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STATIC AND DYNAMIC ELASTICITY MODULE ANALYSIS OF CEMENT COATING MORTARS

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ABSTRACT

Deformability studies of coating mortars contribute to minimize one of the most common anomalies in building facades which is crack appearance and propagation. Many of these cracks appear due to internal stresses in the coating mortar, as a result of imposed displacement or of imposed restriction by the underlying support structure. These deformability studies should include one or more experimental methods to determine the modulus of elasticity (*E*) of the coating mortars in question. This paper presents a series of experimental tests carried out to determine *E* for cement coating mortar specimens, namely two dynamic experimental procedures and a novel procedure to determine the static *E* value. The results from the dynamic and static tests are compared to further verify the reliability of the new procedure.

Keywords: coating mortar, static modulus of elasticity, dynamic modulus of elasticity.

INTRODUCTION

Coating mortars should have the ability to deform, without critical failure, when subjected to loading actions due to thermal cycles or shrinkage of the mortar itself. When the mortar cannot cope with these deformations, internal stresses arise in the coating, which can lead to cracking. This is a common cause for the occurrence of one of the most frequent and most damaging anomalies in building facades, which compromises their aesthetic and protective purposes. To minimize this issue, knowledge of the coating mortars modulus of elasticity (*E)* is essential during the design process, in order to achieve proper compatibility between the mortar and the underlying support structure regarding material deformability. Although the importance of *E* in the characterization of mortars is well known, scientific publications on the subject are still scarce and widely dispersed regarding which one is the best evaluation method to determine *E*. The lack of consensus regarding which method is more appropriate to use for these tests makes it difficult to characterize and compare mortars.

There are two major methodologies to experimentally determine *E* for coating mortars: static experimental procedures and dynamic experimental procedures (Tamin, 1986). The results obtained from static procedures are more reliable than those obtained with dynamic procedures (Mehta, 2001), but since there is no consensus on a reliable and viable static test procedure for mortars, civil engineers are led to use dynamic *E* values (Farinha, 2015). This study aims to develop an experimental procedure to determine the static *E* for mortars, beginning with cement coating mortar specimens, and compare these results with those obtained with two dynamic experimental procedures. The final goal is to establish a standard experimental procedure to determine the static *E* to be applied in LNEC studies, and eventually for widespread application by other entities.

EXPERIMENTAL CAMPAIGN

For this study, the experimental procedures used to determine the static and dynamic *E* made use of standard prismatic 40x40x160 mm test specimens (European Committee for Standardization, 2006a) (Figure 1).

Fig. 1 - Group of specimens used in the experimental tests performed in this study

The experimental campaign was performed with two cement coating mortar compositions with a volumetric binder aggregate ratio of 1:2 and 1:4 (cement: aggregate). Mechanical characterization tests were performed on each cement mortar composition after an initial curing process. The mechanical characterization testing campaign included several tests, namely: determination of the flexural and compressive strength of the coating mortar specimens and determination of the dynamic *E* by the Resonance Frequency method and by the Ultrasonic method.

Then the dynamic and static *E* values were determined on specimens from both cement coating mortar compositions for different curing ages, using both dynamic experimental methods previously mentioned and the novel static experimental method. For each type of test, three specimens were used. Table 1 summarizes the types of tests performed on the test specimens produced for this study, specifying the curing age for each test performed.

Table 1 - Experimental campaign summary

Specimen identification	**Binder aggregate ratio**	**Characterization tests**	**Resonance Frequency**	**Ultrasonic**	**Static procedure**
Ri6/14_EES_1 Ri6/14_EES_2 Ri6/14_EES_3	1:4	83 days of age	-	-	-
Ri6/14_EES_4 Ri6/14_EES_5 Ri6/14_EES_6		-	166 days of age	161 days of age	132 days of age
Ri6/14_EES_10 Ri6/14_EES_11 Ri6/14_EES_12	1:2	-	115 days of age	110 days of age	83 to 94 days of age
Ri6/14_EES_16 Ri6/14_EES_17 Ri6/14_EES_18		32 days of age	-	-	-

The mortar was mixed using a laboratory mixer. Fresh-mortar workability tests were carried out for all trial mixes, according to the standard EN 1015-3 (European Committee for Standardization, 2006b). Mortar plasticity values on the shaking table ranged from 160 to 170 mm. Table 2 describes the composition of the cement coating mortars used.

