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Technical note

Fibre-reinforced cemented soils compressive and tensile strength assessment as a function of filament length

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ABSTRACT

This study aims to develop a dosage methodology based on tensile and compressive strength for artificially cemented fibre reinforced soils considering filament length. The controlling parameters evaluated were the fibre length (l), the cement content (C), the porosity (η) and the porosity/cement ratio (η/C_{iv}). A number of unconfined compression and split tensile tests were carried out in the present work. The results show that fibre insertion in the cemented soil, for the whole range of cement content studied, and the increase of reinforcement length improve unconfined compressive and split tensile strengths. It was shown that the porosity/cement ratio, in which volumetric cementitious material content is adjusted by an exponent (0.28 for all the fibre-reinforced and non-reinforced cemented soil mixtures) to end in unique correlations for each mixture, is a good parameter in the evaluation of the unconfined compressive and split tensile strength of the fibre-reinforced and non-reinforced cemented soil studied. Analysis of variance (ANOVA) performed on the results of a factorial experiment considering the effect of adjusted cement content, fibre length and porosity showed that all of these factors are significant in affecting the measured changes in split tensile and unconfined compressive strength values. Finally, unique dosage relationships could be achieved linking the unconfined compressive strength (q_u) and the split tensile strength (q_t) of the sandy soil studied with porosity/cement ratio (η/C_{iv}) and fibre length (l).

1. Introduction

Randomly distributed tensile inclusions, such as polypropylene fibres, incorporated into soils improve their mechanical behaviour (e.g. Consoli et al., 2009a, 2009b, 2010a, 2012; Chen et al., 2015; Diambra and Ibraim, 2015). Fibres capture and redistribute loads through their tensile strength, mobilizing a wider mass of soil, and then improve the mechanical response of the material. Fibre reinforcement has been satisfactorily used in pavement cemented base layers, channel linings, cemented paste backfills, mine tailings, cemented base layer to shallow foundations and to prevent sand liquefaction (e.g. Crockford et al., 1993, Consoli et al., 2003, 2009a, Festugato et al., 2013, 2015, Ibraim et al., 2010). Regardless of the numerous potential applications, dosage methodologies for fibre reinforced cemented soils are limited. Consoli et al. (2010a) proposed a dosage methodology for fibre reinforced cemented soils where unconfined compression strength (q_u) was related to mixtures porosity/cement volumetric content ratio (η/C_{iv}). The study was limited to a specific fibre content (F) and a specific fibre length (l), and to compressive behaviour. The previous findings were expanded by Consoli et al. (2011a) that showed the use of porosity/cement volumetric content ratio (η/C_{iv}) was also appropriate to assess unconfined compression strength (q_u) of fibre reinforced cemented soils with a number of distinct fibre contents (F). This study was limited to a specific fibre length (l) and to compressive behaviour. Consoli et al. (2011b) investigated the tensile behaviour of fibre reinforced cemented soils. The authors observed that mixtures split tensile strength could satisfactorily be related to porosity/cement volumetric content ratio (η/C_{iv}). In this investigation, a specific fibre content (F) and a specific fibre length (l) were used. This work therefore aims to develop a dosage relationship that can be achieved linking the unconfined compressive strength (q_u) and also the split tensile strength (q_t) of the sandy soil studied with porosity/cement ratio (η/C_{iv}) and fibre length (l).

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2. Experimental program

The experimental program was carried out in two parts. First, the geotechnical properties of the studied soil were characterized. Then a series of splitting tensile and unconfined compression tests for both the fibre-reinforced and non-reinforced cemented specimens were carried out as discussed below.

2.1. Materials

The soil used in this study was derived from a weathered sandstone and was obtained from a borrow site in the region of Porto Alegre, southern Brazil. The sample was collected in a disturbed state, by manual excavation, in sufficient quantity to complete all the tests.

The results of the characterization tests are shown in Table 1. This soil is classified as non-plastic clayey sand (SC) according to the Unified Soil Classification System.

Portland cement of high early strength [Type III according to ASTM C150-07 (2007)] was used as the cementing agent. Its fast gain of strength allowed the adoption of 7 days as the curing time. The used cement physical and mechanical properties are presented in Table 2.

