Acta Scientiarum
http://periodicos.uem.br/ojs/acta
ISSN on-line: 1807-8664
Doi: 10.4025/actascitechnol.v41i1.37596

CIVIL ENGINEERING

Use of steel waste for the application in urban paving

Taciano Oliveira da Silva[1*], Heraldo Nunes Pitanga[1], André Luís dos Santos[2], Dario Cardoso de Lima[1] and Ana Cláudia Bernardes Silva[2]

[1]Departamento de Engenharia Civil, Universidade Federal de Viçosa, Avenida Peter Henry Rolfs, s/n., 35570-000, Viçosa, Minas Gerais, Brazil. [2]Programa de Pós-Graduação em Tecnologias para o Desenvolvimento Sustentável, Universidade Federal de São João Del-Rei, Ouro Branco, Minas Gerais, Brazil. *Author for correspondence. E-mail: taciano.silva@ufv.br

ABSTRACT. This study evaluated the technical potential of a stabilizer derived from the intimate mixture of steel waste (powder electric arc furnace oxidizing slag - PES) and fly ash to improve soil engineering properties for application in urban paving. This evaluation was performed by laboratory tests to characterize, through CBR tests and unconfined compression tests, the mechanical behavior of compacted residual soil samples of the Alto Paraopeba region, state of Minas Gerais, Brazil, and mixtures of these soils with the stabilizer. For the peculiarities of the research, it was possible to demonstrate the technical viability of the use of steel waste in urban paving works, highlighting the relevance of the proposal in meeting the needs of steel companies to confer a sustainable disposal of waste materials, and the need of municipalities surrounding such companies to providing for, with low-cost materials, significant demands of unpaved road networks.

Keywords: tropical soil; soil stabilization; sustainable development.

Received on June 12, 2017.
Accepted on October 1, 2018.

Introduction

The Southeast region of Brazil accounts for approximately 95% of Brazilian production of crude steel, and the state of Minas Gerais represents 34% of this total. In this context, the Alto Paraopeba region in the state of Minas Gerais, is known for its mining and steel character, evidenced by the significant presence of mining companies and steel industries, whose activities generate inevitable negative impacts on the environment, either by mineral extraction activities or by waste resulting from processing.

In Brazil, the use of steel slag in paving is not new, there are several experimental road test sections constructed decades ago that show the satisfactory performance of the material in such engineering works. In this context, several researches have demonstrated the technical feasibility of using steel slag waste in layers of pavement structures (Rohde, Núñez & Ceratti, 2003a; 2003b; Velten et al., 2006; Huang, Bird, & Heidrich, 2007; Ahmedzade & Sengoz, 2009; Pasetto & Baldo, 2011; Patil, Bachhav, & Kshirsagar, 2016).

Fly ash is an artificial pozzolan produced by burning coal or organic matter in industries of cement, cellulose paper, ceramics, food, grain drying, steel, and especially thermoelectric industry. Pozzolan is defined by the standard C 125 (American Society for Testing and Materials [ASTM], 2018) as a siliceous or silico-aluminous material which, alone, has little or no ability to cementation, however, in finely divided form and in the presence of moisture, it reacts chemically with alkali and alkaline earth hydroxides at room temperature to form or assist in forming compounds with cementing properties. Example of research involving the use of such material in the improvement of soil engineering properties for paving includes Vizcarra, Casagrande, and Motta (2013).

From the perspective previously presented, this study evaluated the technical potential of a stabilizer derived from the intimate mixture of powder electric arc furnace oxidizing slag (PES) and fly ash, in order to improve engineering properties of residual gneiss soil for application in urban road pavement. The deficit of urban pavements is great in almost all Brazilian cities, ranging from main roads of large cities to traffic routes of districts and housing estates. For instance, in the state of São Paulo, there are highly developed cities such as São Paulo, with a deficit of approximately 20 million square meters of roads. In other regions, the situation considering the deficit of urban pavements is even more serious. This shows the need and the importance of developing a paving technology that minimizes the costs of urban pavements (Villibor, Nogami, Cincerre, Serra, & Zuppolini Neto, 2009).

In this study, this analysis was undertaken by means of an experimental program of laboratory tests to characterize, through CBR testing (California Bearing Ratio) and unconfined compression tests, the mechanical behavior of compacted residual soil samples of the Alto Paraopeba, state of Minas Gerais, and mixtures of these soils with PES and fly ash. It is important to emphasize that the consideration of these mechanical parameters in the development of this research is justified by the fact that, in Brazil, most of the specifications of the federal, state and municipal road organs (DNIT, DER, Siurb/PMSP, for example) still use the same references for purposes of choice of materials and design of urban flexible pavement layers, without expecting to omit the need for discussion of the limitations of empirical methods based on these parameters, compared to the theoretical-mechanistic and mechanistic-empirical methods.

