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Continuous monitoring of sand–cement stiffness starting from layer compaction with a resonant frequency-based method: Issues on mould geometry and sampling

Jacinto Silva[a,b], Miguel Azenha[a,*], A. Gomes Correia[b,1], José Granja[a]

[a]ISISE – Institute for Sustainability and Innovation in Structural Engineering, University of Minho, School of Engineering, Department of Civil Engineering, Campus de Azurém, 4800-058 Guimarães, Portugal

[b]C-TAC – Territory, Environment and Construction Research Centre, University of Minho, School of Engineering, Department of Civil Engineering, Campus de Azurém, 4800-058 Guimarães, Portugal

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Abstract

The application of a vibration-based methodology for the continuous measurement of the stiffness of sand–cement has recently been proposed by the authors of this work. Such methodology consists of placing the sand–cement sample into a mould, then placing the mould in simply supported conditions, and finally monitoring it over time to assess the evolution of its resonant frequency. This evolving resonant frequency of the system can be analytically correlated to the stiffness of the tested material. Based on the success of the pilot application, this work has been extended to the methodology of in situ sampling. Such an extension involves the use of new geometries and materials for the moulds. The performance of the adapted technique is verified by comparing its results to those obtained through uniaxial compression cyclic tests up to the age of 28 days. This work also encompasses the characterisation of the hydration kinetics of a cement paste, made with the same cement as that used for cementing sand, and draws conclusions about the relationship of stiffness evolution in both materials.

Keywords: Cement-stabilized soil; Stiffness monitoring; Resonant frequency; Sample collection

1. Introduction

The quality control of sand–cement layers is usually performed by means of in situ tests for the assessment of a performance criterion, such as stiffness. For that purpose, some of the most frequently used techniques are the plate load test (PLT) (Gomes Correia et al., 2009a), the light falling weight deflectometer (LFWD) (Benedetto et al., 2012; Gomes Correia et al., 2009a; Alshibli et al., 2005) and the soil stiffness gauge (SSG) (Gomes Correia et al., 2009a; Alshibli et al., 2005). Despite the general acceptance of the PLT, this is a time-consuming test that involves heavy work and usually provides a very limited quantity of data (Gomes Correia et al., 2009a). The LFWD and the SSG have the advantages of being portable and easier to conduct. However, the results provided by these two techniques frequently differ from those determined by PLT (Gomes Correia et al., 2009a; Fleming et al., 2000;

*Corresponding author. Tel.: +351 253 510 248; fax: +351 253 510 217.
E-mail addresses: miguel.azenha@civil.uminho.pt, miguel.azenda@gmail.com (M. Azenha).
[1]Tel.: +351 253 510 200; fax: +351 253 510 217.
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Alshibli et al., 2005). Recently, several approaches have been taken to develop a technique for application to sand–cement, namely, wave propagation-based techniques such as ultrasonic pulse velocity (US) (Khan et al., 2006), bender–extender elements (BE) (Ferreira, 2009; Amaral et al., 2011; Viana da Fonseca et al., 2009a; Rios Silva et al., 2009; Consoli et al., 2012; Seng and Tanaka, 2011); torsional ring transducers (Sharma et al., 2011) and the spectral analysis of surface waves (SASW) (Yuan and Nazarian, 1993; Nazarian et al., 1996). Resonant column methods have also been utilised to assess the wave speed propagation in granular materials (including stabilized soils) induced by compressive, torsional and flexural excitations to cylindrical specimens (Cascante and Santamarina, 1997; Cascante et al., 1998). However, the interpretation of the results obtained with these wave propagation techniques is frequently challenging and usually involves some uncertainty, due to the influence of geometrical effects, experimental setups and the algorithms used for data processing (Amaral et al., 2011; Ferreira, 2009; Viana da Fonseca et al., 2009b; Yuan and Nazarian, 1993; Beaty et al., 2002). Nonetheless, it is worth remarking that the interpretation of resonant column-based methods has been extended to the assessment of stiffness properties with a basis on the resonant frequencies of the specimen (Cascante et al., 1998; Guimond-Barrett et al., 2013).

