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Modelling tensile/compressive strength ratio of fibre reinforced cemented soils

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A R T I C L E I N F O

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A B S T R A C T

The present work proposes a theoretical model for predicting the splitting tensile strength (q_t) - unconfined compressive strength (q_u) ratio of artificially cemented fibre reinforced soils. The proposed developments are based on the concept of superposition of failure strength contributions of the soil, cement and fibres phases. The soil matrix obeys the critical state soil mechanics concept, while the strength of the cemented phase can be described using the Drucker-Prager failure criterion and fibres contribution to strength is related to the composite deformation. The proposed developments are challenged to simulate the experimental results for fibre reinforced cemented Botucatu residual soil, for 7 days of cure. While the proposed analytical relation fits well the experimental data for this material, it also provides a theoretical explanation for some features of the experimentally derived strength relationships for artificially fibre reinforced cemented clean sands. A parametric study to analyse the effect of adding different fibre contents and fibre properties is provided. The proposed modelling developments also confirm the existence of a rather constant q_t/q_u ratio with moulding density, cement and fibre contents .

1. Introduction

The addition of fibres for improving engineering properties of soils has been widely observed in nature over the years, especially with the presence of plant roots. Early studies showed that the inclusion of plant roots into the soil on slopes significantly increased shear strength (Waldron, 1977; Wu et al., 1979). More recently, the addition of artificial fibres has been used in several engineering applications, such as embankments and subgrade stabilisation beneath footings and pavements. In the last decades, an important engineering material has emerged with the advantages of quality control and easy installation: the geosynthetics (Koerner, 2012). Moreover, the inclusion of randomly distributed short fibres has been reported as an effective and cost attractive technique for increasing the strength of near surface soil layers in field applications (e.g. Consoli et al., 2009a; Diambra, 2010; Festugato et al., 2015).

Additionally, Portland cement has been widely employed in the enhancement of clayey or granular soils (e.g. Abdulla and Kiousis, 1997a; Ismail *et al.*, 2002). The effect of cementation includes an increase in stiffness and peak strength with increasing cement content and density (e.g. Saxena and Lastrico, 1978; Huang and Airey, 1998), as well as a noticeable gain in tensile strength, cohesion and friction angle (e.g. Lade and Overton, 1990). Concerning field applications, Consoli et al. (2009a) revealed the importance of the tensile strength of cemented sands, as the failure mechanism of cemented sand top layers vertically loaded begins with tensile stresses.

The coupling of both techniques (cementation and fibre-reinforcement) gave rise to fibre-reinforced cemented soils and it has also been studied by several researchers. The addition of fibres in cemented soils is of particular interest in those sands that show a brittle failure pattern (Park, 2009). Maher and Ho (1993) showed that the inclusion of randomly oriented fibres into artificially cemented sands caused a significant increase in both friction angle and cohesion, as well as in compressive and tensile strengths for such specimens. The same behaviour has been reported by other authors in clayey soils and fly ash-soil mixtures (Kaniraj and Havanagi, 2001; Tang et al., 2007).

Potential dosage methodologies for soil-cement blends must consider the influence of distinctive variables, such as porosity and

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quantity of cement. Consoli et al. (2010) found out experimentally that an index named porosity/cement ratio (η/C_{iv}) controls the unconfined compressive strength (q_u) through a power relationship for a given soil treated with Portland cement. This relationship was shown to be also adequate for fibre-reinforced cemented specimens (Consoli et al., 2011a, 2013a; Festugato et al., 2017) [see Eq. (1)].

$$q_u = X\left[\frac{\eta}{C_{iv}^{exp}}\right]^Z \quad (1)$$

where porosity (η) is expressed as percentage of the volume of voids divided by total volume of the specimen while volumetric cement content (C_{iv}) is expressed as percentage of the volume of cement divided by the total volume of the specimen, X, Z and exp are parameters that possibly depend on the soil and binder used. Consoli et al. (2011a) showed that the exponent X depends on the fibre content whereas Consoli et al. (2016) found that Z depends exclusively on the type of soil.

Consoli et al. (2011b) demonstrated that such index is also useful in controlling splitting tensile strength (q_t). These studies employed the same soil, fibre and Portland cement used in previous research, and a similar power relationship was obtained [see Eq. (2)].

$$q_t = Y\left[\frac{\eta}{C_{iv}^{exp}}\right]^Z \quad (2)$$

where Y, Z and exp are parameters that might depend on the soil and binder used. At that moment, Consoli et al. (2011b) detected that the power Z and the exponent exp were the same for both q_u and q_t, but X and Y were distinct. In order to check if a q_t/q_u relationship for the studied fibre reinforced Botucatu residual soil – Portland cement blend was a function of porosity, cement content or porosity/cement ratio, Consoli et al. (2013a) divided Eq. (2) by Eq. (1), yielding a scalar [see Eq. (3)].

$$\frac{q_t}{q_u} = \frac{2.55x10^6\left[\frac{\eta}{C_{iv}^{0.28}}\right]^{-2.90}}{17.96x10^6\left[\frac{\eta}{C_{iv}^{0.28}}\right]^{-2.90}} = 0.14 \quad (3)$$

Accordingly, the authors found out that there was a straight proportionality between tensile and compressive strengths, being independent of porosity, cement content and porosity/cement ratio, which was valid for the whole studied porosity and cement ranges (see Fig. 1 for fibre reinforced Botucatu residual soil – Portland cement blend).

