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Dosage method for unconfined strength and fatigue life of fiber-reinforced cement-treated sand

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Technical Note

Keywords
Polypropylene fibers
Portland cement
Soil-cement
Fatigue life
Rational dosage methodology

Abstract
Fiber-reinforcement has been reported as an effective and cost-attractive technique to improve the mechanical behavior of cemented soils. However, the dosage methodologies for these mixtures are still limited, especially regarding dynamic loading. The objective of this research was to analyze the dynamic response and strength behavior of fiber-reinforced cement-treated sand. In this sense, fatigue life, unconfined compressive strength, and split tensile strength tests were conducted. Results indicated that the mechanical behavior of the soil-cement mixtures was governed by fiber content, cement content and void ratio. The presence of fibers, the increase in cement content and the decrease in void ratio improved the overall mechanical behavior of all specimens. The porosity/cement content index resulted in a viable dosage method to predict both the monotonic and cyclic behavior of the mixtures. Lastly, the statistical analysis of variance corroborated the experimentally observed findings.

1. Introduction

Fiber-reinforcement and Portland cement stabilization have been widely utilized to improve the engineering properties of soils structures, such as embankments (Bieliatynskyi et al., 2021; Zhao et al., 2021) and subgrade stabilization for footings (Nasr, 2014), pavements (Li et al., 2022; Ozturk & Ozyurt, 2022), earth dams (Sangma & Tripura, 2020), and barriers for landfills and containment pounds (Mukherjee & Kumar Mishra, 2021). Cement addition increases strength and stiffness of the soils (Bruschi et al., 2022; Bruschi, Santos, Ferrazzo, et al., 2023; Queiróz et al., 2022; Quiñónez Samaniego et al., 2021); however, it also increases brittleness, leading the enhanced soil to fail in a brittle way (Consoli et al., 2007, 2021a). On the other hand, fiber addition increases the ductility and durability of the reinforced soil without compromising the strength of the composite (Festugato et al., 2017). The addition of fibers to cemented soils has been reported as an effective and cost attractive technique to increase the mechanical characteristics such as strength, ductility, and post-rupture bearing capacity (Chen et al., 2015; Consoli et al., 2009a, 2009b, 2011a). Even though fiber-reinforcement has been proved effective, dosage methodologies for these mixtures are still limited.

Consoli et al. (2010) created the first rational dosage methodology for fiber-reinforced cemented soil, considering the porosity/cement content ratio (η/Civ), as an appropriate parameter to evaluate the unconfined compressive strength (*qu*). Later, Consoli et al. (2013) quantified the influence of the amount of cement, the porosity and the porosity/cement ratio in the assessment on tensile strength (*qt*) and compressive strength (*qu*) of fiber-reinforced artificially cemented sand, as well as in the changes of *qt*/*qu* relationships and particular increases in *qt* and *qu* due to fiber insertion. Festugato et al. (2017) studied a dosage methodology based on the tensile and compressive strength of fiber-reinforced cemented soils, considering the fiber length. Authors indicated that the length of the filaments and the porosity/cement ratio are key parameters in the evaluation of the tensile strength and the compressive strength of the mixture studied. For each fiber length, there is a linear proportionality between the tensile and compressive strength, being independent of the porosity/cement ratio. As a consequence, rational dosing methodologies can be centered on tensile or compression tests on reinforced or unreinforced samples.

Despite these extensive findings, most of the experimental work regarding the mechanical behavior of fiber-reinforced cemented soils and their dosage methodologies entails exclusively the analysis of these composites under monotonic/static loading. The porosity/cement content ratio (η/Civ) dosage framework has recently started to be investigated for mixtures under dynamic loading. Festugato et al. (2021) studied mixtures of unreinforced cemented sand and showed such ratio was able to assess resilient modulus and fatigue life. Piuzzi et al. (2021) observed the porosity/cement ratio could be used for the assessment of asphalt concrete mixtures mechanical behavior under cyclic loading.

