil samples used in this study came from a young residual gneiss soil (called Soil 1) and a mature residual gneiss soil (called Soil 2) representing, respectively, horizons B and C of cut slopes in the rural area of the municipality of Ouro Branco, state of Minas Gerais, in the Alto Paraopeba region.

The steel slag used in the experimental tests was provided by the steel unit VSB (Vallourec & Sumitomo Tubos do Brasil), in the municipality of Jeceaba, state of Minas Gerais, Alto Paraopeba region, derived from the electric furnace and collected on the storage yard in the open air with 6-month curing period. The fly ash used was furnished by Pozosul cement plant, in the municipality of Capivari de Baixo, state of Santa Catarina.

For each type of soil, the percentages of waste *powder electric arc furnace oxidizing slag* and *fly ash* were used according to the dry mass of mixtures between these materials (soil and waste), in the proportions set in Table 1 (mixtures X, Y and Z). These waste mixtures were used in the proportions of 10% and 20% relative to the dry mass of soil-waste mixtures (soil- electric arc furnace oxidizing slag –fly ash). Thus, for exemplification purposes, a mixture of 10% waste was composed of soil 90%, 100% dry mass (no moisture) of soil-waste mixture.

2.2. Methods

2.2.1. Collection, reduction and preparation of samples

Samples of the materials used in experimental tests were collected according to the guidelines DNER - PRO 003 (DNER, 1994a), for soil, DNER - PRO 120/97 (DNER, 1997) and NBR 10007 (ABNT, 2004), for waste. Procedures for reduction and preparation of samples for the tests followed the guidelines NBR 9941 (ABNT, 1987) and NBR 6457 (ABNT, 1986), for soil, and DNER - PRO 199/96 (DNER, 1996), for waste. Important, after size reduction, samples of electric arc furnace oxidizing slag were ground in Los Angeles Abrasion machine, followed by screening through 0.6 mm mesh sieve (sieve #30) to obtain the powder slag for the composition of compacted soil-steel slag-fly ash mixtures.

Table 1 – Designation of mixtures of soil- electric arc furnace oxidizing slag- fly ash according to waste percentages.
Tabela 1 *– Designação das misturas do tipo solo-escória oxidante de aciaria elétrica-cinza volante em função das percentagens dos resíduos.*

Mixture	Type of waste	
	Fly ash	Electric arc furnace oxidizing slag
X	12.5%	87.5%
Y	0%	100%
Z	25%	75%

2.2.2. Physical characterization

Samples of the materials used in experimental tests were physically characterized according to the following regulatory guidelines: (i) Soils - NBR 7181 – Particle size distribution (ABNT, 1984a); NBR 6459 - Liquid limit (ABNT, 1984b); NBR 7180 - Plastic limit (ABNT, 1984c); NBR 6508 - Specific gravity of soil grains (ABNT, 1984d); (ii) Waste - NBR 11589 - Fineness index (ABNT, 1991); NBR 7224 - Blaine specific area (ABNT, 1984e); NBR NM 23: 2001 - Specific gravity (ABNT, 2001); (iii) Soil-waste mixtures - NBR 6459 - Liquid limit (ABNT, 1984b); NBR 7180 - Plastic limit (ABNT, 1984c); NBR NM 23: 2001 - Specific gravity (ABNT, 2001).

2.2.3. Geotechnical characterization: MCT classification

The MCT (Miniature, Compacted, Tropical) classification of samples of soil and soil-waste mixtures used was carried out according to the procedures prescribed in DNIT classification method - CLA 259 (DNIT, 1996) and based on the results of the tests DNER - ME 258 of Mini MCV (DNER, 1994b) and DNER - ME 256 of mass loss by immersion (DNER, 1994c).

3. RESULTS

3.1. Physical characterization

The results of the physical characterization tests of the materials used in this study are listed in Table 2.

The results of the physical characterization tests of soil-steel slag-fly ash mixtures referred to in this study (mixtures X, Y and Z, proportions of 10% and 20% of waste in relation to the total dry mass of the mixture) for the soils 1 and 2 are shown in Table 3.

