Soils and Rocks

An International Journal of Geotechnical and Geoenvironmental Engineering

www.soilsandrocks.com

ISSN 1980-9743
ISSN-e 2675-5475

Unconfined compression strength of an artificially cemented aeolian dune sand of Natal/Brazil

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Article

Keywords
Unconfined compression
Cemented sand
Dune sand
Natal sand
Strength compression

Abstract

Soil behavior is influenced by the void ratio and bonds between grains. The aim of this study was to describe the strength behavior of an aeolian sand from the dunes of Natal, Brazil, artificially cemented in unconfined compression tests. The influence of cement content and moisture on molding and the validity of using the void/cement factor in estimating unconfined compression strength (UCS) were assessed. Tests were conducted with samples using three molding moisture contents (6, 9 and 12%), four cement contents (2.5, 5.0, 7.5 and 10%) and a void ratio of 0.6 (D_r = 95%). The results showed that unconfined compression strength rises with increase in cement content and decreasing in molding moisture. The void/cement factor proved to be a reliable parameter in predicting the behavior of sand from Natal for the dosage of soil cement.

1. Introduction

Mixing cemented agents with soil is a traditional soil enhancement technique that has been used for highway paving, foundations, retaining walls and to prevent liquefaction. In recent decades, a number of studies have been conducted to understand the behavior of cemented soil (in which the grains are held together by a chemical agent) (Saxena & Lastrico, 1978; Clough et al., 1979, 1981; Acar & El-Thair, 1986; Das et al., 1995; Schnaid et al., 2001; Haeri et al., 2005). Studies demonstrate that an increase in cement content causes a rise in strength and stiffness of the mixture.

Consoli et al. (2007) studied the influence of cement content, porosity and molding moisture on the compression strength of cemented soil and found that compression strength increases with cement content and exponentially as porosity declines, thereby obtaining a correlation between strength and the void-volumetric cement content ratio. Based on these findings, Consoli et al. (2007) proposed a rational method to determine the cement content and porosity necessary to obtain a given strength. According to Consoli et al. (2007), strength is a function of the η/C_{iv} ratio, with the volumetric cement content adjusted by an exponent x.

Several studies have assessed the validity of using the void/cement factor to estimate the strength of soil-cement mixtures. According to Cruz (2008), studies with sand from Osorio, Rio Grande do Sul state (RS) show that the void/cement factor is an effective and reliable parameter for predicting the behavior of the material according to the dosage of cemented soil in geotechnical projects. Similar results were obtained by Severo (2011) for lateritic soils from the Barreiras Formation on the coast of Rio Grande do Norte state (RN). What differed from one result to another was the value of the adjustment coefficient (x). Rios et al. (2013) showed that parameter x depends on the grain size and mineralogy of the soil.

Baldovino et al. (2018) studied the treatment of the Guabirotuba geological formation soil (Paraná Basin, Brazil) by lime addition for improve its usability in pavement construction, in protection of hillsides and slopes, or as shallow foundation support. It was observed that the q_t/q_u ratio is between 0.17 and 0.2 in relation to the curing time, and an exponential relation exists between them. Baldovino et al. (2020b) optimized and compared the behavior of soil-cement compacted blends against several molding and climate conditions under optimum compaction and non-optimum compaction parameters. The results show an increase in strength and durability properties of the blends when cement

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Submitted on April 6, 2020; Final Acceptance on January 27, 2021; Discussion open until May 31, 2021.

DOI: https://doi.org/10.28927/SR.2021.049920

is added and reasonable dosages employing η/C_{iv} index to stabilize the soil were presented considering the strength and the durability parameters.

Baldovino et al. (2020a) evaluates the development of splitting tensile strength (q_t) and unconfined compressive strength (q_u) of two silty soils artificially cemented over 28 days. The results show an increase of the mechanical resistance with the increase of the cement content and with the decrease of the voids. A dosing equation for q_u and q_t of the soils studied and mixed with cement was developed using the η/C_{iv} ratio adjusted to an exponent 0,44 to make η/C_{iv} - q_u and η/C_{iv} - q_t variation rates compatible. The dosage equations obtained coefficients of determination above 94%.