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However, the use of η/Civ has not yet been investigated for the study of fiber reinforced cement mixtures behavior under not monotonic loading. Dynamic loading is especially important on pavement design, reinforcement of areas susceptible to earthquakes, foundations of coastal structures, and even wind turbines. Pavements design, for instance, usually considers the fatigue life of the subgrade constituent materials. Fatigue is the process of localized progressive permanent structural change which occurs in a point of the material subjected to stresses of variable amplitude, below the ultimate strength of the material, that causes cracks that lead to failure after a certain number of cycles (ASTM, 2013).

In this sense, the objective of this research was to analyze dynamic response and strength behavior of fiber-reinforced cement-treated sand. To that extent, fatigue life, unconfined compressive strength, and split tensile strength tests were conducted on fiber-reinforced and non-reinforced cemented mixtures. In addition, all results were correlated with the porosity/cement content index to create a rational dosage methodology for the stabilized mixtures.

2. Materials and methods

2.1 Materials

The soil utilized in this research was a clean sand, known as Osorio sand (*OS*). The material was collected nearby Porto Alegre, in southern Brazil. *OS* was classified as a poorly graded sand (*SP*) in accordance with the Unified Soil Classification System (*USCS*) (ASTM, 2020) with a specific weight of grains of 2.65 g/cm^3 [D854 (ASTM, 2014)]. This sand is composed of approximately 99.5% quartz (Consoli et al., 2009a). For the cementing agent, high initial strength Portland cement (type III) was utilized, with a specific weight of grains of 3.15 g/cm^3. This cement was selected considering its high capacity of generating considerable strength over short periods of time. Regarding the fiber-reinforcement, monofilament polypropylene fibers were applied. These fibers presented average dimensions of 50 mm length and 0.1 mm diameter, with a specific weight of grains of 0.91 g/cm^3, elastic modulus of 3 GPa, tensile strength of 120 MPa, and strain failure of 80%. The materials physical properties are summarized in Table 1, while Figure 1 shows the grain size distribution.

2.2 Molding and curing procedures

For unconfined compressive strength and split tensile strength tests, triplicates of specimens of 10 cm diameter and 20 cm in height were utilized. As for fatigue life tests, duplicates of cylindrical specimens of 10 cm in diameter and 5 cm in height were applied. The cement addition was 1, 2, 3, 5, and 7%, in accordance with the indications of the Portland Cement Association (PCA, 1992) and previous studies (Consoli et al., 2020; Consoli & Tomasi, 2018). The fiber addition was 0.5% for all samples. Previous studies shown the increase of fiber content improves materials mechanical behavior up to a limit, from which mixing and compaction processes become not effective and reinforcement benefits are negatively affected. For the studied polypropylene fibers, considering mixture preparation and compaction, an optimum value of 0.5% observed (e.g. Festugato et al., 2018, 2021). To explore a wide range of porosities and its effect on the mechanical properties, three void ratios were also selected (0.64, 0.70, and 0.78) based on Proctor compaction tests under standard energy (ASTM, 2021). All specimens were molded with the 9% optimum moisture content from the compaction tests. The fiber reinforced compacted cemented soil specimens were prepared by hand-mixing, in this order, dry soil, cement, water and polypropylene fibers. It was found important to add water prior the addition of fibers to prevent their floating. The quantity of fibers for each mixture was calculated by the mass of dry soil plus cement.

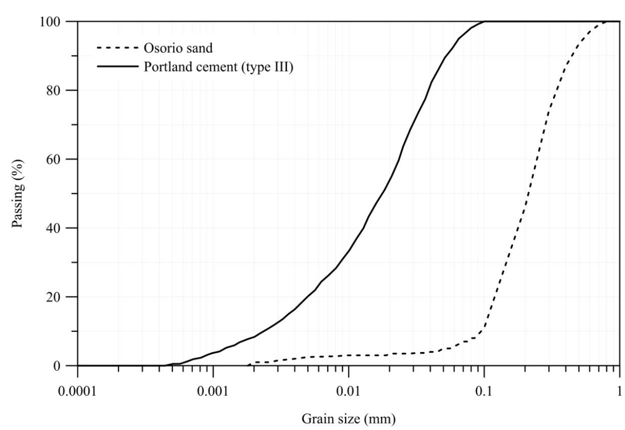

Figure 1. Grain size distribution.