Material and methods

Soil samples used in this study are 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 slope in the rural area of the municipality of Ouro Branco, state of Minas Gerais, in the Alto Paraopeba region. For each soil sample, it was added percentages of stabilizing mixtures consisting of PES and fly ash. These stabilizers were used in proportions of 10 to 20% relative to the total dry weight of the soil-stabilizer mixtures (soil-PES-fly ash).

The soil samples used in the experimental program of laboratory tests were collected in accordance with the guidelines established by PRO 003 (*Departamento Nacional de Estradas de Rodagem* [DNER], 1994) and samples of slag and fly ash were collected according to the regulatory guidelines of PRO 120 (DNER, 1997) and the technical standard NBR 10007 (*Associação Brasileira de Normas Técnicas* [ABNT], 2004). Procedures for reduction and preparation of samples for the tests followed the guidelines established for soil, according to NBR NM 27 (ABNT, 2001) and NBR 6457 (ABNT, 2016a) and for stabilizing materials, PRO 199 (DNER, 1996). After size reduction, samples of PES were grounded in the Los Angeles Abrasion machine, followed by screening through 0.6 mm mesh sieve (sieve#30) to obtain the PES for the composition of compacted soil-PES-fly ash specimens. The minimum curing time of the PES used in the study was 6 months.

After determining the respective compaction curves of soils at natural state and soil-stabilizer mixtures, at energies of standard Proctor and modified Proctor compaction efforts, the corresponding compaction parameters were obtained [optimum moisture content (w_{opt}) and maximum dry density (γ_{dmax})], which were adopted as reference in molding compacted specimens for unconfined compression and CBR tests, according to requirements contained in the technical standards NBR 12025 (ABNT, 2012a) and NBR 9895 (ABNT, 2016b), respectively. For each soil sample, the percentages of the stabilizers were used according to the mixtures dry masses, in the proportions listed in Table 1.

The samples of the materials used in the experimental program of laboratory testing were characterized according to the standards listed in Table 2. In addition to physical characterization, samples of PES and fly ash were subjected to chemical (X-ray Fluorescence), mineralogical (X-ray Diffraction) and microstructural (Scanning Electron Microscopy) characterization tests.

Table 1. Description of mixtures of soil-PES-fly ash according to relative percentages of stabilizing materials in relation to the total dry weight of the stabilizer mixture.

Mixture	Stabilizing material	
	Fly ash	PES
X	12.5%	87.5%
Y	0%	100%
Z	25%	75%

Table 2. Technical standards used in the physical characterization of materials used in the research.

Materials	Technical standards
Soils	NBR 7181 –Soil particle size distribution (ABNT, 2016c); NBR 6459 –Liquid limit (ABNT, 2016d); NBR 7180 –Plastic limit (ABNT, 2016e); NBR 7182 – Soil compaction (ABNT, 2016f).
Stabilizing materials	NBR 11579 –Fineness index (ABNT, 2012b); NBR NM 76 - Blaine specific area (ABNT, 1998).
Soil-stabilizer	NBR 7182 – Soil compaction (ABNT, 2016f).

Results and discussion

Physical characterization

The results of physical characterization tests of soils indicate that Soil 1 shows, regarding particle size, a sandy-silty-clayey texture with slightly plastic consistency. By the TRB (Transportation Research Board) soil classification system it is an A-7-6 soil, and by the USCS (Unified Soil Classification System) soil classification system it is a CH soil. Soil 2 shows, in turn, silty-sandy-clayey texture with medium plasticity, being classified as A-7-5, by TRB system, and as MH, by the USCS. Regarding the TRB soil classification system, it is estimated that both soils have regular to poor behavior as subgrade soils and, respectively, regular to poor drainage characteristics.

Therefore, according to these classification systems, which are based on North American and European road traditions, these soils would be unfit for road works, since the presence of fine in percentages above the tolerable would be technically inadmissible because of the potential to reduce soil permeability and stiffness, and to increase soil deformability and, especially, volumetric expansion in the presence of water, causing reduction of the mechanical efficiency of the pavement structure. Bernucci, Motta, Ceratti, and Soares (2008) emphasize that these unwanted characteristics of fines may not be observed in tropical soils, such as those studied herein, whose nature, structure and mechanical properties can differ substantially from thin soils occurring in regions with cold and temperate climate, where most of the paving technology was developed.

The MCT (Miniature, Compacted, Tropical) classification of these same soils leads to the conclusion that soil 1 belongs to the class NA' (sandy non-lateritic) and that soil 2 belongs to class LG' (clayey lateritic). According to Nogami and Villibor (1995), NA' class soils are not the priority for use in road works, while soils of the LG' class would be better suited for erosion protection layers and as primary coating layer of these works. In agreement with these same authors, none of these materials is among the most recommended for use as a pavement base, subgrade reinforcement, compacted subgrade and as a compacted landfill body, which justifies the technical necessity of stabilization, aiming at the employment in these applications previously mentioned.

