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Influence of discrete fibre reinforcement on the uniaxial compression response and seismic wave velocity of a cement-stabilised sandy-clay

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ABSTRACT

A sandy clay from the northeast region of Portugal has been reinforced with polypropylene fibres and cement, and seismic wave velocity measurements and uniaxial compression strength tests were performed. Results showed that the fibre induce variations on the wave's velocity that cannot be related to real changes in the material stiffness. Therefore, care should be used when using this technique in fibre reinforced soils. The addition of fibres resulted in an increase of compression strength of the mixtures, for every cement content. Regarding the stiffness, the fibres proved to be increasingly effective with an increase in cementation, especially at the early stages of the stress–strain curve, when the secant deformability modulus increases with fibre content. However, no influence of the discrete reinforcement was detected on the peak and post-peak stages of the loading process. Fibre length showed also to be influential on strength and stiffness.

1. Introduction

Short and randomly distributed fibres are often used to reinforce brittle materials, due to their decisive contribution to the delay of crack initiation and, especially, crack propagation. The appearance of fibre reinforced concrete dates back to the early sixties (ACI 544, 2002), and nowadays is widely used on full load bearing structural applications of laminar structures, e.g. tunnels, bridges and industrial slabs on-grade. Moreover, the use of fibres in cementicious materials is not restricted to structural applications, since they are also frequently used in coating mortars of façades to prevent cracking due to shrinkage and thermal loads. The use of fibres in brittle materials is relatively old when compared to the advent of fibre reinforced concrete and, even more so, of fibre reinforced soil, since this solution was popular in ancient civilizations, which used either straw or bamboo fibres to reinforce lime and soil mortars.

Several types of fibres are used in the construction industry to reinforce cement based materials, e.g. steel, polypropylene, glass and carbon fibres (ACI 544, 2002). Nonetheless they are not constrained to inorganic materials. Within a sustainability perspective, the use of natural fibres in the reinforcement of cementicious materials is gathering some expression. Examples of the aforementioned are the research studies regarding the use of recycled micro-cellulose fibres (Mohamed et al., 2010), as well as other plant fibres, such as eucalyptus pulp, coir or eucalyptus (Savastano et al., 1999), sisal (Silva et al., 2010), kenaf (i.e. hibiscus cannabinus) (Elsaid et al., 2011), cotton (Pinto et al., 2013), or even other unforeseeable materials, such as human hair (Jain and Kothari, 2012).

More recently, an increasing interest in the use of discrete fibres in soil reinforcement has been reported, partially driven by the successful results achieved with concrete, but also as a result of its wide dissemination throughout the construction industry. In the past few decades, several studies have been conducted to assess the structural benefits of reinforcing soils with randomly distributed discrete fibres. Uniaxial and triaxial compression and direct shear behaviour have been thoroughly analysed (Al-Refeai, 1991; Chauhan et al., 2008; Consoli et al., 2010, 1999, 1998; Diambra et al., 2010; Fatahi et al., 2012; Hamidi and Hooresfand, 2013; Lovisa et al., 2010; Michalowski and Čermák, 2003; Miller and Rifai, 2004; Ranjan et al., 1996; Tang et al., 2007; Yetimoglu and Salbas, 2003). Polypropylene fibres are predominantly used for

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soil reinforcement, with fibre contents ranging from 0.05% to 3%. Glass fibres were also used in some earlier studies (Al-Refeai, 1991; Consoli et al., 1999, 1998). However, they were quickly abandoned, probably due to the fact that the glass used in the earlier fibres was not alkali-resistant (AR). Even with AR-glass fibres, which are found to be stable in Portland cement-based matrices, both a strength and ductility reduction was observed when the fibre reinforced composite was exposed to moist environments over long periods (Kopecskó, 2004). Tire fibres have also been studied for soil reinforcement, and Edinçliler and Ayhan (2010) have found a strong correlation between fibre aspect ratio and shear strength in granular soils.

The benefits promoted by the fibres, regarding mechanical properties, are mainly due to the fibres crossing micro/macro cracks. These fibres guarantee a certain level of stress transfer between both faces of the crack, providing a residual strength to the composite, with magnitude depending on a multiplicity of interconnected mechanisms and factors. Within these factors, the fibre (i.e. material, geometry and fibre content), the soil matrix and the fibre/soil interface properties, as well as fibre distribution and orientation, may be highlighted (Banthia and Trottier, 1994; Cunha et al., 2011, 2010; Naaman and Najm, 1991; Tang et al., 2010). In general, the fibre addition to a soil matrix leads to an increase in uniaxial compression strength, in terms of peak and especially in terms of residual strength (post-cracking). When the soil is also stabilised with a cementitious binder, like cement, then the level of improvement is intrinsically connected to both fibre and cement content. Nevertheless, some authors (Hamidi and Hooresfand, 2013; Tang et al., 2007) have observed a reduction of the stiffness of fibre reinforced soils with the inclusion of fibres, which was attributed to the reduction in brittleness.