Table 1. Materials physical properties.

Properties	Osorio Sand	Portland cement	Polypropylene fiber
Mineralogy	Quartz	-	-
Specific unit weight of grains (g.cm^{-3})	2.65	3.15	0.91
Medium sand (%)	33	-	-
Fine sand (%)	67	-	-
USCS classification (ASTM, 2020)	SP	-	-

Visual and microscope examination of exhumed specimens showed the mixtures to be satisfactorily uniform. The molding procedures followed the undercompaction method proposed by Ladd (1978). After confection specimens were measured and stored at 23 ± 2°C and 95 ± 2% controlled moisture for 7 days curing. The acceptance criteria were as follows: degree of compaction between 99% and 101%; water content within 0.5% of the target value; diameter within 0.5 mm of the target value; and height within 1 mm of the target value. Figure 2 depicts the aspect of a prepared specimen after fatigue life testing.

2.3 Unconfined compressive strength (*qu*)

Unconfined compression strength (*qu*) tests were conducted in accordance with the procedures of ASTM D2166 (ASTM, 2016), with an automatic loading machine (50 kN load capacity and 1.14mm/min displacement rate).

2.4 Split tensile strength (*qt*)

Split tensile strength tests (*qt*) tests were conducted in accordance with the procedures of ASTM D6931 (ASTM, 2017); performed in an automatic loading machine with a maximum load capacity of 50 kN, with a ring of 10 kN load capacity and resolution of 0.005 kN.

2.5 Fatigue life (*Nf*)

Fatigue life tests were conducted in accordance with the procedures of BS EN 12697-24 (BSI, 2016). The cyclic load (haversine-shaped pulse of 2 Hz) was applied with a pneumatic load machine. The magnitude of the applied load was 90% of the specimens' tensile strength. A 10 kN loading cell with a resolution of 0.0001 kN was employed to measure the applied load. In addition, two linear variable differential transformers (*LVDT*) located on the opposite side of the specimens, were responsible to measure radial displacements with a resolution of 0.001 mm.

2.6 Porosity/cement content index (η/Civ)

Resilient modulus, split tensile strength, and durability results were also expressed in function of the porosity/cement index proposed by Consoli et al. (2007) and defined by Equations 1 and 2.

$$\eta = 100 - 100\left\{\left[\frac{\gamma_d}{\frac{OS}{100}+\frac{F}{100}}\right]\left[\frac{\frac{OS}{100}}{\gamma_{s_{OS}}}+\frac{\frac{F}{100}}{\gamma_{s_F}}\right]\right\} \tag{1}$$

$$Civ = \frac{V_C}{V} = \frac{m_C / \gamma_{s_C}}{V} \tag{2}$$

Porosity (η) is a function of the dry unit weight (γ_d) and unit weight of solids (γs_{OS} and γs_F) of the Osorio sand (*OS*) and the fibers (*F*). The cement content (*Civ*) results from the volume occupied by Portland cement (*PC)* divided by the total volume of the sample. This index allows the unification of all experiments in a single relation, resulting in a rational dosage methodology for cemented soil mixtures. However, such equations are valid for the cemented mixtures studied herein and are only functional if the boundary conditions of the applied variables are ensured.

3. Results and discussion

3.1 Unconfined compressive strength (*qu*)

The unconfined compressive strength results are presented in Figure 3. The data was presented as a function of the porosity/cement content index (η/Civ).