Given this approach, the present study aimed to describe the strength behavior of a cemented sand and assess the influence of molding moisture content on the strength of the sand-cement mixture. This study used Aeolian sand sediments that form dunes, situated on the campus of the Federal University of Rio Grande do Norte (UFRN).

2. Materials and methods

2.1 Materials

The sand used here originated in dune sediments from the Dunes Park of Natal, a dune field on the coast of Natal, with an average width of 1.5 km and length of 9 km. Nearby is the Federal University of Rio Grande do Norte, where the samples were collected. This soil accounts for most of the subsoil of the city of Natal.

According to Jesus (2002), the geology of the area is essentially formed by materials of sedimentary origin, like the entire city of Natal. In Dunes Park it is possible to observe the outcrop of sediments from aeolian dunes field, study material of this work. These sediments are made up of quartzous sands, with grains sub-rounded to sub-angular, poorly selected, with a solid aspect.

The soil grain size distribution curve is presented in Figure 1 and the physical indices in Table 1. The soil is composed of approximately 72% medium sand and 4% fine grains. According to grain size analysis, this material can be classified (ASTM, 2006a) as a uniform, poorly graded medium-grained sand (SP).

High early-strength Portland cement (Type III) was used as cementing agent (ASTM, 2009). Portland cement was selected because it was used in previous studies (Consoli et al., 2007, 2012a, b; Cruz, 2008; Cruz & Consoli, 2010; Severo, 2011; Rios et al., 2013).

In geotechnics, the void ratio (e) is one of the most important parameters for expressing the engineering behavior of soils (Monkul, 2005). Çellek (2019) investigated the linear relationship between e_{max} and e_{min}. considering 3 types of clean marine sand. Figure 2 shows the line describing this relationship between e_{max} and e_{min}. Plotting on the chart the point referring to the sand of Natal dune, it is clear that it is consistent with the studies of Çelek (2019).

2.2 Experimental program and test methods

Unconfined compression tests were conducted for 3 molding moisture (6, 9 and 12%) and 4 cement contents (2.5%, 5.0%, 7.5% and 10.0%). The 0.6 void ratio used was near the minimum value.

The cement content values adopted are within the range reported in the literature. Consoli et al. (2007) used percentages between 1 and 7%; Cruz (2008) between 1 and 12%; Consoli et al. (2012a) between 3 and 9% and Severo (2011) between 2 and 5%. The moisture content values studied

Table 1. Physical indices for sand from Natal.

Specific gravity	2.62
Coefficient of Uniformity C_u	1.861
Coefficient of Curvature C_c	0.971
Effective Diameter, D_{10}	0.153
Mean Diameter, D_{50}	0.25
Minimum Void Ratio e_{min}	0.59
Maximum Void Ratio e_{max}	0.80

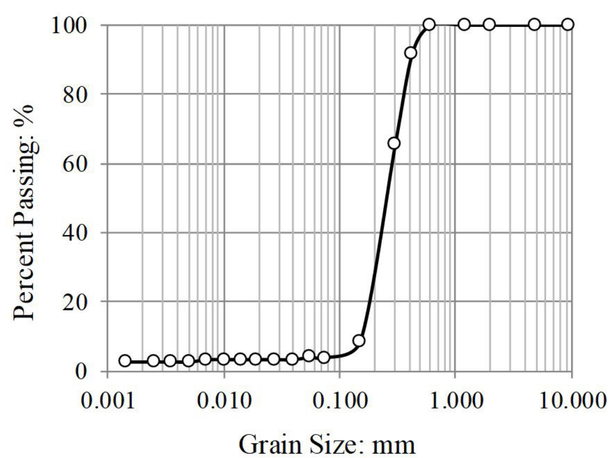

Figure 1. Grain size distribution curve.

