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Sample dimension effect on cement-stabilized sandy soil mechanical behavior

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Article

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Soil-cement
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Abstract

Stabilized soil with cement has been a widely used solution in geotechnical projects and requires the molding of numerous specimens to investigate their properties in destructive tests, restraining the reuse for other analysis. Also, distinct sample dimension has been utilized in the research without taking this effect into account. Recognizing these needs, the height and diameter (H/D) ratio effect on cement-stabilized soil mechanical behavior was assessed in the present work. Using sandy soil, Unconfined Compression Strength (UCS), Indirect Tensile Strength (ITS) and Ultrasonic Pulse Velocity tests were performed varying the curing period (7 and 28 days), cement type (I and III) and content (6, 7, 8, 9 and 10%), based on conventional (127 x 100 mm) and reduced dimension (105 x 50 mm) specimens. All variables, individually and combined, affected the compression and tensile strengths of the mixtures, resulting in greater gains for the ones molded with type III cement in reduced dimension, at 28 days of curing. The dimension as an influential variable was statistically established using the variance analysis (ANOVA) at a significance level (α) of 0.05, in which reduced dimension showed an average superior resistance of 21.3%. Mixtures molded with H/D $\geq$ 2 demonstrated strong correlation (R2 = 0.93), pointing to the possibility of ITS prevision through the P-wave velocity nondestructive tests.

1. Introduction

The improvement of properties and behavior of local soils through the incorporation of stabilizing agents has great applicability in geotechnical projects. Satisfying technical, economic and environmental requirements, the stabilization technique can be used for canal lining, support layers for shallow foundations, stabilization and protection of slopes, preventing liquefaction of loose granular soils and pavement base layers.

The most common agents applied in the stabilization technique are cement, lime, fly ashes, asphalt emulsion, and construction and demolition residue (Abdullah & Al-Abdul Wahhab, 2018; Baldovino et al., 2018; Consoli et al., 2010, 2011, 2013; Ingunza et al., 2015; Mohammadinia et al., 2014; Su et al., 2017; Sukprasert et al., 2019). Herein, the use of cement has been extensively investigated in the literature from the perspective of the chemical reactions involved and the cementation influence on the mechanical behavior (Clough et al., 1981; Croft, 1967; Horpibulsuk et al., 2006; Ismail et al., 2002; Lorenzo & Bergado, 2004), the determination of variables and relations that rule the behavior and its prevision (Baldovino et al., 2020; Cardoso et al., 2017; Consoli et al., 2007; Diambra et al., 2017; Ferreira et al., 2021; Stracke et al., 2012).

Increases in strength, stiffness, durability, volumetric stability, as well as reduction in permeability and compressibility occur through hydration and hardening reactions of the cement and its interactions with clay minerals. In this sense, the properties of soil-cement mixtures depend on factors such as the soil grain size and mineralogy, cement type and content, moisture content, mixture porosity, compaction effort and curing conditions (Gajewska et al., 2017; Joel & Agbede, 2011; Le Kouby et al., 2017; Mandal et al., 2017).

Notwithstanding the gains from the technique, the molding of numerous samples used in destructive tests, besides the requirement of high volume of soil, restrain the reuse for other analysis. Nondestructive tests using acoustic emission have been investigated for geotechnical applications in non-stabilized and stabilized soil. Khan et al. (2006) applied the pulse-velocity method to characterize a cemented sand, identifying changes in wave velocity according to the

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initial water and cement content; Toohey & Mooney (2012) provided satisfactory estimation of the elastic modulus growth by seismic tests of a lime-stabilized soil during curing; correlating flexural strength and P-wave velocity for clay, silt, sand and gravel materials stabilized with fly ash and lime, strong relationships were reported by Mandal et al. (2016); even though velocity is a low-strain property and strength is a large-strain property of the material, Kutanaei & Choobbasti (2016) obtained satisfactory correlations between unconfined compression strength and ultrasonic velocity, evaluating the nanosilica particle and polyvinyl alcohol (PVA) fibers' effect on the ultrasonic pulse velocity and mechanical properties of cemented sand.

