

Advances on dosages for cement stabilized rammed Guabirota silt depending on climate conditions

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Article

Keywords

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Abstract

This paper optimizes and compares the behavior of soil-cement compacted blends against several molding and climate conditions under optimum compaction and non-optimum compaction parameters. For this, an intensive laboratory study of silty soil samples treated with different percentages of high early strength Portland cement (PC) was investigated by a series of compaction, unconfined compressive, splitting tensile and durability tests using several climate conditions (i.e. wetting-drying and freeze-thaw cycles). The effects of porosity/cement index (η/C_v) on the unconfined compressive strength (q_u), splitting tensile strength (q_t) and durability by accumulated loss of mass (ALM, in %) of blends for optimum (i.e. maximum dry unit weight and optimum water content) and non-optimum compaction conditions (i.e. the variety of molding dry unit weight and molding moisture content (ω), between 13 and 16 kN/m³ and 10 % and 34 %, respectively) is the main paper focus. The results show an increase in strength and durability properties of the blends when cement is added, however, the mechanical resistance decreases if the blends are subjected to freeze-thaw (F-T) cycles. The opposite happens when blends are subjected to wet-dry (W-D) cycles where they reach resistances higher than those of curing at 23 °C in a wet chamber. Finally, reasonable dosages employing η/C_v index to stabilize the soil were presented considering the strength and the durability parameters.

1. Introduction

The soils from Guabirota geological formation, located in the city of Curitiba, (Brazil), and its metropolitan area are composed predominantly of clayey and silty soils (Baldovino, 2018). Given the low load-bearing capacity and high expansive degree of these soils owing to their physical-mechanical properties, they are not used in construction earthworks, so a technique for the stabilization of soils with cement materials is practical (Baldovino et al., 2020a). Soft soil can be found in numerous places, particularly in coastal areas, which imposes various challenges on geotechnical engineers during the construction process. Low shear strength and bearing capacity are common problems encountered in various geotechnical projects owing to the poor engineering properties of the soil. Therefore, soft soils must be improved before any ground improvement work can commence (Baldovino et al., 2018a). One of the techniques of improvement is to use typical binders such as

lime or cement, but the high consumption and emissions of gases during the production of these binders have led researchers to look for new binders based on waste to replace partially the cement or lime.

Despite the negative environmental impacts produced during cement production (CO₂ emissions, mainly) and the use of natural resources such as limestone rock, these aspects have forced the soil stabilization area to look for alternative solutions to improve the engineering properties of soils using binders such as natural pozzolans, fly ash, fibers (natural and synthetic), construction and demolition waste, and new techniques like biocimentation, bioclogging and geopolymerization (Ivanov & Chu, 2008). However, cement continues to be one of the most consumed materials by engineering industry, the fact that demonstrates the great development of the great metropolises in countries around the world. In this way, studies of the soil-cement dosage to find the smallest amounts of cement

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and compacting effort in the field are necessary to reduce as much as possible the indiscriminate consumption of the binder when it is required to use it in engineering works, either by the economy, workability, access, the durability of the material or its efficiency (Baldovino et al., 2018b; Baldovino & Izzo, 2019).

As a result, several investigations had been conducted on Guabirotuba silts stabilization to calculated reasonable dosages for cement-soil compacted blends. Baldovino et al. (2018a) determined the empirical relationships between the splitting tensile strength (q_t or STS) and q_u of a Guabirotuba silty soil artificially cemented with hydrated lime. To calculate the q/q_u ratio, soil-lime specimens were molded by controlling the dry unit weight, lime content (3-9 %), porosity, and water content, followed by curing for 15, 30, 60, 90, and 180 days. The authors calculated a $q/q_u = 0.16$ relationship using a reasonable criterion named porosity/lime index (i.e. voids divided by volumetric lime content) independent of curing time and lime content. They suggested a minimum percentage lime of 5 % to stabilize the soil. Baldovino et al. (2018c) evaluated the effects of lime content, curing time, moisture content (ω), and porosity/lime index (η/L_v) on compaction and strength parameters of a Guabirotuba sandy clay. Lime content addition increased the optimum moisture content and decreased the maximum dry density of compacted blends. The study suggests a q/q_u between 0.17 and 0.20 dependent of curing time (28-90 days), using the porosity/lime index and the application of the 0.68 exponents on the index [i.e. $(\eta/L_v)^{-0.68}$]. The results showed an increasing strength of the soil-lime mixtures. Baldovino & Izzo (2019) calculated the tensile/compressive index (q/q_u) as 0.15 for soil-cement compacted blends cured under 7-days. For 7, 14 and 28-days of curing, Baldovino et al. (2020a) suggested the q/q_u index for soil-cement compacted blends as 0.15-0.17. Moreira et al. (2019a) investigated the effects of molding dry unit weight, cement content and porosity/cement index on unconfined compressive strength (UCS or q_u) for cement-roof tile waste-silty soil (from Guabirotuba formation) compacted blends. The increase in dry unit weight and cement content increases the UCS for all blends. The UCS was directly affected by η/C_v , optimized to 0.28 exponent to improve the coefficient of determinations. In the end, the authors calculated an equation to estimate UCS for any mold condition. Moreira et al. (2019b) evaluated the impact of sustainable granular materials (from construction and demolition) on the behavior sedimentary silt from Guabirotuba formation for road application. The porosity/binder index was employed firstly by Consoli et al. (2009) and extended to study the influence of moisture on strength for soil-cement mixes (Consoli et al., 2016a; 2016b). Baldovino et al. (2019a) calculated the equations that controlling the strength of sedimentary silty soil-cement blends influenced by porosity/cement ratio (η/C_v) and types of cement (pozzolanic PC, high early strength PC, and low hydration heat PC). The results

concluded the unconfined compressive strength of the specimens of soil-cement mixtures increased with the addition of cement content and with the increase of the molding dry unit weight. The highest UCS values obtained were with the addition of high early strength PC, followed by pozzolanic PC and finally by low hydration heat PC. To reach 1200 kPa was necessarily added, on average, 6 % cement by weight. Baldovino et al. (2019b) optimizing the evolution of strength for lime-stabilized rammed earth comparing two silty soils employing 28, 90 and 360 days of curing. The study demonstrates the efficiency of porosity/lime index to estimate the unconfined compressive strength of the silt-lime compacted blends for several molding conditions. Finally, Baldovino et al. (2020b) improved the q_u of silty soil-cement mixes using recycled-glass powder in three quantities: 5 %, 15 %, and 30 % by weight.

The literature demonstrates the formulation of reasonable dosage equations for stabilized soils with several binders. Consoli et al. (2019) have already evaluated the effect of three distinct amounts of rice husk ash (RHA), PC and dry unit weights on the ALM, maximum shear modulus at small strains (G_0) and q_t of stabilized sands subjected to 12 W-D cycles. The RHA addition improves the q_t values and decreases the ALM. When subjected to W-D cycles, the G_0 and q_t of the cement-stabilized silty sands with 10-30 % RHA increased up to the sixth cycle and remained practically constant thereafter. Consoli et al. (2016a) determined a unique relationship determining strength of silty/clayey soils (London clay, Paraguayan dispersive clay, Portugal silty sand, Botucatu clayey sand, Nova Santa Rita organic soft clay, and Cachoeirinha red silty clay) improved with PC. Consoli et al. (2011) studied the influence of water content, porosity, and cement content on the strength of artificially cemented silty soil. The authors linked the η/C_v with q_u to establish a general dosage equation considering molding conditions as dry unit weight and curing time. The influence of freeze-thaw on engineering properties of a silty soil was systematically investigated by Qi et al. (2008). The engineering properties of a silty soil were studied under different freezing conditions and with the dry unit weight from 15.3 to 17.3 kN/m³. It is found that under the same freezing condition, there is a critical dry unit weight, for the change in soil density after freeze-thaw. Arulrajah et al. (2016) combined coffee ground (CG) with Fly ash (FA) as a geopolymer precursor active with Na₂SiO₃-NaOH composites. By replacing 30 % FA into CG at 50/50 Na₂SiO₃-NaOH index, geopolymerization occurred after 7-days cure. Strong geopolymers are obtained at 50 °C and CG-FA stabilized compacted blends are suitable for embankment structural fill material in road embankments. Kua et al. (2016) introducing slag as a geopolymer precursor in CG-FA blends active with Na₂SiO₃ and NaOH. In this research, authors obtained good q_u values of combined raw materials to use them in road construction projects.

Although dosage equations have been found to stabilize soils of the Guabirotuba formation, it has not yet been researched dosage equations for strength and durability when stabilized depending on the climatic conditions (considering wetting-drying and freezing-thawing cycles). Thus, this paper investigates dosage equations for cement stabilized rammed silt using several molding and climate conditions no shown in the literature for the Guabirotuba sedimentary soils.

