Evaluation of the incorporation of construction waste (CW) for the stabilization of soil-cement mixtures

Avaliação da incorporação de resíduos de construção civil (RCC) na estabilização de misturas de solo-cimento

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Abstract

The reuse of construction waste (CW) has been increasingly adopted as a way to reduce the environmental impact from inadequate disposal of this material worldwide. The stabilization of soils with cement is a common practice, enabling the use of this material in a variety of projects. However, depending on the type of soil, frequently large quantities of cement are needed, making the technique impracticable. The use of CW in the soil stabilization process may be an alternative for reducing the amount of cement and improving the strength of the mixture. The objective of this work was to investigate the use of CW to partially replace a lateritic clay soil in soil-cement mixtures. Besides the natural soil (S), a mixture of soil and CW (S-CW) was used with proportions of 50% of each. The cement content levels evaluated were 0%, 4%, 6% and 8% and the curing periods varied from 7 to 28 days. The results showed superior strength values for the S-CW compared to the soil-cement. This confirms that the use of CW reduces the percentage of cement necessary for the stabilization of a clayey soil and presents an alternative, more environmentally appropriate destination for this material.

Keywords: Construction waste. Soil-cement. Clay soil. Soil stabilization. Strength.

Resumo

A reutilização dos resíduos de construção civil (RCC) vem sendo adotada como uma maneira de reduzir os impactos causados pela geração e disposição inadequada desse material em todo o mundo. A estabilização de solos com cimento é uma prática comum para viabilizar a utilização desse material em diversas obras, entretanto, dependendo do tipo de solo, são necessárias grandes quantidades de cimento, tornando a técnica inviável. O uso do RCC no processo de estabilização do solo pode ser uma alternativa para reduzir o teor de cimento utilizado e melhorar a resistência da mistura. O objetivo desse trabalho foi investigar o uso do RCC em substituição parcial de um solo argiloso laterítico em misturas de solo-cimento. Além do solo natural, foi utilizada uma mistura de solo e RCC (S-RCC) usando proporções com 50% para cada material. Os teores de cimento avaliados foram 0, 4, 6 e 8% e os períodos de cura variavam de 7 a 28 dias. Os resultados indicaram que a mistura S-RCC com cimento apresenta resistência superior ao solo-cimento. Isto confirma que o uso de RCC reduz os teores de cimento necessários à estabilização de um solo argiloso e se apresenta como uma alternativa mais ambientalmente apropriada para a destinação deste material.

***Palavras-chave**: Resíduo de construção civil. Solo-cimento. Solo argiloso. Estabilização de solos. Resistência.*

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Recebido em 29/01/20
Aceito em 02/06/20

Introduction

Construction waste (CW) represents a significant portion of the solid waste generated worldwide (HIDALGO; CARVAJAL; MUÑOZ, 2019; BRASILEIRO; MATOS, 2015). In 2017, about 45 million tons of construction and demolition waste were generated in Brazil, which corresponds to more than 50% of all solid urban waste in the country (ASSOCIAÇÃO…, 2017). The problems associated with this material are related to the cost of disposal and the significant negative environmental impact. This waste is either disposed of in landfills, which are limited in area and costly to manage, or it is disposed of at inappropriate sites, causing urban sanitation and environmental contamination problems (HIDALGO; CARVAJAL; MUÑOZ, 2019; ARTUSO; LUKIANTCHUKI, 2019; SILVA *et al*., 2018). Analysis of these negative impacts affirm the need to find new alternative uses, in order to provide an appropriate final destination for such waste.

Construction waste exhibits characteristics advantageous for use in engineering projects, including good strength and low expansion (LEITE *et al*., 2011). Jiménez (2011) reported that construction waste has the potential to replace the aggregates used in concrete and pavement layers and replacing the use of graded gravel and sands of varying granulometry. However, the use of construction waste to replace a lateritic clay soil in soil-cement mixtures for backfill in shallow foundation has not been extensively investigated, especially when considering a foundation system for electricity transmission.

Soils, in general, are very important construction materials, in terms of availability, application possibilities and cost. However, clay soils are sensitive to changes in humidity and are susceptible to contraction and expansion (PRUSINSKI;BHATTACHARJA, 1999). Therefore, the construction of geotechnical designs such as bridges, subways, retaining walls, embankments and pavement layers over clay soils can be considered as a challenging task (SHARMA; SHARMA, 2019).

The use of cement is a common method of chemical stabilization of clay soils and has been extensively used worldwide. The soil-cement is a mixture of the selected soil, the cement and the water which are mixed and compacted in a specific dry density. The water causes the cement hydration and therefore the calcium-silicate-hydrate (C-S-H) and the calcium-aluminate-hydrate (C-A-H) are formed. During the cement hydration, the excess of calcium hydroxide (CaOH) is released (PARSONS; MILBURN, 2003). The cement hydration products will be formed until the unreacted cement particles and free water remain in the mixture (FIROOZI *et al*., 2017).

The soil-cement is used to change the soil properties and improve its performance for engineering applications. The significant effects of this chemical stabilization are the reduction in shrinkage and swell potential and the increase of the strength and the elastic modulus (FIROOZI *et al*., 2017). The addition of cement for the stabilization of clay soils may lead to the appearance of small shrinkage cracks, due to the use of water to initiate the cement hydration. Therefore, for such soil mixtures, minimal amounts of cement are recommended. However, in order to obtain increased strength, higher proportions of cement are needed, which can lead to more cracking, impairing the behavior of the material (ESTABRAGH; NAMDAR; JAVADI, 2012).

As an alternative, to minimize such problems and avoid the excessive use of cement, the addition of construction waste to clay soils may be considered as a way to improve the grain size characteristics and the mechanical performance of the material. The use of cement in granular soils leads to an economical and effective solution because smaller amounts of cement are required (FIROOZI *et al*., 2017). Soil stabilization through the incorporation of construction waste improves the load capacity of the soil and fatigue crack resistance, in addition to making the material more durable (HIDALGO; CARVAJAL; MUÑOZ, 2019; BANZIBAGANYE; TWAGIRIMANA; KURAMAN, 2018; JOSHI *et al*., 2019). When this waste is added to clayey soils, the dry density decreases and, consequently, the unconfined strength increases, yielding a more resistant, stiffer and less deformable mixture (KIANIMEHR *et al*., 2019). In soil-cement mixtures, the addition of CW contributes to strength gain and improves compaction characteristics (MOREIRA *et al*., 2018; REIS *et al*., 2015; REIS *et al*., 2018; SULUGURU *et al*., 2018). Some practical applications of this alternative material are pavement layers, earth structures, impermeable layers, embankment and backfill material.

Therefore, the present work is focused to evaluate the use of CW to partially replace a lateritic clay soil in soil-cement mixtures as an alternative material in backfills of shallow foundations. Some regions of Brazil have a predominance of lateritic clay soils and scarcity of natural aggregates for geotechnical designs. Thus, geotechnical engineers are often challenged to find an alternative solution by using different materials. The study was conducted evaluating the behavior of soil-cement (S) and soil-CW-cement (S-CW) mixtures. The performance of the mixtures was evaluated by means of mechanical strength tests for four different cement levels and curing times. The cement was added to the soil and soil-CW in proportions of 0, 4, 6 and 8%, in terms of dry mass. The results enabled the evaluation of the impact of adding CW to the soil-cement mixture and the analysis of the feasibility of using this alternative material in shallow foundations.

Material and methods

Material

The soil was collected at Universidade Estadual de Maringá, in the city of Maringá, in the northwest region of the state of Paraná, Brazil. It is characterized as a lateritic soil, with a clayey texture, classified as a dystrophic Red Latosol (GUTIERREZ; NÓBREGA; VILAR, 2008) (Figure 1a). The material was dried until it reached a hygroscopic water content, then it was removed and passed through a 4.8 mm sieve and stored in an appropriate container.