Additionally, there is the sample dimension variability in improvement and stabilization studies. Consoli et al. (2007) applied samples of 100 mm high and 50 mm in diameter on the analysis of the parameters that control the resistance to compression of artificially cemented sands. The same cylindrical size was applied by Ho et al. (2017) under drying curing condition of cemented-treated soils; specimens of 140 x 70 mm and 76 x 38 mm (high and diameter, respectively) were used by Rios et al. (2013; 2012), based on the pressure level of triaxial compression tests; Reis et al. (2015) utilized molds of 127 x 100 mm (height and diameter, respectively) when studying the use of soil, cement and residues of construction and demolition for pavement; Cardoso et al. (2017) used samples of 140 cm high and 7 cm in diameter, when verifying the influence of the curing period, cement content and water-cement relation on the bonding effect in soil-cement mixtures.

All the studies were performed according to normalizations, although the variation of the factor H/D may affect the mechanical behavior for the same dosing conditions. Thus, the present paper focuses on evaluating the effect of varying the relation H/D in laboratorial soil-cement mixtures for different curing period, contents and types of cement, seeking to establish relations between the investigated variables and the mechanical behavior, in destructive (UCS and ITS) and nondestructive tests of Ultrasonic Pulse Velocity.

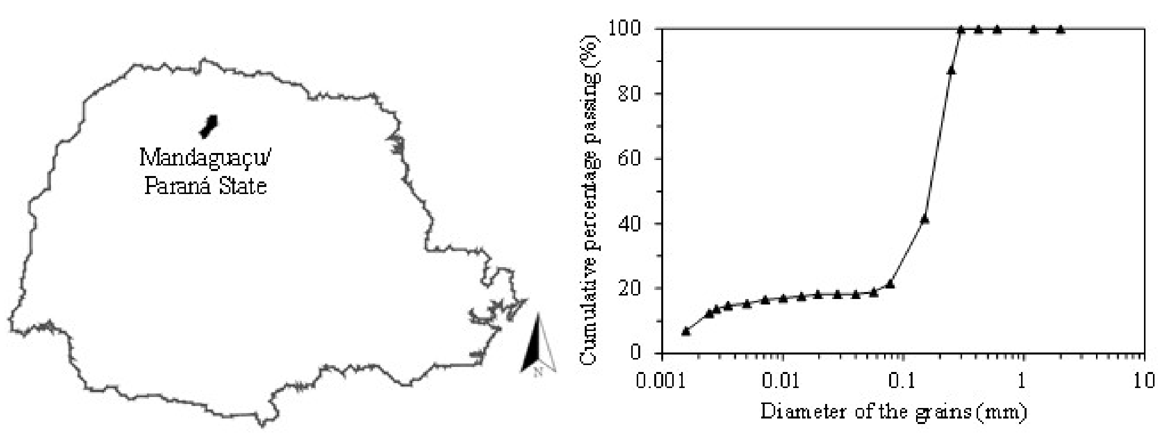
2. Materials and methods

2.1 Materials

The soil used in this study, granulometrically characterized as a medium silty fine sand, was obtained near the Federal Highway BR-376 in the city of Mandaguaçu, in the northwest of the Paraná State, Brazil (Figure 1). The soil belongs to the Caiuá formation, made up mainly of fine and very fine sandstones (França Junior et al., 2010). From the chemical soil characterization by X-ray fluorescence analyzer was seen the presence of Si (55.1%), Al (27.9%), Fe (13.4%), and Ti (2.7%), in agreement with the mineral composition identified in X-ray diffraction, consisted mainly by quartz (SiO_2), iron oxide (Fe_2O_3) and kaolinite ($Al_2Si_2O_5(OH)_4$).

The Atterberg limits are liquid limit of 27% and plastic limit of 17%. The specific gravity of solids is 2.69. According to the Unified Soil Classification System (USCS) and American Association of State Highway and Transportation Officials (AASHTO), the soil can be classified as clay sand (SC) and belongs to group A-2-4, respectively.

Portland cement (PC) with addition of pozzolan (Type I) and Portland cement of high initial strength (Type III) were used as the cementing agents, presenting specific gravity of 3.13 and 3.24 for type I and III, respectively. Distilled water was used for characterization of materials and homogenization of the mixture during the compaction.



(a) (b)

Figure 1. Sandy soil used: (a) Collection site; (b) Particle-size distribution curve.

2.2 Specimen preparation

Cement contents of 6, 7, 8, 9 and 10%, in relation to the dry mass of soil, were used in the study, based on literature and Brazilian experience, in which these cement percentages are commonly used for base and subbase layers of road pavement (Antunes et al., 2017; Baldovino et al., 2018; 2020; Consoli et al., 2007, 2017; Ferreira et al., 2021; Mola-Abasi et al., 2018).