In the present work, the influence of synthetic discrete fibres (0.10, 0.15 and 0.25% by dry weight) and Portland cement (0, 5 and 10% by dry weight) on the mechanical properties of clayey soils, was assessed. An extensive experimental campaign was carried out. In a first stage, a thorough characterization of the soil used in this research was performed, including its main geotechnical and microstructural properties, using scanning electron microscope (SEM), X-ray energy dispersive spectrometry (EDS) analysis and X-ray diffraction mineralogical identification (XRD). The stress–strain response of the material was then thoroughly assessed using non-destructive ultrasonic pulse tests and uniaxial compression tests. The main motivation for this research was the contribution for a clearer definition of the response of low to highly cemented soils, when reinforced with polypropylene fibres. The choice of the modulus as a primary concern is related to the importance of such parameter in structural design, associated with the difficulties regarding its experimental assessment. It is essential that the complex behaviour of this two-phase material (soil + fibre) is well understood and also that simple experimental techniques are used properly and correctly interpreted.

2. Methodology

2.1. Materials characterisation

The soil was collected from a location inside the Campus of the University of Trás-os-Montes e Alto Douro (UTAD), in the north of Portugal. Geotechnical characterisation was performed according with BSi 1377-1 (1990), BSi 1377-2 (1990) and BSi 1377-4 (1990) standards. Fig. 1 and Table 1 summarise the obtained results. Based on the properties shown in Table 1, the soil was classified as CL – Sandy Lean Clay, according to ASTM D2487 (2011).

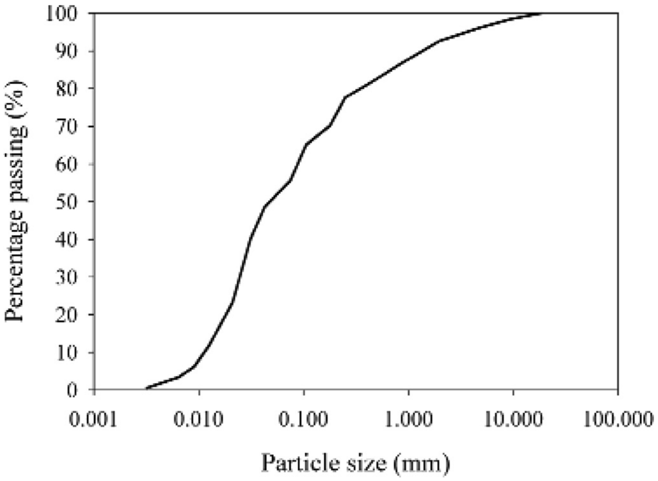

Fig. 1. Grain size distribution of the soil.

The SEM analyses were performed on a FEI QUANTA – 400 electronic microscope, with a tungsten filament electron source and 29.97 kV accelerating voltage, and conducted in low vacuum mode. An X-ray energy dispersive spectrometry (EDS) system from EDAX was used to analyse the chemical composition of the original soil and also of the soil–cement mixture after 28 days curing (Table 2). The EDS results presented correspond to the average values of five different acquisition points, performed over three different specimens. An input count-rate of 300 counts per second was used, with a mean acquisition time of 150s to accumulate each spectrum. EDS data revealed that almost 80% of the soil is made of silica and alumina, while the addition of cement contributed, as expected, to a significant increase in the calcium content, relatively to the original soil composition (Fig. 2).

The minerology was examined by a PANalytical X'Pert Pro diffractometer, fitted with an X'Celerator detector. The scans covered the range 7–77° 2θ, with a nominal step size of 0.017° 2θ and time of 100 s per step. CuKα radiation, with a wavelength of $\lambda = 1.54180$ Å, was used. Qualitative phase identification was carried out using *High Score Plus* software and the International Centre for Diffraction Data Database, Sets 1–49 [ICDD, 1999]. The X-Ray diffraction patterns (Fig. 3) of the soil and the soil–cement mixture showed the presence of quartz, calcite, illite, nacrite and muscovite on the mineralogical composition, which are common for this type of soil.

A Portland cement CEM I-42.5R was used. The fibres were made of polypropylene (C_3H_6) and specifically cut having in mind their application in concrete and mortar, for enhanced impact on strength and crack resistance. Table 3 presents their main properties, accordingly to the manufacture's specification sheet. Due to the well-known difficulty to achieve proper homogenisation in the soil–fibre mixture (Ibraim et al., 2012), a preliminary separation of the fibres, prior to the mixing process, assumes a key role. Therefore, compressed air was injected in a chamber containing the

Table 1
Main geotechnical properties of the soil.

Plastic limit	14.59	%
Liquid limit	23.46	%
Organic matter content	2.64	%
Specific gravity	26.83	kN/m^3
D_{50}	0.045	mm
Fines fraction (sieve N° 200)	55.6	%
Uniformity coefficient	6.92	
Curvature coefficient	0.53	
Optimum water content (Standard Proctor Test)	13.5	%
Maximum dry unit weight (Standard Proctor Test)	18.9	kN/m^3