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

Jair de Jesús Arrieta Baldovino, Ronaldo Luis dos Santos Izzo, Juliana Lundgren Rose

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 \( \frac{\eta}{C_v} \) 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 \( \omega_o \), between 13 and 16 kN/m\(^3\) 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 \(^\circ\)C in a wet chamber. Finally, reasonable dosages employing \( \eta/C_v \) index to stabilize the soil were presented considering the strength and the durability parameters.

1. Introduction

The soils from Guabirotuba 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 (CO\(_2\) 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...
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 ($q_s$ or STS) and $q_s$ of a Guabirotuba silty soil artificially cemented with hydrated lime. To calculate the $q/q_s$ 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 $q/q_s = 0.16$ 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 ($\omega$), and porosity/lime index ($\eta/L_\omega$) 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 $q/q_s$ 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. $(\eta/L_\omega)^{0.68}$. The results showed an increasing strength of the soil-lime mixtures. Baldovino & Izzo (2019) calculated the tensile/compressive index ($q/q_s$) 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 $q/q_s$ 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 $q_s$) 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 $\eta/C_s$ 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 ($\eta/C_s$) 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-line compacted blends for several molding conditions. Finally, Baldovino et al. (2020b) improved the $q_s$ of silty soil-cement mixtures 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 (Go) and $q_s$ of stabilized sands subjected to 12 W-D cycles. The RHA addition improves the $q_s$ values and decreases the ALM. When subjected to W-D cycles, the Go and $q_s$ 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 silt-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 $\eta/C_s$ with $q_s$ 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/m$^3$. 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 Na$_2$SiO$_3$-NaOH composts. By replacing 30% FA into CG at 50/50 Na$_2$SiO$_3$-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 Na$_2$SiO$_3$ and NaOH. In this research, authors obtained good $q_s$ 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 not 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 consolidation 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/m$^3$. 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 ($D_{95}$), 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 ($\sigma'$), kPa | 300 |
| Coefficient of Consolidation ($C_c$), 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 SiO₂, Al₂O₃, and Fe₂O₃, which are usually found in sedimentary soils and participate actively in the process of chemical soil stabilization.

A high early strength Portland cement (Type V in Brazil) (ASTM C150, 2016) is composed principally of calcium oxide (CaO), Silicon dioxide (SiO₂) and aluminum oxide (Al₂O₃) 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 $23 \pm 2$ °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 2. Soil sample chemical composition.

| Compost | Concentration (%) |
|---------|------------------|
| SiO₂    | 48.78            |
| Al₂O₃   | 44.51            |
| Fe₂O₃   | 0.61             |
| K₂O     | 0.84             |
| TiO₂    | 0.92             |
| SO₃     | 4.12             |
| CaO     | -                |
| Na₂O    | -                |
| MgO     | -                |
| Loss on Ignition | 0.22 |

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

| Property          | Value          |
|-------------------|----------------|
| Al₂O₃, %          | 4.30           |
| SiO₂, %           | 18.96          |
| Fe₂O₃, %          | 2.95           |
| CaO, %            | 60.76          |
| MgO, %            | 3.26           |
| SO₃, %            | 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           |
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 also tested to check the mold moisture by oven drying.

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 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.

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**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/m³ | 10, 14.67, 19.33, 24, 28.87 and 33.34 % | Type V: 3, 5, 7 and 9 % | 28-d | qₒ and q₉ - 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 | qₒ and q₉ - 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 | qₒ and q₉ - 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 | qₒ and q₉ - 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/m³) | OMC- Optimum moisture content (%) |
|--------------------|---------------------------------|---------------------------------|
|                    | Standard effort-SE | Intermediate effort-IE | Modified effort-ME | Standard effort-SE | Intermediate effort-IE | Modified effort-ME | Standard         |
| 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               |                                |
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.

### Table 6. Optimization for \( A_q \) parameter for each mix using the coefficient of determination/MAPE and its corresponding normalization resistance with the parameter \( \eta / C_{v=30} \) = 20.