2. Experimental program

The experimental program was divided into four stages:

- (1) the first stage comprised the physical characterization tests of the sedimentary soil and cement: granulometry of the soil according to ASTM D2487 (ASTM, 2017), Atterberg limits of the soil according to ASTM D4318 (ASTM, 2010), the specific gravity of the soil according to ASTM D854 (ASTM, 2014), one-dimensional consolidation properties of soil using the ASTM D2435 (ASTM, 2011a), the direct soil shear parameters of soil (internal angle and cohesion) were obtained according to ASTM D3080 (ASTM, 2011b), the chemical composition of the soil sample using the X-Ray Fluorescence (XRF) technology, and the actual specific gravity of the grains of the cement was calculated according to Brazilian standard ABNT NBR 16605 (ABNT, 2017);
- (2) the second stage consisted of molding, curing, and rupture the specimens subjected to unconfined compression tests and splitting tensile tests using curing time between 7 and 28 days.
- (3) the third stage comprised molding and curing the specimens subjected to durability test using severe freeze-thaw and wetting-drying cycles; and
- (4) The last stage consisted of molding, curing, and rupture the specimens subjected to unconfined compression tests and splitting tensile tests after 3, 6 and 12 freeze-thaw and wetting-dry cycles.

2.1 Materials

The three materials used in the present study were sedimentary Guabirotuba silty soil, early strength (PC), and distilled water.

The soil sample was manually collected in undeformed and deformed state from the southeast zone of the city of Curitiba (Brazil), in the municipality of São José dos Pinhais (metropolitan area of Curitiba), avoiding possible contamination and taken in sufficient quantity to perform all tests. The soil was collected on a road slope and was extracted at a depth of 2~2.5 m. The soil belongs to the second layer of the Guabirotuba Formation (the layer has thicknesses ranging from 1 to 5 m deep). Undeformed samples were collected to perform the unconfined compression, splitting tensile, direct shear and one-dimensional consoli-

ation tests in natural soil state. The undeformed soil was sampled in 15 cm edge blocks, under Brazilian Standard ABNT NBR 9604 (ABNT, 2016). The soil in the natural state had hygroscopic moisture of 40 % and a dry unit weight of 11.60 kN/m³. The test results of soil sample characterization at deformed state performed conforming to the description in the experimental program, are presented in Table 1. In Table 1, note that the largest soil size corre-

Table 1. Properties of the soil sample.

Properties	Value
Liquid limit, %	50.82
Plastic limit, %	35.96
Plastic index, %	14.86
Specific gravity of soil	2.62
Coarse sand (0.6 mm < diameter < 2 mm), %	5
Medium sand (0.2 mm < diameter < 0.6 mm), %	12
Fine sand (0.06 mm < diameter < 0.2 mm), %	18
Silt (0.002 mm < diameter < 0.06 mm), %	60
Clay (diameter < 0.002 mm), %	5
Effective size (D_{10}), mm	0.003
Mean particle diameter (D_{50}), mm	0.038
Uniformity coefficient (C_u)	8.33
Coefficient of curvature (C_c)	1.33
Classification (USCS)	MH
UCS in natural state, kPa	104.58
STS in natural state, kPa	16.62
STS/UCS ratio in natural state	0.16
Internal friction angle in natural state, degrees	26
Expansion, %	7.5
Cohesion in natural state, kPa	23
Color	Yellow
pH in water	5.5
Preconsolidation pressure (σ'_c), kPa	300
Coefficient of Consolidation (C_v), cm ² /sec	0.02
Optimum moisture content (from Standard effort-SE), %	26.5
Maximum Dry unit weight (from Standard effort-SE), kN/m ³	13.72
Optimum moisture content (from Intermediate effort-IE), %	20.50
Maximum Dry unit weight (from Intermediate effort-IE), kN/m ³	15.43
Optimum moisture content (from Modify effort-ME), %	14.50
Maximum Dry unit weight (from Modify effort)-ME, kN/m ³	16.75

sponds to silt (60 %). The specific gravity was 2.62. The predominant color of the soil is yellow due to the oxidation and important presence of goethite in the subtropical climate in southern Brazil (Baldovino et al., 2020a). The particle diameters corresponding to 10 %, 30 %, 50 %, 60 % and 90 % finer (or passing) were measured as $D_{10} = 0.003$ mm, $D_{30} = 0.01$ mm, $D_{50} = 0.025$ mm, $D_{60} = 0.038$ mm and $D_{90} = 0.3$ mm. Besides, the coefficients of uniformity and curvature were measured as $C_u = 8.33$ and $C_c = 1.33$, from which soil was characterized as silt of high plasticity with sand (MH) per the Unified Soil Classification System (USCS) criterion.

The total quantitative chemical composition of soil samples was researched through the energy-dispersive X-ray spectroscopy (EDX) using an energy-dispersive X-ray fluorescence spectrometer. Table 2 shows the chemical composition of soil samples, mainly SiO_2 , Al_2O_3 , and Fe_2O_3 , which are usually found in sedimentary soils and participate actively in the process of chemical soil stabilization.

Table 2. Soil sample chemical composition.

Compost	Concentration (%)
SiO_2	48.78
Al_2O_3	44.51
Fe_2O_3	0.61
K_2O	0.84
TiO_2	0.92
SO_3	4.12
CaO	-
Na_2O	-
MgO	
Loss on Ignition	0.22

Table 3. Chemical composition and some physical properties of cement.

Property	Value
Al_2O_3 , %	4.30
SiO_2 , %	18.96
Fe_2O_3 , %	2.95
CaO, %	60.76
MgO, %	3.26
SO_3 , %	3.18
Insoluble residue, %	0.77
Strength at 7 days, MPa	44.7
Strength at 28 days, MPa	54.2
Fineness, %	0.04
Specific gravity	3.11

A high early strength Portland cement (Type V in Brazil) (ASTM C150, 2016) is composed principally of calcium oxide (CaO), Silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3) and is produced and sold in the south of Brazil. The test results of the cement characterization performed conforming to the description in the experimental program, are presented in Table 3. The specific gravity of cement was 3.11.

To prevent undesired reactions and limit the number of variables, distilled water at 23 ± 2 °C was used to conduct all the characterization tests of the soil and for molding the test specimens for UCS and durability.

2.2 Unconfined compressive, splitting tensile and durability program

The types of mixes and their respective stabilizations with cement are shown in Tables 4 and 5. Four strategic traces were made with silt and cement. Each trace comprises a type of stabilization with one type of cement, mold moisture, molding dry unit weights, curing times and splitting tensile and compressive strength tests. Each splitting tensile and compression test comprises 15 types of mixtures, which can be seen in detail in Table 6. Some samples also were molded for tensile/compression tests after 3, 6 and 12 wet-dry (W-D) and freeze-thaw (F-T) cycles. This study used high early strength Portland cement (named CP V in Brazil). Its rapid increase of resistance permitted selecting 7 days as the curing period for durability and UCS specimens. In addition, for UCS tests 14 and 28 days of curing periods were chosen. Thus, all compacted silt-cement blends were studying using 7, 14, and 28 days (when convenient as reported in Tables 4-6).

2.3 Preparing specimens

Test specimens having height and diameter of 100 mm and 50 mm, respectively, were molded for the unconfined compression and splitting tensile tests. For the wetting-drying (W-D) and freezing-thawing (F-T) durability tests (to calculate the loss of mass per cycle or accumulated loss of mass), specimens measuring 10 cm in diameter and 12.73 cm in height were molded. However, for measuring UCS and STS after W-D and F-T cycles, specimens measuring 50 mm in diameter and 100 mm in height were used.

The silt soil was dried in an oven at a temperature of 100 ± 5 °C and divided into uniformly distributed portions to be mixed with different cement contents. The percentages of cement chosen for this research were: 3 %, 5 %, 7 % and 9 % about the dry mass of the soil; taking into consideration the current literature and Brazilian experience (Consoli et al., 2016a). Thus, a quantity of dry cement was added to achieve the three different addition contents (3, 5, 7, and 9 %). The mixture of the soil with cement was prepared to be homogenous to the maximum extent. Subsequently, a percentage of water was added, determined about the water

Table 4. Molding points for silt-cement compacted blends.

Silt Type	Molding dry unit weight (γ_d)	Molding moisture (ω)	Type of cement and percentages	Curing time-days	Test
Yellow silt (YS)-mix 1	13, 14.5 and 16 kN/m ³	10, 14.67, 19.33, 24, 28.67 and 33.34 %	Type V: 3, 5, 7 and 9 %	28-d	q_u and q_t - saturated conditions
Yellow silt (YS)-mix 2 (1)	Optimum compaction conditions*	Optimum compaction conditions*	Type V: 3, 5, 7 and 9 %	7, 14 and 28-d	q_u and q_t - saturated conditions
Yellow silt (YS)-mix 3	Optimum compaction conditions*- with wet-dry cycles	Optimum compaction conditions*- with wet-dry cycles	Type V: 3, 5, 7 and 9 %	3, 6 and 12 cycles	q_u and q_t - saturated conditions
Yellow silt (YS)-mix 4	Optimum compaction conditions*- with freeze/thaw cycles	Optimum compaction conditions*- with freeze/thaw cycles	Type V: 3, 5, 7 and 9 %	3, 6 and 12 cycles	q_u and q_t - saturated conditions

*Optimum compaction conditions for yellow silt-cement Type V mixes in details in Table 5.

Table 5. Molding points for yellow silt-cement mixes on optimum molding conditions.