The construction waste material (Figure 1b) was supplied by Usina Nova Obra, located in the city of Arapongas, in the state of Paraná. The collected CW is mainly composed of concrete elements (structural elements) and the remains of walls with large amounts of mortar (Figure 2a). The waste was processed at the plant itself and went through manual separation and a coarse sieving process. Subsequently, the material was taken to the crusher, where granulometric separation was performed automatically (Figure 2b). According to information provided by the plant, the ceramic composition of the CW ranges from 30 to 35%. The waste was dried until it reached the hygroscopic water content and stored in containers protected from contact with other materials.

Figure 1 - **Visual aspect of (a) the natural soil and (b) the CW**

(a) (b)

Figure 2 – **Image of (a) the materials that make up the CW and (b) the crusher**

(a) (b)

The present study selected a specific CW sample with a grain size of less than 2 mm, called *artificial sand*. It is important to highlight that the CW is a widely variable and heterogeneous material. Further studies using different CW composition are necessary to evaluate the behavior of different wastes for soil stabilization.

The cement used was Votoran - CP II-Z 32, with 6 to 14% pozzolan and up to 10% carbonate material in its composition, ensuring a mixture with good workability and impermeability.

The mixtures used were soil-cement (S) and soil-CW-cement (S-CW) with different cement content levels and curing times. The soil-CW mixtures were prepared in terms of dry weight and in proportions of 50% for soil and 50% for CW. The proportions of soil and CW was defined based on previous studies (LUKIANTCHUKI *et al*., 2019; SILVA *et al*., 2015) while the cement contents were established according to the chemical-physical method (CHADDA, 1971). Table 1 presents the principal information about the mixtures.

Table 1 – **Sample characteristics (Soil, CW, cement and days of cure)**

Mixture	S (%)	CW (%)	C (%)	t (days)	Nomenclature
S	100	0	0.0	7	S-00 (7d)
				14	S-00 (14d)
				21	S-00 (21d)
				28	S-00 (28d)
	96	0	4.0	7	S-04 (7d)
				14	S-04 (14d)
				21	S-04 (21d)
				28	S-04 (28d)
	94	0	6.0	7	S-06 (7d)
				14	S-06 (14d)
				21	S-06 (21d)
				28	S-06 (28d)
	92	0	8.0	7	S-08 (7d)
				14	S-08 (14d)
				21	S-08 (21d)
				28	S-08 (28d)
S-CW	50	50	0.0	7	S-CW-00 (7d)
				14	S-CW-00 (14d)
				21	S-CW-00 (21d)
				28	S-CW-00 (28d)
	48	48	4.0	7	S-CW-04 (7d)
				14	S-CW-04 (14d)
				21	
				28	S-CW-04 (21d)
	47	47	6.0	7	S-CW-06 (7d)
				14	S-CW-06 (14d)
				21	S-CW-06 (21d)
				28	S-CW-06 (28d)
	46	46	8.0	7	S-CW-08 (7d)
				14	S-CW-08 (14d)
				21	S-CW-08 (21d)
				28	S-CW-08 (28d)

Note: S is the soil; CW is the construction waste; C is the cement; and t the days of cure.
The pH of the natural soil and the S-CW mixture was measured with distilled water and potassium chloride (1M - KCL). Nine readings were taken, starting 10 minutes after preparing the solution and ending after 72 hours.

Methods

The methodology used in the development of this research is divided into the following stages: physical and chemical characterization of materials, mechanical strength tests, and scanning electron microscopy (SEM).

Experimental program

The physical and chemical characterization stage consisted of the following tests: granulometric analysis (ABNT, 2016a), particle size distribution by laser diffraction for cement, particle density of the materials and the cement (NBR 6458 (ABNT, 2016b) and DNER-ME 085 (DEPARTAMENTO…,1994), respectively), consistency limits (ABNT, 2016c, 2016d), pH value measurements (AMERICAN…, 2001), X-ray diffraction (XRD) and compaction test (ABNT, 2016e). The standard for the compaction test establishes different levels of compaction energy. In this study, the compaction curves were obtained for normal energy (600 kJ/m³). The maximum dry density (ρ_{dmax}) resulting from the compaction test represents the relationship between the mass of the grains and the total volume of the material, which refers to the density when the degree of saturation is equal to zero.

The XRD analyses were performed for the soil and CW samples prepared in the No. 200 sieve (0.075 mm). The mineralogical composition of the samples was identified by means of a PANalytical X´Pert PRO MPD diffractometer, using CuKα radiation and a voltage and current of 40 kV and 30 mA, respectively. The angular step was 0.04°, with a scanning interval from 3° (initial 2θ) to 70° (final 2θ) and a counting time per point of 2 seconds.

The unconfined compressive strength (UCS) (Figure 3a) of the soil and soil-CW mixtures was assessed according to D2166 (AMERICAN…, 2016a) and the UCS for each mixture was represented by average values of four specimens tested. The indirect tensile strength (TS) (Figure 3b) was assessed according to the Brazilian test method (AMERICAN…, 2016b) (Equation 1) and the TS for each mixture was represented by average values of four specimens tested. The tests were performed using a manual press, load cells with a maximum capacity of 20 kN and 2 kN for UCS and TS, respectively (Figure 3a and Figure 3b) and two linear variable displacement transducers (LVDTs) with a maximum capacity of 5 mm.

$$TS = \frac{2F}{\pi DL} \qquad \text{Eq. 1}$$

Where:

F is the maximum applied load (kgf);

D is the specimen diameter (cm); and

L is the specimen height (cm).

The tests for unconfined compressive strength and indirect tensile strength were performed until the failure of the samples (Figure 4a and Figure 4b). From the information generated, the stress-strain curves of the samples were drawn and the modulus of elasticity (E) was estimated for a specific point (elastic region). For the tests carried out in this research, the modulus of elasticity was determined by evaluating the relationship between the stress corresponding to 50% of the failure stress ($\sigma_{50\%}$) and the strain ($\varepsilon_{50\%}$) for a given point (Equation 2).

$$E = \frac{\sigma_{50\%}}{\varepsilon_{50\%}} \qquad \text{Eq. 2}$$

The analysis of the internal morphology and the reaction products of the stabilized mixtures was carried out on the same specimens after the mechanical strength tests through scanning electron microscopy (SEM). For SEM tests, small pieces of the specimens were used , which were fixed on a carbon tape and coated with gold (conductive material). The tests were carried out using Shimadzu Superscan SS-550 equipment, operating with an acceleration voltage of 10 kV, with a magnification capacity of 20 to 300,000 times.

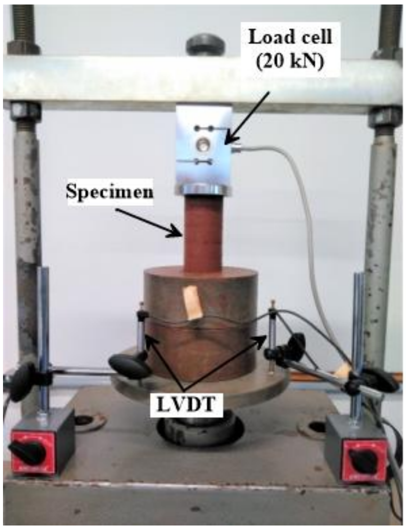
Preparation, molding and curing of the specimens

For the unconfined compressive strength and indirect tensile strength tests, four cylindrical specimens were prepared for each specific condition (Table 1). The specimens were molded using the parameters of the soil compaction curve as a reference: maximum dry density and optimum moisture content.