Table 2 – Physical characterization tests of materials used in the research.
Tabela 2 – *Dados dos ensaios de caracterização física dos materiais empregados na pesquisa.*

Physical property	**Soil 1**	**Soil 2**
Specific mass of solids (g/cm^3)	2.91	2.92
Liquid limit [w_L] (%)	35	59
Plastic limit [w_P] (%)	31	38
Plasticity index [I_p] (%)	04	21
Gravel fraction [2mm<ϕ<60mm] (%)	1	1
Sand fraction [0.06mm<ϕ<2mm] (%)	69	34
Silt fraction [0.002mm<ϕ<0.06mm] (%)	22	61
Clay fraction [f<0.002mm] (%)	8	4
	Steel slag	**Fly ash**
Specific mass of solids (g/cm^3)	3.75	1.95
Fineness index (%)	25.75	48.81
Blaine specific area (m^2/kg)	542.31	438.91

ϕ: Particle diameter; $I_p = w_L - w_P$

Table 3 – Physical characterization tests of Soils 1 and 2 and mixtures thereof with waste (steel slag powder and fly ash) at 10% and 20% relative to total dry mass of the mixture.
Tabela 3 – *Dados dos ensaios de caracterização física dos Solos 1 e 2 e de suas misturas com os resíduos (escória de aciaria em pó e cinza volante), nas proporções de 10% e 20% destes em relação à massa seca total da mistura.*

Physical property	Natural Soil 1	10% waste			20% waste		
		Mixture X	Mixture Y	Mixture Z	Mixture X	Mixture Y	Mixture Z
Specific mass of solids (g/cm^3)	2.91	3.02	3.13	3.07	3.01	3.15	3.11
Liquid limit (%)	35	35	36	36	33	34	34
Plastic limit (%)	31	29	30	29	28	29	27
Plasticity index (%)	4	6	6	7	5	5	7
Physical property	Natural Soil 2	10% waste			20% waste		
		Mixture X	Mixture Y	Mixture Z	Mixture X	Mixture Y	Mixture Z
Specific mass of solids (g/cm^3)	2.92	3.00	3.06	3.02	3.09	3.11	3.07
Liquid limit (%)	59	45	45	43	42	39	46
Plastic limit (%)	38	35	32	31	30	28	32
Plasticity index (%)	21	9	13	12	12	11	15

3.2. Geotechnical characterization: MCT classification

The results of the characterization tests of soils analyzed aiming at classification according to the MCT (Miniature, Compacted, Tropical) method allowed obtaining the soil classification indices and, therefore, the classification of soil in one of the classes or groups of this classification system for tropical soils, as shown in Table 4.

A similar procedure on samples of the tested mixtures of soil-steel-slag-fly ash allowed to obtain the classification indices according to the MCT method, which are also shown in Table 4, which resulted in the classification of the mixtures in one of the classes or groups of this classification system. This classification allowed to conclude the respective suitability of these compacted mixtures in the context of their potential use in forestry road works, which are summarized in Table 5.

4. DISCUSSION

The results of physical characterization tests of materials used in this study (Table 2) demonstrated that Soil 1 shows, regarding particle size, a sandy-silty-clayey texture and slightly plastic consistency. By the TRB (Transportation Research Board) system for soil classification, it is an A-7-6 soil, and by the USCS (Unified Soil Classification System) system of soil classification, it is a CH soil. Soil 2 shows, in turn,

Table 4 – MCT Classification of soils and mixtures of soil-steel slag-fly ash analyzed.
Tabela 4 *– Classificação MCT dos solos e das misturas solo-escória de aciaria-cinza volante pesquisadas.*