Cement content (%)	MDD-Maximum dry density (kN/m ³)			OMC- Optimum moisture content (%)			Standard
	Standard effort-SE	Intermediate effort-IE	Modified effort-ME	Standard effort-SE	Intermediate effort-IE	Modified effort-ME	
3	13.85	15.65	16.85	26	18	15	Brazilian NBR 7182 (ABNT 2016)
5	13.8	15.55	17.05	26.5	18	15	
7	14	15.55	16.95	26	18.5	14.5	
9	14	15.55	16.95	25.5	18	15	

content of the molding points shown in Table 4 and 5 (when convenient). For the compacted specimens, the required mass of soil plus cement was mixed with the appropriate amount of distilled water to prepare an initial moisture content. The samples for molding the test specimens were statically compacted in three layers (the top of each layer was slightly scarified) with a stainless-steel mold. The molding was done with the help of a manual hydraulic press and the time required for the preparation of each test specimen was approximately 15 min. The specimens were extruded from its molds using a hydraulic device. To ensure the dry unit weight of molding, the mold volume and weight of the wet mixture necessary for each test specimen were calculated, following which the required quantities for each specimen were weighed. The time used to prepare, mix and compact the specimens was always less than 30 min, to avoid the early reactions of soil-cement in water's presence. The test specimens were weighed on a 0.01 g precision scale, and the dimensions were measured using a caliper with a 0.01 mm error. Three wet samples of the mixture were taken to check the mold moisture by oven drying.

The extracted test specimens were wrapped in a transparent plastic film to maintain the moisture content. Finally, the test specimens were stored in a wet chamber for the curing process for 7, 14, and 28 days (when appropriate), at a mean temperature of 24 ± 2 °C and relative humidity

above 95 % to prevent significant changes in the moisture until the testing day. After curing, the specimens were submerged in a tank of distilled water for 24 h (1 day) expecting to try to minimize the possibility that the suction would influence the final strength value. This procedure has been used in the current literature to reduce the effect of suction (Moreira et al., 2019a). Additionally, moisture content in the soil-cement mixes was cross-checked by oven drying after the completion of the UCS and STS tests.

The following maximum errors were taken into account when conducting the unconfined compression, splitting tensile and durability for the samples: sample dimensions with a diameter of ± 0.5 mm and height of ± 1 mm, dry unit weight (γ_d) of ± 1 %, and water content (ω) of ± 0.5 % (Baldovino et al., 2018a; Consoli et al., 2009; Moreira et al., 2019a). For each molding point, curing period, cement content, three test specimens were molded. Three replicate samples were tested for each compaction state to check repeatability in UCS and STS results. To perform the unconfined compression and splitting tensile tests, an automatic press was used along with rings calibrated for an axial load with a capacity of 10 kN. The tests were conducted using an automated system at a test speed of 1 mm/min to measure the applied force with a resolution of 2.5 N and deformation with a sensitivity of 0.01 mm. The procedures for the unconfined compression and splitting tensile tests adhered to

Table 6. Optimization for A_q parameter for each mix using the coefficient of determination/MAPE and its corresponding normalization resistance with the parameter $\eta / C_{iv}^{0.50} = 20$.

Mix	Test	Code	A_q ($\times 10^4$) in kPa	R^2	MAPE (%)	q_u and q_t (kPa) at $\eta / C_{iv}^{0.50} = 20$
Yellow Silt+CPV+ mold moisture of 10 % (28-d)	UCS	YS+CPV+[$\omega = 10$ %]+UCS	117.36	0.92	5.9	1291
	STS	YS+CPV+[$\omega = 10$ %]+STS	17.21	0.91	5.5	189
Yellow Silt+CPV+ mold moisture of 14.67 % (28-d)	UCS	YS+CPV+[$\omega = 14.67$ %]+UCS	160.41	0.92	5.4	1765
	STS	YS+CPV+[$\omega = 14.67$ %]+STS	21.46	0.88	9.8	236
Yellow Silt+CPV+ mold moisture of 19.33 % (28-d)	UCS	YS+CPV+[$\omega = 19.33$ %]+UCS	203.55	0.95	4.3	2240
	STS	YS+CPV+[$\omega = 19.33$ %]+STS	27.54	0.90	8.1	303
Yellow Silt+CPV+ mold moisture of 24 % (28-d)	UCS	YS+CPV+[$\omega = 24$ %]+UCS	242.26	0.98	2.8	2666
	STS	YS+CPV+[$\omega = 24$ %]+STS	38.76	0.92	6.3	427
Yellow Silt+CPV+ mold moisture of 28.67 % (28-d)	UCS	YS+CPV+[$\omega = 28.67$ %]+UCS	220.31	0.97	2.3	2424
	STS	YS+CPV+[$\omega = 28.67$ %]+STS	34.68	0.94	5.8	382
Yellow Silt+CPV+ mold moisture of 33.34 % (28-d)	UCS	YS+CPV+[$\omega = 33.34$ %]+UCS	183.57	0.97	4.1	2020
	STS	YS+CPV+[$\omega = 33.34$ %]+STS	25.44	0.92	7.4	280
Yellow silt+CPV+ optimum compaction conditions (7-d)	UCS	YS+OC+7-d+UCS	137.61	0.92	9.5	1514
	STS	YS+OC+7-d+STS	20.45	0.95	6.8	225
Yellow silt+CPV+ optimum compaction conditions (14-d)	UCS	YS+OC+14-d+UCS	167.86	0.90	9.7	1847
	STS	YS+OC+14-d+STS	26.76	0.96	4.2	295
Yellow silt+CPV+ optimum compaction conditions (28-d)	UCS	YS+OC+28-d+UCS	208.83	0.96	5.1	2298
	STS	YS+OC+28-d+STS	35.14	0.96	3.3	387
Yellow silt+CPV+ optimum compaction conditions (3 wet-dry cycles)	UCS	YS+CPV+3W-D+OC+UCS	226.12	0.94	1.8	2488
	STS	YS+CPV+3W-D+OC+STS	30.86	0.96	2.7	340
Yellow silt+CPV+ optimum compaction conditions (6 wet-dry cycles)	UCS	YS+CPV+6W-D+OC+UCS	540.33	0.99	2.4	5946
	STS	YS+CPV+6W-D+OC+STS	64.52	0.99	3.1	710
Yellow silt+CPV+ optimum compaction conditions (12 wet-dry cycles)	UCS	YS+CPV+12W-D+OC+UCS	575.94	0.98	2.9	6338
	STS	YS+CPV+12W-D+OC+STS	83.08	0.97	3.7	914
Yellow silt+CPV+ optimum compaction conditions (3 freeze-thaw cycles)	UCS	YS+CPV+3F-T+OC+UCS	108.93	0.92	8.4	1199
	STS	YS+CPV+3F-T+OC+STS	16.96	0.94	7.2	187
Yellow silt+CPV+ optimum compaction conditions (6 freeze-thaw cycles)	UCS	YS+CPV+6F-T+OC+UCS	94.98	0.96	4.3	1045
	STS	YS+CPV+6F-T+OC+STS	15.09	0.98	1.9	166
Yellow silt+CPV+ optimum compaction conditions (12 freeze-thaw cycles)	UCS	YS+CPV+12F-T+OC+UCS	69.32	0.94	7.5	763
	STS	YS+CPV+12F-T+OC+STS	11.40	0.96	5.9	125

Brazilian ABNT NBR 5739 (ABNT, 2007) and ABNT NBR 7222 (ABNT, 2011), respectively.

The tests followed the recommendations and procedures of the American Standard ASTM D559 (ASTM, 2015) and ASTM D560 (ASTM, 2016) for W-D and F-T cycles, respectively. The specimens were prepared with the different cement content and molding conditions defined in

Table 5 (optimum compactions conditions). Additionally, specimens only for W-D cycles, containing 25 % moisture content and dry unit weight of 13, 14 and 15 kN/m³ were also molded. After hydration of the cement (i.e. 7 days), the W-D and F-T cycles were started. After the W-D and F-T cycles, the samples were subjected to brushing to measure the loss of mass. They were 18 to 19 brushed on the side

faces covering them twice, and 4 brushed on the two transverse faces of the test cups applying an average force of 15 N, which was calibrated on a precision scale. To avoid as much as possible operational error variables, all brush tests were performed by the same operator during the 12 cycles. Various specimens employed the standard effort after 12 F-T cycles are presented in Figure 1. The amount of soil-cement mass lost during brushing was measured with the help of an accuracy scale of 0.01 g. Finally, the mass values of the samples before and after brushing in each cycle were recorded. The specimens for UCS and STS tests using W-D and STS cycles (i.e. 3, 6, and 12) were molded under the same conditions as the specimens for mechanical resistance (Figure 1) with normal curing. Consequently, each W-D and STS started after 7-d curing time. Each W-D cycle started with the wet cycle at 23 °C for 5 h in a distilled water tank. After wetting, samples were taken and placed in an oven at 71 ± 2 °C for 42 h. On the other hand, each F-T cycle started with the freeze cycle at -23 °C for 23 h (Figure

re 1) in a freezer with the capacity to reach a temperature of up to -40 °C. After freezing, samples were taken and placed in a wet chamber for 24 h to thawing. Finally, UCS and STS were conducted after 3, 6 and 12 W-D and STS cycles.