For the purpose of investigating the effect of the sample dimension on the mechanical behavior, dimensions of Proctor cylinder (127 mm high and 100 mm in diameter), denominated Conventional Dimension (CD), and Reduced Dimension (RD), with height and diameter of 105 x 50 mm were adopted, based on the Brazilian standard for studies of soil-cement dosing (ABNT, 2012a), and the recommendation of height and diameter relation between 2 and 2.5 (ASTM, 2017). It is important to highlight that the dimensions used in the study are in agreement with soil stabilization works present in the literature (Baldovino et al., 2020; Consoli et al., 2007; Ferreira et al., 2021; Ho et al., 2017; Lukiantchuki et al., 2020; Portelinha et al., 2012; Reis et al., 2015).

The specimens molding proceeded similar to the compaction using normal energy in Proctor cylinder (600 kJ/m3). Considering the mixtures molded in reduced dimension, the energy imposed was varied, controlling the height of each of the three layers. Although the conventional and reduced dimension demand distinct compaction processes, the compaction control was strictly followed to ensure that for the same experimental condition the samples in the conventional and reduced dimensions were statistically identical regarding the defined compaction parameters.

Samples with compacting degree tolerances of 100 ± 2% and optimum moisture content variation ($\Delta\omega$) of ± 0.5% were stored in plastic bags and taken to the humidity chamber, at the temperature of 23 ± 2 ºC and air relative humidity not inferior to 95%. The curing periods were 7 and 28 days.

2.3 Testing methods

Unconfined Compression Strength (UCS) tests for the soil and mixtures were carried out following the ABNT (2012b), in triplicate, which is similar to standard ASTM (2017). Subsequent to the curing stage, the mixtures were immersed for 4 hours. This stage was not performed for the soil, due the occurrence of disaggregation. The test was performed with controlled deformation in 1.27 mm/min average rate, and the maximum load recorded. The Indirect Tensile Strength (ITS) tests was assessed per Brazilian test method (ASTM, 2016b), in duplicate, adopting a similar procedure to UCS.

In order to statistically verify the investigated variables (dimension, curing period and cement content) and interactions on the mixtures mechanical behavior, variance analysis (ANOVA) at the level of significance (α) of 0.05 for each type of cement was carried out, through the hypothesis test if the mean values are equal (null hypothesis), or if they differ in at least one treatment (alternative hypothesis).

The test conclusion may be expressed by the comparison of the F-value with the critical value obtained from the theoretical distribution or from the significance probability (p-value), calculated assuming that the null hypothesis is true. Thus, values equal or lower than 0.05 indicate the existence of significant differences between the treatments. All mixtures presented normal distribution of probability, verified by Shapiro-Wilk normality test.

The ultrasonic tests were performed in specimens referred to the ITS, since the tests are nondestructive, using Pundit Lab equipment. The test consists in measuring the ultrasonic pulse velocity (P-wave) emitted and received through two transducers (emitter/receptor) located in opposing faces of the material – direct transmission. Before testing, the equipment was calibrated and settings as transducer frequency of 54 kHz, pulse width (automatically adjusted), and correction factor (1 – standard recommended by the manufacturer) were established, according to ASTM (2016a).

To minimize the effects of refraction and reflection of the ultrasonic pulse occasioned by the presence of air between the surfaces of the sample and transducer, a fine layer of industrial gel was applied on both surfaces prior to testing. Two readings were performed on each face of the specimens, inverting both transducers with the view to eliminate bias during the data acquisition, which occurred before (Pulse I) and after the immersion phase (Pulse II). The execution scheme is illustrated in Figure 2.

3. Results and discussion

3.1 Compaction parameters

The average results for the maximum dry unit mass (ρd max) and optimum moisture content (ωopt) are presented in Figure 3.

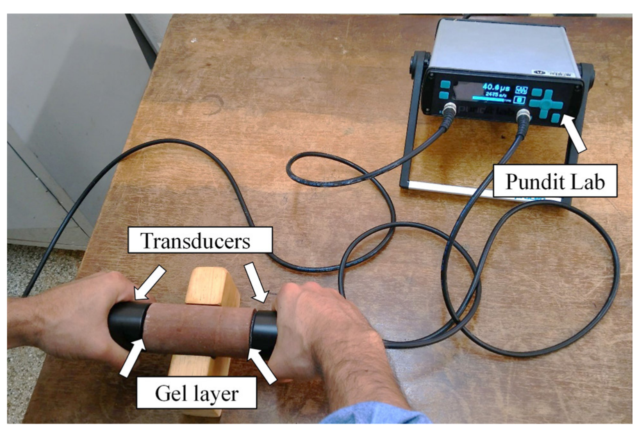


Figure 2. Ultrasonic test execution.