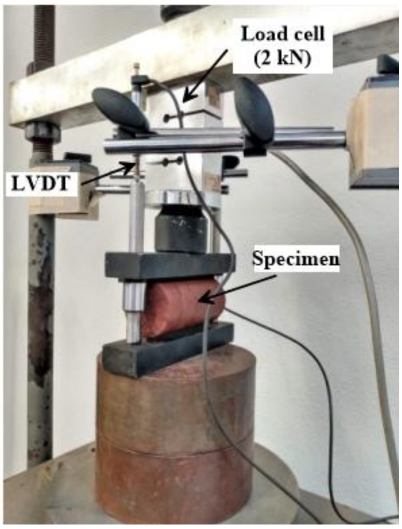
The preparation of the mixture was carried out in terms of dry mass. The mixtures were prepared manually. First, cement was added to the soil and to the soil-CW mixtures. Next, water was added, in a mixture, reaching a water content similar to the optimum water content corresponding to the equivalent compaction curve. The mixtures were sieved in a #2.0 mm sieve and homogenized during the process. The specimens were molded in five layers and had a diameter and height corresponding to 50 and 100 mm, respectively. The scarification was performed to ensure the adhesion between the layers. As the specimens were molded in a metallic cylinder, a metallic ruler was used to correct the top and the bottom of the specimens and roughness was not observed. For each specimen the water content was determined and the dimensions were measured. The specimens were wrapped in waterproof plastic and stored (wet room) to cure for 7, 14, 21 or 28 days before testing.

The specimens were placed in water immersion 24 hours before reaching the pre-established curing period. This process was carried out to increase the saturation of the specimens and decrease the effects of suction on the strength measurements. After water immersion, the mass of the samples was measured and the strength tests were performed.

Figure 3 – **Unconfined compression test (a) and indirect tensile strength test (b)**

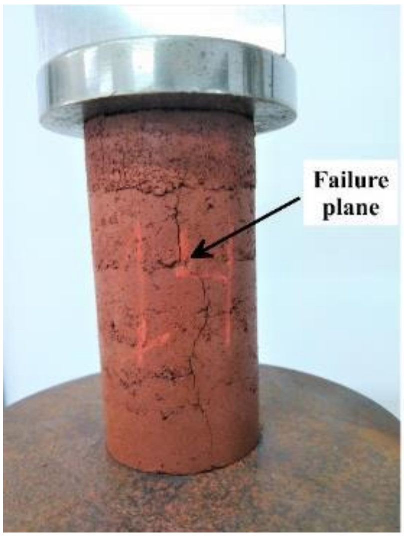


(a)



(b)

Figure 4 – **Failure planes from the unconfined compressive strength test (a) and indirect tensile strength test (b)**



(a)

(b)

The dry density (ρ_d) (Equation 3) and the degree of compaction (DC) (Equation 4) were determined for each specimen. The dry density depends on the moisture content (w) and the density (ρ) of each specimen and the degree of compaction is related to the maximum dry density (ρ_{dmax}) determined in the compaction test. In this study, a minimum degree of compaction of 95% was established.

$$\rho_d = \frac{\rho}{1+w} \quad \text{Eq. 3}$$

$$DC = \frac{\rho_d}{\rho_{d\,máx}} \quad \text{Eq. 4}$$

Results and discussion

Physical and chemical characterization

Table 2 presents the results of the characterization of each of the materials and the mixture. The particle density (ρ_s) was greatest for the natural soil, because the soil has iron oxides, minerals characteristic of lateritic soils. The CW had a value close to 2.65 g/cm3, a typical value for quartz, indicating that the material possibly has sand in its composition. The S-CW mixture showed an intermediate value between the values of the pure materials.

The CP II Z-32 is composed of oxide of magnesium (MgO), trioxide of sulfur (SO3) and dioxide of carbon (CO2) and the loss of fire is not more than 6.5% in terms of mass (ABNT, 1997). The particle density of the cement was 3.05 g/cm³, consistent with the value found in the test. According to the Brazilian Portland Cement Association (ASSOCIAÇÃO…, 2019), the average specific gravity for CP II Z-32 is 3.00 g/cm³. This parameter was determined to calculate the density of the specimens with the addition of cement, making it possible to obtain more specific values for the physical phases (solids, water, voids) of the mixtures.

Due to the low quantity of clay and silt in the construction waste, it was not possible to obtain the limits of liquidity and plasticity for this material. In contrast, the natural soil showed highly plastic behavior, as it is composed predominantly of fines. The reduction in the plasticity of the S-CW mixture was not as significant as expected, indicating that the fine fraction of the soil has the capacity to develop plasticity even when a non-plastic material with granular behavior is added. The addition of waste construction in 50% of proportion reduces about 21% of the plasticity index, changing the soil from high plastic to intermediate plastic.

The incorporation of the CW into the soil provided a decrease in the proportion of fines and an increase in the amount of sand in the material, resulting in a mixture with better grain-size distribution, as seen in the grain-size distribution curves (Figure 5). For the cement, particle size distribution by laser diffraction identified that most of the particles size varies from 0.01 mm to 0.10 mm. According to Udden-Wentworth Classification (CHRISTOFOLETTI; MORENO, 2017) the cement can be classified as fine siltite to very fine sandstone. The cement also presented particles size from 1 to 10 µm (32.36%) and its classified as fine siltite to clay.

Table 3 shows the average pH values for each sample, and Figure 6 shows all the measurements made during the test. Although the pH of the pure CW was not measured, its value was estimated to be approximately 10.5, taking into account that the pH of the S-CW mixture is an average between the pH values of the materials that compose it. Jiménez (2011) worked with a construction waste with a pH value of 11.2 and Artuso and Lukiantchuki (2019) studied two CW samples with pH values of 9.72 and 11.03. The composition of the waste material used in the present research is similar to the CW used by Artuso and Lukiantchuki (2019) with a pH of 9.72. According to the authors, the lower pH value can be explained by the carbonation of small fractions of concrete and cementitious mortar. Alkaline environments can alter silica minerals and are essential for the stabilization of clay with calcium oxide, given that calcium silicate is hydrated and forms cementitious materials using the silica from the clay minerals (JIMÉNEZ, 2011). According to Blankenagel (2005), pozzolanic reactions can only occur in environments with a pH above 10, which is the threshold for silica to become soluble.

In light of this, the CW used in this study can be considered suitable for clay stabilization and confirms the self-cementation effect described by Artuso and Lukiantchuki (2019). Since the clay in this study is lateritic and composed of kaolinite, when this mineral is dissolved in the S-CW mixture, a reaction occurs between the alkali and the anhydrous grains of the concrete and cementitious mortar. This makes the environment more favorable to cement hydration reactions and contributes to the strength gain of the matrix.

Figure 7 shows the diffractograms of the S and S-CW samples. In the case of the soil (Figure 7a), there is a predominance of quartz, which comes from basaltic rocks. Hematite was observed due to iron oxides and hydroxides, and the existence of kaolinite, which is the prevalent clay in lateritic soils, as is the case of this soil. For the CW (Figure 7b), the diffractogram shows the predominance of the mineral calcite, which is found in sedimentary rocks and characterizes it for the manufacture of cements and mortars. In the case of the construction waste, the large quantity of this mineral is due to the composition of the CW being mainly from concrete structures, rich in mortars. The presence of quartz in the CW is due to the sandy fraction of the material.

