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Technical feasibility of adding healthcare solid waste to soil-cement mixtures

Victor Lindemberg de Lima Alencar[1], Maria del Pilar Durante Ingunza[2#], Olavo Francisco dos Santos Júnior[2], Enio Fernandes Amorim[3]

Case Study

Keywords
Soil stabilization
Waste management
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Roads

Abstract

Incineration is one of the most widely used techniques to manage solid waste worldwide, thereby reducing it by up to 90%. However, this process produces ash, requiring suitable final disposal. Therefore, the aim of this research is to investigate the feasibility of using healthcare solid waste (HCSW) ash as a soil substitute in chemical stabilisation with Portland cement as a sustainable solution to reduce the use of conventional materials. The methodology involves a geotechnical characterisation (Atterberg limits, particle density, granulometric analysis, California Bearing Ratio) and chemical and mineralogical characterization. The mechanical behaviour was analysed using unconfined compressive strength tests in soil-cement mixtures with increasing cement content, in order to obtain an ideal dosage to mix with HCSW ash. According to the results obtained, adding up to 20% HCSW ash to soil-cement mixture (containing 9% cement) using normal energy produced a gain in unconfined compressive strength. In all the mixtures studied, the strength of the mixtures increased and the minimum requirements for pavement layer applications were met. HCSW ash can be used as a soil substitute in the chemical stabilisation with Portland cement, decreasing the use of conventional materials, indicating a feasible final disposal for HCSW ash.

1. Introduction

Incineration is a widely used technique to manage solid waste worldwide. This technique reduces weight and volume by up to 70 and 90%, respectively (Campuzano & González-Martínez, 2016). Each 1000 kg of incinerated municipal solid waste (MSW) produces 15-40 kg of hazardous waste, requiring additional treatment (Lu et al., 2017). Thus, adequate disposal of incinerated waste is a problem that must be solved, and its application in road construction projects has proven to be technically feasible (Specht et al., 2002; Xue et al., 2009; Romeo et al., 2018).

The main reason for adding ash to soil and using it in paving is to find a sustainable alternative for suitable final disposal, in addition to requiring fewer conventional materials. In the United Kingdom and the USA, heavy ash produced by coal-fired thermoelectric power plants is used in paving (Dawson & Nunes, 1993). In Germany, around 50% of incinerated waste is used in the acoustic insulation of walls and urban road layers (Anastasiadou et al., 2012). In India, approximately 25% of ash is applied to cement production, road construction and brick manufacture (Bhattacharjee & Kandpal, 2002), In Brazil, research in the geotechnical area has meaningfully contributed to the modern concept of sustainability (Boscov & Hemsi, 2020). More specifically, the authors highlight, among other activities, the reuse of wastes as geomaterial. Likewise, recent studies show the geotechnical behaviour of unconventional materials, such as healthcare solid waste (Morais et al., 2023; Juarez et al., 2023; Silva et al., 2023).

According to Ingunza et al. (2015), MSW ash added to mixtures of soil-cement or lime-added soil frequently increased strength and improved soil mechanical properties. The authors reported that this is due to the pozzolanic activities of ash, which contributes to reactions with the free silica and lime present in the cement.

Experimental studies confirmed that fly ash improves the geotechnical properties of soils, enabling its use in road construction, mainly as base or subbase layers of pavements (Edil et al., 2002; Azni et al., 2005). HCSW ash can be

#Corresponding author. E-mail address: maria.ingunza@ufrn.br
[1]Universidade Federal do Rio Grande do Norte, Programa de Pós-graduação em Engenharia Civil, Natal, RN, Brasil.
[2]Universidade Federal do Rio Grande do Norte, Departamento de Engenharia Civil e Ambiental, Natal, RN, Brasil.
[3]Instituto Federal do Rio Grande do Norte, Diretoria Acadêmica de Construção Civil, Natal, RN, Brasil.