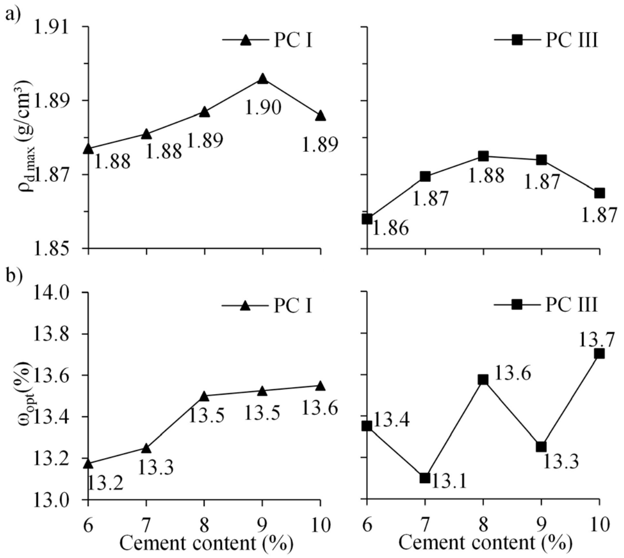


Figure 3. Maximum dry unit mass (a) and optimum moisture content (b) of the mixtures.

Considering both cementing agents, it was observed a tendency of increasing the maximum dry unit mass until a given content, from which occurs decrease. The increase is attributed to filling the soil voids through the addition of cement particles, which presented superior specific gravity in comparison to the soil grains, while the reduction is possibly caused by the formation of transitional components that presented higher densities for a specific range of addition, as seen by Osinubi (1998), Osinubi & Nwaiwu (2006), and Portelinha et al. (2012).

Since this event was observed for both stabilizing agents, it is assumed the mixture density becomes less sensitive to cement addition. This behavior is related to the granulometric characteristics of the soil, a very graduated sand (uniformity coefficient Cu of 9.7 and gradation coefficient Cc of 2.9), with approximately 23% of the material smaller than 0.075 mm, indicating the compacted non-stabilized soil already presents satisfactory grain and particle interlocking.

The additions of cement result in the increase of surface to be hydrated and, consequently, demand more water, as verified by the type I cement. Nevertheless, the decrease on the optimum moisture content may be related to the increase of ions exchange reactions, resulting in a significant flocculation and, therefore, an increase on the grain size, so the mixture demands less water for compaction, as presented by type III cement (Osula, 1989).

3.2 Sample dimension effect

The mechanical behavior depending on the type and cement content, sample dimension and curing period, for unconfined compression strength and indirect tensile strength are shown in Figure 4 and Figure 5, respectively. Satisfactory coefficients of determination were obtained for the addition range investigated in this research (R2 > 0.88), under second order lines of exponential tendency.

Comparing unconfined compression responses of the mixtures and pure soil, corresponding to 0.43 MPa in conventional and 0.62 MPa in reduced dimension, the minimum and maximum gain for the type I was about 3.5 (6% cement, 7 days, RD) and 10.8 times (10% cement, 28 days, CD), while for the type III, these increases were about 5.2 (6% cement, 7 days, RD) and 14.1 times (10% cement, 28 days, CD).

For the type I cement, the minimum and maximum gains considering indirect tensile strength, in relation to the non-stabilized soil (0.07 MPa for CD and 0.06 MPa for RD), were of 3.3 (6% of cement, 7 days, CD) and 11.3 times (10% of cement, 28 days, RD); as for the cement Type III, the increments were about 5.0 (6% cement, 7 days, CD) and 12.8 times (10% of cement, 28 days, RD).

Independently of the experimental condition, the increase of the curing period improved the strength of the natural soil (Aiban et al., 1998; Baldovino et al., 2020; Cardoso et al., 2017; Joel & Agbede, 2011). The mixtures performed with the Portland cement of high initial strength presented superior resistance for both curing periods. In contrast, the average increases of strength with the increment of curing period were superior for the type I. The unconfined compressive strength increments were between 63% and 59% for the CD and RD, when compared to the Type III – 43% and 37% for the CD and RD. Considering the indirect tensile strength, the same trend was seen; gains of 65% (CD) and 50% (RD) were obtained for type I, while increments of 37% (CD) and 39% (RD) were reached under type III cement. This behavior is derived from the limestone and clay dosing process and the cement finer milling of type III cement, leading to high initial strength.