3. Results and discussions

3.1 Effects of initial moisture content and curing time on strength

Figures 2 and 3 shows the effects of initial molding moisture content on unconfined compressive and splitting tensile strength, respectively. Compressive and tensile strength values depending on curing time and porosity/cement index (η/C_{iv}) (named porosity-to-volumetric cement content index, where C_{iv} is a volume of cement divided by the volume of the specimen where it's contained). Good relationships (with R^2 above 0.92 to q_u and 0.88 to q_t) between η/C_{iv} - q_u and η/C_{iv} - q_t are obtained depending on initial moisture content and a curing time of 28 days. Compressive and

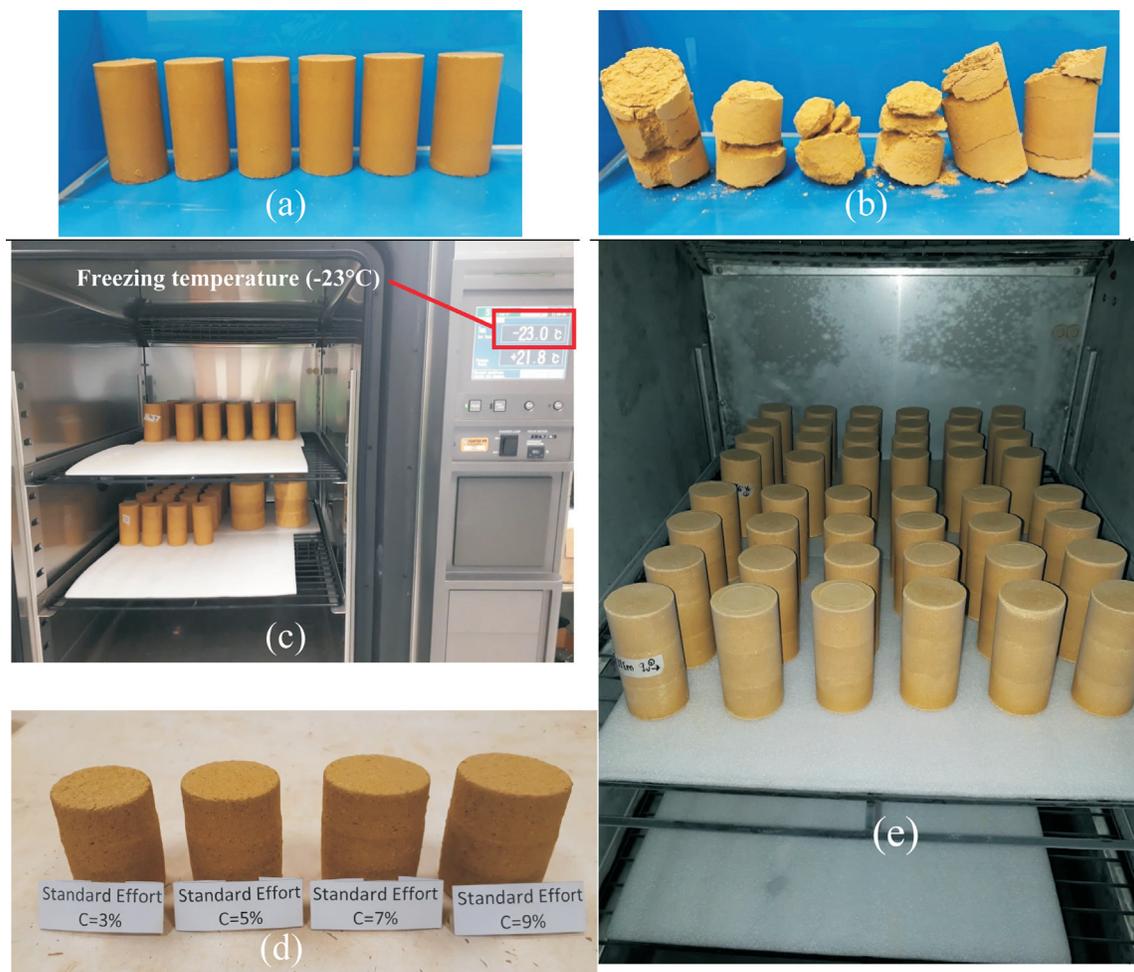


Figure 1. Photos of the specimens: (a) compacted specimens with 9 %C employing the standard effort after 12 W-D cycles for UCS and STS tests. (b) UCS and STS compacted specimens with 3 %C using the standard effort after the first W-D cycle. (c) UCS, STS and Durability specimens into a freezer before start freezing cycle for 23 h. (d) Comparing durability specimens compacted at standard effort after 12 F-T cycles. (e) UCS and STS compacted specimens employing standard, intermediate, and modified effort after F-T cycle at -23 °C.

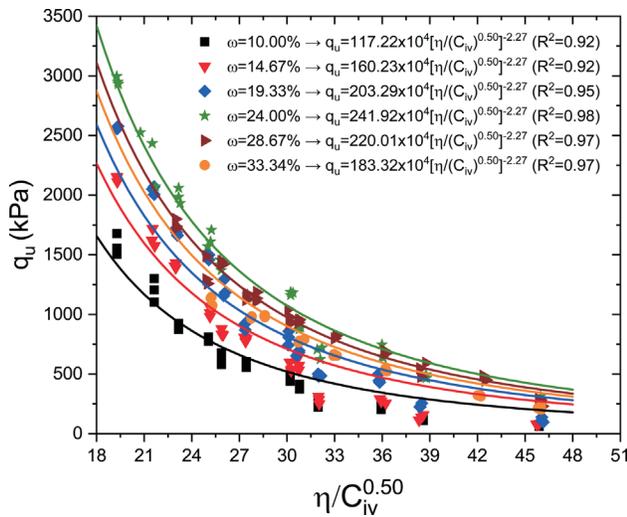


Figure 2. Influence of porosity/cement index ($\eta / C_{iv}^{0.50}$) on unconfined compressive strength considering initial molding moisture of 10, 14.67, 19.33, 24, 28.67, and 33.34 % and considering 28 d-curing time.

splitting tensile values increases when initial moisture content increases between 10 % and 25 %. Above 25 % moisture content, both compressive and tensile strength decreases. To make compatible η and C_{iv} , C_{iv} was raised to exponent $b = 0.50$ and to make compatible $\mu = \eta / C_{iv}^{0.50}$ and q_t or q_u as a power function, μ factor was raised to exponent $c = -2.27$. These exponents (b and c) depending on the type of soil and cement properties as related in previous studies (Baldovino et al., 2018a; Consoli et al., 2016b; Moreira et al., 2019a). The variation in the power functions (see Figures 2 and 3) clearly shows that moisture can increase or decrease

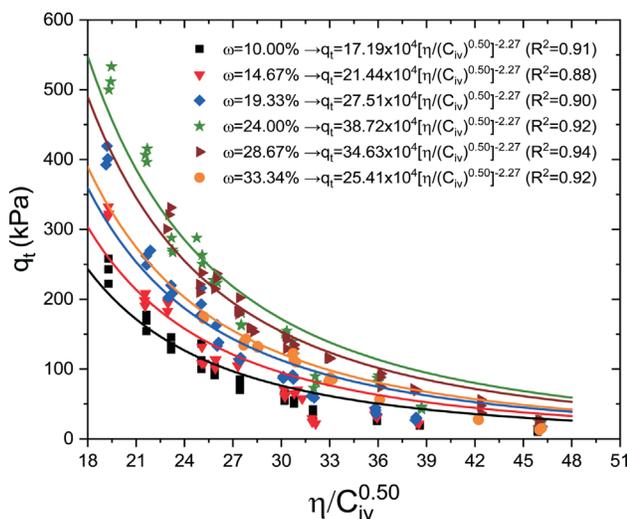


Figure 3. Influence of porosity/cement index ($\eta / C_{iv}^{0.50}$) on splitting tensile strength considering initial molding moisture of 10, 14.67, 19.33, 24, 28.67, and 33.34 % and considering 28 d-curing time.

the mechanical resistance of compacted soil-cement mixtures after 28-days curing. According to molding points presented in Table 5 and Figures 2 and 3, the amount of μ varies from 19 to 46, for compressive and tensile specimens.

One can observe in Figure 4 the influence of porosity/cement index (η / C_{iv}) on unconfined compressive and splitting tensile strength considering optimum compaction conditions (molding points in Table 5) using 7, 14, and 28 days as curing time periods. Figure 4 shows an increase in q_u and q_t when curing time increases. Porosity/cement index controlling q_u and q_t values depending on a power function (with R^2 between 0.90 and 0.96- Figure 4). Optimum compaction conditions are controlling by μ ratio (raised to 0.50 and -2.27 exponents). For specimens compacted on optimum points of compaction curve, the amount of μ varies from 16 to 42 for compression and tensile. Excellent relationships between compression- μ and tensile- μ were reached independently of curing time between 7-28 days. Equations presented in Figures 2 to 4 describe a potential increase (i.e. power function) in tensile strength and unconfined compression for each molding moisture or curing period. Note that growth follows the form: $q_u \propto q_t = A_q [\eta / C_{iv}^b]^{-c}$, where A_q is a constant expressed in kPa. The A_q parameter depends on the type of soil and the type of binder (Baldovino et al., 2019a; MolaAbasi et al., 2019). The physical meaning of this single empirical parameter A_q requires further analysis and additional knowledge of the inherent fabric characteristics of the mixtures tested (Consoli et al., 2019). The existing data clearly show that A_q has a strong correlation, increasing with the curing time, molding moisture and W-D cycles present in the mixtures tested. Diambra et al. (2018), developed a theoretical framework based on the superposition of the individual

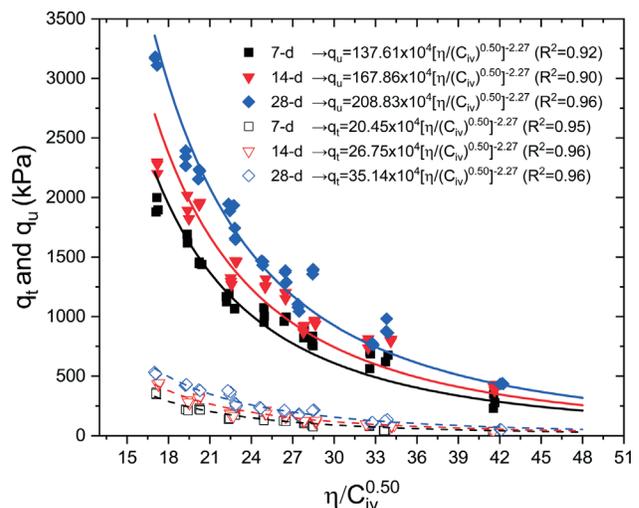


Figure 4. Influence of porosity/cement index ($\eta / C_{iv}^{0.50}$) on unconfined compressive and splitting tensile strength considering optimum compaction conditions (molding points in Table 5) and 7, 14, and 28 days curing time.

