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Technical note

A practical methodology for the determination of failure envelopes of fiber-reinforced cemented sands

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ABSTRACT

This study aims to estimate the Mohr–Coulomb failure envelope of fiber-reinforced and non-reinforced artificially cemented sands based on splitting tensile strength (σ_t) and unconfined compressive strength (σ_c) of such materials, without the necessity of carrying out triaxial testing. Based on the concept previously established by Consoli et al. that the σ_t/σ_c relationship is unique for each specific soil, fiber and cement agent, it is shown that the effective angle of shearing resistance of a given fiber-reinforced or non-reinforced cemented sandy soil (ϕ') is dependent of the σ_t/σ_c ratio of such geomaterials and that effective cohesion intercept (c') is a direct function of the unconfined compressive strength (σ_c) [or splitting tensile strength (σ_t)] and σ_t/σ_c ratio of the fiber-reinforced/non-reinforced improved soil. Finally, the concepts presented herein are successfully checked for glass fiber-reinforced/non-reinforced silty sand treated with ordinary Portland cement, considering weak, moderate and strong cementation levels.

1. Introduction

Determination of Mohr–Coulomb failure envelope parameters of fiber-reinforced/non-reinforced artificially cemented soils requires carrying out triaxial tests (e.g., Clough et al., 1981; Consoli et al., 2007, 2009, 2012a, 2013; Dalla Rosa et al., 2008), simple shear (Festugato et al., 2013), amongst many other complex and time consuming tests.

An alternative methodology to estimate Mohr–Coulomb failure envelope parameters of fiber-reinforced/non-reinforced artificially cemented soils is suggested in present work. The concept is to carry out basic tests, such as unconfined compression and splitting tensile tests, whose equipment (loading machine and proving rings) can be found even under slight laboratory facilities. Besides, the methodology to be presented herein intends to allow increasing reliability and widening range of validity of the results, once the setup of basic (splitting tensile and unconfined compression) tests carried out for a given sandy soil and a specific cement agent will allow determining c' and ϕ' for any specific condition comprised inside the range of porosity and amount of cement employed during basic testing. Types of applications could fit improvement behavior of shallow foundations bearing on soil layers enhanced with cement and fiber (Consoli et al., 2003) and enhanced uplift performance of anchor plates embedded in fiber-reinforced cement stabilized backfill (Consoli et al., 2012b). During design considerations, once major difficulties usually occur during mixture procedures, the precision obtained using the methodology proposed to estimate Mohr–Coulomb failure envelope parameters of fiber-reinforced/non-reinforced artificially cemented materials is usually good.

2. Mohr–Coulomb failure theory

The Mohr–Coulomb failure theory is represented in the shear strength (τ) versus effective normal stress (σ') space by plotting Mohr semi-circles representing stress states at failure and then drawing a tangent to these semi-circles, which represents the Mohr–Coulomb failure envelope. As presented in Fig. 1a, in the Mohr–Coulomb failure theory, the shear strength (τ) of a given material is assumed, considering effective stress conditions, to vary linearly with effective normal stress (σ'), according to two parameters: effective cohesion intercept (c') and effective angle of shearing resistance (ϕ'), as shown in Eq. (1).

$$\tau = c' + \sigma' \tan \phi' \quad (1)$$

Using unconfined compression and splitting tensile tests principal stress states at failure, in which, the minimum effective

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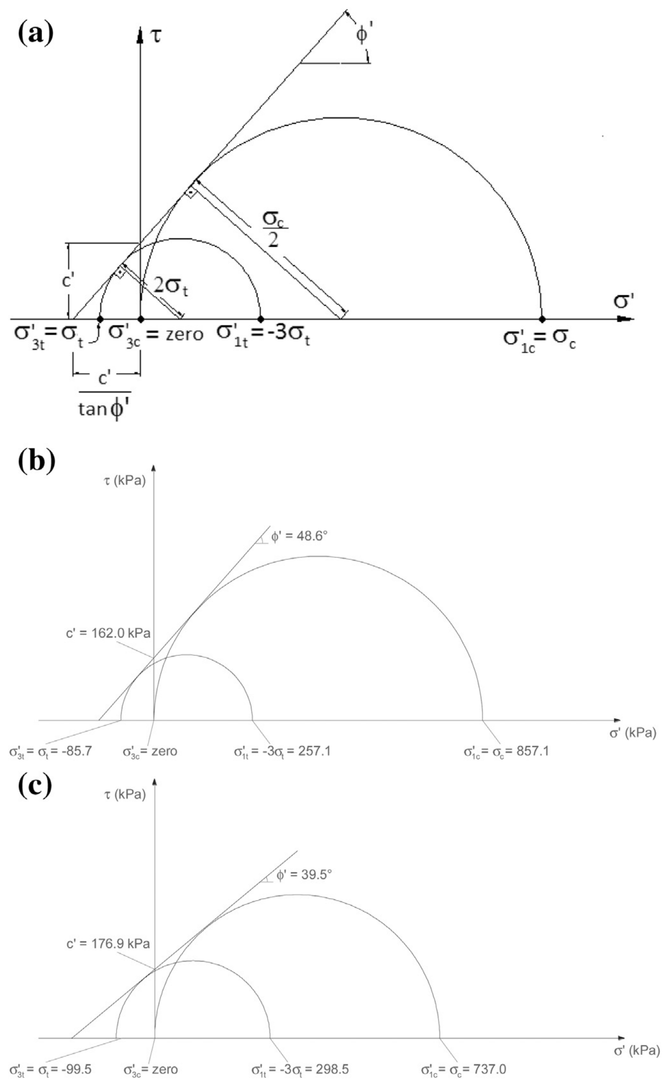