Table 2 – **Results of the geotechnical characterization of the materials**

Geotechnical parameters	S	CW	S-CW
Particle density (ρ_s) - (g/cm³)	3.24	2.77	2.93
Liquid limit - LL	61	-	42
Plasticity index - IP	19	-	15
D_{10} (mm)	-	0.12	0.002
D_{30} (mm)	-	0.29	0.040
D_{60} (mm)	0.005	0.50	0.025
C_u	-	4.16	131
C_c	-	1.40	3.36
Sand content (%)	15	93	63
Silty content (%)	34	8.5	25
Clay content (%)	51	0.5	12
HRB Classification	A-7-5	A-3	A-7-6
SUCS Classification	MH	SW-SM	SM

Note: Where: D_{10}, D_{30} and D_{60} are the diameters corresponding to 10, 30 and 60% of the material, respectively; and C_u and C_c are the coefficients of uniformity and curvature, respectively. The coefficients are estimated by: $C_u = \frac{D_{60}}{D_{10}}$ and $C_c = \frac{(D_{30})^2}{D_{60} \times D_{10}}$.

Figure 5 – **Grain-size distribution curves**

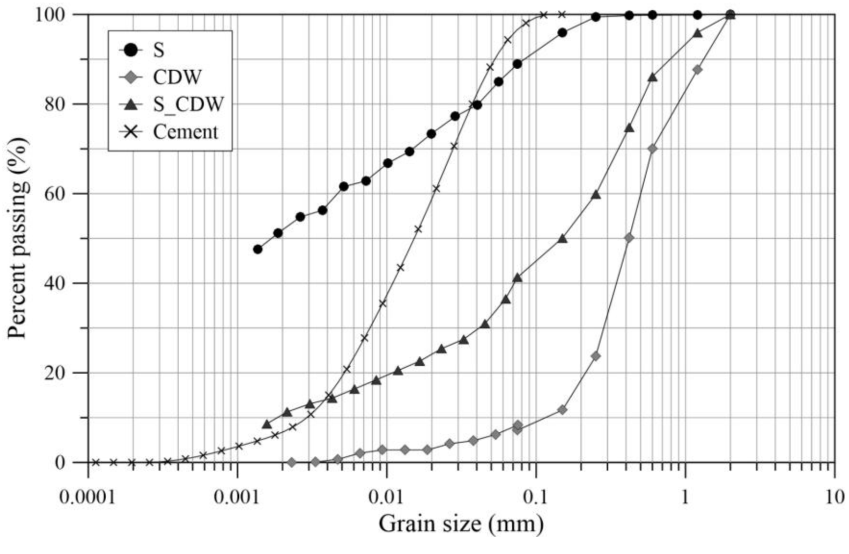


Table 3 - **Results of the pH test**

pH	S	S-CW
Distilled water	7.71	7.11
KCl (1 M)	4.38	7.44
ΔpH	-3.33	0.33

Figure 6 - **pH test measurements**

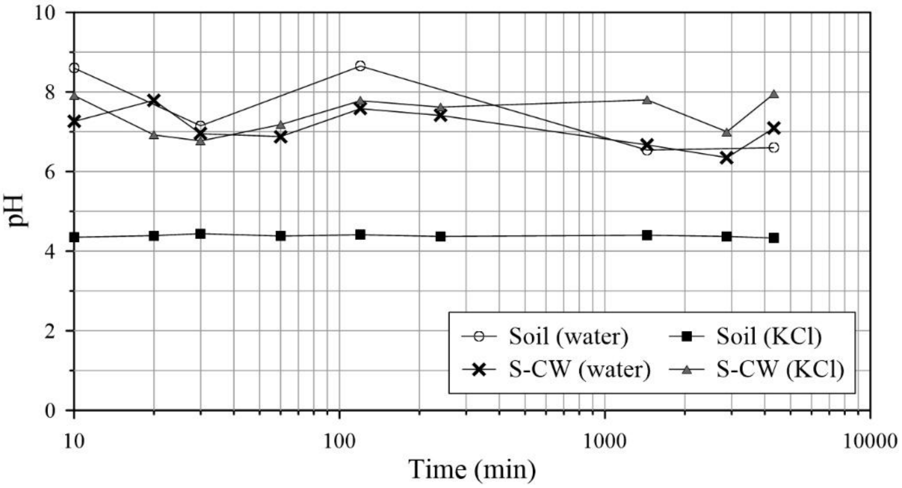
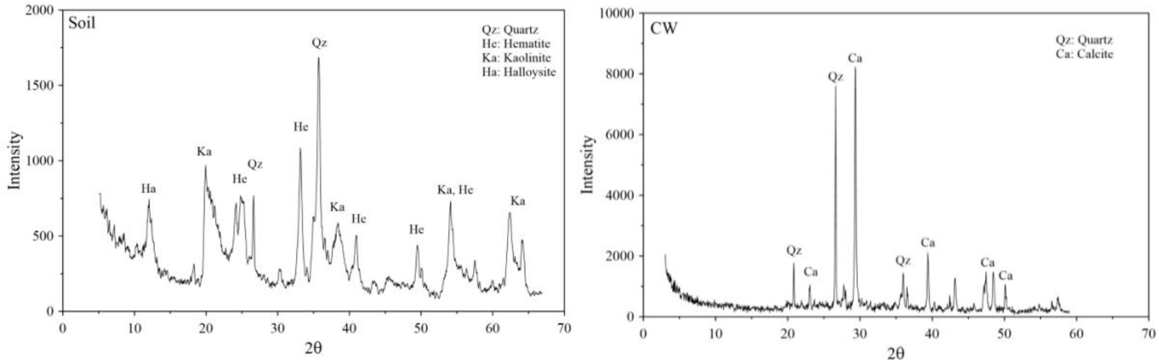


Figure 7 - **XRD Analysis of the Soil (a) and CW (b)**



(a) (b)

Artuso and Lukiantchuki (2019) worked with similar materials and the XRD analyses of the soil and CW showed similar results. Silva *et al.* (2018) divided the construction waste into samples of different grain sizes, and the diffractograms indicated the presence of quartz and calcite in all portions. In the analysis conducted by Jiménez (2011), the presence of quartz, feldspars and calcite from cementitious materials was identified in the waste material, as well as mica from rocks and ceramics, and small fractions of clay materials.

Compaction test

Figure 8 and Table 4 show the results of the compaction test for the S and S-CW mixtures with the cement content levels defined for the study. The results indicate that the soil-cement mixtures (S) have maximum dry density values slightly higher than that of natural soil, because the cement fills some of the voids in the mixture (Figure 8a). On the other hand, the optimum moisture content decreases with the incorporation of cement into the natural soil, a behavior that may be related to the beginning of cement hydration reactions.

For the S-CW mixture (Figure 8b), there is an increase of about 12% in the values of maximum dry density when compared to the soil-cement. This is possibly because the S-CW mixture has a more uniform granulometric distribution, providing better filling of the voids. In addition, as expected, the S-CW mixture has an optimal moisture content approximately 45% lower than that of the soil-cement. Furthermore, the addition of cement to the S-CW mixture did not result in significant variations in the compaction parameters.

