Soil-Cement Mechanical Characterization Using Acoustic Vibration

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Abstract. The execution of small and medium-sized foundations (for houses, townhouses, sheds, etc.), has often been proven unfeasible because the use of semi-empirical equations results in low load capacity values, generally leading to the use of piles. However, this is not always an economical alternative, due to the low level of loads on the pillars. There are alternatives for improvement such as the use of cement. The mechanical characterization of these materials is needed; therefore, the use of acoustic vibrations appears as a non-destructive and economical technique. This technique is used for materials such as concrete and hasn't been often applied in the soil area. In this work, the feasibility of mechanically characterizing the dynamic modulus of elasticity and damping ratios is studied for soil-cement-compacted (SCC). The experimental program consists of carrying out acoustic tests on SCC specimens with cement dosage of 6, 9 and 12% in relation to the total weight of the mixture.

Keywords: Soil-Cement, Mechanical Properties, Acoustic Tests.

1 Introduction

Generally, deep foundations are used when the soil surface do not have sufficient bearing capacity to withstand the demands of the structure, making the use of shallow foundations unfeasible [1]. However, the solution of deep foundations is not always a technical and economical viable solution, due to its high cost, especially for small and medium-sized works [2]. Therefore, alternative solutions are sought to improve mechanical properties such as elastic modulus, shear modulus, Poisson's coefficient and damping ratio of the material. There are several methods to improve the mechanical properties of the soil, one of them is the soil-cement mixture [3]. Typically, ultrasonic tests and bender element test are used to measure mechanical properties such as modulus of elasticity and damping ratio [4]. The acoustic test arises as a simples alternative and less expensive and is based on the impact of a hammer, and the subsequent measurement of the sound with a low-cost microphone, data acquisition on a computer, and post-processing of the result in dedicated software to identification of resonance frequencies [5]. A ASTM E1876-15 (2015) provides many procedures for determining the dynamic modulus of elasticity, shear modulus, and Poisson's ratio based on fundamental resonance frequencies of known geometries and mass. Futhermore, resonant frequency tests have proven to be an excellent non-destructive alternative for determining the elastic properties of wood, ceramics, concrete and mortars [7].

The objective of this work is to study the feasibility of mechanically characterizing (dynamic modulus of elasticity and damping ratio) the soil and SCC by means of acoustic tests on specimens with cement dosage of 6,9 and 12% in relation to the total mixture weight. To obtain the mechanical properties, the standard ASTM E1876-15 was used. The UNILAstic software uses this standard capturing the sound of the specimens and performs the spectral analysis of the signals to identify the resonant frequencies.

2 Materials and methods

2.1 Impulse Excitation Technique (IET)

The method of the Impulse Excitation technique is fundamentally based on the dynamic elasticity modulus determination from the ressonant frequencies. The test consists of exciting a specimen of known regular geometry (cylindrical, prismatic, plates) with a slight manual or mechanical impulse of short duration in a longitudinal, flexural or torsional manner, in order to obtain the resonant frequency of the acoustic response captured by an accelerometer or microphone equipment [8].
Upon excitation, the specimen vibrates and for each frequency mode there is a characteristic fundamental frequency. Figure 1 shows the vibration modes for a cylindrical specimen for the three types of excitation, where the blue colored regions reflect the points at which the vibration amplitude is minimum, while the red colored regions represent the maximum vibration amplitude [9].

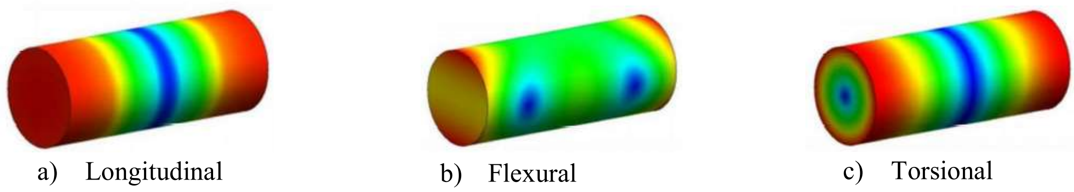

Figure 1. Fundamental modes of vibration for a cylindrical sample
Fonte: Pereira e Otani (2017)