The results of the physical characterization of samples of PES and fly ash used in the study are presented in Table 3. In relation to the fineness index and specific surface of the stabilizing materials, it is expected that the greater the magnitude of these physical parameters, the greater the respective pozzolanic activities and, consequently, higher the potential soil stabilization capability of these materials. This stabilization can be reflected in the better performance of compacted mixtures compared to soils in the natural state under the same compaction conditions.

The results of the physical characterization tests of soil-PES-fly ash mixtures provided in this study (mixtures X, Y and Z, proportions of 10 and 20% of stabilizing mixture relative to the total dry mass of the soil-stabilizers mixture), for soils 1 and 2, are shown, respectively, in Table 4 and 5. The results of the compaction tests indicate, for mixtures of Soil 1and Soil 2 with 10 and 20% in mass of stabilizing mixture, an increase in values of maximum dry density compared to the same soils in natural state, for the two applied compaction efforts, with a single exception for mixture X of Soil 1 in the proportion of 10% in mass of stabilizing mixture tested under modified Proctor compaction effort. These results are significant since in road engineering applications it is usual to associate better mechanical response (higher bearing capacity and stiffness) of soils to their higher dry density.

Chemical, mineralogical and microstructural characterization of the stabilizing materials

Table 6 lists the respective semi-quantitative analysis of chemical compounds of samples of electric arc furnace oxidizing slag and fly ash used in this study by the analytical method of Energy Dispersive X-ray Fluorescence. The results indicate that samples of electric arc furnace oxidizing slag analyzed are composed mainly of calcium oxide (CaO) and iron oxide (Fe_2O_3), while samples of fly ash are composed mainly by silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3).

Table 3. Physical properties of the PES and fly ash used in the research.

Physical properties	Unit	Stabilizing materials	
		PES	Fly ash
Fineness index	(%)	25.75	48.81
Blaine specific area	(m^2/kg)	542.31	438.91

Table 4. Physical characterization of mixtures of Soil 1 with stabilizing materials, in the proportions of 10 and 20% relative to total dry mass.

Physical properties	Natural Soil	10% stabilizing mixture			20% stabilizing mixture		
		Mixture X	Mixture Y	Mixture Z	Mixture X	Mixture Y	Mixture Z
w_{opt} (%) (MP)	15	15	14	12	15	14	13
ρ_{dmax} (g cm^{-3}) (MP)	1.80	1.74	1.85	1.84	1.86	1.86	1.87
w_{opt} (%) (SP)	17	18	18	19	15	14	13
ρ_{dmax} (g cm^{-3}) (SP)	1.61	1.62	1.64	1.62	1.62	1.69	1.66

MP – Modified Proctor compaction effort; SP – Standard Proctor compaction effort.

Table 5. Physical characterization of mixtures of Soil 2 with stabilizing materials, in the proportions of 10 and 20% relative to total dry mass.

Physical properties	Natural soil	10% stabilizing mixture			20% stabilizing mixture		
		Mixture X	Mixture Y	Mixture Z	Mixture X	Mixture Y	Mixture Z
W_{opt} (%) (MP)	22	23	22	24	22	22	23
ρ_{dmax} (g cm^{-3}) (MP)	1.67	1.74	1.85	1.84	1.72	1.74	1.77
W_{opt} (%) (SP)	28	23	25	25	27	28	28
ρ_{dmax} (g cm^{-3}) (SP)	1.48	1.52	1.53	1.51	1.53	1.53	1.50

Table 6. Chemical characterization of the PES and fly ash used in the research.

Materials	Chemical compounds (%)											
	Al_2O_3	SiO_2	CaO	TiO_2	Fe_2O_3	MgO	K_2O	MnO	P_2O_5	Cr_2O_3	SO_3	ZnO
PES	3.54	10.20	39.97	0.47	32.39	3.82	0.19	5.96	1.75	1.23	0.28	nd
Fly ash	27.35	57.00	2.25	1.46	5.96	0.84	4.02	0.04	nd	0.03	0.64	0.04

nd – non-detected.

The slag expansibility is mainly due to the hydration of calcium oxide and magnesium oxide, observing, for the used material, high levels of CaO and Fe_2O_3 and a comparatively low level of MgO. The X-ray Diffraction tests conducted to identify the crystalline mineral phases of stabilizing materials indicated the predominant presence of sillimanite, vaterite and ferrosilite for PES, and sillimanite and tridymite for fly ash. Through these same tests, it can be seen that the fly ash used is a material with a more pronounced crystallinity, which may favor the development of chemical interactions with other components of the soil-stabilizers mixtures, while the PES is a more amorphous material, although having crystallographic peaks.