Table 2 - Cement coating mortar compositions used in this study

Cement mortar composition	Water/powder ratio [%]	Bulk density of the fresh mortar [kg/m^3]	Consistency [mm]
1:2	13.6	2050.0	166
1:4	17.9	1996.8	163

The initial curing process of the specimens was performed in a controlled environment, following the requirements of the standard EN 1015-11 (European Committee for Standardization, 2006a). This process begins with the placement of the mould inside a plastic bag of polyethylene for 2 days, ensuring a relative humidity of 95 ± 5%, in a room at 20 ± 2 °C and relative humidity of 65 ± 5%. Subsequently, the specimens were demoulded and kept under the same curing conditions for 5 days, after which the specimens were removed from the bag and remained in the conditioned room until the date of the tests.

EXPERIMENTAL PROCEDURES DESCRIPTION

For the dynamic *E* tests, the two procedures used were the Resonance Frequency dynamic procedure, according to the standard CSN EN 14146 (European Committee for Standardization, 2004a), and the Ultrasonic dynamic procedure according to the standard CSN EN 12504-4 (European Committee for Standardization, 2004b).

The Resonance Frequency dynamic procedure is a non-destructive test that consists in inducing a vibration signal along the test specimen, in order to determine its resonance frequency and then the corresponding *E* value. This procedure was performed on a Zeus ZRM 2005 test machine, using the longitudinal resonance frequency. The specimen is attached to the measuring apparatus through its mid-section, thus placing the actuator on one end and the signal receiver in the other, forcing the vibration signal to pass through its entire length (Figure 2, left). This signal induces small amplitude displacements on the specimen, proportional to how close the frequency of the signal is to the resonance frequency of the specimen. Displaying the output data in a frequency spectrum, the frequency with the highest peak corresponds to the fundamental resonance frequency (*F*) of the specimen. The dynamic *E* can then be calculated using the following formula:

$$E_d = 4L^2 * F^2 * \rho * 10^{-9} \quad (1)$$

where:

- E_d is the dynamic modulus of elasticity [GPa];
- L is the length of the specimen [m];
- F is the fundamental resonance frequency [Hz];
- ρ is the bulk density of the specimen [kg/m^3].

The Ultrasonic dynamic procedure is another non-destructive test that determines the specimen's *E* value based on the speed that ultrasonic waves propagate through the specimen.

This procedure was carried out using a Steinkamp Ultrasonic tester BP-7 (Figure 2, right) with the indirect method. This method requires several readings along the specimen using the two test probes, with the receiver probe staying near one end of the specimen and the transmitter probe moving at regular intervals along the specimen's length. The travel time, measured in microseconds, between probes is acquired for each point along the specimen. This data is then plotted against the corresponding displacement of the transmitter probe along the specimen to determine the average ultrasonic speed for the specimen (v). Then the *E* value is calculated according to the following formula:

$$E_d = \frac{(1+\upsilon)*(1-2*\upsilon)}{(1-\upsilon)} * \mathrm{v}^2 * \rho * 10^{-9} \qquad (2)$$

where:

- E_d is the dynamic modulus of elasticity [GPa];
- v is ultrasonic speed for the specimen [m/s];
- υ is the Poisson coefficient of the specimen's mortar [Hz];
- ρ is the bulk density of the specimen [kg/m^3].