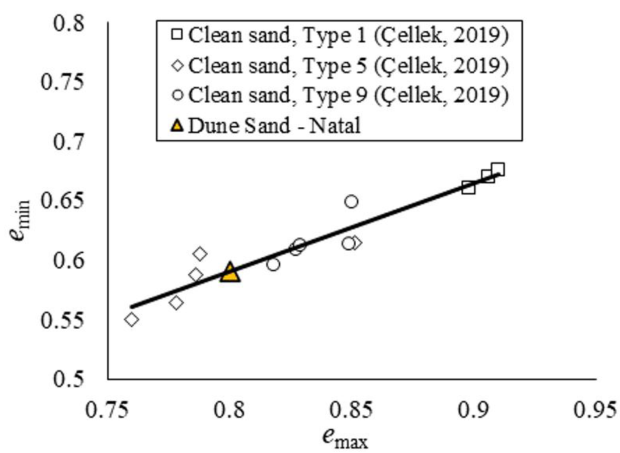

Figure 2. Relationship between e_{min} and e_{max} for marine sands (Çellek, 2019) and Natal Dune Sand.

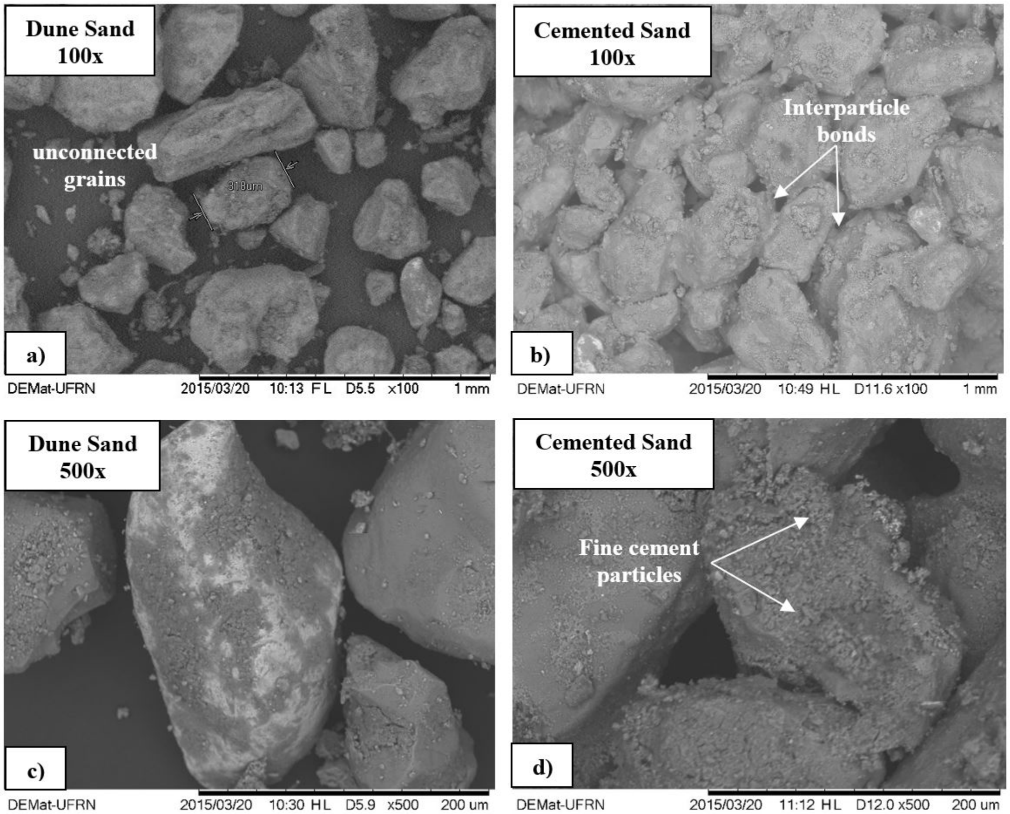

Figure 3. (a) Dune sand grains, - 100x magnification; (b) Cemented sand - 100x magnification; (c) Dune sand - 500x magnification grains; (d) cemented sand - 500x magnification.

were within the range used by Consoli et al. (2007), between 4 and 13.4%, and Consoli et al. (2012b), between 6 and 14%.