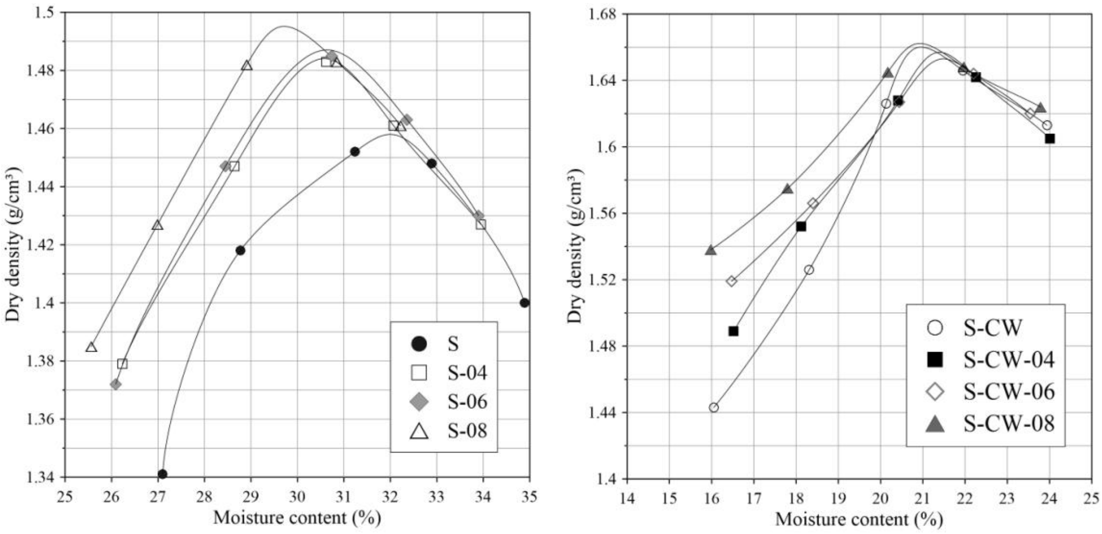
In the compaction of pure CW, an increase in the moisture content resulted in the expulsion of water from the cylinder during the application of energy, demonstrating that the material has a draining behavior. The dry density remained practically constant with the variation in moisture content. The average value for the dry density of the construction waste is 1.54 g/cm³ and the coefficient of variation for the other values is less than 2%. The behavior of this material is similar to that of the construction waste analyzed by Silva *et al*. (2018), with performance typical of granular materials.

Mechanical characterization

Table 5 shows the UCS and TS average values, standard deviation (SD) and the coefficient of variation (CV) for the experimental data. For each specific situation, the average values based on four specimens with similar parameters of molding were calculated. For UCS tests, experimental data shows that the coefficient of variation for S specimens were higher than the S-CW specimens. Results also show that the coefficient of variation for the TS tests were higher than the UCS test, which can be associated with the mechanism of failure of the test due to the cylindrical surface.

The unconfined compressive strength increases with the increase in cement content for the two mixtures studied, as shown in Figure 10. This behavior has already been confirmed by other researchers, and is due to the hydration reactions that occur during the cement curing process which enable this increase in strength. Regarding the curing time, most of the samples exhibited a tendency to stabilize the strength or even a decrease in the strength (Figure 10). The only sample that showed strength gain over time was S-CW-08, indicating that with 8% cement, the hydration reactions of the cement were possible. For the other samples, the cement content levels were inefficient for strength gain over time.

Figure 8 - **Compaction curves for the S (a) and S-CW (b) mixtures**



(a) (b)

Table 4 - **Compaction parameters**

Materials	ρ_{dmax} (g/cm³)	w_{op} (%)
S	1.46	32.00
S-04	1.48	30.65
S-06	1.49	30.70
S-08	1.50	29.62
S-CW	1.66	20.90
S-CW-04	1.66	21.40
S-CW-06	1.65	21.50
S-CW-08	1.66	20.83

Table 5 – **Statistical results for UCS and TS tests**

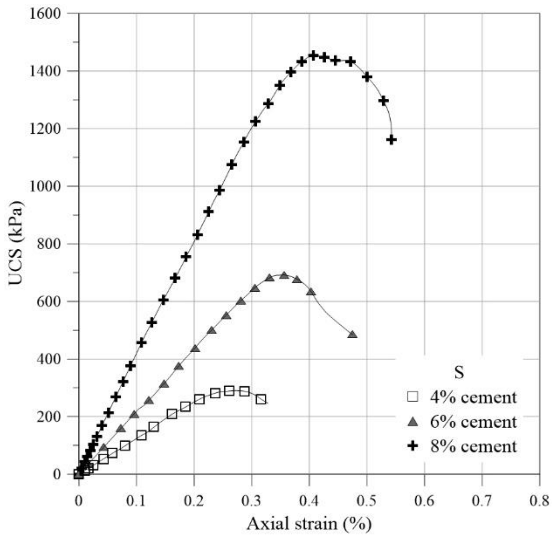
UCS							
C (%)	t	S			S-CW		
		UCS (kPa)	S_D	C_V (%)	UCS (kPa)	S_D	C_V (%)
0	7	266.3	15.7	6	389.3	20.7	5
4	7	266.6	10.8	4	747.7	68.9	9
	14	268.1	29.6	11	848.7	86.8	10
	21	279.6	35.1	13	878.0	48.6	6
	28	255.6	54.6	21	884.0	57.0	6
6	7	654.8	61.0	9	1549.0	69.0	4
	14	702.0	93,50	13	1955.6	73.2	4
	21	815.3	51.2	6	1982.0	24.9	1
	28	726.3	97.3	13	1955.6	256.9	13
8	7	1412.9	97.8	7	2519.2	68.7	3
	14	1559.7	99.9	6	2630.0	374.4	14
	21	1301.1	187.8	14	3043.0	220.8	7
	28	1554.4	160.1	10	3106.3	425.6	14

TS							
t	C (%)	S			S-CW		
		TS (kPa)	S_D	C_V (%)	TS (kPa)	S_D	C_V (%)
7	0	37.6	6.0	16	37.9	4.3	11
	4	29.2	7.6	26	119.7	22.2	19
	6	105.2	10.3	10	319.6	58.0	18
	8	210.3	35.0	17	365.4	88.9	24

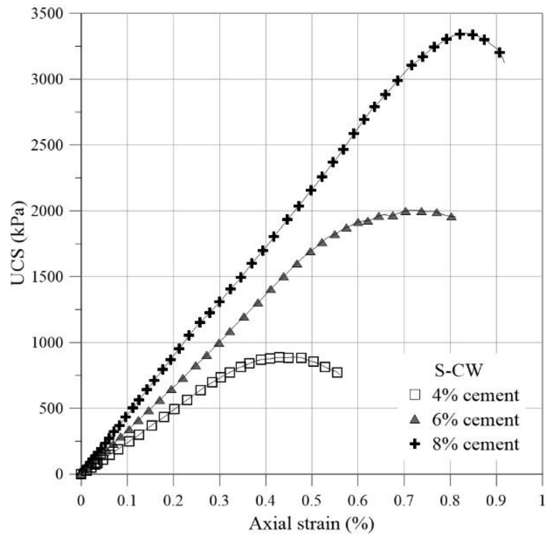
Note: S is the soil; CW is the construction waste; C is the cement; t the days of cure.

Figure 9 shows typical stress-strain curves at 28 days of cure for UCS tests. The curves also allow observing the behavior of the materials for each cement content. The modulus of elasticity was estimated at 50% of the failure stress, which correspond to elastic region of the materials (Figure 9).

Figure 9 – **Typical stress-strain curves at 28 days of curing for the S (a) and S-CW (b) mixtures**



(a)



(b)

Figure 10 – **Unconfined compressive strength results**

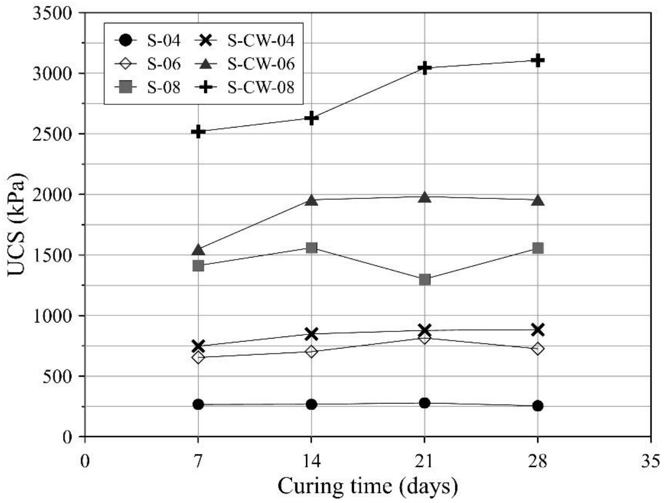


Figure 11 shows the normalized results for the samples tested. Normalization was calculated by dividing the unconfined compressive strength value for a given cement content (UCS-C) by the unconfined compressive strength value for the sample without cement (UCS). The results show an increase in the strength of the samples with cement in relation to the mixtures without cement. Based on the S mixture normalization (Figure 11a), a cement level of 4% is a very low content for the stabilization of this soil and does not change the strength of the material. At 6% cement, it is possible to achieve a strength 2 to 3 times greater than natural soil, and at 8% cement the UCS value is up to 6 times higher than that of natural soil.