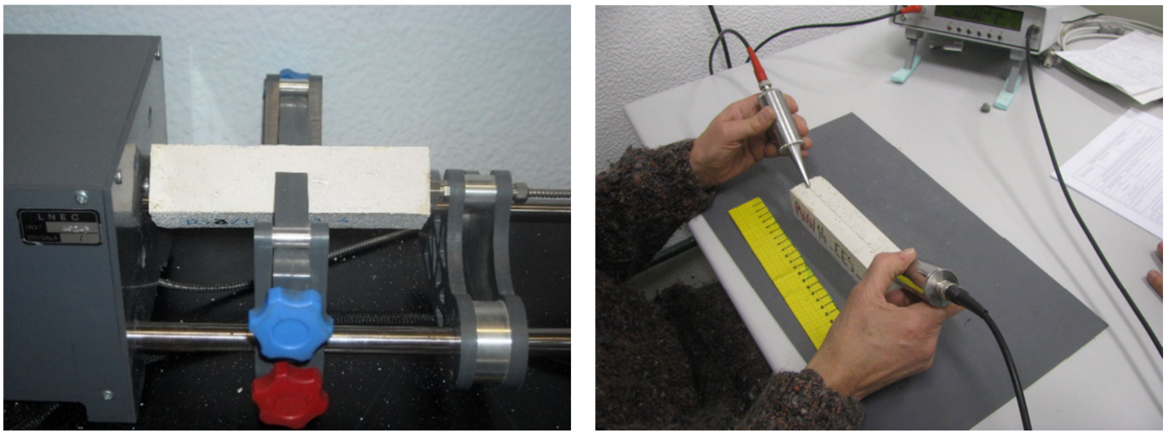

Fig. 2 - (left) Resonance Frequency dynamic test and (right) Ultrasonic dynamic test

The test to determine the flexural strength was performed in accordance with the standard EN 1015-11 (European Committee for Standardization, 2006a). The purpose of this test is to obtain the flexural strength of the hardened mortar, by applying a half-span load to a simply supported prismatic specimen, as depicted in Figure 3. The specimen is placed on the test machine and is centred with the longitudinal axis perpendicular to the two supports. The load is applied at the mid-span through an upper bearing point, by imposing a loading rate between 10 and 50 N/s. The loading rate chosen must ensure that specimen's failure occurs between 30 to 90 seconds after the test start. The applied load is monitored through a load cell until the end of the test. The flexural strength is given by the following formula:

$$f_t = 1.5 * \frac{F_f * l^2}{b * d} \qquad (3)$$

where:

- f_t is the flexural strength [MPa];
- F_f is the maximum flexural load applied to the specimen [N];
- l is the distance between the bottom supports [mm];
- b is the width of the test specimen [mm];
- d is the height of the test specimen [mm].

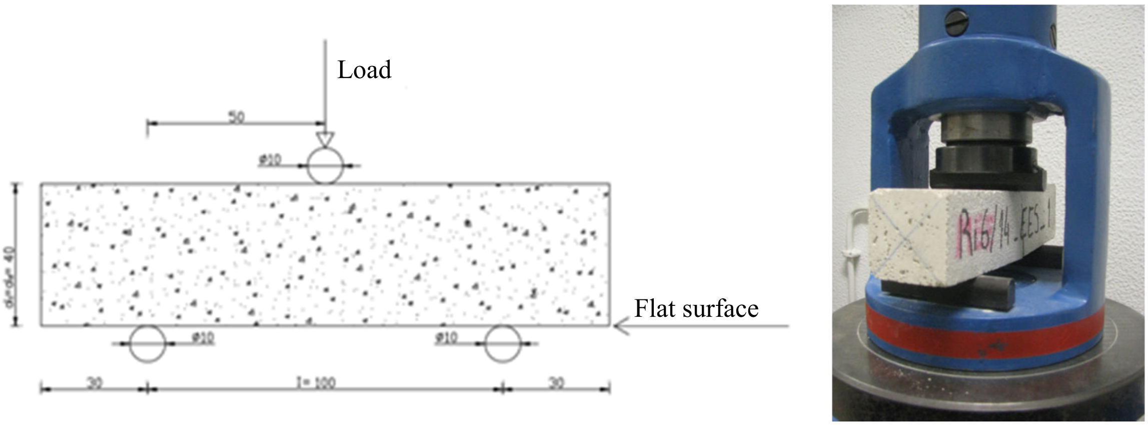

Fig. 3 - Flexural strength test: (left) representative diagram of the test and (right) specimen being tested