The microstructural characterization of powder electric arc furnace oxidizing slag and fly ash by Scanning Electron Microscopy (SEM) is shown in Figure 1. Analyzing the SEM images in Figure 1a and b, it can be observed grains of different sizes with remarkable roughness of different angles, characteristics that tend to favor the mobilization of larger friction and interlocking between the particles of PES and other particles from the compacted soil-stabilizers system. In Figure 1, it can be seen that the grains of the PES have varying sizes, which can assist in the rearrangement of particles of soil-PES-fly ash mixtures and, consequently, contribute to form a solid skeleton less susceptible to deformation.

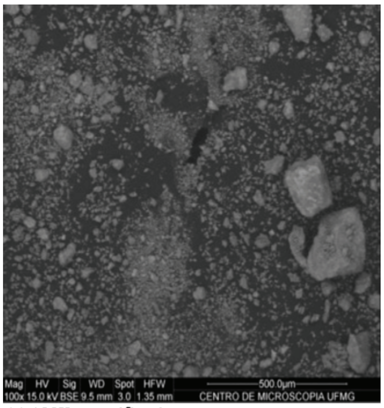
In Figure 1c and d, it is possible to observe more homogeneous fly ash grain size when compared to PES. In Figure 1d, it is observed the presence of cenospheres (microspheres) inside spherical particles of larger diameter, called plerospheres and lumped into angular particles. Microspheres have a surface area greater than the remaining particles, thus they have a higher ability to chemical interaction. These generate extra reaction products, packaging the microstructure and generating significant increases in mechanical strength. Also, the fly ash particles have rounded shape, which can facilitate the physical interaction with the particles of the analyzed soil and also with smaller particles of PES, which can contribute to a better stabilization of mixtures analyzed, reducing the void content when such mixtures are compacted.

Mechanical characterization

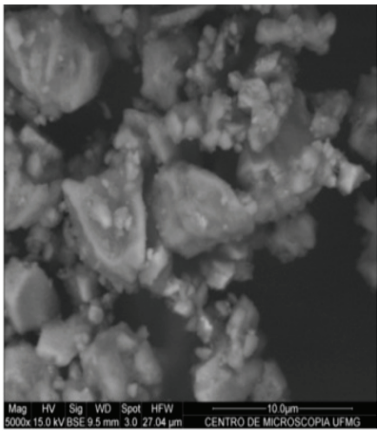
For the unconfined compression tests conducted on soil-stabilizers mixtures, it was considered the effect of curing time on the mobilization of the strength (curing times of 7, 14 and 28 days) of specimens compacted at the standard Proctor compaction effort. Figure 2 presents the mean values of triplicate determinations of unconfined compressive strength of soils 1 and 2 and their mixtures (10 and 20% of stabilizing materials). Data from Figure 2 show that all treatments, including the specimens curing times, were responsible for increases in the unconfined compressive strength of soils.

Unpublished studies conducted by this research group, involving the determination of Mini-CBR of residual soils chemically stabilized by fly ash and steel slag, evidenced the low sensitivity of soils to the stabilizer mixture, since the test specimens of the mixtures of these soils with the waste were not subjected to previous curing;

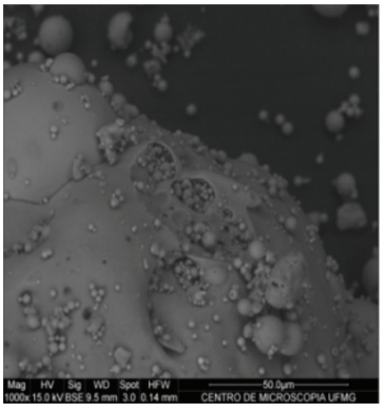
therefore, before shear failure, there is no time to mobilize the chemical reactions responsible for the gain of mechanical strength of the stabilized soil, differently from that experimentally observed in this set of tests by means of the unconfined compressive strength. This trend is thus similar to that found in other types of soil chemical stabilization, such as soil-lime stabilization and soil-cement stabilization.