The cement and molding moisture used contributed to form interparticle bonds, making the soil structured by cementation. According to Prietto (2004), the structure provides the soil, when it is compared to the same material in the reconstituted (unstructured) state, with significantly superior strength and stiffness. This aspect is illustrated in Figure 3, where can be seen scanning electron microscopy (SEM) images of the dune sand sample and the cemented sand sample. As shown in Figure 3a and 3b, there is no interparticle bonds in the dune sand grains of Natal. When cement and water are added, as shown in Figure 3c and 3d, there is a connection between the grains of sand that are surrounded by fine cement particles.

2.2.1 Test specimen molding and curing

For all the tests, the samples were molded with a diameter of approximately 50 ± 1 mm and height of 100 ± 5 mm. The mixtures were prepared with the required amounts of sand, distilled water and cement, in order to reach the percentage of cement, moisture content and void ratio established for each sample. The soil-cement-water mixtures were compacted into a tripartite cylindrical mold. The samples were compacted into four layers, aimed at reaching the void ratio specified for each sample. Three test specimens were molded for each test condition.

After molding, the samples were cured for 30 days. During curing, the samples remained in conditions of high humidity in a humid box with a bottom covered with saturated sand to avoid premature evaporation of the water necessary for the hydration of the cement. The samples were cured for 30 days to ensure that the specimens reached the maximum possible strength.

2.2.2 Unconfined compression strength tests

The unconfined compression tests followed the procedures described in NBR 12025 (ABNT, 2012a), which is equivalent to ASTM D 2166-06 (ASTM, 2006b). For these tests, the strain rate applied in the tests was 1 mm/min.

After 30 days' curing, the test specimens were submerged in water for 4 hours before the test, in line with NBR 12025 (ABNT, 2012a). Just before the test, the test specimens were removed from the water and superficially dried with an absorbent fabric.

The eligibility criterion adopted for the unconfined compression strength test was that recommended by NBR 12253 (ABNT, 2012b). As such, the individual strengths of the three identical specimens could not be more than 10% different from their average. Thus, in the present study, in which 36 unconfined compression tests were performed, 30 tests that met the eligibility criterion will be presented.

3. Results and analyses

This section presents the results of the unconfined compression tests specified in the previous item. Figures 4 to 10 show the graphs obtained in the tests. The graphs show unconfined compression strength as a function of the cement content, molding moisture and void/cement ratio.

3.1 Effect of cement and molding moisture content

Figure 4 presents the results of the unconfined compression strength of the samples as a function of molding moisture content.

Unconfined compression strength increases with an increasing in cement content, for the three moisture contents analyzed. For the lowest cement content (2.5%), molding moisture content has little influence on unconfined compression strength. Thus, the higher the cement content, the greater the influence of molding moisture content. All the fitted curves exhibited similar shape, and all coefficients of determination (R^2) were above 0.97 (see the equations in Figure 4). This beneficial effect from an increase in cementation was reported by Consoli et al. (2009).

Figure 5 presents the results of the unconfined compression strength as a function of molding moisture content, for the samples with different cement content. An increase in strength with a decline in molding moisture content was observed. This graph also demonstrated the minor influence that molding moisture content exerts on samples with low cement content, compared to their counterparts with higher levels (7.5 and 10%). All the fitted curves exhibited coefficients of determination (R^2) above 0.87 (see the equations in Figure 5).

3.2 Effect of the water/cement ratio

The data illustrated in Figure 5 for cement contents of 2.5 to 10% were used to construct Figure 6, which shows unconfined compression strength as a function of the water/cement (w/C_i) ratio (defined as the weight of the water divided by the weight of the cement). A relationship can be established between these two factors, and compression strength rises with a decline in the w/C_i ratio. This relationship was reported by Horpibulsuk et al. (2003), in which the water/cement ratio was a useful parameter for analyzing the strength of materials, as occurs in concrete, where the amount of water once again reflects the amount of voids in mixture.