In the case of the S-CW mixtures (Figure 11b) with 4% and 6% cement, the curing period that shows the greatest gain in terms of strength is from 7 to 14 days, with UCS remaining practically constant after this period. For S-CW-08, the greatest increase in strength occurs between 14 and 21 days, after which there is not much variation in the UCS values. From this, it can be concluded that S-CW-04 and S-CW-06 reach maximum strength values at 14 days of cure, and for S-CW-08 this occurs at 21 days indicating the occurrence of hydration reactions in the cement.

In the normalization graph of the S-CW mixture (Figure 11b) this behavior is very clear, in addition to showing that for 21 and 28 days of curing the increase in the UCS values is linear and proportional to the cement content. Yet it is possible to observe that the addition of only 4% cement in the S-CW mixture reflects a significant increase in strength, with UCS being twice that of the mixture without cement, unlike the behavior in the soil and cement mixtures. The strength of the S-CW-06 mixture is 5 times higher than the same mixture without cement and approximates the values for S-08. For S-CW-08, the increase in strength ranges from 6 to 8 times in relation to the mixture without cement, depending on the curing period.

A factor that contributes to the strength gain of S-CW is the reduction of the passing portion in the N^{o}. 200 sieve. The S-CW mixture has about 45% of material with a diameter less than 0.075 mm, which represents 43% less fines than in the soil. However, the amount of fines in the mixture is still greater than recommended by Reis *et al.* (2015) and the DNIT 143:2010-ES (DEPARTAMENTO..., 2010) standard. Reis *et al.* (2015) states that for the best efficiency of the soil-cement, the fraction of material passing through the N^{o}. 200 sieve must be between 20 and 30%, resulting in greater void filling and greater dry density. According to DNIT 143:2010 – ES (DEPARTAMENTO..., 2010), for the execution of soil-cement the quantity of material with a diameter of less than 0.075 mm must be between 5 and 35%. Therefore, it would be possible to increase the percentage of construction waste in the mixture at the expense of decreasing the percentage of natural soil, enabling a reduction in the exploitation of natural soil deposits.

Another aspect that influences the development of strength in the mixtures is the water-cement (w/c) ratio (Figure 12). In the S mixture, since the water-cement ratio is high, the condition is not favorable for the occurrence of cement hydration reactions. It is notable that even with an increase in the cement content, there is no change in the w/c ratio. In the case of the S-CW mixture, the material has a lower water-cement ratio and with an increase in the cement content, the w/c ratio decreases. The reduction in the water-cement ratio creates a more favorable environment for the hydration of the cement, enabling greater formation of cement bridges, directly influencing the strength of the material. In addition, recent studies (ARTUSO;

LUKIANTCHUKI, 2019) have shown that CWs exhibit a self-cementing property followed by strength gain over time.

The void index (e) of a mixture is the relationship between the void volume and the volume of solid particles. The void index is related to the grain size of the sample, that is, the lower the value of this parameter, the better the grain size distribution of the material and the disposition of the particles. Figure 13 represents the void index for the S and S-CW mixtures with respect to the curing periods. The S-CW has approximately 43% fewer voids than the S, indicating that the mixture with construction waste has a better grain size distribution, favoring the development of the strength of the material. Based on the results of their research, Consoli *et al.* (2011) explains that the greater the number of contacts between the particles of a soil, the greater the number of cementitious bonds that will receive small amounts of loads when the load is applied, and as a consequence the material performs better.

Figure 11 - **Normalization of the results of the UCS test for S (a) and S-CW (b)**