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used in the chemical stabilisation of soil-cement, with the application of additives, thermofusion and hydrothermal techniques (Wang et al., 2015; Tang et al., 2015). The use of HCSW ash for lime-added soil in landfills had positive results (Paswan & Jawaid, 2014). Similarly, the use of one type of MSW, incinerator slag, showed satisfactory results on the mechanical behaviour of tailings (Jing et al., 2023). Some researchers report heavy metals in mixtures with ash, and additional leaching tests are needed to assess environmental contamination (Yang et al., 2018; Jawaid & Kaushik, 2012).

Zhang et al. (2019), Forteza et al. (2004) and Zekkos et al. (2013) concluded that HCSW mixed with soils can be used in different pavement layers, making it possible to achieve the geotechnical properties needed to execute this type of project, according to the results obtained in shear strength, modulus of resilience and *CBR* tests.

Therefore, the aim of this research is to investigate the feasibility of using healthcare solid waste (HCSW) ash as a soil substitute in chemical stabilisation with Portland cement as a sustainable solution to reduce the use of conventional materials. For this purpose, an experimental programme commonly used in the field of geotechnical engineering for road construction was studied.

2. Materials and methods

To achieve the aim of this work, which was to find a suitable destination for HCSW ash as an additive to soil-cement mixtures, a common experimental programme used in the field of road geotechnics was explored.

The bottom ash used was collected from the burning of different types of HCSW provided by a private company in Northeastern Brazil. Incineration occurred in two ovens with capacities of 0,028 and 0,056 kg/s. The ash was obtained from the incineration of waste collected in hospitals, laboratories, medical, dental, and veterinary clinics, drugstores and all the companies that produce this type of waste in the region. HCSW exhibited heterogeneous properties, with the presence of drug ampoules and metallic sheets. The ash was greyish in appearance. The ash was classified as "non-hazardous and non-inert" by Brazilian norms (ABNT, 2004), in accordance with American norms (U.S. Environmental Protection Agency, 2006).

Figure 1 illustrates the ash used, after thermal treatment and removal of coarse materials.

The soil collected is a soil being applied, with and without additions, in direct soil-cement foundation reinforcement and sub-base for semi-flexible paving, respectively. The cement used was the Portland cement CP-II-E-32.

Geotechnical characterisation of the soil was conducted by determining the Atterberg limits, whose tests are recommended by NBR 6459 (ABNT, 2016b) and NBR 7180 (ABNT, 2016c) for liquid limit (w_L) and plasticity limit (w_P), respectively. The guidelines are the same as those established by ASTM (2017b). The particle density of the materials was determined according to NBR (ABNT, 2016a, 2017). The guidelines used for the tests correspond to ASTM (2014) and ASTM (1995) respectively.

Soil particle size was obtained using granulometric analysis described in NBR (ABNT, 2016d), and the fine soil fraction by applying the sedimentation test. The methodology used was that described in ASTM (2017c, 2021b).

Chemical composition of HCSW ash was determined by X-ray fluorescence (XRF) and its minerals analysed using X-ray diffraction (XRD).

CBR tests were conducted in soil samples to determine the feasibility of use in pavement layers. The *CBR* test was standardized by NBR (ABNT, 2017), which is equivalent to the method described by ASTM (2021a).

Mechanical behaviour was analysed using unconfined compressive strength (UCS) tests in soil-cement mixtures with increasing cement content, in order to obtain an ideal dosage to mix with HCSW ash. UCS tests were conducted based on NBR (ABNT, 2012) (similar to ASTM, 2017a) which uses three compaction energies: normal, intermediate and modified. Figures 2 and 3 illustrate the procedures.

Table 1 describes the nomenclature used for the dosages studied.

Figure 1. Ash of HCSW.

Table 1. Nomenclature of specimens.