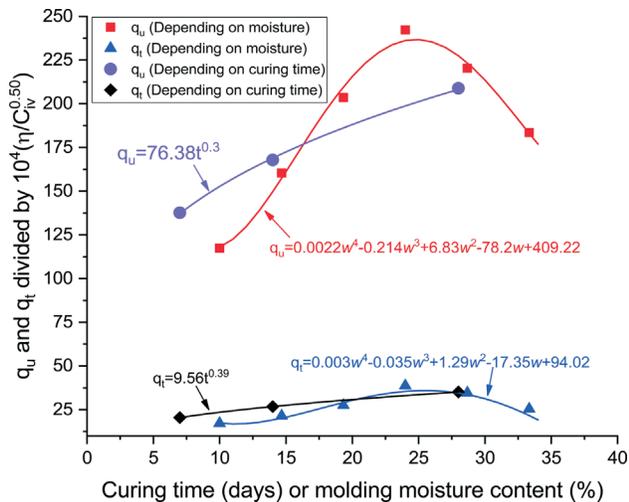


Figure 5. Normalization of UCS and STS depending on curing time periods and molding moisture content.

failure strength contributions of both constituents to link the empirical coefficients A_q and c governing the unconfined compressive strength (q_u) and split tensile strength (q_t) to both sandy soil and cement properties. The authors concluded that A_q and c depend on the constituents' physical parameters like the critical state soil strength ratio (M), critical state soil porosity (η_{cs}), Poisson's ratio of cement and Poisson's ratio of composite material. However, the measuring of these constituents' physical parameters is outside the scope of the present paper. Diambra et al. (2018) suggested $b = 1/c$ for cemented sands, where theoretically b would be $1/2.27 = 0.44$ but noted in the present study as $1.135/c = 0.50$ for the cemented silt with cement reported on the present study.

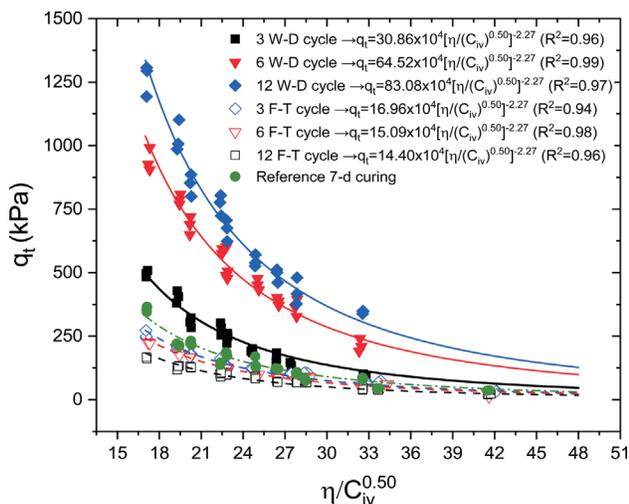


Figure 7. Influence of porosity/cement index ($\eta/C_{iv}^{0.50}$) on splitting tensile strength against 3, 6, and 12 wet/dry and freeze/thaw cycles, considering optimum compaction conditions (molding points in Table 5) and 7 days as curing period.

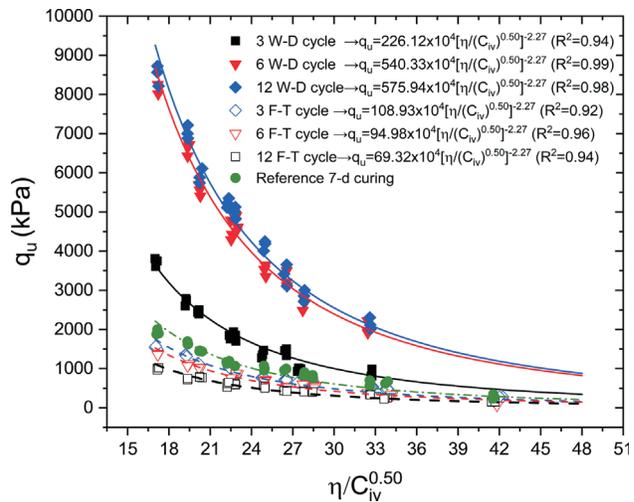


Figure 6. Influence of porosity/cement index ($\eta/C_{iv}^{0.50}$) on unconfined compressive strength against 3, 6, and 12 wet/dry and freeze/thaw cycles, considering optimum compaction conditions (molding points in Table 5) and 7 days as curing period.

When water is mixed with cement, its hydration occurs, which means that cementitious compounds of calcium-silicate-hydrate (C-S-H) and calcium-aluminate-hydrate (C-A-H) are formed, and an excess of calcium hydroxide (CaOH) is released to form extra C-S-H because of the reaction between the soil silica and $Ca(OH)_2$ in cement (MolaAbasi et al., 2019; Puppala, 2016). The formation of C-S-H results in the growth in strength as soon as the cement hydration happens. Meanwhile, Kezdi & Rethati (1988) explain the mechanism by which the stabilizing action of cement is accomplished in fine soils. In fine-grained (silts and clays), the hydrated cement develops strong bonds between the mineral particles, resulting in a ce-

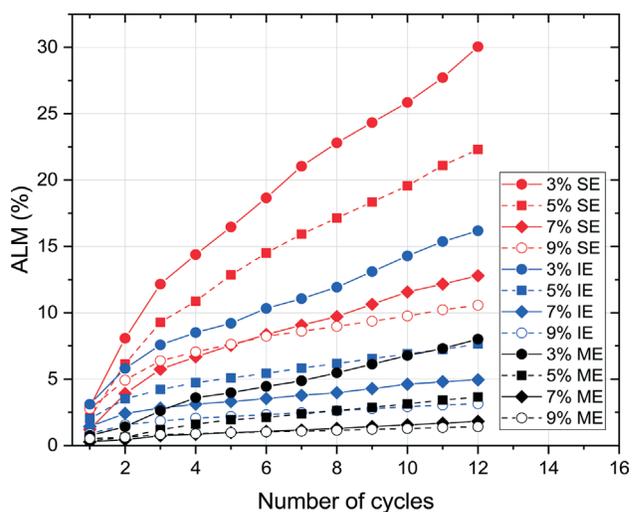


Figure 8. Accumulated Loss of Mass (ALM) vs. freeze/thaw cycles for a silty soil-cement compacted blends considering 3, 5, 7, and 9 % of cement; distinct compaction efforts (dry unit weight of molding) indicated in Table 5 and considering 7 days of curing.

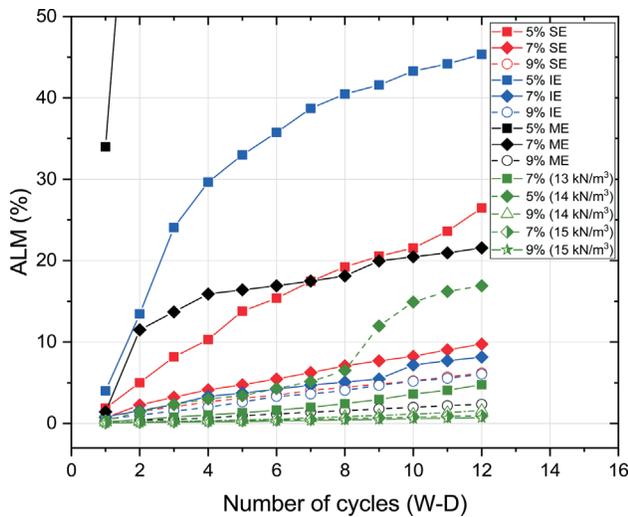


Figure 9. Accumulated Loss of Mass (ALM) vs. wet/dry cycles for a silty soil-cement compacted blends considering 3, 5, 7, and 9 % of cement; distinct compaction efforts (dry unit weight of molding) indicated in Table 5 and specific dry unit weight (13, 14, and 15 kN/m³) of molding at $\omega = 25\%$, and considering 7 days of curing.