3.3 Effect of the void-cement ratio

Figure 7 presents unconfined compression strength as a function of the void/cement ratio, defined by the following equation:

$$\frac{V_v}{V_{ci}} = \frac{Void\ volume}{Cement\ volume} \qquad (1)$$

The data exhibited in Figure 7 shows a correlation between this ratio and the unconfined compression strength (q_u) of the soil-cement mixture studied, whereby the larger the V_v/V_{ci}, the lower the sample strength, because the higher the void space. In addition, the larger this ratio, the smaller the effect of molding moisture content. This is probably because as the void volume becomes significantly greater

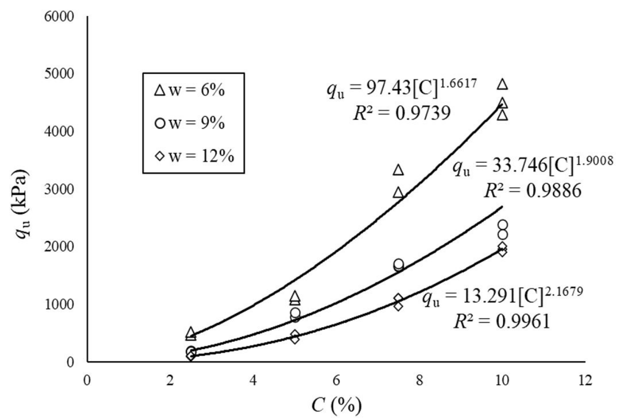

Figure 4. Variation in unconfined compression strength with cement content.

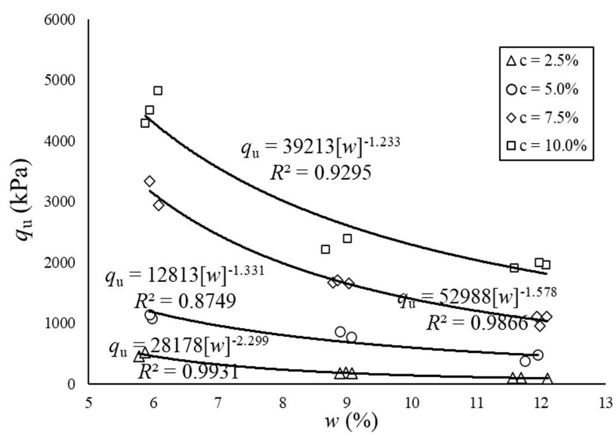

Figure 5. Effect of molding moisture content on unconfined compression strength.

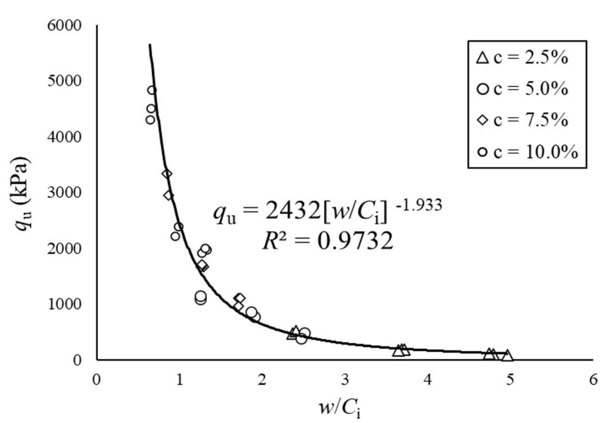

Figure 6. Variation in unconfined compression strength with the water/cement ratio.

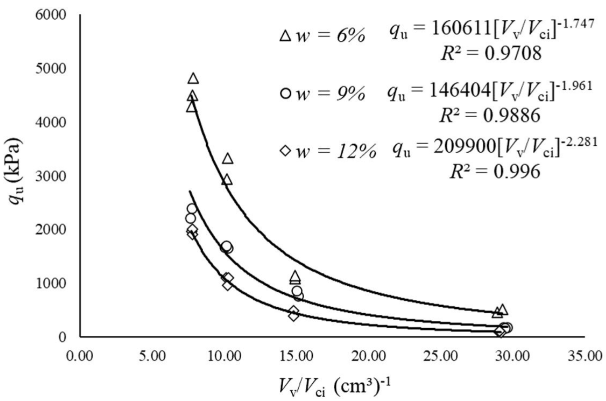

Figure 7. Variation in unconfined compression strength with the void volume/cement volume ratio.