Percentage of waste in the mixture	Soil	Mixture	Coefficient			Mass loss by immersion (%)	MCT Group
			c´	d´	e´		
0%	Soil 1	-	1.055	19.90	1.1515	52.20	NA´ (sandy non-lateritic)
	Soil 2	-	1.884	64.15	0.6781	0.00	LG´ (clayey lateritic)
10%	Soil 1	X	1.021	21.02	1.0347	15.64	LA´ (sandy lateritic)
		Y	1.410	58.19	0.8016	17.13	LA´ (sandy lateritic)
		Z	1.344	33.19	0.9176	17.00	LA´ (sandy lateritic)
	Soil 2	X	1.478	81.56	0.6259	0.00	LA´ (sandy lateritic)
		Y	0.889	26.34	1.0849	51.70	LA´ (sandy lateritic)
		Z	1.038	5.18	1.6110	32.00	LA´ (lateritic sandy)
20%	Soil 1	X	0.749	21.79	1.0281	16.89	LA´ (sandy lateritic)
		Y	0.937	35.28	0.928	16.89	LA´ (sandy lateritic)
		Z	0.749	35.28	0.9028	16.89	LA´ (sandy lateritic)
	Soil 2	X	1.270	26.79	0.988	0.40	LA´ (sandy lateritic)
		Y	1.670	48.82	0.7457	0.50	LG´ (clayey lateritic)
		Z	1.557	79.74	0.6548	3.00	LG´ (clayey lateritic)

Table 5 – Technical suitability of mixtures of soil-steel slag-fly ash analyzed according to MCT classification.
Tabela 5 *– Aptidões técnicas das misturas do tipo solo-escória de aciaria-cinza volante pesquisadas segundo a classificação MCT.*

Percentage of waste in the mixture	Soil in the mixture	Mixture	MCT Group	Technical suitability for road work
	Soil 1	X	LA´ (sandy lateritic)	Pavement basis of low volume traffic roads Subgrade reinforcement Compacted landfill Erosion protection layer Primer coating
		Y	LA´ (sandy lateritic)	
		Z	LA´ (sandy lateritic)	
	Soil 2	X	LA´ (sandy lateritic)	
		Y	LA´ (sandy lateritic)	
		Z	LA´ (sandy lateritic)	
20%	Soil 1	X	LA´ (sandy lateritic)	
		Y	LA´ (sandy lateritic)	
		Z	LA´ (sandy lateritic)	
	Soil 2	X	LA´ (sandy lateritic)	Erosion protection layer Primer coating
		Y	LG´ (clayey lateritic)	
		Z	LG´ (clayey lateritic)	

silty-sandy-clayey texture and high plasticity, and is classified as A-7-5 by TRB system, and as MH soil, by USCS system.

Considering the TRB soil classification system, it is estimated that Soil 1 and Soil 2 (clayey soils) show regular-poor behavior as a pavement structure layer of traffic roads. According to the USCS soil classification system, Soil 1 (very plastic inorganic clay) presents regular-poor quality as foundation material and poor drainage characteristics, while Soil 2 (elastic inorganic silt) has poor quality as foundation material and regular-poor drainage characteristics.

According to these classification systems, based on European and North American road tradition, these soils would be inappropriate for forestry road works, once the presence of fines in percentages above the tolerable would be technically unacceptable because of the potential to reduce the material permeability, reducing the stiffness, increase the deformability and, especially, increasing the volumetric expansion thereof in the presence of water, causing a reduction of mechanical efficiency. However, Bernucci et al. (2008) emphasize that these unwanted characteristics of fines may not be observed in tropical soils, such as those studied, whose nature, structure and mechanical properties can differ substantially from thin soils occurring in cold and temperate regions, where most of the paving technology was designed and developed.

The results of the physical characterization of samples of powder electric arc furnace oxidizing slag and fly ash confirm the expectation of greater specific mass of powder electric arc furnace oxidizing slag compared to other materials, which is justified by the particular chemical composition, especially by the presence of iron. Regarding the fineness index and specific surface of waste, it is expected that the greater the magnitude of these physical parameters, the greater the respective pozzolanic activities and, consequently, the higher the potential for soil stabilization for these materials. This stabilization can be reflected in the better performance of compacted mixtures compared to compacted soils under the same conditions.