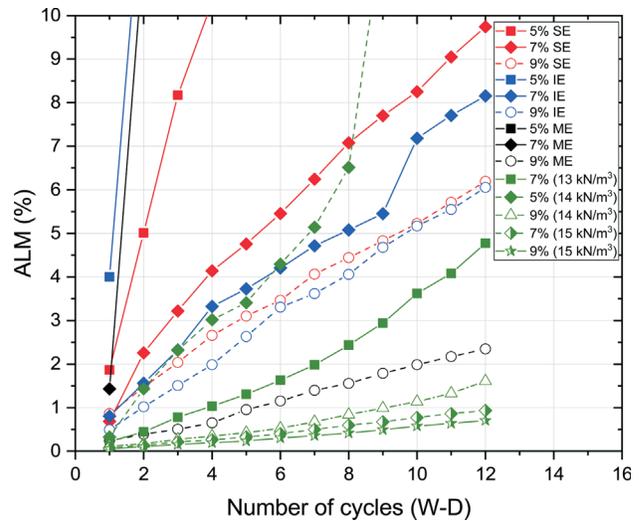


Figure 10. Enlargement of Figure 9 (0-10 % ALM) for different soil-cement compacted blends depending on number of Wet-Dry cycles.

mented matrix, which encases the unbonded soil grains. The honeycomb structure of the matrix is responsible for the strength of the final product. The strength of the clay particles within the matrix is rather low. The bonds prevent the particles from moving towards one another, thereby minimizing the plasticity index and increasing shear resistance. The clay particles are coagulated by the lime liberated during the hydration, reducing their affinity for water and thus the swelling and shrinking properties of the soil.

Thus, the quantity of water to reach maximum strength must be enough to form the optimum C-S-H and matrix structure. Comparing the effects of molding moisture content (see Figures 2 and 3) and compaction effort (see Figure 4) on strength depending on the $\eta / C_{iv}^{0.50}$ index, the highest values of strength are obtained when compacted in $\omega = 25\%$, these values correspond to 1 % below the average optimum moisture content of soil-cement mixes at standard effort (i.e. $\omega = 26\%$). Consequently, maximum UCS-STs values reported in Figures 2-4 are not dependent on the optimum compaction water content. In that sense, maximum strength values depending on the final honeycomb structure affect by $\eta / C_{iv}^{0.50}$, molding ω , and curing time. On the other hand, independent of moisture content and using three compaction efforts combination with three optimum moisture content, A_q value is higher when blends were compacted at ω between 24 and 28.33 % than the blends compacted on optimum compacted parameters (MDD and OMC), but the effort necessary to reach those dry unit weights requires more energy comparing the employed when MDD and OMC are used.

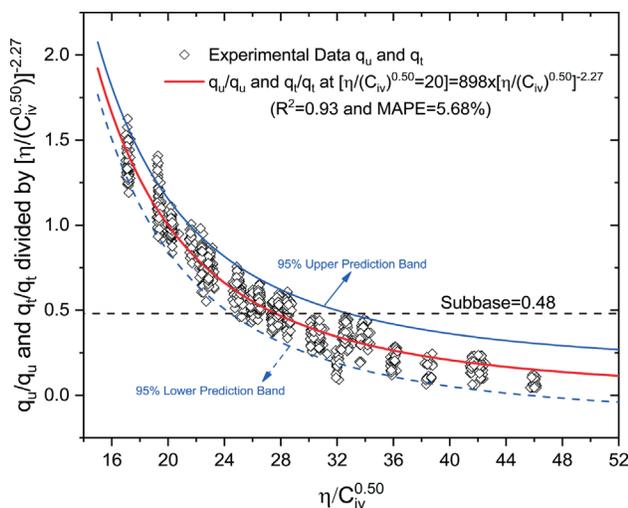


Figure 11. Normalization of q_u and q_t (for the whole range of $\eta / C_{iv}^{0.50}$) by dividing for q_u and q_t at $\eta / C_{iv}^{0.50} = 20$ (Details in Table 6) considering strength of cement- treated silty soil using distinct cement contents, different initial moisture content, dry unit weight, various W-D and F-T durability cycles, and 7, 14, and 28-d of curing time.

The equations shown in Figures 2 to 4 can be normalized in terms of $\eta / C_{iv}^{0.50}$, for the same values of molding moisture or curing period. The power functions that describe the growth of q_u and q_t as a function of $\eta / C_{iv}^{0.50}$ can be divided by the same value of $10^4 [\eta / C_{iv}^{0.50}]^{-2.27}$, ensuring, thus, a constant calculated to its corresponding value of molding moisture or curing time, both for q_u and q_t . Therefore, if it is correlated to its respective moisture/curing time with its normalized constant q_u divided by $10^4 [\eta / C_{iv}^{0.50}]^{-2.27}$ or q_t divided by $10^4 [\eta / C_{iv}^{0.50}]^{-2.27}$, a point in the Cartesian plane is found. In this way, the variation of normalized q_u and q_t depends on the moisture content or t (curing time) (see Figure 5). Figure 5 shows that the

prime parameter controlling UCS and STS after $\eta / C_{iv}^{0.50}$ is the molding moisture content followed by the curing time. Dosages equations controlling UCS (Equation 1) and STS (Equation 2), according to Figure 5 (depending on molding moisture), are expressed respectively as:

$$q_u = (0.0022\omega^4 - 0.215\omega^3 + 6.83\omega^2 - 78.2\omega + 409.22) \times 10^4 [\eta / C_{iv}^{0.50}]^{-2.27} \quad (R^2 = 0.96) \quad (1)$$

$$q_t = (0.0003\omega^4 - 0.035\omega^3 + 1.29\omega^2 - 17.35\omega + 94.02) \times 10^4 [\eta / C_{iv}^{0.50}]^{-2.27} \quad (R^2 = 0.96) \quad (2)$$

Good relationships ($R^2 = 0.96$ for UCS and $R^2 = 0.95$ for STS) were obtained normalizing strength in terms of w . On the other hand, dosage equations controlling UCS (Equation 3) and STS (Equation 4) according to Figure 5 (depending on curing time t periods in days) are expressed respectively as:

$$q_u = 79.38t^{0.30} \times 10^4 [\eta / C_{iv}^{0.50}]^{-2.27} \quad (R^2 = 0.97) \quad (3)$$

$$q_t = 9.56t^{0.39} \times 10^4 [\eta / C_{iv}^{0.50}]^{-2.27} \quad (R^2 = 0.96) \quad (4)$$

Excellent relationships ($R^2 = 0.97$ for UCS and $R^2 = 0.96$ for STS) were obtained normalizing strength in terms of curing time (t). The strength of compacted blends was achieved at humid room considering curing time and molding moisture. These strengths are suitable for engineering earthwork because they reached a minimum value of 1.2 MPa and could be used in subbase construction (see Figures 2-4). But field strength can be modified due to the local climatic conditions (cold or hot). Thus, the effects of freeze/thawing and wet/dry cycles on the resistance and durability of the mixtures are underestimated.

3.2 Effects of wetting-drying and freeze-thawing cycles on strength and durability

Figures 6 and 7 show the impact of η / C_{iv} index on unconfined compressive and splitting tensile strength, respectively; against 3, 6, and 12 wet/dry and freeze/thaw cycles, considering optimum compaction conditions. For these several climates conditions, η / C_{iv} also controlling the strength of silt-cement compacted blends. When specimens were subject W-D cycles the strength increases. On the other hand, when F-T cycles were employed, the strength decreases when the number of cycles was increased to 12 as shown in Figures 6 and 7. It is evident that W-D cycles increases and accelerating the pozzolanic reactions between soil and cement, reaching maximum values of 8500 kPa and 1270 kPa in compression and tensile, respectively. Specimens with $C = 3\%$ could not handle W-D cycles as shown in Figure 1. The specimens partially disintegrated due to the short curing time and the small percentage of cement. The value of A_q decreased with an increasing number of F-T cycles for both q_u and q_t . That is, the strength of the blends was negatively shaved by exposure to extreme freezing temperatures. The creation and formation of cracks

due to the cold and deceleration of the pozzolanic reactions and cement hydration promoted the loss of resistance. Thus, UCS = 1.2 MPa is attended when a large amount of cement (above 7 %) was added and compaction energy of 15 kN/m³ was used.

According to Figure 8, the increase in freeze-thaw cycles means an increase in the mass loss of each mixture due to brushing. These losses are directly related to the amount of cement added and the compaction energy employed since an increase in the density of compaction and cement content caused the mixtures to suffer less mass loss. Thus, Figure 8 also presents the accumulated loss of mass (ALM) of blends subject F-T cycles and considering 7-days curing. The decrease in characteristic loss of mass (i.e. ALM in % per cycle) with increasing, compaction energy was noted. In standard effort, the characteristic loss of mass (CLM) varied, on average, from 2.5 % to 0.88 % of mass loss per cycle. In the intermediate and modified efforts, the CLM value decreased by 1.35 % and 0.67 %, respectively. The loss of mass per cycle is associated with the force applied during brushing (~ 15 N) and the surface strength of the mixtures to abrasion, which increases when adhesion- cementation of the soil-cement particles is increased.

Figure 9 shown the ALM vs. W-D cycles for the blends used. Most of the mixtures did not have mass losses greater than 10 % as presents in detail in Figure 10. Compacted blends using 3 % cement and curing for 7 days did not stand the immersion in water for 5 h (wet cycle). Initial moisture content influences the durability of the blends. Using 5 % cement in different energies, the durability increased when the moisture content increases. Thus, the durability was directly related to the amount of water added to compaction. For this reason, specimens were also compacted with $\omega = 25\%$ (optimum moisture content to compact the blends considering the strength- according to Figures 2-3) as shown in Figures 9 and 10. On average, increasing the moisture content of compaction to 25 % improved the durability (W-D) of the mixes by 32 %. In this way, 9 % ME ($\gamma_d = 16.95$ kN/m³ and $\omega = 15\%$) expected to be the most durable blend, but Figure 9 demonstrates the opposite, decreasing γ_d to 15 kN/m³ and increasing ω to 25 % the ALM decreases from 2.4 % to 1.7 % (improving ALM in 40 %). Besides, other compacted blends with $\omega = 25\%$ and 9 % (with $\gamma_d = 14$ kN/m³) or 7 % (with $\gamma_d = 14$ kN/m³) also increase the durability in reference to 9 % ME. However, 3 % of cement compacted blends in $\omega = 25\%$ also did not resist the first wet cycle. Consequently, 3 % of cement is not recommendable to stabilization in terms of durability.