Fig. 1. Mohr–Coulomb envelope based on Mohr circles from splitting tensile and unconfined compression tests: (a) theoretical, (b) real data for fiber-reinforced cemented (3% cement) soil and (c) real data for non-reinforced cemented (3% cement) soil.

principal stress (σ_3') and maximum effective principal stress (σ_1') are $\sigma_{3c}' =$ zero and $\sigma_{3c}' = \sigma_c$ for unconfined compression and $\sigma_{3t}' = \sigma_t$ and $\sigma_{1t}' = -3\sigma_t$ (Jaeger et al., 2007) for splitting tensile tests, it is possible to establish the following equations, based on triangle–rectangle shown in Fig. 1a, respectively for unconfined compression [Eq. (2)] and splitting tensile [Eq. (3)] test results.

$$\sin\phi' = \frac{\frac{\sigma_c}{2}}{\left(\frac{\sigma_c}{2} + \frac{c'}{\tan\phi'}\right)} \tag{2}$$

$$\sin\phi' = \frac{2\sigma_t}{\left(\sigma_t + \frac{c'}{\tan\phi'}\right)} \tag{3}$$

Substituting $[c'/(\tan\phi')]$ of Eq. (2) into Eq. (3) and rearranging it in terms of ($\sin\phi'$), ends up in Eq. (4).

$$\sin\phi' = \frac{\sigma_c - 4\sigma_t}{\sigma_c - 2\sigma_t} \tag{4}$$

In the development of a rational dosage methodology for soil–Portland cement Consoli et al. (2010, 2013) have shown that the porosity/cement ratio (η/C_{iv}), defined as the porosity of the compacted mixture divided by the volumetric cement content, is an appropriate parameter to evaluate the unconfined compressive strength (σ_c) and the splitting tensile strength (σ_t) of Osorio sand–cement and fiber-reinforced clayey sand–cement mixtures, considering the whole range of cement content and the porosity studied. The σ_t/σ_c ratio was shown to be a scalar for the sand–cement and fiber-reinforced clayey sand–cement mixtures studied, being independent of porosity/cement ratio. As a consequence, dosage methodologies based on rational criteria can concentrate either on tensile or compression tests, once they are interdependable. Further studies by Consoli et al. (2012c) have corroborated that the σ_t/σ_c ratio was also a scalar for other soils and cementing agents, such as silt–lime blends. Considering such findings, it is proposed herein to consider that $\sigma_t = \xi\sigma_c$, where ξ is a scalar be introduced into Eqs. (3) and (4), ending in ϕ' and c' being given by Eqs. (5) and (6).

$$\phi' = \arcsin\left(\frac{1-4\xi}{1-2\xi}\right) \tag{5}$$

$$c' = \frac{\sigma_c\left[1 - \left(\frac{1-4\xi}{1-2\xi}\right)\right]}{2\cos\left[\arcsin\left(\frac{1-4\xi}{1-2\xi}\right)\right]} \tag{6}$$

As a consequence, it can be observed that for a given soil, fiber and cementing agent, ξ is a scalar and the effective angle of shearing resistance (ϕ') [given by Eq. (5)] is a constant and consequently is independent of the unconfined compressive strength (σ_c) and the splitting tensile strength (σ_t), as well as of the cement content, porosity or porosity/cement ratio of the studied blend, being a function only of the σ_t/σ_c ratio. On the other side, the effective cohesion intercept (c') of the blend is a function of ξ and σ_c, the latter being a function of porosity/cement ratio (η/C_{iv}). Consequently, c' is a function of the ξ, η and C_{iv}.

3. Checking the proposed methodology

In order to check the accuracy of the methodology presented herein, it will be applied to experimental results carried out by Consoli et al. (1998, 1999) in a glass fiber-reinforced silty sand (as well as in non-reinforced blends) treated with three distinct amounts of ordinary Portland cement (base soil was kept the same throughout the whole experiments).

3.1. Fiber-reinforced silty sand treated with Portland cement

Ulbrich (1997) and Consoli et al. (1998, 1999) carried out complementary studies on the mechanical behavior of fiber-reinforced silty sand treated with Portland cement. Ulbrich (1997) carried out unconfined compressive strength (σ_c) and splitting tensile strength (σ_t) of fiber-reinforced silty sand–cement blends [repeatability of the data was assessed by using three (3) specimens, for each specific cement content], maintaining constant several factors throughout the experiment [fiber percentage of 3% (by weight of dry soil), specimens porosity of about 33.8%, curing period of 7 days and degree of saturation above 95%]. The silty sand had 1%, 3% and 5% (by weight of dry soil plus fiber) of ordinary Portland cement content added to it, resulting in unconfined compressive strengths (σ_c) of 449 kPa, 857 kPa and 1134 kPa [average values of three (3) specimens for each cement content], respectively, being characterized as weak to strongly cemented geomaterials. The relation splitting tensile strength (σ_t) to unconfined compressive strength (σ_c) was found to be $\xi = 0.10$. Nine (9) drained triaxial tests under low confining pressures of 20, 60 and 100 kPa were carried out with