To identify the mechanical properties of the material, it is first necessary to properly support the sample at its resonance nodes (0.224L at each end, where L is the length of the sample) [5]. Soon after the test is finished, the data are collected and converted from the time domain to the frequency domain by applying Welch spectral method, thus determining an approximate set of resonance frequencies (fr) of the tested material [10]. The calculation of the elastic modulus of the material is possible because the resonance frequencies (fr) depend on the mass, dimensions and elastic properties of the sample tested [11].
The procedures of ASTM E1876-01 [5], the method proposed by Kolluru, Popovics e Shah [12] were the methodologies implemented in the UNILAstic software [13] to determine the elastic properties of cylindrical soil-cement specimens. The application of the method ASTM E1876-01 [5] to estimate the dynamic modulus of elasticity requires the definition of the flexural fundamental frequency. Based on the method of Kolluru, Popovics and Shah [12], it is possible to determine the modulus of elasticity from the first longitudinal frequency.
The equations 1,2 e 3 show the correlation, defined by the norm ASTM E 1876 (2015), between the longitudinal fundamental frequency (f_L), flectional (f_F) or torcional (f_T) and the elastic characteristics of the material.

$$E_d = \frac{5,093 * (L * m * f_L^{\,2})}{d^2 k} \tag{1}$$

$$E_d = \frac{1,6067 * (L^3 * m * f_F^{\,2} T_1)}{d^4} \tag{2}$$

Being E_d the dynamic modulus of elasticity (Pa), L is the length of the specimen (mm), d is diameter (mm), m is the mass (g), f_L is the longitudinal fundamental frequency (Hz), f_F the inflectional fundamental frequency (Hz), f_T is the torsional fundamental frequency (Hz), k is the longitudinal mode correction factor, T_1 is the correction factor of the flexural mode, the latter represented by the eq. 3

$$T_1 = 1 + 4,939\left(1 + 0,0752\upsilon_d + 0,810\upsilon_d^{\,2}\right)\left(\frac{D}{L}\right)^2 - 0,4883\left(\frac{D}{L}\right)^4 - \left[\frac{4,691\left(1 + 0,2023\upsilon_d + 2,173\upsilon_d^{\,2}\right)\left(\frac{D}{L}\right)^4}{1 + 4,754\left(1 + 0,1408\upsilon_d + 1,536\upsilon_d^{\,2}\right)\left(\frac{D}{L}\right)^2}\right] \tag{3}$$

Damping ratio is determined by using curve fitting method near to one resonance frequency. This region is considered as a single degree of freedom. These methods and equations were configured in the UNILAstic software to investigate the dynamic elasticity modulus through the IET.

2.2 Application

Table 1 presents the dimensions and masses of the specimens. The construction of the SCC specimens was based on their compactation in metallic molds.

Table 1. Physical properties of SCC specimens

Cement	γ_d	h	V	PCP	H	D
%	g/cm^3	%	cm^3	g	mm	mm
0	1,623	21,3	771,2	1487,9	170	76
6	1,539	23,4	771,2	1435,31	170	76
9	1,598	21,5	771,2	1467,39	170	76
12	1,574	21,6	771,2	1446,54	170	76

γ_d =Unit weigth ; h water content; V volume; H=Hight of the sample; PCP Total weigth D=Diameter de prova.

To make the SCC, high strength CP V ARI cement was used in the molding of the specimens. Initially, compaction tests were carried out at Proctor Normal to determine the maximum specific masses and their respective optimal humidity. (table 1), later with these data, soil and SCC specimens were molded with different percentages of cement, as shown in Figure 2. In a second step, the molded SCC specimens were placed in a humid chamber for the curing process. (figure 2).

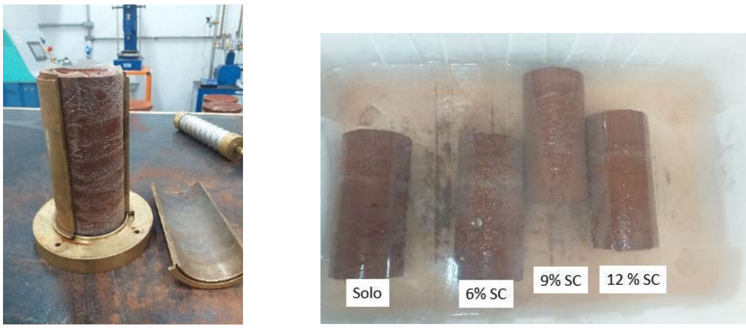

Figure 2. Molding and curing of specimens with different percentage of cement.

After the curing process, the specimens were tested in the UNILAstic equipment at the moment of molding and for 7, 14, 21 days of curing. Figure 3 shows the test performed for a specimen using the IET.

2.2 Frequency detection and module calculations

Initially, the mass data and dimensions of each specimen were entered to later be tested by the IET (Figure 3).After applying the excitation to the specimen, a response spectrum graph was obtained. The spectrum response in figure 3 corresponds to the specimen with 12% of SCC, where the first frequency (maximum peak) is the flexural mode that will be used in the calculation of the dynamic elasticity modulus, and later, the damping ratio corresponding to this flexural frequency. This process was carried out for all soil specimens, 6.9 and 12% of compacted cement soil at different times of the curing process.