| Mix                                      | Test Code                      | \( A_q \times 10^3 \) in kPa | \( R^2 \) | MAPE (%) | \( q_u \) and \( q_t \) (kPa) at \( \eta / C_{v=30} \) = 20 |
|------------------------------------------|--------------------------------|-----------------------------|------|--------|--------------------------------------|
| Yellow Silt+CPV+ mold moisture of 10 % (28-d) | UCS YS+CPV+[\( \omega = 10 \% \)]+UCS | 117.36 | 0.92 | 5.9   | 1291                                  |
| Yellow Silt+CPV+ mold moisture of 14.67 % (28-d) | UCS YS+CPV+[\( \omega = 14.67 \% \)]+UCS | 160.41 | 0.92 | 5.4   | 1765                                  |
| Yellow Silt+CPV+ mold moisture of 19.33 % (28-d) | UCS YS+CPV+[\( \omega = 19.33 \% \)]+UCS | 203.55 | 0.95 | 4.3   | 2240                                  |
| Yellow Silt+CPV+ mold moisture of 24 % (28-d) | UCS YS+CPV+[\( \omega = 24 \% \)]+UCS | 242.26 | 0.98 | 2.8   | 2666                                  |
| Yellow Silt+CPV+ mold moisture of 28.67 % (28-d) | UCS YS+CPV+[\( \omega = 28.67 \% \)]+UCS | 220.31 | 0.97 | 2.3   | 2424                                  |
| Yellow Silt+CPV+ mold moisture of 33.34 % (28-d) | UCS YS+CPV+[\( \omega = 33.34 \% \)]+UCS | 183.57 | 0.97 | 4.1   | 2020                                  |
| Yellow silt+CPV+ optimum compaction conditions (7-d) | UCS YS+OC+7-d+UCS | 137.61 | 0.92 | 9.5   | 1514                                  |
| Yellow silt+CPV+ optimum compaction conditions (14-d) | UCS YS+OC+14-d+UCS | 167.86 | 0.90 | 9.7   | 1847                                  |
| Yellow silt+CPV+ optimum compaction conditions (28-d) | UCS YS+OC+28-d+UCS | 208.83 | 0.96 | 5.1   | 2298                                  |
| Yellow silt+CPV+ optimum compaction conditions (3 wet-dry cycles) | UCS YS+CPV+3W-D+OC+UCS | 226.12 | 0.94 | 1.8   | 2488                                  |
| Yellow silt+CPV+ optimum compaction conditions (6 wet-dry cycles) | UCS YS+CPV+6W-D+OC+UCS | 540.33 | 0.99 | 2.4   | 5946                                  |
| Yellow silt+CPV+ optimum compaction conditions (12 wet-dry cycles) | UCS YS+CPV+12W-D+OC+UCS | 575.94 | 0.98 | 2.9   | 6338                                  |
| Yellow silt+CPV+ optimum compaction conditions (3 freeze-thaw cycles) | UCS YS+CPV+3F-T+OC+UCS | 108.93 | 0.92 | 8.4   | 1199                                  |
| Yellow silt+CPV+ optimum compaction conditions (6 freeze-thaw cycles) | UCS YS+CPV+6F-T+OC+UCS | 169.96 | 0.94 | 7.2   | 187                                  |
| Yellow silt+CPV+ optimum compaction conditions (12 freeze-thaw cycles) | UCS YS+CPV+12F-T+OC+UCS | 69.32 | 0.94 | 7.5   | 763                                   |

Brazilian ABNT NBR 5739 (ABNT, 2007) and ABNT NBR 7222 (ABNT, 2011), respectively.
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 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 ($\eta/C_\text{iv}$) (named porosity-to-volumetric cement content index, where $C_\text{iv}$ 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 $q_t$ and 0.88 to $q_t$) between $\eta/C_\text{iv}$ and $\eta/C_\text{iv}$, 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.
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 $\eta / C_{104}$ and $C_{104}$, $C_{104}$ was raised to exponent $b = 0.50$ and to make compatible $C_{109} = C_{104} / C_{104}^{0.50}$ and $\mu$ or $q_t$ as a power function, $\mu$ 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 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 $\mu$ varies from 19 to 46, for compressive and tensile specimens.

One can observe in Figure 4 the 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) using 7, 14, and 28 days as curing time periods. Figure 4 shows an increase in $q_t$ and $q_s$ when curing time increases. Porosity/cement index controlling $q_t$ and $q_s$ values depending on a power function (with $R^2$ between 0.90 and 0.96– Figure 4). Optimum compaction conditions are controlling by $\mu$ ratio (raised to 0.50 and -2.27 exponents). For specimens compacted on optimum points of compaction curve, the amount of $\mu$ varies from 16 to 42 for compression and tensile. Excellent relationships between compression-$\mu$ and tensile-$\mu$ 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: $q_t \propto q_s = A_t \left[ \eta / C_{iv}^{0.50} \right]^{-c}$, where $A_t$ is a constant expressed in kPa. The $A_t$ 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 $A_t$ 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 $A_t$ 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 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 days curing time.

**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 days curing time.

**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.
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 ($n_{cs}$), 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.

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 (Ca(OH)$_2$) 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 5.** Normalization of UCS and STS depending on curing time periods and molding moisture content.

**Figure 6.** Influence of porosity/cement index ($\eta/C_{w}^{0.50}$) 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.

**Figure 7.** Influence of porosity/cement index ($\eta/C_{w}^{0.50}$) 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 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.
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 at $\omega = 25\%$, 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 $\omega$, 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 $\omega$ 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.