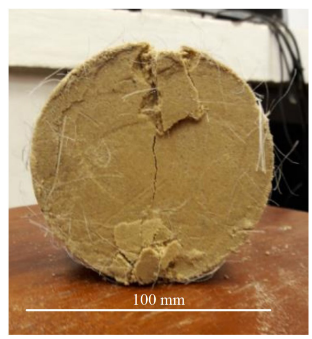

Figure 2. Typical aspect of tested specimen.

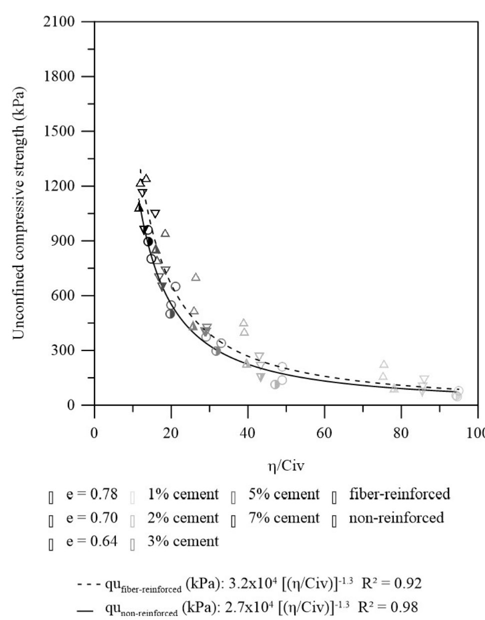

Figure 3. Unconfined compressive strength.

For all studied combinations, the increase in cement content and decrease in porosity (lower η/Civ values) resulted in higher *qu*. Cement content presented a considerable effect on *qu*, for both unreinforced and fiber-reinforced specimens. The increase in cement content (1% to 2% and latter to 3%, 5% and 7%) also increased the hydrated products of the mixture, contributing to the further development of a stiffer soil-cement matrix and, consequently, an increase in strength (Consoli et al., 2007, 2011b; Festugato et al., 2018); a small addition of cement was enough to generate significant gains in strength. Regarding the porosity effect, the reduction in mixtures void ratio resulted in an increase in the rate of *qu* gain with cement content (Carvalho Queiróz et al., 2022; Pereira dos Santos et al., 2022; Queiróz et al., 2022). At lower porosities the contact area between particles is enlarged, enhancing the interlocking phenomenon and friction mobilization resulting in an increase in strength, and so the effectiveness of the cement and the fibers is greater (Festugato et al., 2017). This physical-chemical phenomenon has also been evidenced in different cemented geotechnical materials (Bruschi et al., 2021; Carvalho Queiróz et al., 2022; Pereira dos Santos et al., 2022; Quiñónez Samaniego et al., 2021; Silva et al., 2022; Tonini de Araújo et al., 2021; Bruschi et al., 2023).

When comparing non-reinforced and fiber-reinforced specimens, the average *qu* of reinforced specimens was 18% higher than non-reinforced ones, indicating that fiber addition contributed for strength development. Consoli et al. (2009b) claim that the efficiency of fiber reinforcement is governed by several factors, such as: fiber content, orientation, geometry, mechanical characteristics, and properties of the soil such as grading, mineralogy, and grain shape. Fiber reinforcement in cemented soils is only effective when the fiber length is large when compared to the grain size of the soil (Michalowski, 2008; Michalowski & Čermák, 2003). Furthermore, Festugato et al. (2017) indicated that an increase of fiber reinforcement length directly improves the strength of cemented soils.

Fair correlations were identified between the η/Civ index and *qu*, as shown by Equations 3 and 4. For the non-reinforced mixtures the determination coefficient (R^2) was 0.98, while for the reinforced ones the coefficient was 0.92. This suggests that through these equations it becomes possible to predict the *qu* of the fiber-reinforced cement-treated mixtures over a wide range of porosities and cement contents, avoiding unnecessary testing on practical soil-cement applications. Furthermore, this index has also been shown to work on the prediction of *qu* in different fiber-reinforced cemented soils (Consoli et al., 2011a, 2017a; Mazhar & GuhaRay, 2021).