The permissible mass loss values for durability tests using F-T/W-D cycles to base construction, for chemically stabilized silt soils, the ALM value should not exceed 7 % or 8 % according to Portland Cement Association (PCA, 2000) and to Corp of Engineer (1994), respectively. All

mixtures (using F-T cycles) in the modified and intermediate effort (except $C = 3 \%$) meet this requirement. When W-D cycles are employed to study the durability of compacted blends, 7 % and 9 % above intermediate effort meet the requirement. Nevertheless, to subbase this requirement it may be less strict. Base on ALM = 15 % compacted blends employing average $C = 6 \%$ above standard effort fulfill the requirement of durability, and, if $\omega = 25 \%$ is used to compact the mixes, cement content and effort can be decreased by up to 1 %. However, the requirements of the earthwork will decide the best soil-cement dosage to make it more resistant and more durable taking into account the weather and the curing time.

3.3 Role of porosity/cement index in normalization terms

Table 6 presents the parameters A_q , $\eta / C_{iv}^{0.50}$, R^2 , and mean absolute percentage error (MAPE, in %) of all the equations that control the resistance of the mixtures depending on the molding moisture, curing time and climatic conditions. All equations depend on $\eta / C_{iv}^{0.50}$ index (independent of ω , curing time, and W-D/F-T cycles). The value of $b = 0.50$ means that porosity (η) and voids in the soil-cement mixture exerts a more compelling influence on q_u and q_t than C_{iv} . For this reason, A_q value increases significantly. The exponent $b < 1$ indicates that the porosity (η) exerts a more significant influence on the splitting tensile and compressive strengths than the volumetric content of binder. A value of b close to 1 means that both parameters (voids and amount of binder) exert the same influence magnitude on q_u and q_t . Therefore, $b < 1$ value is more frequent when cement and lime are used in fine soils while b closer to 1 is more common for cement-sandy soil mixes considering previously studies (Baldovino et al., 2018a; 2018c; Consoli et al., 2009; 2016a; 2019b; Moreira et al., 2019a).

Considering A_q and $\eta / C_{iv}^{0.50}$ values reported in Table 6, it is possible to determine a normalized equation for all the silt-cement compacted blends as a function of η and C_{iv} . For this, the methodology used by Consoli et al. (2016a; 2016b) and Moreira et al. (2019a) was employed. To normalize (i.e. divide) the equations as a function of $\eta / C_{iv}^{0.50}$, it is necessary to (i) Dividing $q_u \vee q_t = A_q [\eta / C_{iv}^b]^{-c}$ by an arbitrary specific value of UCS and STS, corresponding to a value of a given adjusted $\mu = \eta / C_{iv}^b$. The value of μ in this study is set to be 20, due to the mathematical approximations of Figures 2 to 4 and Figures 6 and 7. (ii) The experimental values of UCS and STS, are divided by the values of constant $\mu = \eta / C_{iv}^{0.50} = 20$ presented in Table 6. The quotients obtained in these mathematical operations form a potential trend with $R^2 = 0.93$ and MAPE = 5.68 %, described by Equation 5. Thus, Figure 11 presents the normalization of strengths of the test samples and their tendency described as:

$$\frac{q_t}{q_t(\eta / C_{iv}^{0.50} = 20)} \vee \frac{q_u}{q_u(\eta / C_{iv}^{0.50} = 20)} = 898(\eta / C_{iv}^{0.50})^{-2.27} \quad (5)$$

In general, 63 % of soil-cement compacted blends to achieve the minimum requirements for use in subbase and base construction according to American standard TxDOT Tex-120-E (TxDOT, 2013) and Brazilian standard DNIT 143 (DNIT, 2010) as shown in Figure 10 (see dotted lines). The minimum requirement is UCS = 1200 kPa (corresponding in average to $q_u/q_{u(normalized)} = 0.48$) and UCS = 2100 kPa for subbase and base construction, respectively. The minimum requirement is achieved with approximately 6 % and 9 % cement and sometimes with 5 % cement when compacted in modified effort and molding γ_d above 14.5 kN/m³. Although 9 % cement is a high content and is not environmentally friendly for stabilization, it is the most efficient content to reach maximum UCS and STS values. In the order to avoid 9 % cement, η / C_{iv} criteria can be employed to achieve 1200 kPa of strength increasing the compaction effort and decreasing the amount of cement up to 5.5 % ~ 6.0 %. There are several technical ways of reaching a q_u (Equations 1 and 3), q_t (Equations 2 and 4) and ALM target value for a given project (different combinations of molding water contents, porosities, and cement contents might be used to get to a chosen q_u , q_t and ALM) and the best solution might change from situation to situation, depending on accessibility to equipment to reach a given porosity, cost of cement and availability of water as suggested by Consoli et al. (2011; 2016a; 2016b) and Moreira et al. (2019a).

4. Conclusions

In this paper, the impact of several climate and molding conditions on strength and durability against wet/dry and freezing/thawing cycles of Guabiro tuba silt-cement compacted blends were studied. According to the type of soil, cement, the methodology and the presentation and analyses of results used in this study, the following conclusions can be drawn:

- For all studied soil-cement mixtures, the reduction in initial molding dry unit weight and the increase in the quantity of cement caused an increase in splitting tensile and unconfined compression strength after 7, 14, and 28 days of curing (when appropriate). Meanwhile, in terms of porosity/cement index, the compressive and splitting tensile strength of all soil-cement mixtures increased up to 25 % of molding moisture and decreased down to 33 % of moisture when specimens were cured at humid room for 28 days.
- It was possible to determine the equations that control q_u and q_t as a function of η / C_{iv} (set to a value of 0.50). There exists an equation for each molding and climate condition (see Table 6). Thus, there is a single normalized po-

tential trend (see Equation 5) of q_u and q , as a function of molding moisture, curing time and the molding dry unit weights used. The single trend can be extended to any molding and climate condition of the silty soil in this study stabilized with high early strength cement. In addition, the scalar b for cemented sands is calculated as $1/c$ ($b = 1/c$), where theoretically b would be $1/2.27 = 0.44$ but in the present study was calculated as $1.135/c = 0.50$ for the cemented silt.

- The cement-silt compacted blends are suitable for subbase construction (UCS > 1.2 MPa and ALM > 15 %) when 5 % of cement is used employing modified effort or when molding moisture of 25 % compacting with a lower effort. Finally, UCS values can be increased when blends are submitted to W-D cycles or decrease when blends are submitted to F-T cycles. Thus, the most convenient thing is to avoid earthworks in winter or in the worst-case increase the amount of cement to 9 % and energy after addressing the 15 kN/m³.

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References

- ABNT NBR 5739. (2007). Mortar and Concrete - Test Method for Compressive Strength of Cylindrical Specimens. *ABNT - Associação Brasileira de Normas Técnicas, Rio de Janeiro, RJ* (in Portuguese).
- ABNT NBR 7182. (2016). Soil-Compaction Testing. *ABNT - Associação Brasileira de Normas Técnicas, Rio de Janeiro, RJ* (in Portuguese).
- ABNT NBR 7222. (2011). Concrete and Mortar - Determination of the Tension Strength by Diametrical Compression of Cylindrical Test Specimens. *ABNT - Associação Brasileira de Normas Técnicas, Rio de Janeiro, RJ* (in Portuguese).
- ABNT NBR 9604. (2016). Well opening and soil profile inspection trench, with removal of disturbed and undisturbed soil samples — Procedure. *ABNT - Associação Brasileira de Normas Técnicas, Rio de Janeiro, RJ* (in Portuguese).
- ABNT NBR 16605. (2017). Portland Cement and Other Powdered Materials: Determination of the Specific Mass. *ABNT - Associação Brasileira de Normas Técnicas, Rio de Janeiro, RJ* (in Portuguese).
- ASTM D 560-16. (2016). Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures. *ASTM International, West Conshohocken, PA*. https://doi.org/10.1520/D0560_D0560M-16
- ASTM D4318-10. (2010). Standard Test Methods for Liquid Limit, Plastic Limit and Plasticity Index of Soils. *ASTM International, West Conshohocken, PA*. <https://doi.org/10.1520/D4318-10>
- ASTM D2435M-11. (2011a). One-Dimensional Consolidation Properties of Soils Using Incremental Loading. *ASTM International, West Conshohocken, PA*. https://doi.org/10.1520/D2435_D2435M-11
- ASTM D3080-11. (2011b). Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions. *ASTM International, West Conshohocken, PA*. https://doi.org/10.1520/D3080_D3080M-11
- ASTM D854-14. (2014). Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer. *ASTM International, West Conshohocken, PA*. <https://doi.org/10.1520/D0854-14>
- ASTM D2487-17. (2017). Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). *ASTM International, West Conshohocken, PA*. <https://doi.org/10.1520/D2487-17>
- ASTM C150-16. (2016). Standard specification for Portland cement. *ASTM International, West Conshohocken, PA*. https://doi.org/10.1520/C0150_C0150M-16
- ASTM D559-15. (2015). Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures. *ASTM International, West Conshohocken, PA*. https://doi.org/10.1520/D0559_D0559M-15
- Arulrajah, A., Kua, T.-A., Phetchuay, C., Horpibulsuk, S., Mahghoolpilehrood, F., & Disfani, M.M. (2016). Spent Coffee Grounds-Fly Ash Geopolymer Used as an Embankment Structural Fill Material. *Journal of Materials in Civil Engineering*, 28(5), 4015197. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0001496](https://doi.org/10.1061/(ASCE)MT.1943-5533.0001496)
- Baldovino, J.A. (2018). *Comportamento mecânico de um solo siltoso da formação geológica Guabirotuba tratado com cal em diferentes tempos de cura* [Master's thesis, Federal University of Technology-Paraná]. Federal University of Technology-Paraná's repository. <http://repositorio.utfpr.edu.br/jspui/handle/1/3408>
- Baldovino, J.A., Moreira, E.B., Izzo, R.L.S., & Rose, J.L. (2018a). Empirical relationships with unconfined compressive strength and split tensile strength for the long term of a lime-treated silty soil. *Journal of Materials in Civil Engineering*, 30(8), 6018008 1-7. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0002378](https://doi.org/10.1061/(ASCE)MT.1943-5533.0002378)
- Baldovino, J.A., Moreira, E.B., & Izzo, R.L.S. (2018b). Discussion of "Control factors for the long term compressive strength of lime treated sandy clay soil". *Transportation Geotechnics*, 15, 1-3. <https://doi.org/10.1016/j.trgeo.2017.11.002>