The test to determine the compressive strength was performed in accordance with the standard EN 1015-11 (European Committee for Standardization, 2006a). This test allows the determination of the compressive strength of hardened mortar by applying load until failure of the specimen. This test is performed on both resulting halves of each specimen after being submitted to the flexural strength test. Each half of the specimen is placed centred on the lower plate of the testing device on one of its flat surfaces. The upper plate of the device is lowered until it contacts the upper surface of the specimen, as shown in Figure 4. The loading rate used must ensure that specimen failure occurs between 30 to 90 seconds after the start of the test. The compressive strength can then be calculated with the following formula:

$$f_c = \frac{F_c}{A_c} \quad (5)$$

where:

- f_c is the compressive strength [MPa];
- F_c is the maximum compressive load applied to the specimen [N];
- A_c is the area of the specimen in contact with the plates of the testing device [mm^2].

Fig. 4 - compressive strength test

The static experimental procedure to determine the *E* value for coating mortars developed in this study aims to solve two of the major issues found by other researcher when working on this subject (Cikrle, 2005), namely improve the reliability of the collected data and solve the issues related to surface conditions of the specimen. The first issue was solved by using displacement transducers (Figure 5, left), which integrate a larger length of the specimen and so obtain more reliable results, as opposed to other solutions like extensometers applied directly to the specimen's surface. The second issue is mainly related with the difficulty of clamping the measuring device to the specimen without damaging the specimen or the device, while obtaining reliable data. This issue was solved by the application of a reinforcement layer of two component polyester putty on the clamping areas of each specimen (Figure 5, right).

Fig. 5 - (left) displacement transducer used and (right) reinforced areas of a test specimen

The static *E* tests were carried out on a mechanical test machine (ETI - HM-S/CPC from PROETI) using displacement control. The resulting load was recorded using a piezoelectric load cell installed in the test machine. The following methodology describes the experimental procedure developed to determine static *E* for coating mortar test specimens:

- Perform a 3-point bending test on a new specimen until failure;
- Perform a compression test on the two halves obtained from the previous test, to determine the failure compression stress for the material. The average value from both halves is taken as the failure compression stress value for the material;
- Perform a final cyclic compression test on a new specimen with 1/3 of the failure compression stress of the material. This test comprises one initial cycle to eliminate any gaps in the contact surfaces, followed by three full cycles. This test makes use of a dedicated device to measure the applied deformation to the specimen.

The dedicated device used in these tests is equipped with two displacement transducers, in opposing surfaces, to improve the quality of the results (Figure 6).

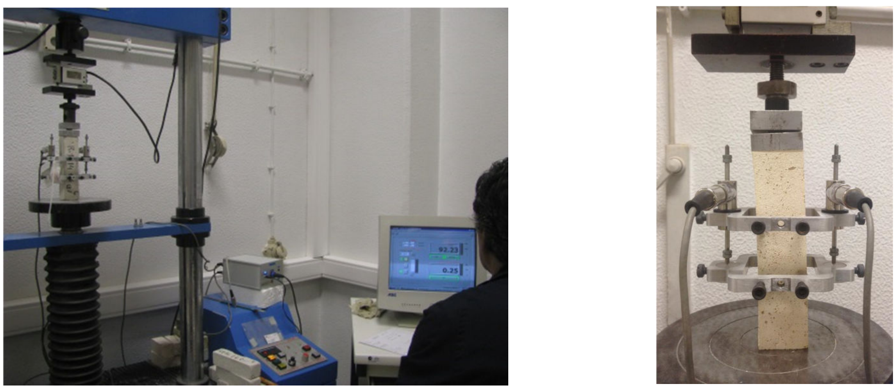

Fig. 6 - instrumented test specimen for a static *E* test

This device is made of two aluminium rings that are clamped to the test specimen by eight sharp pointed pressure screws, against the previously mentioned reinforced areas. The rings are attached to two different sections of the specimen as the test is taking place, allowing the displacement transducers to measure the displacement applied to the specimen between these sections.