Specimen	codes
Soil-T_1	S100
Dosage 97% soil + 3% cement- T_2	S97C3
Dosage 94% soil + 6% cement- T_3	S94C6
Dosage 91% soil + 9% cement-T_4	S91C9
Dosage 86% soil + 9% cement + 5% ash-T_5	S86C9CRSS5
Dosage 81% soil + 9% cement + 10% ash-T_6	S81C9CRSS10
Dosage 71% soil + 9% cement + 20% ash-T_7	S86C9CRSS20

Table 2. Particle density of materials.

Material	ρ_s (kg/m^3)
Soil	2672
Cement CP-II-E 32	2951
Ash of HCSW	1766
S97C3	2688
S94C6	2690
S91C9	2704
S86C9CRSS5	2660
S81C9CRSS10	2616
S71C9CRSS20	2524

Figure 2. Moulded specimen for the Unconfined Compressive Strength Test (UCS).

3. Results and discussion

3.1 Physical and mineralogical characterisation

The results of the particle density of the materials are in Table 2. These are within the expected for quartz-rich soils. Miura & Yamanouchi (1975) reported similar results (2646 kg/m^3) for sand with 79.7% quartz. Sadrekarimi's (2008) findings were expected for a sandy soil, with particle density of 2650 kg/m^3.

The results obtained for HCSW ash are below those found by Silva & Lange (2008), who analysed three bottom ash samples, found the following values: 1930 ± 40 kg/m^3; 2180 ± 30 kg/m^3 and 2130 ± 10 kg/m^3. This difference may be due to the wide variability of waste produced by the different health institutions. In addition, some companies incinerate MSW along with HCSW. There is no standard for incinerated waste or for the ash produced.

The results of the tests to determine the soil consistency limits classified it as nonplastic. Figure 4 shows the granulometric curve of the soil used in the study. The results showed that in granulometric terms, the soil can be classified as sand, with the presence of 96.4% sand, 1.03% gravel and 2.73% fines.

The data obtained from plotting the granulometric curve were used to calculate the uniformity coefficient (C_u). In the case of the soil studied C_u = 4.47, the result indicated that the soil is uniform (C_u < 5). According to the Unified Soil Classification System, the material is classified as SP, that is, poorly graded, and under the Transportation Research Board (TRB) system, as A-1-a.

The chemical composition of HCSW ash samples is presented in Table 3. The main elements found were calcium (53.80%) and sodium (13.14%). The XRD results are shown in Figure 5.

a) b) c)

Figure 3. Specimens of soil and soil-cement mixtures. (a) Specimens of soil and soil- cement mixtures, (b) Breakage of soil specimens and (c) Breakage of soil-cement mixture specimens.

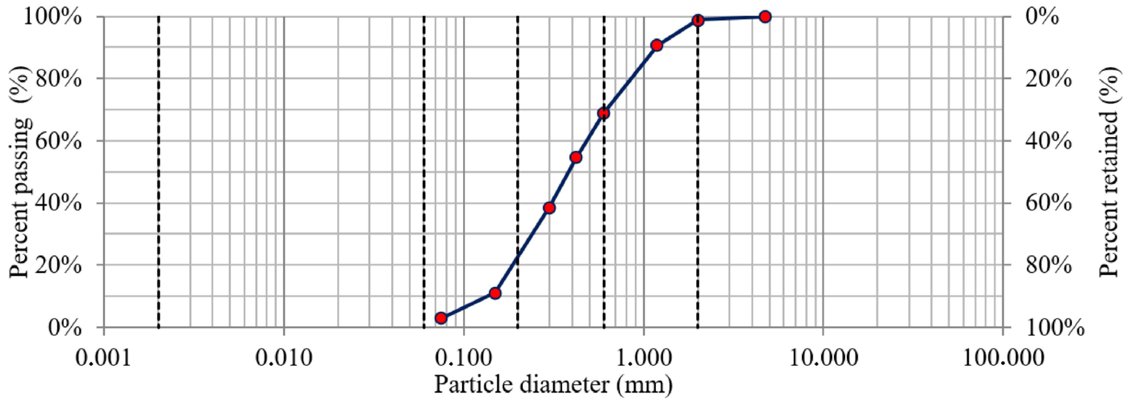

Figure 4. Particle size distribution curve.