The effect of the H/D relation, for the same experimental condition (cement content, type of cement and curing period), varying only the specimen dimension, indicated a higher resistance in reduced dimension mixtures, which is emphasized in Figure 6.

It is assumed that the increase of the relation improved the stress distribution, owing to the effects of the geometry. Yilmaz et al. (2015) supplemented that the samples in low volume reduce the number of microfissures and matrix pores, resulting in superior strength.

Furthermore, at a lower level of effect, the variation of the microstructural arrange resultant from the compaction process possibly contributes for the different mechanical behavior. In conventional dimension the energy was applied over the area of subsequent blows, due to its diameter (Ø = 100 mm) being larger than the diameter of the rammer used for the hits (Ø = 50 mm); considering the specimens of reduce dimension (Ø = 50 mm), there is compatibility between these two dimensions, so the energy of each blow is distributed over the entire area. Thus, the variation of

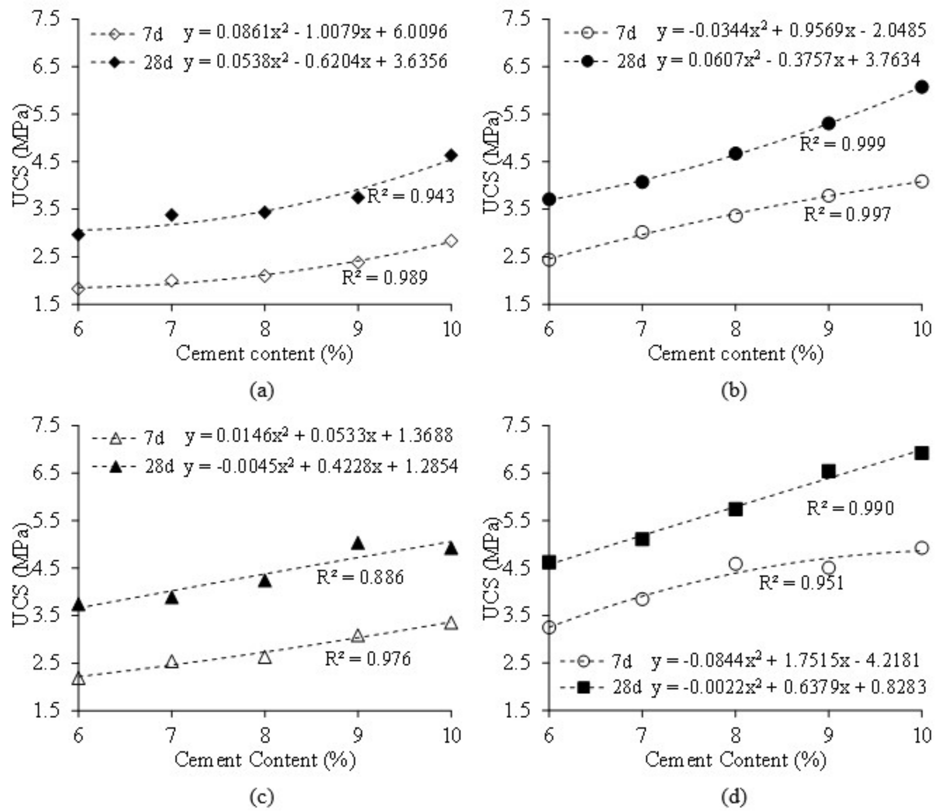


Figure 4. UCS for cement type and dimension: (a) PC I, CD; (b) PC III, CD; (c) PC I, RD; (d) PC III, RD.