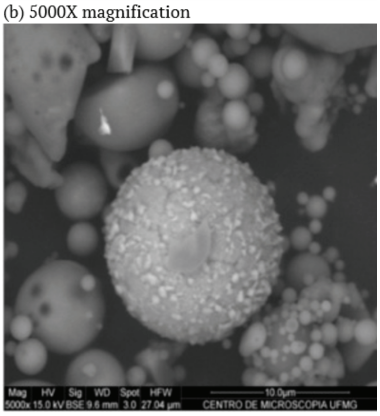
(a) 100X magnification



(b) 5000X magnification

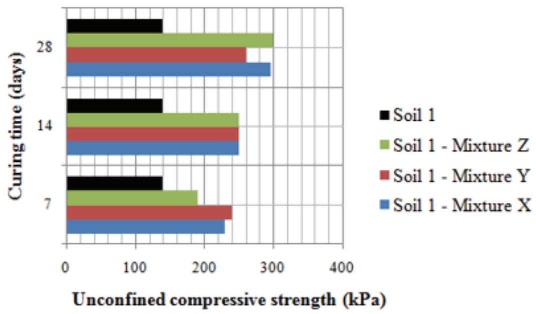


(c) 1000X magnification

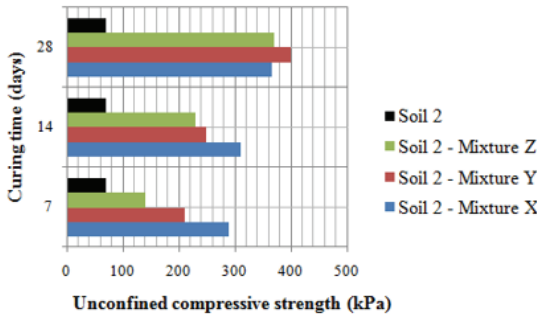


(d) 5000X magnification

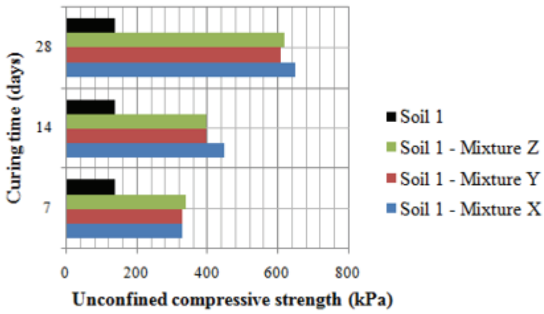
Figure 1. Images of Scanning Electron Microscopy (SEM) of samples of PES [(a) and (b)], and fly ash [(c) and (d)] used in the research.



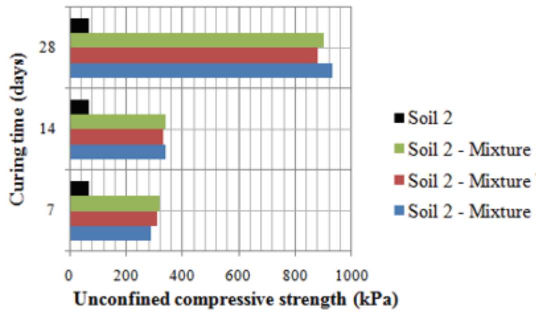
(a) Soil 1 with and without stabilizing mixtures



(b) Soil 2 with and without stabilizing mixtures



(c) Soil 1 with and without stabilizing mixtures



(d) Soil 2 with and without stabilizing mixtures

Figure 2. Mean values of unconfined compressive strength of compacted samples (standard Proctor) of the analyzed soils and mixtures of soil with stabilizer at 10% [(a) and (b)] and at 20% [(c) and (d)] in mass.

For mixtures at 10% stabilizers, considering the specimens subjected to 28 days of curing in a humid chamber with controlled temperature and relative humidity air (25°C and 95%, respectively), the results show that combinations of Soil 2 with PES and fly ash mixtures showed the highest values of unconfined compressive strength, and the strength gains in relation to the natural soil were respectively, 471%, when treated with mixture Y (100% of PES) and 429%, when treated with mixtures Z (75% of PES and 25% of fly ash) and X (87.5% of PES and 12.5% of fly ash). Based on these results, it was noticed that, for Soil 2 in the proportions of materials tested in this study, the PES was able to, exclusively, produce a greater increase in the mechanical strength than the fly ash.

Up to 14 curing days of specimens of mixtures Y and Z, it was found that combinations of Soil 1 with 10% in mass of stabilizing mixture have produced specimens with higher unconfined compressive strength than the same combinations with Soil 2, behavior that inverts up with 28 curing days, since under this condition the mixtures with Soil 2 were more resistant in all analyzed combinations. Thus, for these mixtures, the cementing reactions of Soil 2 and stabilizers impose greater gains in the mechanical strength at older ages. In light of the results of unconfined compression tests data for specimens with 10% of stabilizing mixture, it is shown that Soil 2 has physical and chemical characteristics that allow a more efficient stabilization process, once for this material, there were obtained more satisfactory results after 28 curing days in all tested mixtures.

For mixtures with Soil 1 and 10% of the stabilizer, the best results relative to strength were obtained for mixtures X and Z, and the gains of this soil in the natural state were 114%. For mixture Y involving this soil, the increase in strength was approximately 86%. In this case, the presence of fly ash seems to be relevant to mobilize increased strength gains of the mixtures, even if these gains were not so significant compared to mixtures made of PES and soil, exclusively.

Regarding mixtures with 20% of the stabilizer, similarly to the behavior of mixtures with 10% of the stabilizer, combinations with Soil 2 exhibited better mechanical strength than those corresponding to Soil 1, highlighting its better response to the stabilization provided by PES and fly ash. For the combinations involving Soil 1, mechanical strength gains of up to 364% were achieved (mixture X), whereas the combination with Soil 2 led to increases in the mechanical strength of up to 1,229% (mixture X). Considering the unconfined compressive strength as the reference, the soils tested were very reactive to the stabilizing mixtures of PES and fly ash, which can be attributed to the cementitious action of these materials in the internal structure of the compacted soils.