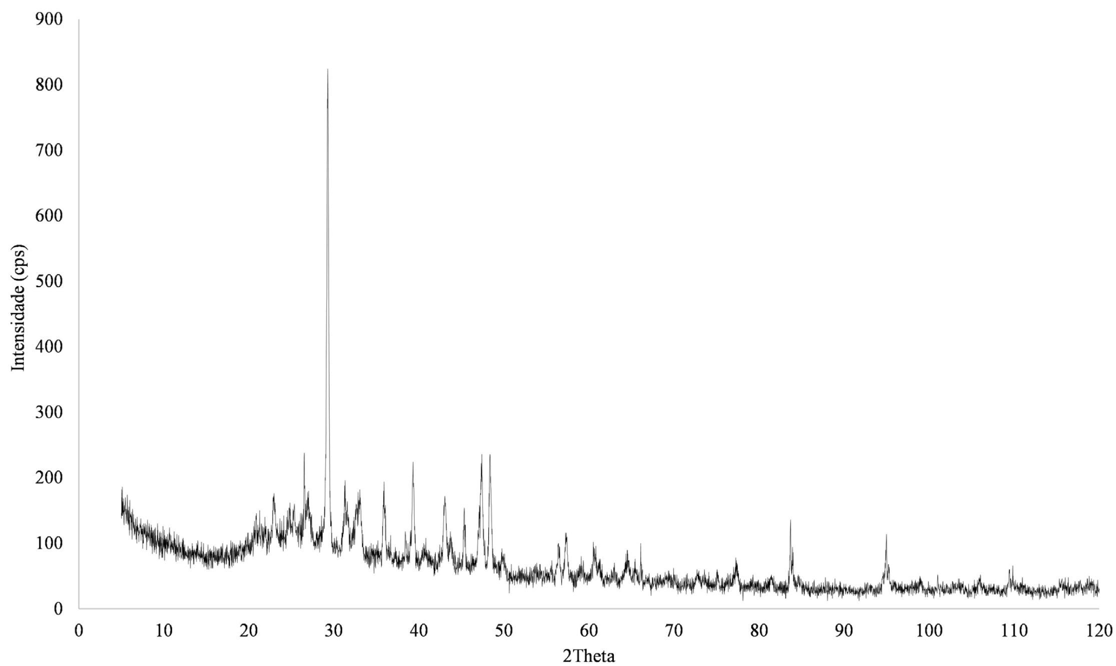

Figure 5. XRD results.

Table 3. Chemical composition of HCSW ash samples.

Element	(%)	Element	(%)	Element	(%)
Calcium	53.80	Silicium	2.77	Phosphorus	0.78
Sodium	13.14	Sulphur	2.11	Bromine	0.68
Zinc	9.90	Aluminium	1.79	Strontium	0.68
Titanium	6.38	Copper	1.64	Other (*)	0.85
Iron	3.90	Potassium	1.58		

The nonlinearity of the diffractogram background (approximately in the 2 Theta range of 20-35 degrees) indicates the presence of amorphous material. The peaks corresponded largely to inorganic calcium compounds, confirming the chemical composition findings. Calcium carbonate ($CaCO_3$) and calcium oxide (CaO) stand out, due to the temperature variations of the oven (calcium carbonate decomposition in calcium oxide occurs at approximately 900ºC). Other peaks show the presence of crystalline material in the form of inorganic, likely difficult-to-identify oxides produced by calcination. Regarding this, the literature reports a significant variation in the chemical and mineralogical composition of the ashes, depending on their origin, but they are generally complex (Lombardi et al., 1998; Azni et al., 2005; Chang & Wey, 2006; Anastasiadou et al., 2012).

The compaction test results are presented in Table 4, exhibiting the findings for soil-cement mixtures with 3%, 6% and 9% cement content, respectively. The apparent dry density (ρ_d) (kg/m^3) and optimum moisture content (w_{ot}) are presented for each compaction energy.