- Baldovino, J.A., Moreira, E.B., Carazzai, E., Rocha, E., Izzo, R., Mazer, W., & Rose, J.L. (2019a). Equations controlling the strength of sedimentary silty soil-cement blends: influence of voids/cement ratio and types of cement. *International Journal of Geotechnical Engineering*, 1-14. <https://doi.org/10.1080/19386362.2019.1612134>
- Baldovino, J.A., Moreira, E.B., Izzo, R.L.S., & Rose, J.L. (2019b). Optimizing the evolution of strength for lime-stabilized rammed earth. *Journal of Rock Mechanics and Geotechnical Engineering*, 11(4), 882-891. <https://doi.org/10.1016/j.jrmge.2018.10.008>
- Baldovino, J.A., Izzo, R.L.D.S., Pereira, M.D., Rocha, E.V.D.G., Rose, J.L., & Bordignon, V.R. (2020a). Equations controlling tensile and compressive strength ratio of sedimentary soil-cement mixtures under optimal compaction conditions. *Journal of Materials in Civil Engineering*, 32(1), 04019320. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0002973](https://doi.org/10.1061/(ASCE)MT.1943-5533.0002973)
- Baldovino, J.A., Izzo, R.L., Silva, É.R., & Rose, J.L. (2020b). Sustainable use of recycled-glass powder in soil stabilization. *Journal of Materials in Civil Engineering*, 32(5), 04020080. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0003081](https://doi.org/10.1061/(ASCE)MT.1943-5533.0003081)
- Baldovino, J.A., & Izzo, R.L.S. (2019). Relação porosidade/cimento como parâmetro de controle na estabilização de um solo siltoso. *Colloquium Exactarum*, 11(1), 89-100 (in Portuguese).
- Baldovino, J.A., Moreira, E.B., Teixeira, W., Izzo, R.L.S., & Rose, J.L. (2018c). Effects of lime addition on geotechnical properties of sedimentary soil in Curitiba, Brazil. *Journal of Rock Mechanics and Geotechnical Engineering*, 10(1), 188-194. <https://doi.org/10.1016/j.jrmge.2017.10.001>
- Consoli, N.C., Rosa, D.A., Cruz, R.C., & Dalla Rosa, A. (2011). Water content, porosity and cement content as parameters controlling strength of artificially cemented silty soil. *Engineering Geology*, 122(3-4), 328-333. <https://doi.org/10.1016/j.enggeo.2011.05.017>
- Consoli, N.C., Vaz Ferreira, P.M., Tang, C.S., Veloso Marques, S.F., Festugato, L., & Corte, M.B. (2016a). A unique relationship determining strength of silty/clayey soils-Portland cement mixes. *Soils and Foundations*, 56(6), 1082-1088. <https://doi.org/10.1016/j.sandf.2016.11.011>
- Consoli, N.C., Quiñonez, R.A., González, L.E., & López, R.A. (2016b). Influence of molding moisture content and porosity / cement index on stiffness, strength, and failure envelopes of artificially cemented fine-grained soils. *Journal of Materials in Civil Engineering*, 29(5), 1-10. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0001819](https://doi.org/10.1061/(ASCE)MT.1943-5533.0001819)
- Consoli, N.C., Silva Lopes, L., & Heineck, K.S. (2009). Key Parameters for the Strength Control of Lime Stabilized Soils. *Journal of Materials in Civil Engineering*, 21(5), 210-216. [https://doi.org/10.1061/\(ASCE\)0899-1561\(2009\)21:5\(210\)](https://doi.org/10.1061/(ASCE)0899-1561(2009)21:5(210))
- Consoli, N.C., Carretta, M.S., Leon, H.B., Schneider, M.E.B., Reginato, N.C., & Carraro, J.A.H. (2019). Behaviour of cement-stabilised silty sands subjected to harsh environmental conditions. *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering*, 173(1), 40-48. <https://doi.org/10.1680/jgeen.18.00243>
- Corp of Engineer. 1994. Soil stabilization for pavement. Washington, DC: Dept. of the Army, the Navy, and the Air force.
- Diambra, A., Festugato, L., Ibraim, E., Silva, A.P., & Consoli, N.C. (2018). Modelling tensile/compressive strength ratio of artificially cemented clean sand. *Soils and Foundations*, 58(1), 199-211. <https://doi.org/10.1016/j.sandf.2017.11.011>
- DNIT. (2010). Pavimentação - Base de solo-cimento - Especificação de serviço DNIT 143. *DNIT - Departamento Nacional de Infraestrutura de Transportes, Rio de Janeiro, RJ* (in Portuguese).
- Ivanov, V., & Chu, J. (2008). Applications of microorganisms to geotechnical engineering for bioclogging and biocementation of soil in situ. *Reviews in Environmental Science and Biotechnology*, 7(2), 139-153. <https://doi.org/10.1007/s11157-007-9126-3>
- Kezdi, A., & L. Rethati. (1988). Soil mechanics of earthworks, foundations, and highway engineering (volume 3). In *Handbook of Soil Mechanics*. Elsevier.
- Kua, T.A., Arulrajah, A., Horpibulsuk, S., Du, Y.J., & Shen, S.L. (2016). *Strength assessment of spent coffee grounds-geopolymer cement utilizing slag and fly ash precursors*. Construction and Building Materials, 115, 565-575. <https://doi.org/10.1016/j.conbuildmat.2016.04.021>
- MolaAbasi, H., Saberian, M., & Li, J. (2019). Prediction of compressive and tensile strengths of zeolite-cemented sand using porosity and composition. *Construction and Building Materials*, 202, 784-795. <https://doi.org/10.1016/j.conbuildmat.2019.01.065>
- Moreira, E.B., Baldovino, J.A., Rose, J.L., & Izzo, R.L.S. (2019a). Effects of porosity, dry unit weight, cement content and void/cement ratio on unconfined compressive strength of roof tile waste-silty soil mixtures. *Journal of Rock Mechanics and Geotechnical Engineering*, 11(2), 369-378. <https://doi.org/10.1016/j.jrmge.2018.04.015>
- Moreira, E.B., Baldovino, J.A., Izzo, R.L.S., & Rose, J.L. (2019b). Impact of sustainable granular materials on the behavior sedimentary silt for road application. *Geotechnical and Geological Engineering*, 38(1), 917-933. <https://doi.org/10.1007/s10706-019-01025-6>
- PCA (1992). *Soil-cement laboratory handbook*. PCA - Portland Cement Association.
- Puppala, A.J. (2016). Advances in ground modification with chemical additives: From theory to practice. *Transportation Geotechnics*, 9, 123-138. <https://doi.org/10.1016/j.tgrgeo.2016.08.004>
- Qi, J., Ma, W., & Song, C. (2008). Influence of freeze-thaw on engineering properties of a silty soil. *Cold Regions*

Science and Technology, 53(3), 397-404.
<https://doi.org/10.1016/j.coldregions.2007.05.010>
TxDOT Tex-120-E. 2013. Test Procedure for Soil-Cement Testing. *TxDOT - Texas Department of Transportation, Austin, TX.*

List of symbols

D_{50} : the mean particle diameter

D_{10} : the effective size

C_v : the volumetric cement content (expressed in relation to the total specimen volume)

C_c : the coefficient of curvature

C_u : the uniformity coefficient

q_u : the unconfined compressive strength (UCS)

q_t : the splitting tensile strength (STS)

ALM: the accumulated loss of mass

γ_d : the dry unit weight

η : the porosity

ω : the moisture content

μ : the value of a given adjusted porosity/cement

R^2 : the coefficient of determination

σ'_c : the preconsolidation pressure of soil

C_v : the coefficient of consolidation of soil

A_q : empirical parameter