For mixtures soil-steel slag-fly ash provided for in this research, it can be seen that, based on the results of the physical characterization tests (Table 3), the modification imposed by the addition of the stabilizing mixture to the physical properties of the original soil is more pronounced for Soil 2 than for Soil 1, mainly with respect to the plasticity of the material, which had significant decreases in all mixtures with Soil 2. It is important to note that, in general, to a lesser plasticity it is associated the expectation of better performance of a soil for application in engineering works. The increase in specific mass of solids in all mixtures of both soils, compared to the original soils, is a striking consequence of the presence of steel slag and the particular iron-rich chemical composition.

The MCT classification of the studied soils (Table 4) showed that Soil 1 belongs to the NA´ class (non-laterite sandy soil) and Soil 2 belongs to the class LG´ (laterite clayey soil). According to Nogami and Villibor (1995), NA´ soils are not priority for use in road works, while LG´ class soils would be more suitable for erosion protection layers and as a primer coating layer of such works. In agreement with these authors, none of these materials can be found among the most recommended for use as pavement base, subgrade reinforcement, compacted subgrade and as compacted landfill, which explains the technical need for stabilization, aiming at the use in these applications previously mentioned.

Particularly interesting in these determinations is the experimental finding, by means of tests of mass loss by immersion, of the high erodibility of Soil 1 (Mass Loss by immersion at 52%), a hydromechanical behavior not observed for Soil 2 (zero mass loss by immersion).

For the studied soil-waste mixtures classified according to the MCT system (Table 4), it is important to highlight the expectation of significant improvement of geotechnical properties of soils analyzed, when combined with waste, in the context of application in forestry road works (Table 5).

With respect to the data in Table 5, for all the proposed combinations, mixtures involving Soil 1 are the most suitable or priority for applications in road works (LA´ group), in contrast to the technical limitations of use of that soil in its original state (non-combined), while mixtures with Soil 2 or expanded its potential application (LA´ group) or remained with the same potential (LG´ group) compared to the technical possibilities of this soil in its original state.

In view of the MCT classification system, compacted geological materials of the LA´ group tend to show, in relation to the interaction with water, low to medium dimensional variation (expansion or contraction), low coefficient of permeability and low absorption coefficient, technical specifications required that favor the appropriate mechanical and hydraulic performance of the materials for the composition of forestry road works. Although, in this particular aspect, the materials of the LG´ group present technical properties similar to those of the LA´ group, it is technically justified only its priority use in restricted applications associated with its best hydraulic performance, mainly as protective anti-erosion and primer coating layers.

Therefore, the classification of mixtures according to the MCT Methodology points to the technical feasibility of using these soils combined with the waste studied (steel slag and fly ash) in forestry road works to an extent that, at first, it was not possible or was restricted considering the soils in original states. It is noted that, among the soil-waste mixtures studied, particular emphasis can be given to the mixture of Soil 2 and the combination of waste X at 10%, because it fits in the group of the MCT classification considered as the most technically suitable for application in road works (LA´ group), and because it also has high resistance to water erosion evidenced by its zero mass loss by immersion (Table 4).

5. CONCLUSIONS

Given the results obtained in this study, it can be concluded that the MCT classification of soil-steel slag-fly ash mixtures analyzed allowed their classification in the technical application possibilities in the context of forest road engineering that were not permissible for natural soils. In addition, the evaluation of the hydromechanical behavior of materials through the mass loss by immersion test of the MCT methodology demonstrated reductions in erodibility of soil studied with the addition of waste at proportions predefined by this research. The different hydromechanical behavior of mixtures compared to respective soil indicates the stabilizing capacity provided by the composition of steel waste employed, which points favorably to the use thereof in forest road works, mainly when inside areas of operation of steel companies. It is important to note that the findings of this research are based on the features of the MCT classification system for the potential application of the material studied in forest road works, not exempting them from the need to evaluate their behavior engineering through mechanical tests, such as of the compressive strength, the California bearing ratio (CBR) and the resilient modulus, commonly considered in the structural design different methods of these routes.

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