Figure 6 illustrates the results of soil-cement compaction with 3%, 6% and 9% cement, respectively.

Figure 6 shows that increasing compaction energy increases the maximum dry density and decreases the optimum water content for the same cement dosage. The moisture content levels on dry side of the compaction curve show a high suction between the particles compromising the compaction effect, while the moisture content levels on the wet side of the compaction curve generate air occlusion, which favours excess water and the occurrence of undesirable pathologies.

Table 4. Compaction test results.

Energy	Soil		S97C3		S94C6		S91C9	
	ρ_d (kg/m^3)	W_{ot} (%)	ρ_d (kg/m^3)	W_{ot} (%)	ρ_d (kg/m^3)	W_{ot} (%)	ρ_d (kg/m^3)	W_{ot} (%)
Normal	1835	9.3	1880	8.2	1900	8.3	1937	7.0
Intermediate	1844	9.3	1891	8.4	1909	8.3	1958	6.7
Modified	1859	9.9	1936	6.6	1958	7.1	2025	5.8

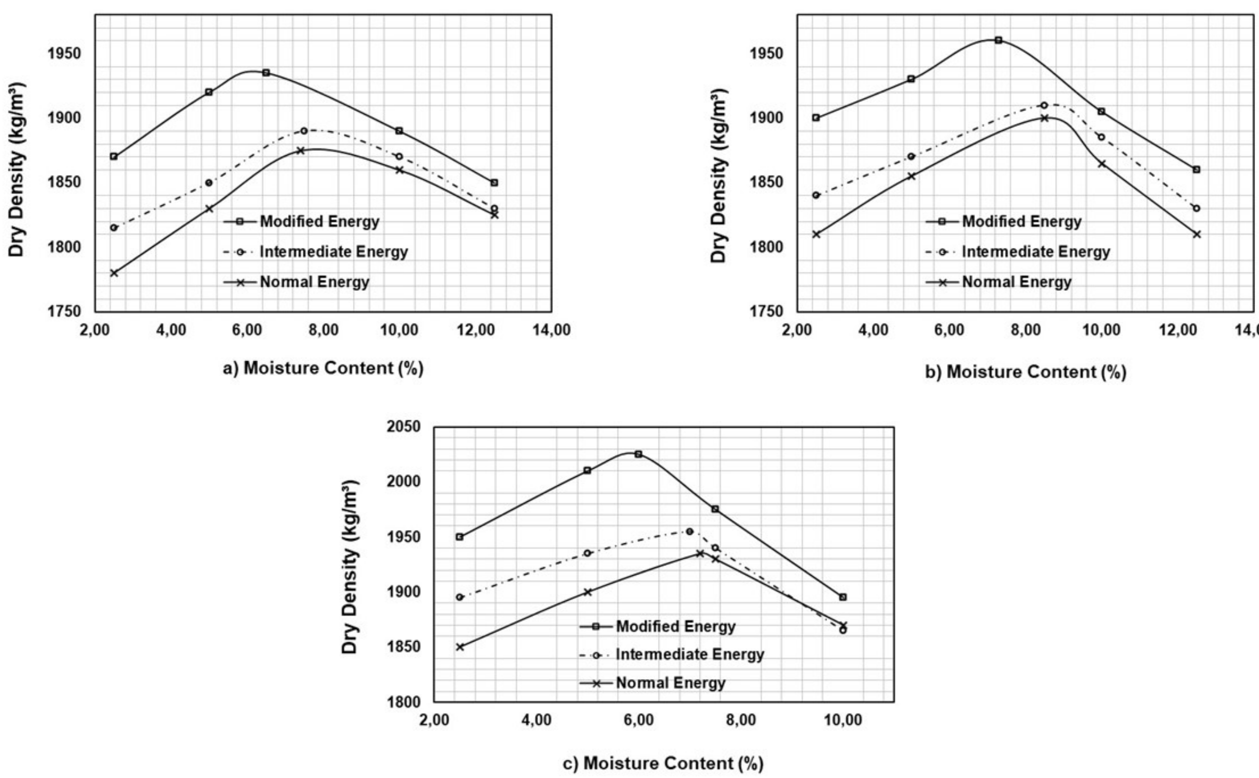

Figure 6. Compaction curves of soil-cement dosages: (a) 3%, (b) 6% and (c) 9%.