The mean values obtained for the California Bearing Ratio (CBR) and expansion CBR of soils and mixtures of soil-PES-fly ash, under the conditions provided in this study and derived from tests in triplicate, are presented in Figure 3.

The addition of PES and fly ash to soils in the proportions studied led to improvements in their engineering behavior, as indicated by the CBR testing parameters. Nevertheless, improvements in these indices are dependent on the particle size of the stabilized soils, since for Soil 1 (sandy-silty-clayey texture), the largest increments in values of CBR compared to non-stabilized soil were obtained for mixtures with 20% in mass of stabilizer, whereas for Soil 2 (silty-sandy-clayey texture), the larger increments of this ratio were reached for the mixtures with 10% in mass of stabilizer.

For stabilizing mixtures with Soil 1, compacted under modified Proctor energy, it was observed that the best mechanical response represented by the CBR was evidenced for mixture Z, for a mass percentage of 20% of stabilizer, of which 75% corresponds to PES and 25% to fly ash. The increase in bearing ratio was, on average, of the order of 330% compared to the mechanical strength of the soil. For mixtures containing Soil 2, compacted under modified Proctor energy, the best mechanical response was evident for mixture X for a mass percentage of 10% of stabilizer, which corresponds to 87.5% of PES and 12.5% of fly ash. The increase in bearing ratio was, on average, around 87% compared to the natural soil.

As for expansion CBR of the studied materials, there was a reduction in values of this parameter for specimens containing the mixture PES-fly ash, in all combinations, compared to the tested soils. For this parameter, which indicates the dimensional variation of compacted materials immersed in water, it was noted best performance (greater reductions in expandability) for mixtures involving 20% in mass of the stabilizer mixture, for the two soils. For mixtures with Soil 1, the highest reduction (73%) was obtained for the mixture X, whereas for Soil 2, similar performances were found for all mixtures (X, Y, Z), with a reduction in the expansion of the order of 90%.

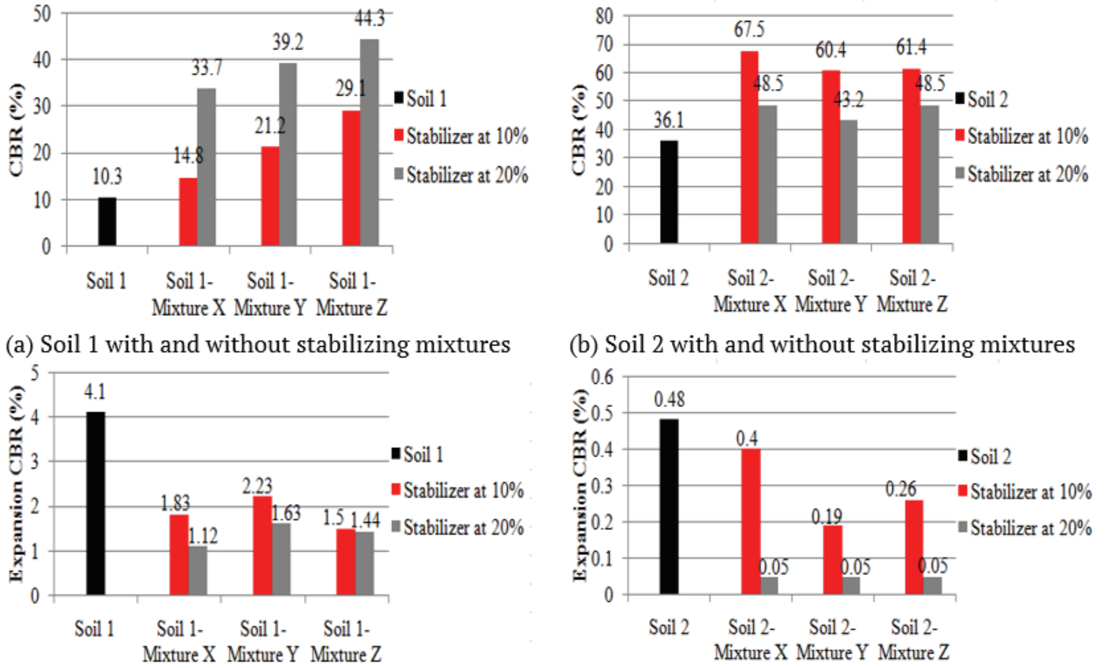


Figure 3. Mean values of CBR [(a) and (b)] and expansion CBR [(c) and (d)] of compacted samples (modified Proctor) of soils and mixtures of soils with stabilizers at 10 and 20% in mass.