Unreinforced cemented mixture:

$$qu\ (\text{kPa}) = 2.7\times10^4\left[\left(\eta/_{Civ}\right)\right]^{-1.3} \qquad (3)$$

Fiber-reinforced cemented mixture:

$$qu\ (\text{kPa}) = 3.2\times10^4\left[\left(\eta/_{Civ}\right)\right]^{-1.3} \qquad (4)$$

3.2 Split tensile strength (*qt*)

Results of split tensile strength tests are presented in Figure 4. Once again, the data was expressed in function of the porosity/cement content index *(η/Civ)*.

As in the case of the compressive strength results, the decrease in the porosity/cement content index led to an increase in split tensile strength. The mechanism by which the reduction in porosity influences the soil-cement strength is again related to the existence of a larger contact area between particles of the cemented mixture, enhancing the interlocking phenomenon. As for the cement content, its increase enhances the cementitious reactions happening on the mixtures, contributing for strength development (Piuzzi et al., 2021).

The average *qt* of reinforced specimens was 20% higher than non-reinforced ones, indicating that fiber addition also contributed for split tensile strength development. Fiber-reinforcement seems to be more efficient for tensile strength than for compressive strength; similar findings were presented by Festugato et al. (2017), while studying the compressive and tensile strength of fiber-reinforced soils.

Adequate correlations between split tensile strength and η/Civ index were shown for all studied combinations. The determination coefficients (R^2) were 0.94 and 0.92 for the unreinforced and fiber-reinforced specimens, respectively, indicating the viability of the η/Civ index on the prediction of the split tensile strength for the analyzed conditions.

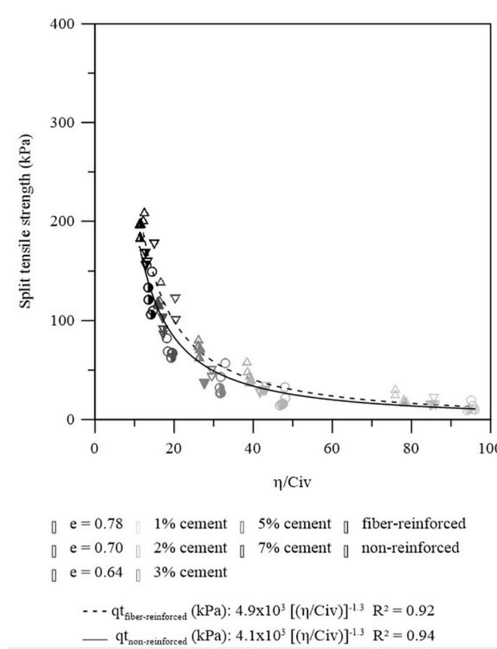

Figure 4. Split tensile strength.

This viability has also been proven for other cemented geotechnical materials (Consoli et al., 2016, 2017b, 2018, 2021b; Piuzzi et al., 2021).

Unreinforced cemented mixture:

$$qt\ (kPa) = 4.1 \times 10^3 \left[\left(\eta / Civ \right) \right]^{-1.3} \quad (5)$$

Fiber-reinforced cemented mixture:

$$qt\ (kPa) = 4.9 \times 10^3 \left[\left(\eta / Civ \right) \right]^{-1.3} \quad (6)$$

3.3 Fatigue life (*Nf*)

Fatigue life results are presented in Figure 5 also expressed in function of the porosity/cement content index *(η/Civ)*.

Analogous to the behavior evidenced for split tensile and compressive strength, a reduction in porosity and increase in cement content led to the improvement of fatigue life for both fiber-reinforced and non-reinforced specimens. This behavior is attributed to the greater friction mobilization and higher contact area between particles, as the porosity decreases and cement content increases. Similar trends have also been reported for fatigue life studies (Consoli et al., 2021c; Piuzzi et al., 2021).