In order to determine the static *E* of the specimen, a linear trend line is applied to the obtained load and displacement data. The slope of this trend line is the specimen's static *E* value, according to Hooke's Law.

RESULTS

This section presents the results of the tests previously described. Table 3 shows the average compressive and flexural strength of both cement coating mortar compositions, after the initial curing process. Table 4 shows their average dynamic *E* values at the same age.

Table 4 - Average compressive and flexural strength of both cement coating mortars compositions

Binder aggregate ratio	Curing age	Flexural strength [MPa]	Compressive strength [MPa]
1:2	32	6.1	29.4
1:4	83	1.5	5.8

Table 5 - Average dynamic *E* values of both cement coating mortars compositions

Binder aggregate ratio	Curing age	Resonance Frequency [MPa]	Ultrasonic [MPa]
1:2	32	25.45	19.6
1:4	83	9.6	8.16

Concerning the analysed coating mortars, the mechanical characterization values obtained are consistent with the available bibliography (Lucas, 2015). A good ratio between *E* and the compressive strength was also obtained. Figure 7 further illustrates these findings by comparing the dynamic *E* data with the compressive strength for both cement coating mortar compositions.

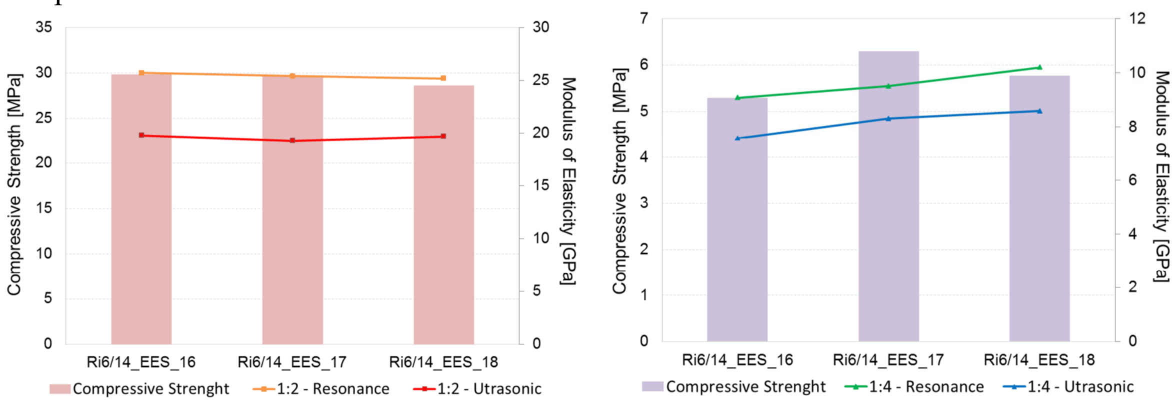

Fig. 7 - Compressive strength and *E* results from the mechanical characterizations tests performed on both cement coating mortar compositions

The main goal of these tests was to establish the reliability of the proposed experimental procedure to determine the static *E* value for coating mortars. To achieve this goal, the obtained results were analysed to ultimately compare the dynamic *E* values with the static *E* values.

Figure 8 illustrates an example of the displacement-time curve obtained from the three loading cycles of a static *E* test. In order to guarantee the quality of the experimental procedure, it was decided that each test would only be accepted if the data collected from both displacement transducers didn't differ between each other by more than 10 % of the maximum value.