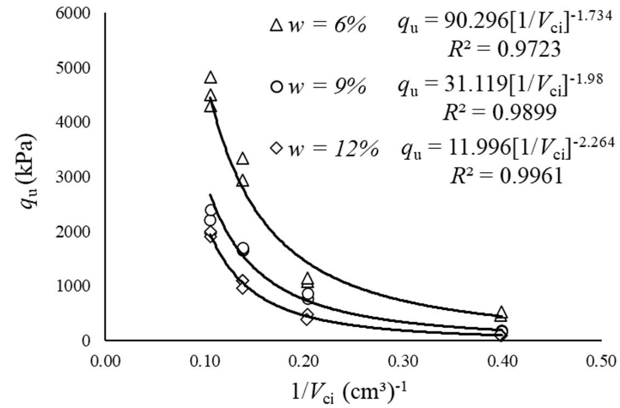

Figure 8. Relationship between inverse cement volume and unconfined compression strength

than the volume of cement becomes more difficult to form the bonds between the particles of cement, water and soil. This behavior was different from that reported by Consoli et al. (2009), who found no correlation between these parameters.

Figure 8 graphically presents the unconfined compression strength variation with an inverse cement volume for the moisture contents studied. The influence of V_v/V_{ci} and $1/V_{ci}$ ratios on strength was found to be very similar. This exponential growth of strength with a decline in the inverse ratio of cement volume was reported by Consoli et al. (2009).

Figure 9 shows unconfined compression strength as a function of the void/cement ratio, defined by the ratio (η/C_{iv}) between the porosity of the compacted mixture (η) and volumetric cement content (C_{iv}) for the three molding moisture contents used in the mixtures and different cement contents applied. Figure 9 shows the influence of the η/C_{iv} factor and moisture content on the unconfined compression strength of the artificially cemented sand. It can be concluded that the higher the void/cement ratio (η/C_{iv}), the lower the unconfined compression strength. Additionally, the lower the molding moisture content, the higher the strength, considering the molding moisture content between 6 and 12% studied here.

The void/cement factor, defined by the η/C_{iv} ratio, adjusted by an exponent ($\eta/(C_{iv})^{\xi}$), has proved to be adequate in assessing unconfined compression and triaxial shear strength for previously studied soils (Consoli et al., 2007). Figure 9 shows that the exponent to which the curve best fits was equal to 1. This fitted exponent (ξ) is bigger than that of the finer soil grains previously studied, and compatible with the fine sand content of the samples. Table 2 presents the exponent values (ξ) for some of the soils previously studied which corroborates the relationship between grain size and the cement void ratio.

Figure 10 shows the comparison of the unconfined compression strength versus void/cement ratio curves for the Natal Dune Sand and the Osório Sand (Consoli et al., 2011). According to Consoli et al. (2011), the exponent that adjusts the curve increases with the increase in the particle

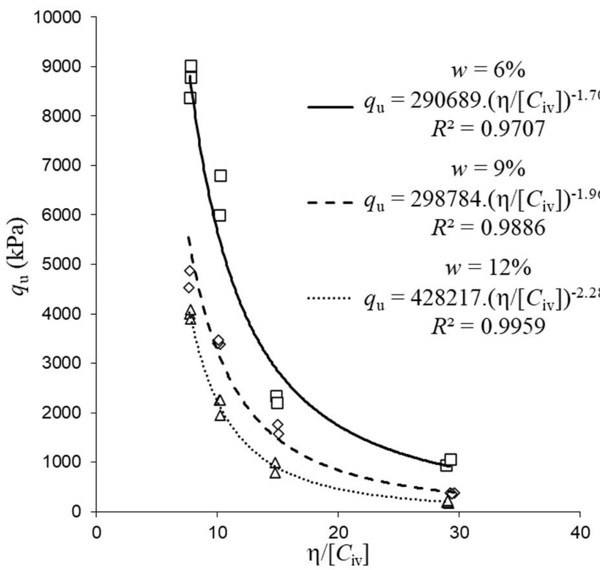

Figure 9. Variation in unconfined compression strength with the adjusted void/cement ratio.