Emmert et al. (2017) found that a rise in compaction energy increases density and reduces optimum moisture content in soil-cement mixtures. For the same optimum moisture content, Specht et al. (2002) obtained higher maximum dry density values with an increase in compaction energy.

3.2 Mechanical behaviour

Table 5 shows ρ_d and *CBR* values according to the variation in soil moisture content. The results obtained demonstrate that, depending on moisture content, the soil studied can be used in flexible pavement subbases, complying with Brazilian guidelines for *CBR* and expansion for moisture contents above 5.9%. However, it cannot be used in the pavement base (DNER, 1997).

Table 6 presents the values obtained for UCS in kPa. According to these results, the increase in strength was directly proportional to cement content at the three compaction energies.

According to DNIT (2010), the minimum soil-cement mixture should be 2059.4 kPa for compressive strength at 7 days. This value was only reached using 9% cement in relation to soil weight at the three energies. The others did not achieve the minimum strength value.

In order to analyse HCSW ash in the soil-cement mixture, the dosage selected after the compression test was T_4 (S91C9) moulded at normal energy. This dosage obtained a strength of 2482.1 kPa, in line with the minimum reference value (2059.4 kPa) established by DNIT (2010) for use as pavement base and subbase material.

Added to the dosage T_4 were 5, 10 and 20% of HCSW ash as a soil substitute. Dosages T_5 to T_7 were then defined, as shown in Table 7.

Comparison of the UCS values (Table 8) demonstrates an increase in strength for all ash content added to dosage $T_{4.}$ The highest strength was obtained by dosage T_5, with an increase of 111.35% over T_4. Even with the addition of 20% HCSW ash, strength rose by 21.16% in dosages T_4.

Table 5. Variation of *CBR*, expansion and ρ_d e with the moisture content.

Soil – Normal Energy					
w (%)	3.3	5.9	7.4	9.3	13.8
CBR (%)	10	20	27	34	25
Expansion (%)	1.02	0.47	0.24	0.12	0.13
ρ_d (kg/m^3)	1770	1790	1820	1830	1790

Table 6. UCS results.

Dosage	Normal Energy			Intermediate Energy			Modified Energy		
	Strength (kPa)								
	Min	Max	Med	Min	Max	Med	Min	Max	Med
T_1(S100)	25.5	42.2	31.4	15.7	43.1	26.5	16.7	35.3	26.5
T_2(S97C3)	306.0	507.0	379.5	256.0	396.2	327.5	306.0	688.4	539.4
T_3(S94C6)	467.8	687.4	559.0	543.3	608.0	582.5	749.2	904.2	814.0
T_4(S91C9)	2482.1	2771.4	2627.2	2737.0	2775.3	2824.3	3159.7	3317.6	3223.4

Table 7. Dosage soil-cement-ash for normal energy.

Energy	Dosage	Nomenclature	Material (%)		
			Soil	Cement	Ash
Normal	T_5	S86C9CRSS5	86	9	5
	T_6	S81C9CRSS10	81	9	10
	T_7	S71C9CRSS20	71	9	20

Table 8. UCS in soil mixtures stabilised with cement and HCSW ash.

Normal Energy				
Dosage	Strength (kPa)			Increase in strength in relation to T_4
	Min	Max	Med	
T_5	5483.9	5681.0	5552.5	111.35%
T_6	3657.9	3909.0	3768.7	43.45%
T_7	3085.0	3245.0	3183.2	21.16%

Lombardi et al., (1998) obtained similar results, namely that the higher the HCSW content in the samples, the lower the strength. The author attributed this finding to the fact that the mixtures prepared with higher ash content require much more water to reach adequate workability, but all the samples obtained greater values than the minimum established.