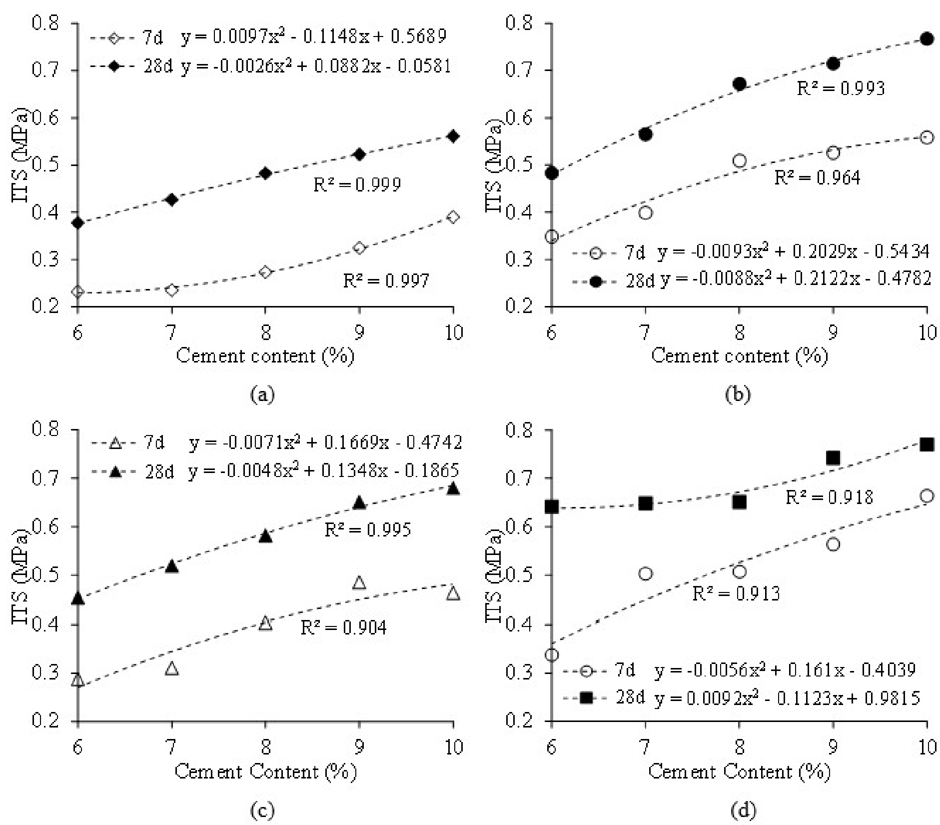


Figure 5. ITS for cement type and dimension: (a) PC I, CD; (b) PC III, CD; (c) PC I, RD; (d) PC III, RD.

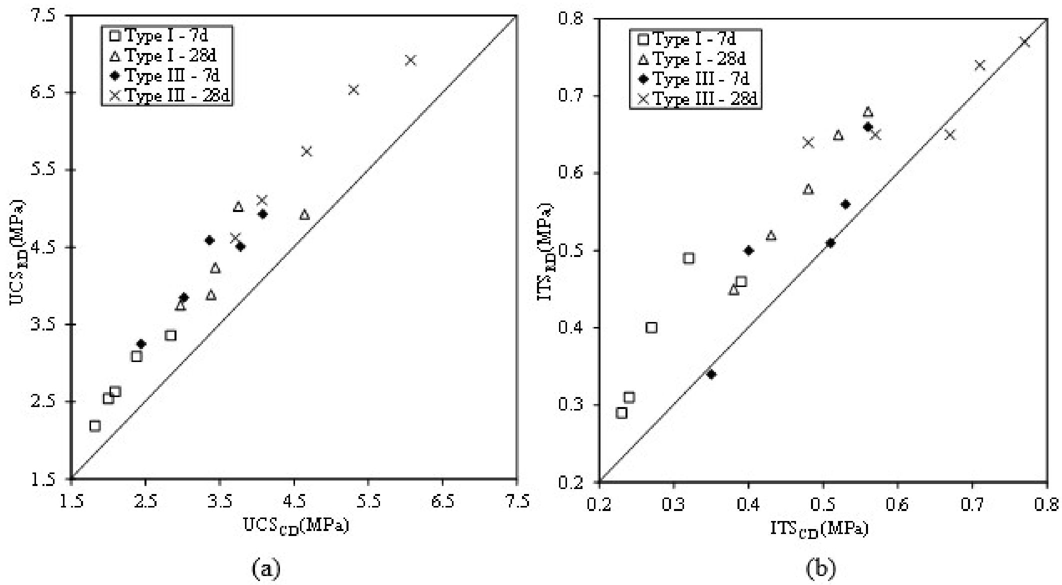


Figure 6. Dimension effect on mechanical behavior: (a) UCS; (b) ITS.

Table 1. P-value results obtained from the variance analysis (ANOVA).

Factor	P-value			
	UCS Type I	UCS Type III	ITS Type I	ITS Type III
Dimension	< 0.0001	< 0.0001	< 0.0001	0.0002
Curing age	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Cement content	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Dimension:Curing age	0.0896	0.436	0.849	0.8772
Dimension:Cement content	0.7486	0.989	0.114	0.2198
Curing age:Cement content	0.0222	0.001	0.447	0.2357
Dimension:Curing age:Cement content	0.4131	0.921	0.994	0.0021

the microstructural arrange resultant from the compaction process contributes for the different mechanical behavior under identical molding parameters (Leandro et al., 2017).