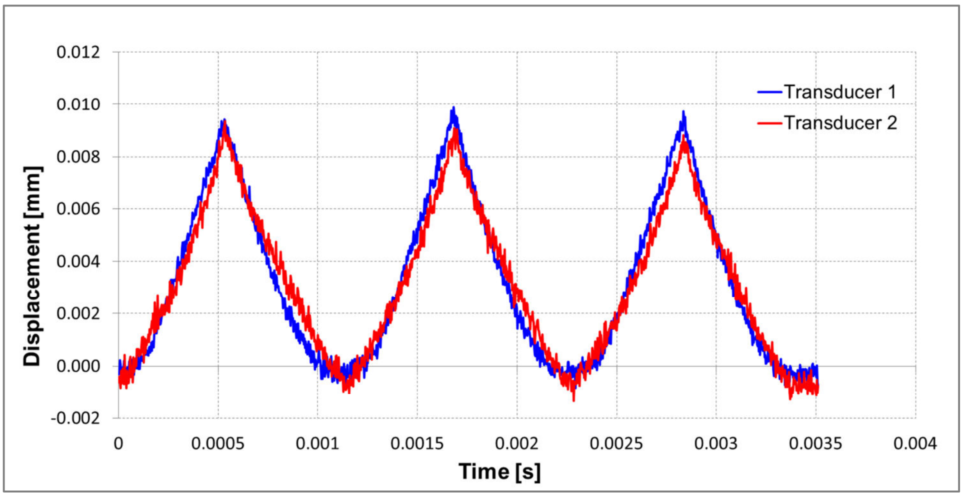

Fig. 8 - Displacement-time curve obtained from a static *E* test

The static *E* for each specimen is determined by tracing a linear trend line with the load and displacement data collected from the three loading cycles. In order to improve the quality of the results, the trend line excludes the data from the start and end of each loading cycle, since these regions tend to have more disturbances. Figure 9 illustrates an example of the stress-strain curve obtained from the three loading cycles, were the slope of the trend line gives a static *E* value of 7.13 GPa for this specimen.

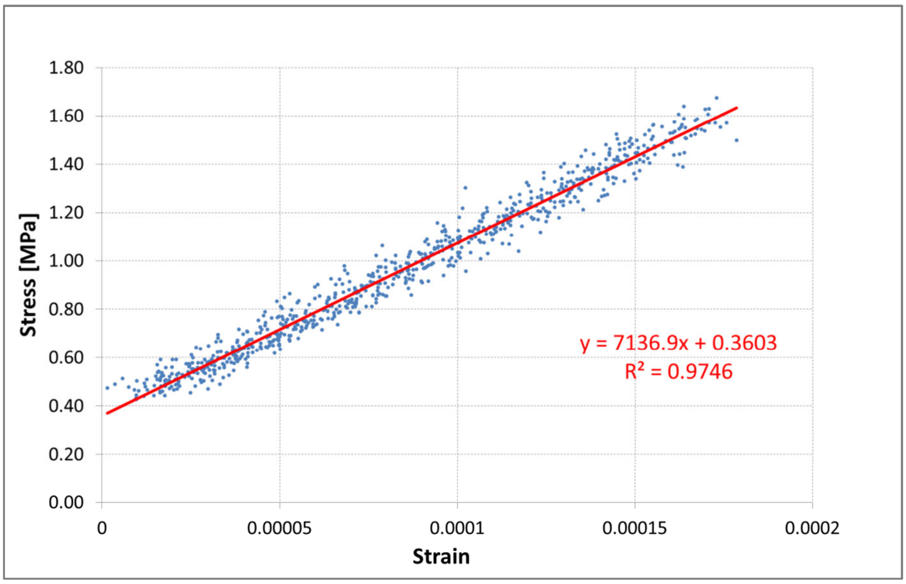

Fig. 9 - Stress-strain curve obtained from a static *E* test

Figure 10 compiles the overall results from the experimental testing campaign, by comparing the results obtained from both dynamic *E* procedures with the values from the static *E* procedure. As expected, the *E* value for cement coating mortars remains constant after the initial curing period, with a slight tendency to decrease with the passage of time. This is true for the dynamic and the static *E* values (Veiga, 2010). Based on this data and previous studies performed in LNEC, the data obtained from the Resonance Frequency procedure is more reliable and closer to the static *E* value than the Ultrasonic procedure. This is in accordance with the bibliography on the subject (Cikrle, 2005).