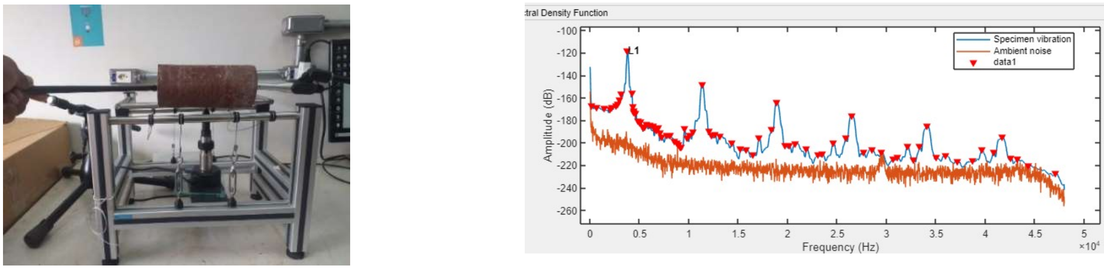

Figure 3. Test by TEI method and response spectrum

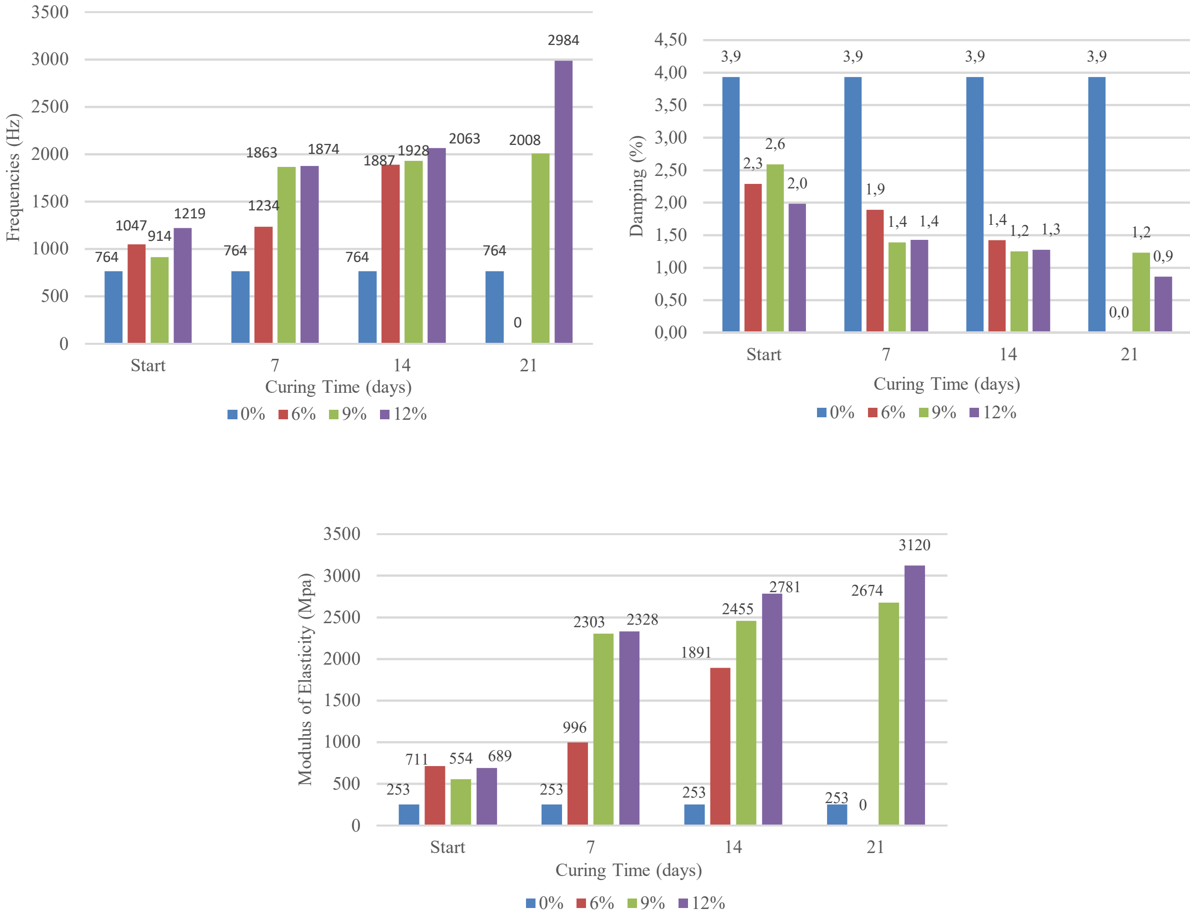

Figure 5. Comparison graph of frequencies, modulus of elasticity and damping vs curing time

In figure 5 it can be seen that with the addition of the percentage of cement, an increase in frequencies can be observed, as well as, the longer the curing time, there is also a considerable increase in frequencies. In the same way, the soil initially presents a high damping ratio that decreases with the addition of cement and with the curing time. The dynamic lasticity modulus increases as the percentage of cement increases and also with time, thus increasing the stiffness of the material. Also, it was not possible to acquire data from the specimen of 6% at 21 days of curing, due to the fact that the specimen was accidentally broken, even so there is a tendency for an increase in the modulus of elasticity, frequencies and a decrease in the damping ratio.