According to the results presented, adding up to 20% HCSW ash to the T_4 soil-cement mixture using normal energy produced a gain in UCS. All the strength values above that required by the DNIT for the use of stabilized soil in pavement layers.

4. Conclusions

This study characterised the technical feasibility of adding solid healthcare waste to soil-cement mixtures in an effort to find a suitable destination for hospital ash. To this end, an experimental programme commonly used in the field of geotechnical engineering for road construction was studied. In particular, it was found that:

- The physical, chemical, and mineralogical characterisation of HCSW ash differed significantly from the values found in the literature. This difference could be due to the great variability of the waste produced by the different healthcare facilities and to the processing method used by each company, highlighting the high complexity of this type of waste.
- Regarding the soil-cement mixtures, those with the addition of 9% cement content, using normal compaction energy, showed the minimum value required by Brazilian standards.
- The addition of 5% ash as a soil substitute increased the UCS by 111.35%. Even with the addition of the highest content studied (20%), HCSW ash increased the UCS by 21.16% compared to the value obtained with T_4 (S91C9); despite the fact that there is a decrease in UCS values with the increase of ash, probably due to workability problems, all the strength values were above those required by DNIT for the use of stabilised soil in pavement layers.

The results obtained show that HCSW ash can be used as a soil substitute in chemical stabilisation with Portland cement, increasing strength and reducing the use of conventional materials, indicating a viable final disposal for HCSW ash. Although the waste used is not hazardous as it is not inert, additional studies need to be carried out to ensure environmental safety.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Victor Lindemberg de Lima Alencar: conceptualization, data curation, methodology, writing - original draft. Maria del Pilar Durante Ingunza: conceptualization, data curation, writing - review & editing, supervision. Olavo Francisco dos Santos Júnior: conceptualization, data curation, writing - review & editing, supervision. Ênio Fernandes Amorim: data curation, writing - review & editing, supervision.

Data availability

All data produced or examined in the course of the current study are included in this article.

Declaration of use of generative artificial intelligence

This work was prepared without the assistance of any generative artificial intelligence (GenAI) tools or services. All aspects of the manuscript were developed solely by the authors, who take full responsibility for the content of this publication.

List of symbols and abbreviations

w	(%) Moisture content
ABNT	Brazilian Association of Technical Standards
ASTM	American Society for Testing and Materials
CBR	California Bearing Ratio
CP-II-E-32	Portland cement with 6 – 34 (% in mass) of slang
C_u	Uniformity coefficient
DNER	National Department of highways
DNIT	National Transport Infrastructure Department
HCSW	Healthcare solid waste
MSW	Municipal solid waste
NBR	Brazilian standard
S100	Nomenclature for 100% soil
S71C9CRSS20	Nomenclature for 71% soil + 9% cement + 20% ash
S81C9CRSS10	Nomenclature for 81% soil + 9% cement + 10% ash
S86C9CRSS5	Nomenclature for 86% soil + 9% cement + 5% ash
S91C9	Nomenclature for 91% soil + 9% cement
S94C6	Nomenclature for 94% soil + 6% cement
S97C3	Nomenclature for 97% soil + 3% cement
SP	poorly graded soil

T_1	Dosage of S100
T_2	Dosage of S97C3
T_3	Dosage S94C6
T_4	Dosage S91C9
T_5	Dosage S86C9CRSS5
T_6	Dosage S81C9CRSS10
T_7	Dosage S71C9CRSS20
TRB	Transportation Research Board system
UCS	Unconfined compressive strength test
w_L	Liquid limit
w_{ot}	Optimum moisture content
w_P	Plasticity limit
XRD	x-ray diffraction
XRF	x-ray fluorescence
ρ_d	Apparent dry density

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