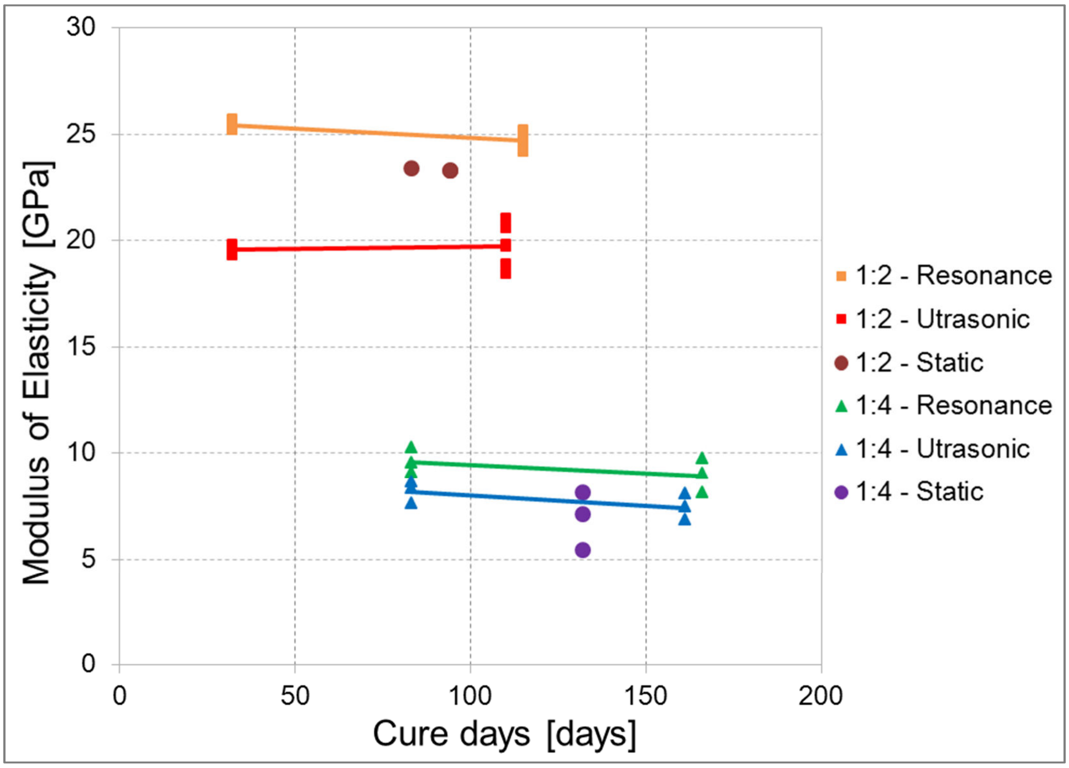

Fig. 10 - Overall *E* values from the entire testing campaign

Using the obtained *E* values, the average ratio (*C*) between the Resonance Frequency *E* and the static *E* was calculated for both cement coating mortar compositions (Table 5). This ratio can be used to estimate the static *E* value for a new specimen with a similar composition, through one of the dynamic *E* tests, thus saving time and resources. These *C* values are within the expectable range that can be found in the bibliography (Cikrle, 2005), and suggest that this ratio tends to decrease for the mechanically weaker coating mortars. A more complete experimental campaign must be performed to confirm this tendency.

Table 5 - Average ratios between the Resonance Frequency *E* and the static *E*

Binder aggregate ratio	Formula	Ratio C
1:2	$E_{static} = C * E_{dynamic}$	0.95
1:4		0.77

CONCLUSION

Based on the data collected from the preliminary tests performed so far, the results for the cement coating mortar specimens are well within the expectable range of static *E* values for cement specimens. These results suggest that this static *E* experimental procedure is valid, at least for cement mortar specimens. This new static procedure also solves some of the major experimental issues related with previous attempts on the subject.

Going forward, it is intended to apply the same procedure to air lime specimens to further verify the reliability of the procedure and of the obtainable static *E* values when compared with the *E* values attained with dynamic methods. Future testing campaigns will also include more tests with higher curing periods, both for cement and air lime specimens.

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