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 $q_4$ and $q_5$ as a function of $\eta/C_{iv}^{0.50}$ can be divided by the same value of $10^{\frac{3}{2}} \eta/C_{iv}^{0.50}$, ensuring, thus, a constant calculated to its corresponding value of molding moisture or curing time, both for $q_4$ and $q_5$. Therefore, if it is correlated to its respective moisture/curing time with its normalized constant $q_4$ divided by $10^{\frac{3}{2}} \eta/C_{iv}^{0.50}$ or $q_5$ divided by $10^{\frac{3}{2}} \eta/C_{iv}^{0.50}$, a point in the Cartesian plane is found. In this way, the variation of normalized $q_4$ and $q_5$ depends on the moisture content or $t$ (curing time) (see Figure 5). Figure 5 shows that the

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**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/m$^3$) 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.

**Figure 11.** Normalization of $q_4$ and $q_5$ (for the whole range of $\eta/C_{iv}^{0.50}$) by dividing for $q_4$ and $q_5$ 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.
prime parameter controlling UCS and STS after $\eta / C_w^{0.50}$ 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:

$$q_u = (0.0022\omega^3 - 0.215\omega^3 + 6.83\omega^3 - 78.2\omega + 409.22) \times 10^{-1} \left[ \frac{\eta}{C_w^{0.50}} \right]^{-2.27} \quad (R^2 = 0.96) \quad (1)$$

$$q_t = (0.0003\omega^4 - 0.035\omega^3 + 1.29\omega^3 - 17.35\omega + 94.02) \times 10^{-1} \left[ \frac{\eta}{C_w^{0.50}} \right]^{-2.27} \quad (R^2 = 0.96) \quad (2)$$

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:

$$q_u = 793.8 \times 10^{-0.30} \times 10^4 \left[ \frac{\eta}{C_w^{0.50}} \right]^{-2.27} \quad (R^2 = 0.97) \quad (3)$$

$$q_t = 956 \times 10^{-0.39} \times 10^4 \left[ \frac{\eta}{C_w^{0.50}} \right]^{-2.27} \quad (R^2 = 0.96) \quad (4)$$

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 $\eta/C_w$ 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, $\eta/C_w$ 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 $A_t$ 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/m$^3$ 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/m$^3$ and $\omega = 15\%$) expected to be the most durable blend, but Figure 9 demonstrates the opposite, decreasing $\gamma_d$ to 15 kN/m$^3$ and increasing $\omega$ 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/m$^3$) or 7 % (with $\gamma_d = 14$ kN/m$^3$) 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 $\alpha = 25\%$ 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 $A_\gamma$, $\eta/C_{iv}^{0.50}$, $R^2$, and mean absolute percentage error (MAPE, in %) of all the equations that control the resistance of the mixes depending on the molding moisture, curing time and climatic conditions. All equations depend on $\eta/C_{iv}^{0.50}$ index (independent of $\omega$, curing time, and W-D/F-T cycles). The value of $b = 0.50$ means that porosity ($\eta$) and voids in the soil-cement mixture exerts a more compelling influence on $q_u$ and $q_t$ than $C_{iv}$. For this reason, $A_\gamma$ value increases significantly. The exponent $b < 1$ indicates that the porosity ($\eta$) 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 $A_\gamma$ and $\eta/C_{iv}^{0.50}$ values presented in Table 6, it is possible to determine a normalized equation for all the silt-cement compacted blends as a function of $\eta$ 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 $q_u$ or $q_t = A_\gamma [\eta/C_{iv}^{b}]^{-c}$ 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 $\mu$ 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:

\[
\frac{q_u}{q_u (\eta/C_{iv}^{0.50} = 20)} \vee \frac{q_t}{q_t (\eta/C_{iv}^{0.50} = 20)} = 898(\eta/C_{iv}^{0.50})^{2.27}
\]

In general, 63% of soil-cement compacted blends 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 $q_u/q_{U\text{C,normalized}} = 0.48$) 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 $\gamma_d$ 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, $\eta/C_{iv}$ 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 Guabirotuba 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 $\eta/C_{iv}$ (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 $q_s$ and $q_e$ 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/m$^2$.

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List of symbols

- $D_{50}$: the mean particle diameter
- $D_{10}$: the effective size
- $C_{iv}$: 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
- $\gamma_d$: the dry unit weight
- $\eta$: the porosity
- $\omega$: the moisture content
- $\mu$: the value of a given adjusted porosity/cement
- $R^2$: the coefficient of determination
- $\sigma'$: the preconsolidation pressure of soil
- $C_v$: the coefficient of consolidation of soil
- $A_q$: empirical parameter

Baldovino et al., Soils and Rocks 43(4): 631-645 (2020)