Regarding the effect of fiber reinforcement, non-reinforced specimens resulted in average *Nf* values 78% lower than fiber reinforced ones. The cement addition increases strength of soil; however, it also increases brittleness, which leads to brittle-like failure. In opposition, fiber addition increases the ductility of the cemented soil, without considerably compromising its strength. In the case of this research, fiber addition enhanced the bridging effect between particles, playing a critical role in the initiation and extension of cracks. This effect can be related to the hydrophilic characteristics and surface roughness of the fibers (Consoli et al., 2012; Festugato et al., 2017). The inclusion of fibers was able to mitigate internal stresses in distinctive orientations, contributing for a more distributed stress field, thus avoiding local fractures.

Satisfactory correlations were identified for both non-reinforced and fiber reinforced specimens and the η/Civ index. For both the non-reinforced and fiber reinforced specimens, R^2 was 0.9. The elevated R^2 indicate the viability of the index in also predicting *Nf* of the cemented mixtures, providing a rational dosage methodology for a wide range of porosities and cement contents.

Unreinforced cemented mixture:

$$Nf\ (cycle) = 8.1 \times 10^5 \left[\left(\eta / Civ \right) \right]^{-1.9} \quad (7)$$

Fiber-reinforced cemented mixture:

$$Nf\ (cycle) = 5.1 \times 10^6 \left[\left(\eta / Civ \right) \right]^{-1.9} \quad (8)$$

3.4 Statistical analysis

Unconfined compressive strength, split tensile strength and fatigue life results were statistically analyzed with an analysis of variance (*ANOVA*). This analysis included three main factors (fiber content, cement content, and void ratio) and their second-order interactions. *ANOVA* results are illustrated through Pareto charts (Figure 6) and main effects plots (Figure 7). The significance of the analysis is shown in the Pareto charts; the horizontal bars portray the magnitude of the studied effects while the dotted vertical line is associated with the significance level (95% confidence) of the analysis. Values exceeding the vertical line represent factors that have significant effects over the mechanical behavior. As for the main effects charts (Figure 7), the dotted line represents the mean result of the tests.

For unconfined compressive strength tests, the Pareto charts (Figure 6) show that all main factors (*B*, *C*, and *A*) were statistically significant, while their second-order interactions showed no influence on the response variable. As for split tensile strength tests, only the main factors (*B*, *C*, and *A*) and the second order interaction *BC* (cement content and void ratio) were statistically significant. Finally, for fatigue life tests all main factors (*A*, *B*, and *C*) and their second-order interactions (*AB*, *AC*, and *BC*) presented a significant influence. As for the main effects (Figure 7) an increase on fiber and cement content and decrease in void ratio resulted in a positive effect for all tests (compressive strength, split tensile strength and fatigue life).

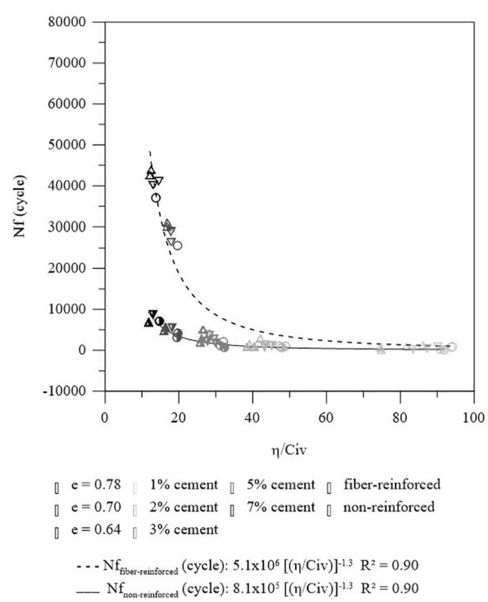

Figure 5. Fatigue life.