The q_t/q_u ratio of fibre reinforced artificially cemented soils is an important parameter once its existence allows determining q_t knowing q_u or vice versa, considering the whole porosity and volumetric cement content studied. Besides, Consoli et al. (2013b) have shown a theoretical framework proving that the friction angle of fibre reinforced cemented granular soil is unique for a given soil and cement and its value is a function only of q_t/q_u. On the other side, the cohesion of cemented granular soil can be determined on both q_u and q_t/q_u.

Consoli et al. (2012) developed similar study with fibre reinforced silty soil treated with lime. Result trends by Consoli et al. (2012) were similar to the ones obtained by Consoli et al. (2013a), as the q_t/q_u relationship for the fibre reinforced silty soil treated with lime yielded a scalar of 0.15. Up to this moment, several authors have developed constitutive modelling approaches concerning fibre-reinforced sands (Villard and Jouve, 1989; Di Prisco and Nova, 1993; Sivakumar Babu et al., 2008; Diambra et al., 2007, 2010; 2011, 2013; Ibraim et al., 2010), cemented sands (Abdulla and Kiousis, 1997b; Vatsala et al., 2001) and concrete fibre mixtures (e.g. Samaan et al., 1998; Teng and Lam, 2004). However, there are no theoretical models able to explain the empirical expression for fibre-reinforced cemented sands exposed above.

Diambra et al. (2017) presented a theoretical derivation for the strength of three unreinforced artificially cemented granular soils. The authors showed that the concept of superposition of failure strength contributions of the soil and cement phases is effective in predicting the compressive strength of cemented granular soils. Based on this derivation, the present technical paper proposes an extended theoretical modelling framework to predict the compressive and tensile strengths of fibre reinforced artificially cemented soils by considering the individual properties of its constituents: the soil matrix, the cementing phase and the fibres. It will be shown that the proposed developments provide an accurate estimation of the experimental results and that they corroborate the experimental observation of the existence of a unique q_t/q_u ratio independent of moulding density and cement content. The proposed modelling approach will also offer an insight into the physical meaning of the coefficients governing the simple empirical relationships (1) and (2) for the compressive and tensile strengths of fibre reinforced cemented soil and their ratio q_t/q_u in Eq (3), increasing the confidence for their broader use in the engineering practice. This process will allow the establishment of meaningful connections between

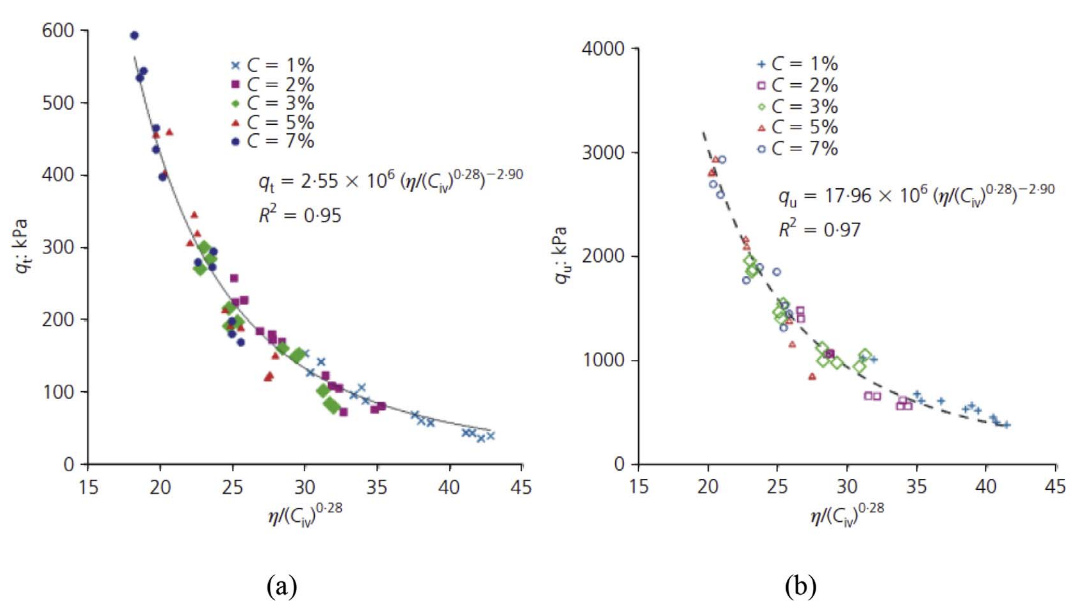

Fig. 1. Variation of q_t (a) and q_u (b)with porosity/cement ratio for fibre reinforced Botucatu residual soil – Portland cement (adapted from Consoli *et al.* 2013a).