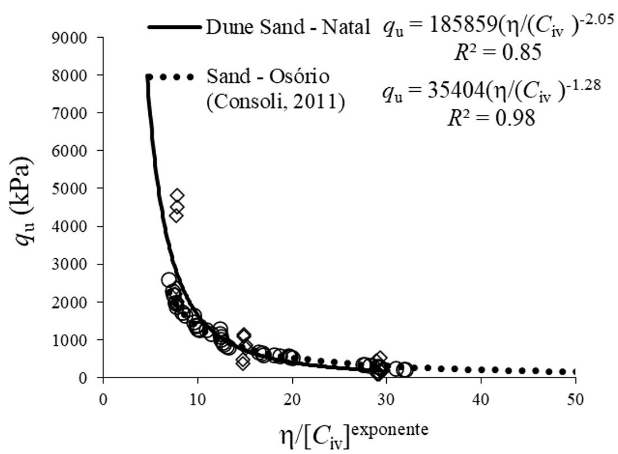

Figure 10. Variation in unconfined compression strength with the adjusted void/cement ratio for the Dune Natal Sand and Osório Sand (Consoli et al., 2011).

Table 2. Exponent values (ξ) of previously studied soils.

Type of soil (USCS)	Fine grains content (%)	Exponent value (ξ) $\eta/(C_{iv})^{\xi}$	Reference
Clayey sand (SC)- Porto Alegre, RS	41	0.28	Consoli et al. (2007)
Fine sand (SP) Osorio, RS	2	1.00	Consoli et al. (2011)
Clayey sand (SC) Ponta do Pirambu, RN	40	0.60	Severo (2011)
Silty sand (SM) Porto, Portugal	32	0.21	Rios et al. (2013)
Yellow and purple silt (MH) Guabirotuba Formation of Curitiba/Brazil	65-67	0.44	Baldovino et al. (2020a)
Aeolian Dune sand (SP) Natal, RN	4	1.00	The present study

size of the material. However, the same exponent was found for both sands and the curves almost intercept.

4. Final considerations

The behavior of the artificially cemented sand from the dunes of Natal depends on the void ratio, cement percentage and molding moisture content.

Unconfined compression strength increases with an increasing in the amount of cement and a decline in molding moisture content for all the samples studied. For the lowest cement content (2.5%), molding moisture content had little influence on unconfined compression strength. Thus, the higher the cement content, the greater the influence of molding moisture content, and the higher the inverse ratio of cement volume, the lower the strength of the samples. It was also found that the higher the inverse ratio of cement volume, the lower the effect of molding moisture content.

Analysis of the void/cement factor reveals that the higher the void/cement ratio (η/C_{iv}), the lower the unconfined compression strength. The fitted exponent of the q_u x η/C_{iv} curve for the sand of Natal is equal to 1. Thus, the void/cement ratio and the water/cement factor are good dosage parameters for mixtures cement- dune sands. Artificially cemented sand can be used below of shallow foundations for improvement the bearing capacity and as backfill in retaining wall, as pure dune sand is not good material for these applications. The results obtained in this work can be useful for the definition of the cement content and the compaction energy to be used to improve the Natal sand.

Acknowledgements

The authors are grateful to FAPERN (Research Support Foundation of Rio Grande do Norte State), CAPES (Coordination of Improvement of Higher Education Personnel) and CNPq (National Council for Scientific and Technological Development) for funding this study.

Declaration of interest

The authors declare the absence of conflicting interests.

Author's contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Tahyara Barbalho Fontoura, Olavo Francisco dos Santos Junior, Ricardo Nascimento Flores Severo, Roberto Quental Coutinho and Paulo Leite de Souza Junior. The first draft of the manuscript was written by Tahyara Barbalho Fontoura and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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List of symbols

D_{50}: mean grain size
D_{10}: effective grain size
C: cement content
C_i: weight of the cement
C_u: uniformity coefficient
C_c: curvature coefficient
e_{min}: minimum void ratio
e_{max}: maximum void ratio
e: void ratio
q_u: unconfined compression strength
q_t: tensile strength
R_2: coefficient of determination
D_r: degree of compactness
η_{civ}: porosity of mixture
C_{iv}: volumetric cement content
V_v: void volume
V_{ci}: cement volume
w: moisture content
x: adjusted exponent