SIMPLE METHOD OF DYNAMIC YOUNG'S MODULUS DETERMINATION IN LIME AND CEMENT MORTARS

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ABSTRACT

This study demonstrates the feasibility of using a simple method to measure the resonant fundamental frequency for determining the MOE (dynamic Young's modulus) of lime and cement mortars.

The procedure follows the instructions stated in the UNE-EN ISO 12680-1 standard for refractory products although in this study the instructions are applied to standardized RILEM 4x4x16 cm test samples made of lime and cement mortars.

The simplicity of the procedure as well as its correlation to other measured variables, suggest that it can be widely applied in studies about the evolution of the physical characteristics in lime mortars, such as mechanical strength, static Young's modulus, carbonation depth, etc.

1.-Introduction

With respect to the mortars used for restoration, it is especially important to know its modulus of elasticity. Usually some of the cement mortars overstiffen the building causing changes in its structural performance.

Since those restoration mortars are formulated from air limes (with or without puzzolana) and hydraulic limes, it is interesting to know the procedure of the carbonating process, the mechanical resistance gain, the stiffness, etc.

One of the basic parameters in the resistance of the materials and therefore in the area of the buildings materials is the Young's modulus, which indicates the deformation capability of a given material in its linear elastic span depending on the strain to which is subjected.

The common method used in laboratory settings is the static testing by which mechanical properties of mortar lime are determined. Bearing in mind the assumption of homogeneity of the investigated media, elastic properties are characterized by a constant-static modulus that determines the relation between the stress and the strain applied.

Another group of techniques involves the application of non-destructive acoustic waves that have been successfully used in other materials such as wood, natural stones and refractory products.

The method enabling the determination of the dynamic modulus is relatively simple, inexpensive and suitable also for field application.

This non-destructive testing minimizes the possibility of rupture of the material or test specimens which represents a saving on the one hand and on the other provides new results for testing in the estimation of the material parameters.

For some of the specific materials, such as natural stone [1] and refractory products [2], the application of analysis methods of its fundamental natural frequency or resonant frequency in order to determine its MOE (dynamic Young's modulus) has been standardized although this standardization has not been made in the case of the mortars.

2.-Objective

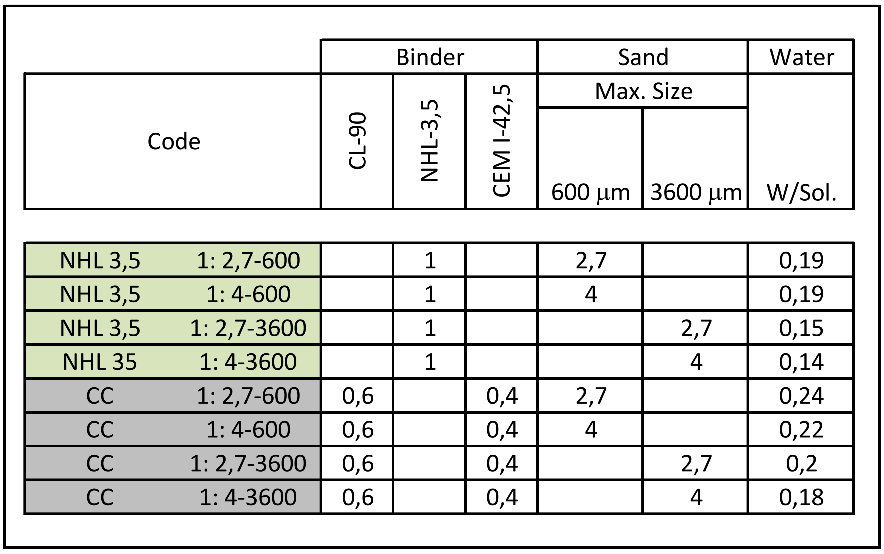
The aim of our work is to obtain some preliminary results for evaluating the possibility of applying the non-destructive test based on the resonant frequency analysis of mortars samples RILEM 4x4x16 made from very simple and economic elements.
With the aim to refine the determination of the mortars modulus of elasticity, some standards could be determined by the investigation.
Some of the tests we can use to calculate the relative reliability of those standards are:

- MOE (dynamic elasticity modulus of elasticity) determination test by impulse excitation of vibration and the subsequent analysis of the resonant basic frequency.
- MOE determination test from the velocity at which ultrasonic impulses propagates through the sample.
- Static flexural test to obtain the linear spam of the stretch-deformation graph.
- Flexural and compressive fracture test.

3.-Mortars to test

Since the main objective of this work is to study the validation and reliability of the non-destructive testing methods, the mention of this point will be brief and only to illustrate results more clearly.