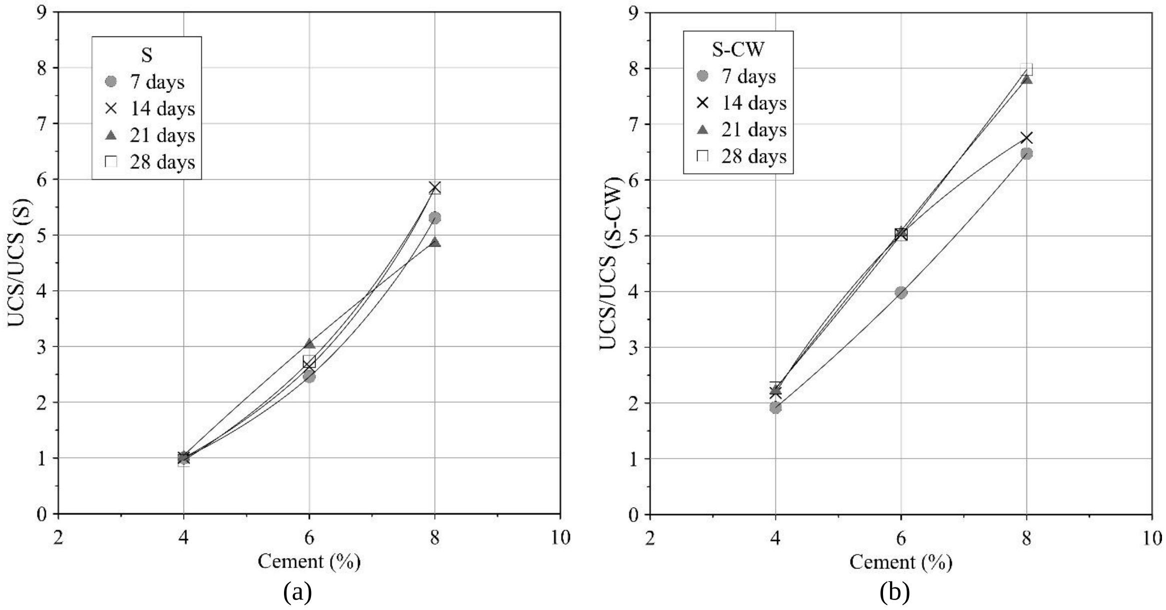


Figure 12 - **Water-cement ratio for the S and S-CW mixtures**

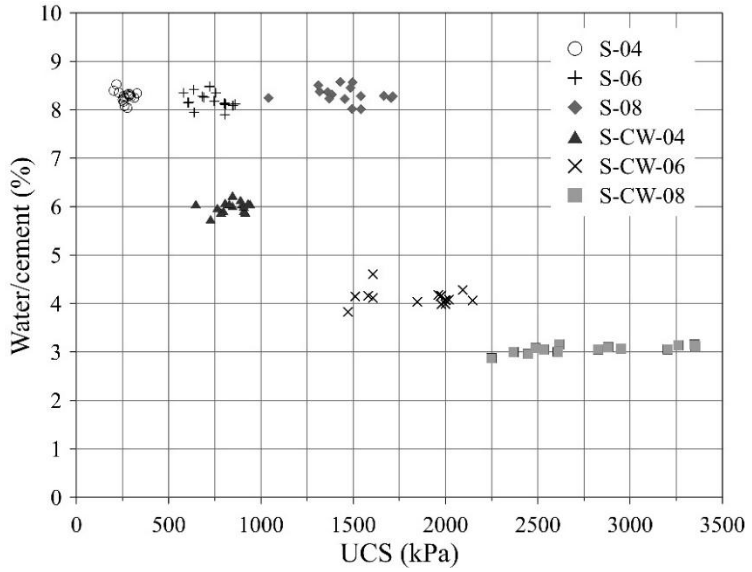


Figure 13 - **Index of voids relative to curing time**

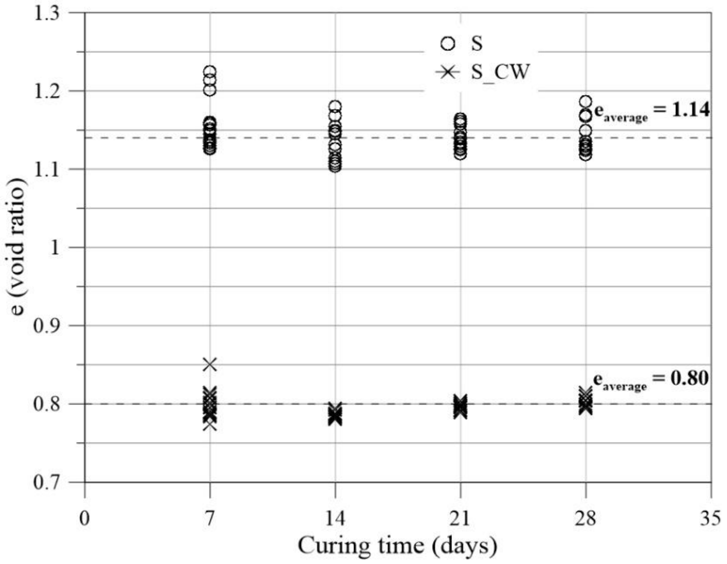


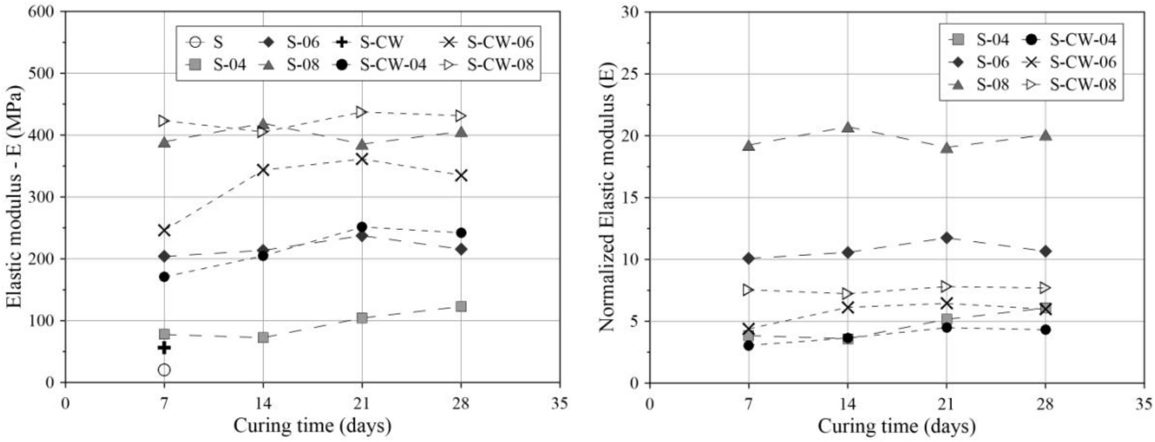
Figure 14 shows the values of the elastic modulus (E) of the mixtures and the normalization graph of the elastic modulus, both in relation to the curing periods evaluated. In Figure 14(a), it is possible to observe that, for 4% and 6% of cement, the S-CW mixture yielded E values greater than S. In the case of 8% cement, the E values for the two mixtures are similar. Therefore, as is evident in the Normalized E graph (Figure 14b), the increase in cement content has less impact on the stiffness of the S-CW mixture, than it does on the S mixture. In the S mixture, the increase in cement content from 4% to 8% reflects an increase of more than 400% in stiffness, while for S-CW the same increase in cement content increases the stiffness of the mixture by only 195%. The fact that the amount of cement has less influence on S-CW can be explained by the better granulometry of the mixture, that is, the granulometric correction of the soil through the incorporation of waste is responsible for a large part of the improvement of the performance of the material. This is corroborated by the result of the elastic modulus of S-CW without cement, which is about 270% higher than that of the natural soil.

Nevertheless, results from previous studies (ARTUSO; LUKIANTCHUKI, 2019) indicate that the stiffness of the S-CW mixture has a tendency to increase due to the self-cementing effect of the CW because the presence of non-hydrated cement particles with the addition of water provokes new reactions in non-inert particles. This effect was evaluated for an CW for up to 224 days of curing, showing that, even after long periods, the material still exhibited stiffness gains.

The results of the indirect tensile strength test (TS) are shown in Figure 15. According to Consoli *et al.* (2007), the indirect tensile strength of soil-cement normally varies between 9 to 14% of the compressive strength. The S mixture confirmed this assertion, however, for the S-CW the TS values represent, on average, 17% of the UCS values. However, since the variation is not very significant, the results obtained were considered satisfactory.

The results of the indirect tensile strength test confirm the information obtained from the unconfined compression test. Figure 16 shows that the normalized TS values achieve results similar to the normalized UCS graph (Figure 11), especially for the soil-cement mixture. Similar to the UCS results, in the TS graph the greatest strength gain occurred when the cement content was raised from 4% to 6%, with this change being more significant.

Figure 14 – **Elastic Modulus (a) and normalized elastic modulus (b)**



(a) (b)

Figure 15 - **Indirect tensile strength**

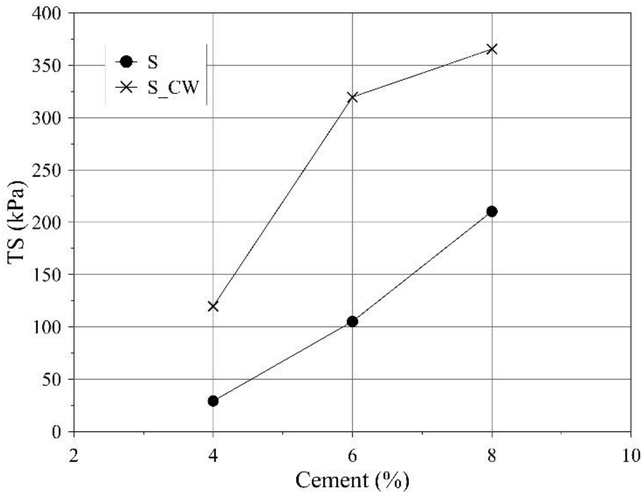
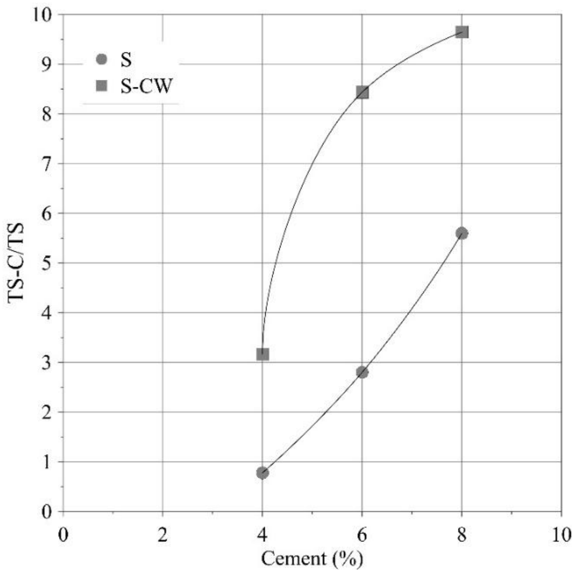