3 Conclusions

With regard to the results obtained, the following points can be highlighted: the greater the addition of cement, the better the mechanical properties of the soil, increasing the dynamic elasticity modulus. Inversely it occurs in the case of the damping coefficient, increasing the stiffness of the material. In the case of soil without cement addition, a very high damping was observed, this may be due to the low cohesion presented in the soil (compared to SCC). Through the application of the IET, it can be concluded that cement improves the mechanical properties of the soil.

It should also be noted that the acoustic vibration technique is viable for the characterization of soil mixed with cement, including soil without cement, provided that it presents a satisfactory cohesion for the test, it is imagined that for non-cohesive soils the same technique could not be used, or for cohesive soils with low cohesion, in this case the tests showed that it was possible to characterize the soil, since the first flexural resonance frequency was detected. It can then be indicated that the high cohesion of the soil allowed its characterization in the compacted form.

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References

[1] SILVA, M. T. Interação Solo Estrutura de Fundação em Estaca de Solo-Cimento e Concreto. 117p. Dissertação (Mestrado) - Curso de Engenharia Civil, Departamento de Engenharia, Universidade de Brasília Faculdade de Tecnologia Departamento de Engenharia, Brasília, 1994.
[2] VENDRUSCOLO, M.A. Análise Numérica e Experimental do Comportamento de Fundações Superficiais em Solo Melhorado. (Dissertação de mestrado) – Curso de Pós-graduação em Engenharia Civil, UFRGS, Porto Alegre, 1996.
[3] SEGANTINI, A. A. S. Utilização de Solo-Cimento em Estacas Apiloadas para Obras de pequeno porte. 1994. 96 f. Dissertação (Mestrado em Engenharia Agrícola) - Curso de Engenharia Civil, Universidade Estatual de Campinas -Unicamp Faculdade de Engenharia Agrícola, São Paulo, 1994.
[4] AMARAL M. F.et al. Compression and shear wave propagation in cemented-sand specimens - Géotechnique Letters, 2011.
[5] MALHOTRA V. M. and CARINO N. J. Nondestructive Testing of Concrete - 2ed., p. 168-180, 2004.
[6] AMERICAN SOCIETY FOR TESTING AND MATERIALS. ASTM E1876-15: Standard Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio by Impulse Excitation of Vibration. ASTM International. West Conshohocken, p. 17.2015.
[7] Ricardo C, Vladimir, G. H., Enrico F. M., Daniel A. M.P. and J.P.C. (2006). Concrete: Mechanical Characterization of Concrete by Impact Acoustics Tests, properties and materials, 3rd Ed., McGraw-Hill, New York, 659.
[8] BAHR, O. et al. Youn’modullus and Poison’s ratio of concrete at high temperatures: Experimental investigation. Materials and Design, v. 45, p. 421-429,2013. Disponivel em: <https://doi.org/10.1016/j.matdes.2012.07.070>.
[9] CALLISTER, W.D. Materials Science and Engineering. 7a. ed. Nova Iorque: John Wiley & Sons, 2007.
[10] CUNHA, Álvaro; CAETANO, Elsa. Experimental Modal Analysis of Civil Engineering Structures. Journal of Sound and Vibration, [S. l.], p. 12-20, 1 jun. 2006.
[11] ROEBBEN, G. et al. The innovative impulse excitation technique for high-temperature mechanical spectroscopy. Journal of Alloys and Compounds, [S. l.], p. 284-287, 28 set. 2000.
[12] KOLLURU, S.; POPOVICS, J.; SHAH, S. Determining Elastic Properties of Concrete Using Vibrational Resonance Frequencies of Standard Test Cylinders. Cement, Concrete and Aggregates, [s. l.], p. 81-89, 1 dez. 2000.
[13] RAMIREZ P. ARAUJO, I.G. UNILAstic: Equipment and software to evaluate mechanical properties of materials by acoustic test. The XLIII Ibero-Latin American Congress on Computational Methods in Engineering CILAMCE 2020
[14] MORSY, R. et al Use of tee random decrement technique for nondetestructive detection of damage to beams. Materials and Structures, [s.l.], p. 4727, 9 fev. 2016. Disponivel em: https://bit.ly/2UPm6ci. Acesso em:05 de jun.2022