As demonstrated by the variance analysis performed for all obtained results (Table 1), the effect of dimension as an influential variable in the compression mechanical behavior was confirmed, besides the variables of curing period and cement content, individually and combined.

The ratio between reduced and conventional dimension [RD/CD] for UCS situated in range from 1.06 to 1.37, while for ITS the established relation was between 0.97 and 1.49, presenting after 28 days a tendency of approximately constant, which was not observed after 7 days of curing. On average, mixtures molded in reduced dimension showed 21.3% higher UCS and ITS results, not being considered the multiplication factor of 1.10 suggested by ASTM (2017). The difficulty to stablish a unique relationship is associated with the interaction between the variables dimension, curing period and content, which is shown by the statistical study as significative.

3.3 Ultrasonic pulse velocity

The use of ultrasonic tests in commonly adopted in the area of concrete materials, although it is an incipient technique in the study of the soil and cement-stabilized soil behavior. As a result of the large quantity of tests required for the verification of the mechanical properties, the use of nondestructive tests has shown to be an important instrument to increase the agility and to facilitate the mechanical investigation.

Figure 7 depicts the P-wave velocity trend obtained on the mixtures, presenting the results for type III cement in CD and RD, at 7 and 28 days, before (pulse I) and after immersion (pulse 2).

Superior pulse magnitudes were obtained in the after-immersion condition for all scenarios. Since the wave is not propagated through the mixture voids, when the open pores are partially filled with water, the time of transmission is decreased.

The P-wave velocity were of 758 and 1039 m/s for the soil and in the range from 2350 to 3050 m/s for cement-stabilized

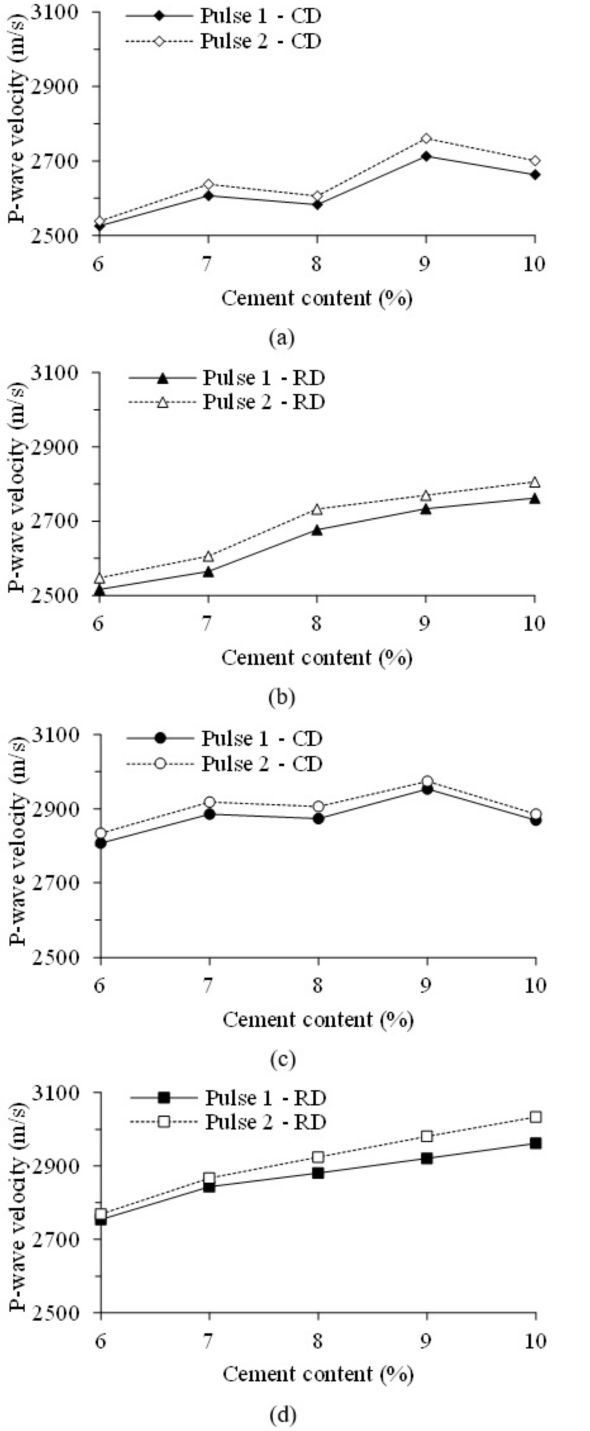


Figure 7. P-wave velocity for PC III cement-stabilized soil at 7 (a, b) and 28 days of curing (c, d).