Considering the technical requirements contained in Flexible Pavement Design Method (*Departamento Nacional de Infraestrutura de Transportes* [DNIT], 2006), which presents the requirements that must be met for the proper design of flexible pavements in rural or urban areas depending on the values of CBR of the materials involved, it has been experimentally found that Soil 1, after stabilization, became technically suitable for the composition of the subgrade reinforcement layer (expansion CBR ⩽ 2%), with the exception of mixture Y with 10% stabilizer, where the result of the expansion CBR was approximately 2.23%.

For Soil 1, with the addition of the stabilizing mixture, there was a reduction of expansion and an increase in strength, indicating that the chemical reaction of fly ash and PES was satisfactory in most of the investigated mixtures. This same soil remains inadequate for subbase layer in all mixtures studied, because although there were increases in the mechanical strength, the expansion still remained above the tolerable (expansion CBR ⩽ 1%).

In turn, in relation to Soil 2, which could already be used in the subbase layer, in its original condition (CBR ⩾ 20% and expansion CBR ⩽ 1%), there was an improvement in mechanical properties (increased CBR) and dimensional stability (drop in the expansion CBR) when stabilized, in all mixtures and percentages of stabilizer provided in the research, although the stabilized material did not become technically feasible for use as pavement base layer (CBR ⩾ 80%, expansion CBR ⩽ 0.5% and number of repetitions of the standard axle during the project period $N > 5x10^6$).

For Soil 2, the results obtained for mixture X at 10% of stabilizer (CBR = 67.5% and expansion CBR = 0.4%) point out to the perspective that additional studies and investigations involving the materials of this combination (Soil 2-PES-fly ash) could result in other combinations that would allow its use as base layer for flexible pavements structures. For Soil 2 at 10% of stabilizing mixture, it is worth noting that the Flexible Pavement Design Method (DNIT, 2006) considers the possibility of using base layer materials with CBR ⩾ 60%, provided that the number of repetitions of the standard axle during the project period, is $N \leqslant 5x10^6$, making technically justified its use in road works.

In this context, and considering the guidelines in Normative Instruction IP-02 (*Prefeitura do Município de São Paulo* [PMSP], 2004), which attaches to urban roads a characteristic N aimed at designing the pavement for a project period of 10 to 12 years (Table 7), it is possible to infer the possibility of using this mixture on pavement base of urban roads for light (local roads), medium (local and collector roads) and heavyweight (collector and structural roads) traffics, in addition to the possibilities of application of the other mixtures investigated to other pavement structure layers of these roads.

Table 7. Classification of urban roads and characteristic corresponding N [adapted from IP-02 (PMSP, 2004)].

Predominant function	Expected traffic	Characteristic N
Local road	Light	10^5
Local and collector roads	Medium	5×10^5
Collector and structural roads	Heavyweight	2×10^6
	Heavy	2×10^7
	Very heavy	5×10^7
Exclusive bus lane	Medium volume	10^7
	Heavy volume	5×10^7

Conclusion

Given the results obtained in this study, it can be concluded that the combinations of soils studied with the proposed stabilizing material (PES and fly ash) were responsible for improvements in their mechanical strength (unconfined compressive strength and CBR). From the results of CBR tests, in particular, it appears that many of the studied soil-stabilizer mixtures present potential for technical application in layers of flexible pavement structures since their values of CBR and expansion CBR were significantly improved when compared to the same parameters of the natural soils. Besides that, these indices meet the relevant technical requirements for conventional methods of designing layers of flexible pavement structures, mainly to meet the paving demands of urban roads with the use of low-cost materials, such as steel waste.

References

Ahmedzade, P., & Sengoz, B. (2009). Evaluation of steel slag coarse aggregate in hot mix asphalt concrete. *Journal of Hazardous Materials, 165*(1-3), 300-305. doi: 10.1016/j.jhazmat.2008.09.105

American Society for Testing and Materials [ASTM]. (2018). *C 125. Standard terminology relating to concrete and concrete aggregates*. West Conshohocken, PA: ASTM.

Associação Brasileira de Normas Técnicas [ABNT]. (1998). *NBR NM 76. Cimento Portland – Determinação da finura pelo método de permeabilidade ao ar (Método de Blaine)*. Rio de Janeiro, RJ: ASTM.

Associação Brasileira de Normas Técnicas [ABNT]. (2001). *NBR NM 27. Redução de amostra de campo de agregados para ensaio de laboratório - Procedimento*. Rio de Janeiro, RJ: ASTM.

Associação Brasileira de Normas Técnicas [ABNT]. (2004). *NBR 10007. Amostragem de resíduos sólidos*. Rio de Janeiro, RJ: ASTM.

Associação Brasileira de Normas Técnicas [ABNT]. (2012a). *NBR 12025. Solo-cimento – Ensaio de compressão simples de corpos-de-prova cilíndricos – Método de ensaio*. Rio de Janeiro, RJ: ASTM.

Associação Brasileira de Normas Técnicas [ABNT]. (2012b). *NBR 11579. Cimento Portland – Determinação da finura por meio da peneira 75 μm (n° 200)*. Rio de Janeiro, RJ: ASTM.