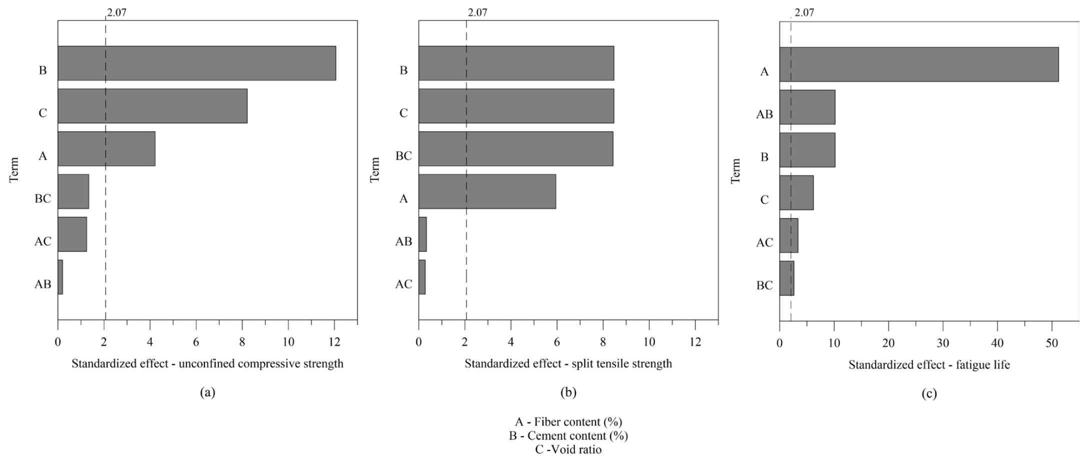

Figure 6. Pareto charts: (a) unconfined compressive strength; (b) split tensile strength; (c) fatigue life.