In view of quality control techniques based on waves (e.g., bender–extender elements), Asaka and Abe (2011) and Asaka et al. (2007) performed extensive work for the establishment of a relationship between the unconfined compressive strength and the shear wave velocity of cement-treated soil for 5 types of soil. Their strategy allowed for the estimation of the in situ strength of cement-treated soil derived by measuring the shear wave velocity of the ground in the field using bender elements. In line with approaches for the quality control of cement-stabilized soils, that are not based on a stiffness assessment, several alternative control properties have been adopted, such as compressive strength (Kim et al., 2010; Piratheepan et al., 2012; Consoli et al., 2009; Horpibulsk et al., 2011; Taheri et al., 2012; Kasama et al., 2012), indirect tensile strength (Hossain et al., 2007; Niazi and Jalili, 2009) and durability (Walker, 1995; Kamei et al., 2013).

In general, the quality control of the stiffness of sand–cement, performed with any of the above-mentioned techniques, is conducted at the reference age of 28 days. This means that a relatively large time lag exists between the actual compaction of the layer and the instant at which conformity is checked, with significant costs of reallocation of equipment/staff in the case of rejection. For this reason, it is desirable for contractors to have information about rejection/acceptance within a short period after compaction. In view of this requirement, the authors of the present paper have adapted a recently developed methodology for concrete and cement paste, which allows for the continuous monitoring of stiffness, starting from the fresh state of the cement-based material (Azenha et al., 2011). The methodology is termed Elasticity Modulus Measurement through Ambient Response Method (EMM-ARM) and its original implementation consists of placing the tested material inside an acrylic mould, which is in turn setup as a simply supported beam (Azenha, 2009; Azenha et al., 2010). By monitoring the accelerations of the composite beam at mid-span, it is possible to perform output-only modal identification, thus obtaining a continuous record of the first flexural resonant frequency of the beam. The corresponding E-modulus (E) of the studied material can be continuously and quantitatively assessed by applying the dynamic equation of motion of the system.

Even though it is possible to think that the existing resonant column method for geomaterials resembles the EMM-ARM, several relevant differences exist that justified the extension of this new approach to sand–cement: (i) the experimental setup for EMM-ARM is far simpler and cheaper; (ii) no explicit excitation device or timing is necessary in EMM-ARM; (iii) support conditions are simpler and clearer. However, EMM-ARM fails to be applicable under confined conditions, making it more advisable to use the resonant column method in distinct contexts.

As mentioned above, the EMM-ARM has recently been extended for application to sand–cement (Azenha et al., 2011), with the conception of a specifically devised mould with a "U"-shaped cross-section, which calls for the compaction of the fresh mix inside the mould. This adapted version of EMM-ARM has been tested at early ages and its results were successfully validated against other experimental techniques. Nonetheless, an important challenge has been identified, namely, the necessity of having an adequate mould for the in situ sampling to assure the same material homogeneity and compaction as that of the stabilized layer. Thus, it was the aim of the work presented in this paper to cover the necessity of a sampling technique suitable for the test moulds of EMM-ARM. Two sampling techniques are proposed, based on lateral access to the compacted layer and access from the top of the compacted layer. Each of these two sampling techniques involves the use of a distinct type of mould, in terms of both geometry and material. The principles that back the design criteria of the moulds are described, and the performance of the proposed moulds is evaluated in view of the established principles. An experimental program with the two sampling techniques and test setups of EMM-ARM for sand–cement is presented, together with complementary cyclic compression tests carried out on cylindrical specimens for a stiffness assessment. This research work was further complemented with a comparative evaluation of the hydration kinetics of the studied sand–cement, and that of a cement paste of the same cement used for the sand stabilisation, which was also measured with EMM-ARM. The purpose of the comparison of the cement hydration kinetics in the sand–cement and in the cement paste was a preliminary evaluation of the possibility of using the results of the cement paste EMM-ARM in homogenisation methodologies (Omine et al., 1998) to predict the mechanical properties of sand–cement.

2. E-modulus measurement with EMM-ARM

2.1. General remarks

The EMM-ARM methodology was originally devised for the continuous assessment of the concrete/cement paste E-modulus