Associação Brasileira de Normas Técnicas [ABNT]. (2016a). *NBR 6457. Amostra de solo - Preparação para ensaios de compactação e ensaios de caracterização*. Rio de Janeiro, RJ: ASTM.

Associação Brasileira de Normas Técnicas [ABNT]. (2016b). *NBR 9895. Solo - índice de suporte Califórnia (ISC) – Método de ensaio*. Rio de Janeiro, RJ: ASTM.

Associação Brasileira de Normas Técnicas [ABNT]. (2016c). *NBR 7181. Solo - Análise Granulométrica*. Rio de Janeiro, RJ: ASTM.

Associação Brasileira de Normas Técnicas [ABNT]. (2016d). *NBR 6459. Solo - Determinação do Limite de Liquidez*. Rio de Janeiro, RJ: ASTM.

Associação Brasileira de Normas Técnicas [ABNT]. (2016e). *NBR 7180. Solo - Determinação do Limite de Plasticidade*. Rio de Janeiro, RJ: ASTM.

Associação Brasileira de Normas Técnicas [ABNT]. (2016f). *NBR 7182. Solo - Ensaio de compactação*. Rio de Janeiro, RJ: ASTM.

Bernucci, L. B., Motta, L. M., Ceratti, J. A. P., & Soares, J. B. (2006). *Pavimentação asfáltica: formação básica para engenheiros*. Rio de Janeiro, RJ: Petrobras.

Departamento Nacional de Estradas de Rodagem [DNER]. (1994). *PRO 003. Coleta de amostras deformadas de solos*. Rio de Janeiro, RJ: DNER.

Departamento Nacional de Estradas de Rodagem [DNER]. (1996). *PRO 199. Redução de amostra de campo de agregados para ensaio de laboratório*. Rio de Janeiro, RJ: DNER.

Departamento Nacional de Estradas de Rodagem [DNER]. (1997). *PRO 120. Coleta de amostras de agregados*. Rio de Janeiro, RJ: DNER.

Departamento Nacional de Infraestrutura de Transportes [DNIT]. (2006). *Manual de Pavimentação* (3a ed.). Rio de Janeiro, RJ: Instituto de Pesquisas Rodoviárias.

Huang, Y., Bird, R. N., & Heidrich, O. (2007). A review of the use of recycled solid waste materials in asphalt pavements. *Resources, Conservation and Recycling, 52*(1), 58-73. doi: 10.1016/j.resconrec.2007.02.002

Instituto Aço Brasil. (2016). *Números de mercado*. Recuperado de http://www.acobrasil.org.br/site/portugues/numeros/numeros--mercado.asp

Nogami, J. S., & Villibor, D. F. (1995). *Pavimentação de baixo custo com solos lateríticos*. São Paulo, SP: Villibor.

Pasetto, M., & Baldo, N. (2011). Mix design and performance analysis of asphalt concretes with electric arc furnace slag. *Construction and Building Materials, 25*(8), 3458-3468. doi: 10.1016/j.conbuildmat.2011.03.037

Patil, S. S., Bachhav, S. S., & Kshirsagar, D. Y. (2016). Use of steel slag in construction of flexible pavement. *International Journal of Engineering and Innovative Technology, 5*(11), 24-27.

Prefeitura do Município de São Paulo [PMSP]. (2004). *IP-02. Classificação das vias*. São Paulo, SP: PMSP.

Rohde, L., Núñez, W. P., & Ceratti, J. A. P. (2003a). Electric arc furnace steel slag; base material for low-volume roads. *Transportation Research Record, 1819*, 201-207. doi: 10.3141/1819b-26

Rohde, L., Núñez, W. P., & Ceratti, J. A. P. (2003b). Escória de aciaria elétrica: uma alternativa aos materiais convencionais. *Transportes, XI*(1), 13-17. doi: 10.14295/transportes.v11i1.115

Velten, R. Z., Sant'Ana, A. P., Lima, D. C., Silva, C. H. C., Carvalho, C. A. B., Couto, L. G., & Machado, C. C. (2006). Caracterização mecânica de misturas solo-escória de alto forno granulada moída para aplicações em estradas florestais. *Revista Árvore, 30*(2), 235-240. doi: 10.1590/S0100-67622006000200010.

Villibor, D. F., Nogami, J. S., Cincerre, J. R., Serra, P. R. M., & Zuppolini Neto, A. (2009). *Pavimentação de baixo custo para vias urbanas* (2a ed.). São Paulo, SP: Arte & Ciência.

Vizcarra, G. O. C., Casagrande, M. D. T., & Motta, L. M. G. (2013). Applicability of municipal solid waste incineration ash on base layers of pavements. *Journal of Materials in Civil Engineering, 26*(6), 06014005/1-06014005/7. doi: 10.1061/(ASCE)MT.1943-5533.0000903