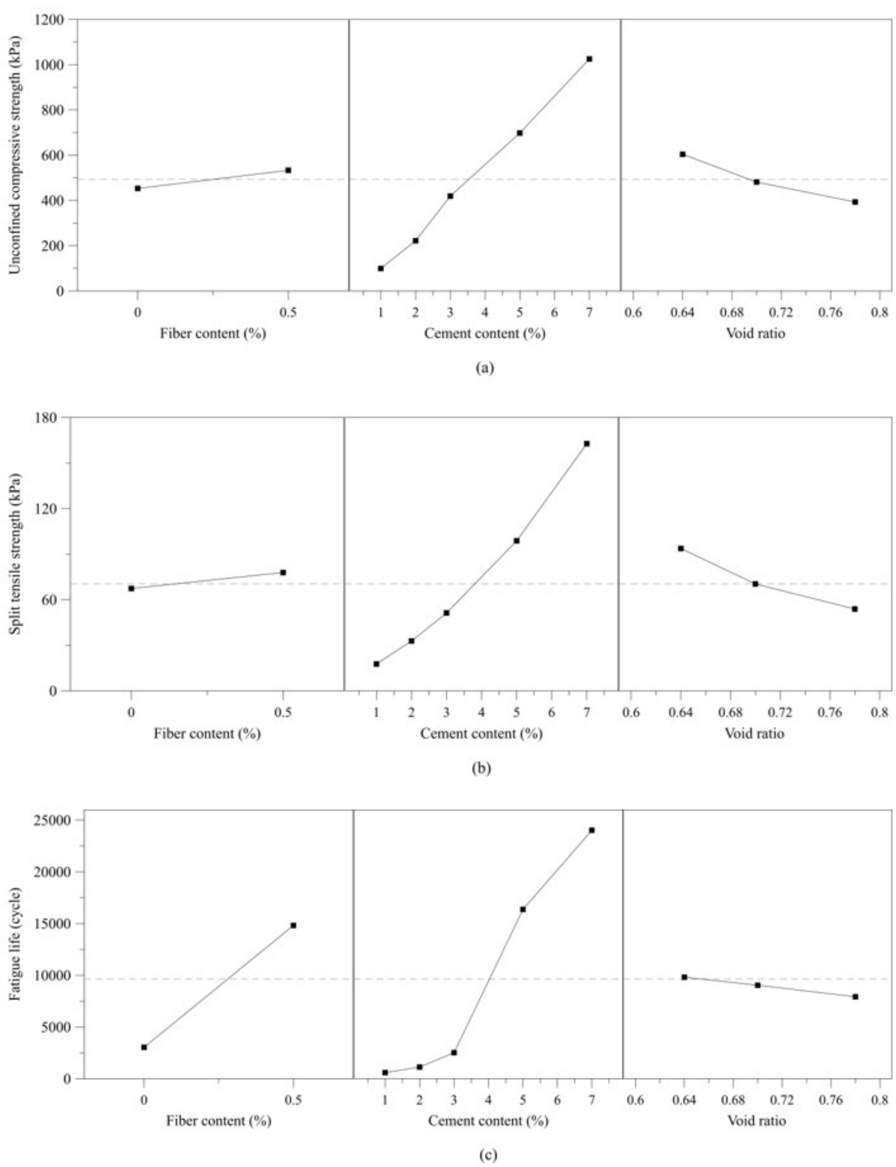

Figure 7. Main effect plots: (a) unconfined compressive strength; (b) split tensile strength; (c) fatigue life.

The statistical analysis corroborates the mechanical results, in which *qu*, *qt*, and *Nf* were governed by fiber content, cement content, and void ratio. It is important to highlight that, fiber content was the main factor that presented the most influence over fatigue life results, once again corroborating the presented results.

4. Conclusions

This study investigated the fatigue life and strength behavior of fiber-reinforced cement-treated sand. In addition, a rational dosage methodology (porosity/cement content index) was also investigated. Based on the findings of this study, for the studied materials and conditions (polypropylene fiber reinforced fine sand cemented with type III Portland cement under unconfined monotonic and cyclic loading), the following conclusions can be disclosed:

a) Fiber-reinforcement improved the mechanical behavior of both monotonic (unconfined compressive strength and split tensile strength) and dynamic loading (fatigue life) tests. This improvement was more pronounced for the fatigue life tests, considering that fiber addition enhanced the bridging effect between particles, playing a critical role in the initiation and extension of cracks;
b) Statistical analysis showed that the mechanical behavior of the fiber-reinforced cemented sand was governed by fiber content, cement content and void ratio of the mixtures. An increase in fiber and cement content and decrease in void ratio resulted in a positive effect while a decrease in void ratio on fatigue life, unconfined compressive strength and split tensile strength;
c) The porosity/cement content index (η/Civ) was shown to be an appropriate parameter to evaluate the stabilization of fiber-reinforced cemented sand in terms of fatigue life, unconfined compressive strength and split tensile strength. The provided equations allow the selection of the best combination of void ratio and cement content for a wide range of options, replacing trial and error experiments with a rational dosage methodology for both monotonic and dynamic loading.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Hernando da Rocha Borges: conceptualization, data curation, visualization, writing – original draft. Marina Paula Secco: conceptualization, data curation, methodology, validation, writing – original draft. Giovani Jordi Bruschi: conceptualization, data curation, methodology, validation, writing – original draft. Lucas Festugato: supervision, validation, writing – review & editing. The authors above kindly granted the permission of using parts of their publications in this template.

Data availability

All data produced or examined in the course of the current study are included in this article.

List of symbols

qt	split tensile strength
qu	unconfined compressive strength
Civ	cement content
F	fibers
LVDT	linear variable differential transformer
OS	Osorio Sand
PC	Portland cement
PCA	Portland cement association
SP	poorly graded sand
γ_d	dry unit weight
γs_F	unit weight of solids fibers
γs_{OS}	unit weight of solids Osorio sand
η	Porosity
η/Civ	porosity/cement content ratio

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