soil. Increasing the curing period from 7 to 28 days caused the growth on the wave velocity for both stabilizing agents, and it is associated with the cement hardening mechanisms and secondary reaction among the stabilizing agent and the soil matrix. In general, the mixtures demonstrated that the pulse velocity rises as the cement content increases, presenting a

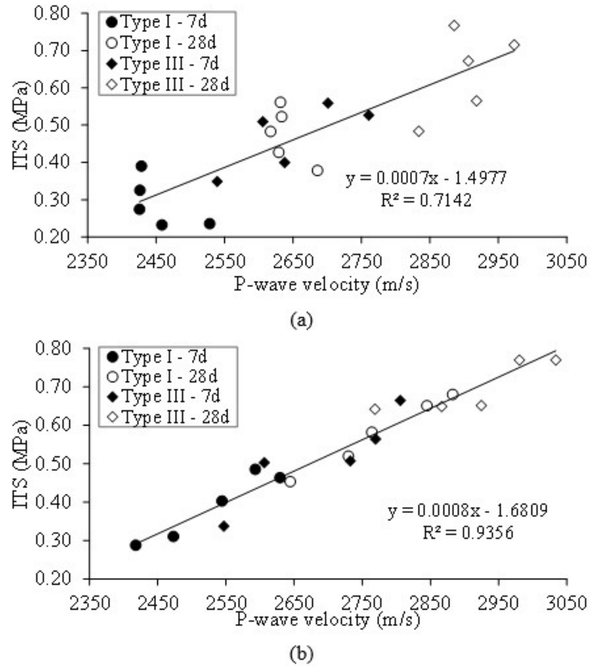


Figure 8. Relation between P-wave velocity and ITS for: (a) CD and (b) RD.

more satisfactory trend to the specimens molded with H/D of 2.1 (Khan et al., 2006; Toohey & Mooney, 2012).

The correlation between P-wave velocity and indirect tensile strength is presented in Figure 8. It is important to note that the non-stabilized soil tests resulted in low values of receiving signal based on the dimension, 2% to 7% and 50% to 55% for CD and RD, in comparison with 100% level obtained from the soil-cement mixtures, even when keeping the compaction parameters equal.

An elevated variability is observed for the mixtures with height and diameter smaller than 2, independently of cement type and curing period, resulting in poor relationship (R2 = 0.71). On the other hand, stabilized sandy soil in reduced dimension proved to be consistent, leading to satisfactory linear agreement (R2 = 0.93) and, further, pointing to the possibility of tensile strength prevision by the ultrasonic pulse velocity.

4. Conclusions

Based on the purpose of verifying the effect of the ratio H/D on the mechanical behavior of soil-cement mixtures, it was observed that:

- Considering the range of cement addition investigated, gains of 3.5 to 14.1 times for compressive strength and 3.3 to 12.8 times for tensile strength in relation to pure soil were obtained, with coefficients of determination R2 > 0.88.
- The variable dimension is statistically significant for UCS and ITS (p-value < 0.05), in which the

mixtures with ratio H/D equal to 2.1 presented higher strengths, regardless of the type of cement.

- Portland cement type III presented superior resistance for both curing periods. Nevertheless, the strength gains between 7 and 28 days were superior for type I, considering both dimensions on UCS and ITS.
- On average, the relation between the reduced and conventional dimension for compression and tensile strength demonstrated 21.3% higher. Factors as curing period, content and type of cement affect the relationship.
- The contribution of increased content and curing time to the response of cemented mixtures was proven in destructive and non-destructive tests, based on the results of UCS, ITS and ultrasonic pulse velocity.
- The addition of cement increased the ultrasonic wave velocity from the range of 758-1039 m/s to 2350-3050 m/s, due to cement hardening mechanisms and secondary reactions. Regardless of the experimental conditions, the ultrasonic pulse velocity tests pointed to the possibility of predicting the indirect tensile strength by the p-wave velocity using the reduced dimension (R2 = 0.93).

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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' contribution

José Wilson dos Santos Ferreira: conceptualization, data curation, analysis, writing – original draft. Michéle Dal Toé Casagrande: conceptualization, supervision. Raquel Souza Teixeira: conceptualization, supervision.

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