Figure 16 - **Normalization of the results of the indirect tensile strength test**



Scanning electron microscopy (SEM)

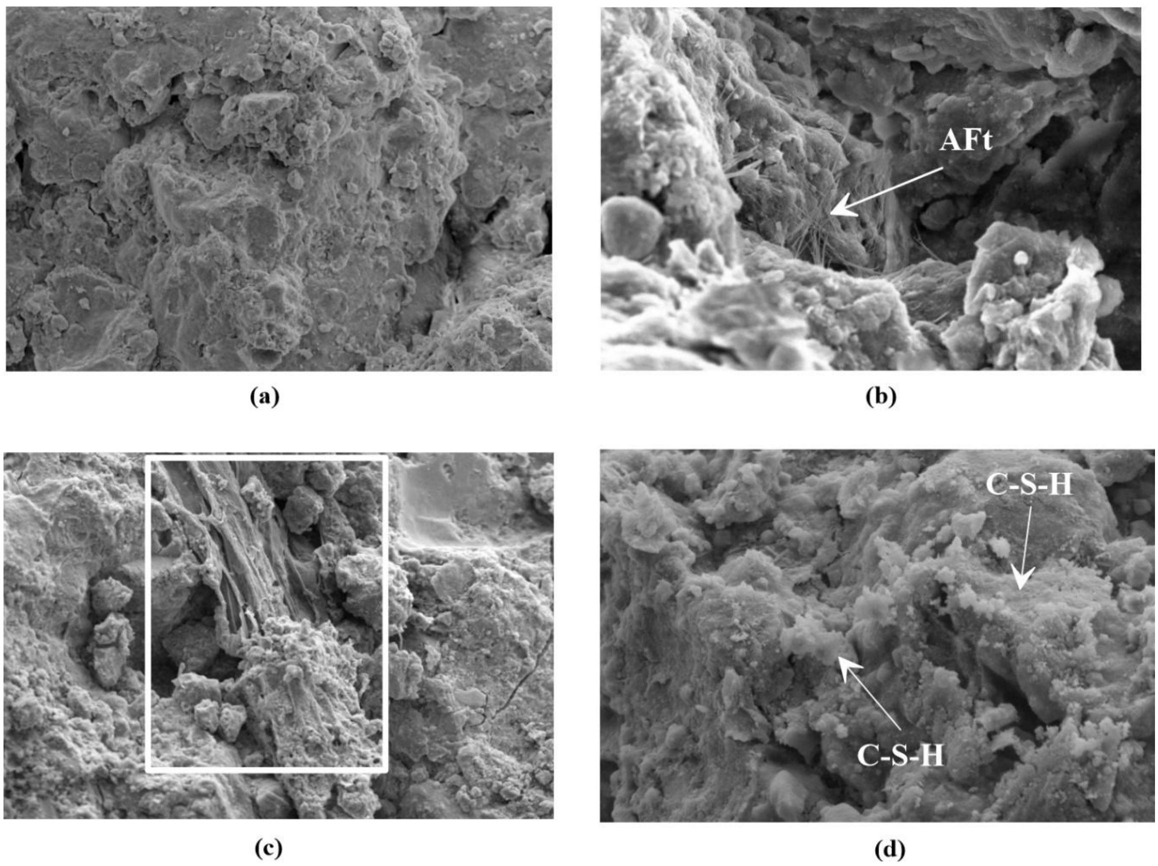
Regarding the morphological characteristics of the mixtures, Figure 17 presents the SEM images generated for the S and S-CW mixtures with 4% cement content, at 28 days of curing.

In the case of the S, when the structure is observed in a superficial way (Figure 17a), there is no evidence of products related to cement hydration. At higher magnification (Figure 17b), the formation of ettringite crystals are visible in the form of short needles and fine bundles, characterizing the initial stages of cement hydration. As the unconfined compressive strength and indirect tensile strength tests confirmed, the hydration reactions are inhibited in the soil-cement mixture due to the large amount of water, preventing the material from developing strength, even at more advanced stages of cure.

On the other hand, in the S-CW mixture, the cement hydration products are visible on the sample surface in the form of an agglomerate adhered to the particle and occupying the free spaces (Figure 17c). At greater magnification (Figure 17d), it is possible to see the formation of agglomerations that fill the spaces between the grains. These groupings represent the formation of calcium silicate hydrate (C-S-H), which in the cement hydration process has the function of covering the particle and at advanced curing stages continues to be formed and to fill the space between the hydration layer and the non-hydrated particle. The presence of these structures, related to advanced stages of cement hydration, confirms the fact that the S-CW mixture exhibits good strength with at low levels of cement content.

Rocha and Rezende (2017) observed similar structures during cement stabilization of a lateritic gravel. For lower levels of cement, the presence of ettringite was found. However, with higher amounts of cement a decrease in fillet-like structures and an increase in isolated agglomerations were observed. These samples being compatible with mixtures with better strength performances.

Figure 17 - **Micrograph at 28 days of curing for the mixtures: S-04 (1000x) (a), S-04 (5000x) (b), S-CW-04 (1000x) (c) e S-CW-04 (5000x) (d)**



Backfill of shallow foundation

The benefits of backfill soil stabilization for the uplift performance of shallow foundations were presented by Rattley *et al.* (2008). The results demonstrated that stiffness and bearing capacity can be improved using small amounts of cement for a non-plastic soil.

In the present work, a specific construction waste was used to improve the grain size characteristics of a lateritic clay soil. The experimental results show that 4% and 6% of cement is suitable to improve the stiffness about 5 and 7 times. Results also shows that S-08 has a stiffness similar to S-CW-08. However, clay soils with larger amount of cement can present problems with shrinkage cracks. Thus, the preliminary study indicates that construction waste can be suitable for replace clay soil and improve the stiffness and strength without larger amount of cement. Further studies are necessary to verify the experimental data presented here.

Final considerations

This study presents experimental tests that evaluated the influence of the incorporation of a specific construction waste in the stabilization process of a soil-cement mixture. Based on the results, the main conclusions of this research are:

(a) the addition of CW to the natural soil results in a mixture with better granulometric distribution and causes a slight decrease in the plasticity of the soil. When compacted, the S-CW mixture has a higher dry density and a lower optimum moisture content compared to the soil, resulting in a significant reduction in voids and the water-cement ratio of the material;

(b) the soil-cement mixture, did not show considerable strength gains over time. The behavior of the material suggests that the high water-cement ratio inhibits cement hydration reactions;

(c) the addition of cement to the mixtures yielded an increase in stiffness for the two mixtures studied, however, the increase in the proportion of cement has more impact on the soil-cement than on the S-CW mixture;

(d) cementitious S-CW mixtures can perform similarly to soil-cement mixtures with higher cement contents, indicating that the use of construction waste can decrease the percentage of cement content necessary for stabilization; and

(e) the results indicate that the substitution of 50% of the natural clayey soil with CW is a viable alternative for the stabilization of this soil. Furthermore, the use of CW in cementitious mixtures decreases the amount of cement necessary to achieve required levels of strength.

This study demonstrates that the soil stabilization process is conducive to the use of construction waste and presents a viable alternative use and destination for this material. In general, the results of this research contribute to the understanding of the potential for the use of a specific construction waste to improve the stabilization process of a cementitious mixture composed of a highly plastic clayey soil. In the environmental context, the partial replacement of soil contributes to a more suitable destination for construction waste material, provides a more sustainable alternative for the stabilization of clay soils and decreases the use of cement, reducing the need for exploitation of natural resources. It is important to highlight that this work is a contribution to this specific construction waste and further analysis are fundamental to evaluate the behavior of different wastes for soil stabilization.

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