Monofilament polypropylene fibres were used throughout this investigation to reinforce (when necessary) the cemented soil. The fibres were 6 mm, 12 mm and 24 mm in length and 0.023 mm [dtex = 3.3 – where dtex is a unit of measure for the linear mass density of fibres (mass in grams per 10,000 m)] in diameter (consequently aspect ratios of 261, 522 and 1043, respectively), with a specific gravity of 0.91, tensile strength of 120 MPa, elastic modulus of 3 GPa and linear strain at failure of 80%. The fibre contents used in the experiments were zero and 0.50% by weight of the sum of dry soil and cement. When fibre content was zero, samples were considered, for comparison, as they were reinforced with 0 mm length fibres.

Distilled water was used both for moulding specimens for the tensile and compression tests, as well as for the characterization tests.

2.2. Methods

2.2.1. Moulding and curing of specimens

For the unconfined compression and splitting tensile tests, cylindrical specimens, 50 mm in diameter and 100 mm high, were used. The fibre-reinforced and non-reinforced compacted soil specimens used in the tests were prepared by hand-mixing dry soil, cement, water and polypropylene fibres (when appropriate). During the mixing process, it was found to be important to add the water prior to adding the fibres, to prevent floating of the fibres. The amount of fibres for each mixture was calculated based on the mass of dry soil plus the mass of cement. Visual and microscope examination of exhumed specimens showed the mixtures to be satisfactorily uniform.

Table 1
Physical properties of the soil sample.

Properties	Value
Liquid limit	23%
Plastic limit	13%
Plasticity Index	10%
Specific gravity	2.64
Medium sand (0.2 < diameter < 0.6 mm)	16.2%
Fine sand (0.06 < diameter < 0.2 mm)	45.4%
Silt (0.002 < diameter < 0.06 mm)	33.4%
Clay (diameter < 0.002 mm)	5.0%
Mean effective diameter (D_{50})	0.12 mm
Coefficient of uniformity (C_u)	50

Table 2
Physical and mechanical properties of the cement.

Properties	Value
Specific gravity	3.15
Specific surface	≥300 m^2/kg
Strength (1 day)	≥14 MPa
Strength (3 days)	≥24 MPa
Strength (7 days)	≥34 MPa
Loss of ignition	≤4.5%
Insoluble residue	≤1.0%

After mixing sufficient material for one specimen, the mixture was stored in a covered container to avoid moisture losses before subsequent compaction. The storage time was less than 10 min, which was shorter than the cement initial setting time of 60 min. Two small portions of the mixture were also taken for moisture content determination.

The specimen was then statically compacted in three layers inside a cylindrical split mould, which was lubricated, so that each layer reached the specified dry density. This was made by controlling the weight and the height of each layer. The top of the first and the second layers was slightly scarified. After the moulding process, the specimen was immediately extracted from the split mould, and its weight, diameter and height were measured with accuracies of about 0.01 g and 0.1 mm. The samples were then placed within plastic bags to avoid significant variations of moisture content before testing. They were cured in a humid room at 23°±2 °C and relative humidity above 95% for 6 days.

The samples were considered suitable for testing if they met the following tolerances: *Dry Density* (γ_d): degree of compaction between 99% and 101% (the degree of compaction being defined as the value obtained in the moulding process divided by the target value of γ_d); *Moisture Content* (ω): within ±0.5% of the target value and *Dimensions*: diameter to within ±0.5 mm and height ±1 mm.

2.2.2. Splitting tensile tests

Splitting tensile tests followed Brazilian standard NBR 7222 (1983). An automatic loading machine, with maximum capacity of 50 kN and proving rings with capacity of 10 kN and resolution of 0.005 kN was used for the splitting tensile tests. The split cylinder test was used for determination of tensile strength so similar samples, prepared under the same conditions, could be evaluated under this test conditions and also under unconfined compression conditions. Furthermore, the split tensile test is relatively inexpensive and of common practice in Brazil.

After curing for 6 days in a humid room, the specimens were submerged in a water tank for 24 h (curing for another day) for saturation to minimize suction (totalling 7 days of curing). Consoli et al. (2007, 2010a), studying similar blends, concluded that specimens suction after one day of immersion in water, measured through the filter paper technique, was insignificant compared to materials peak strength and could be disregarded as variable in the analysis. The water temperature was controlled and maintained at 23 ± 3 °C. Immediately before the test, the specimens were removed from the tank and dried superficially with an absorbent cloth. Then, the splitting tensile test was carried out and the maximum load recorded. As acceptance criteria, it was stipulated that the individual strengths of three specimens, moulded with the same characteristics, should not deviate by more than 10% from the mean strength.