The natural frequency analysis test will be applied on standard specimens according to RILEM 4x4x16 cm. The mortars are of 8 different types depending on the conglomerates and sand dosage, but the study is centred on two types of conglomerates (hydraulic lime NHL-3,5 and air lime CL-90 and Portland cement CEM I-42,5) and two types of aggregate granulometric curves of calcareous origin (Table 1).



Code		Binder			Sand		Water
		CL-90	NHL-3,5	CEM I-42,5	Max. Size		W/Sol.
					600 μm	3600 μm	
NHL 3,5	1: 2,7-600		1		2,7		0,19
NHL 3,5	1: 4-600		1		4		0,19
NHL 3,5	1: 2,7-3600		1			2,7	0,15
NHL 35	1: 4-3600		1			4	0,14
CC	1: 2,7-600	0,6		0,4	2,7		0,24
CC	1: 4-600	0,6		0,4	4		0,22
CC	1: 2,7-3600	0,6		0,4		2,7	0,2
CC	1: 4-3600	0,6		0,4		4	0,18

Table 1: Nomenclature and dosage

The quantity of water for the mixture has been defined by a settlement in a 155±5 mm shaking table according to standard [3] and the curing process has followed this schedule:

- 7 days in a saturated environment in a wet chamber (R.H. >95% and 18◦±1).
- 21 days in laboratory environment (RH 50% ±5 and 20◦C ±2)
- Drying in a mould dryer at 60◦C until even temperature.

4. Young's modulus determination

In order to find the density of each of the mortar types that constitute the specimens, it is necessary to determine its weight with a precision balance of 0,01 g as well as its length, width and thickness with a gauge (as the slide-gage of 0,01 mm).

4.1. Longitudinal MOE by impact (MOE $_{long}$)

The most important task is to obtain the fundamental mode resonant frequency when the specimen is subjected to an instantaneous pulse (beating) and to register the signal or the frequency spectrum that this beating produces. The analysis of the signal is made by a software obtained in Fakopp [4] and based in the fast Fourier transform (FFT) that directly identifies the value of the higher intensity frequency.

A drawing of the equipment is shown in Figure 1. It match the diagram of blocks of the device as shown in [2].

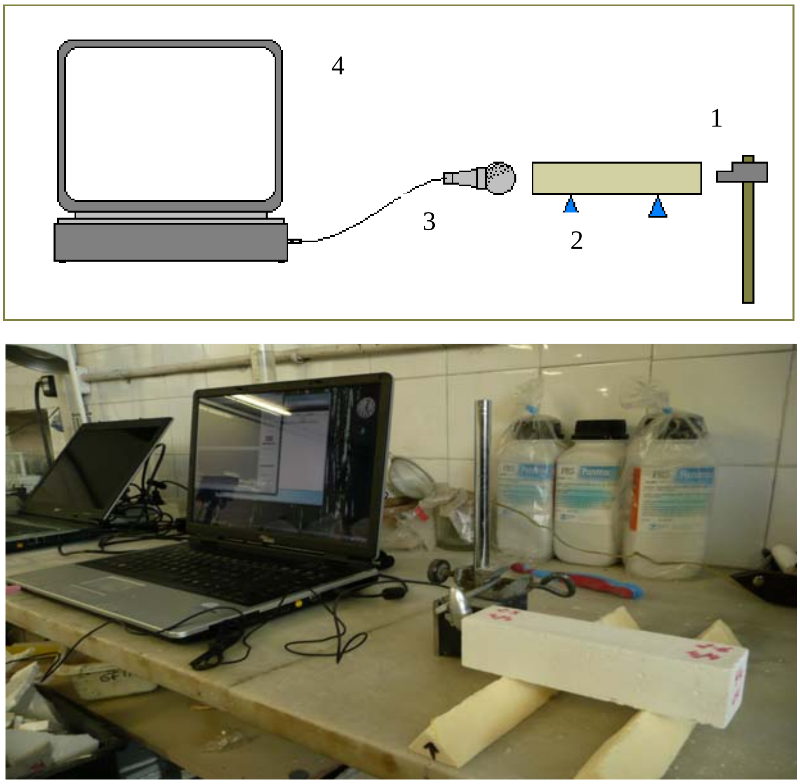


Fig. 1. Drawing and picture of the equipment

The device is composed of:

1. A plexor with an end made of steel or hardwood; its weight has to be suitable for preventing a physical movement of the specimens when the beating is produced. Appropriate plexor weight has to be a 5% of the specimen weight. The handle of the flexor has to be made of a nonrigid polymer material (methacrylate in this work).

2. Items for supporting the specimens or test samples. The role of the holders in this method is very important since they isolate mortar specimens from external vibrations and their position defines the vibration mode of the samples.

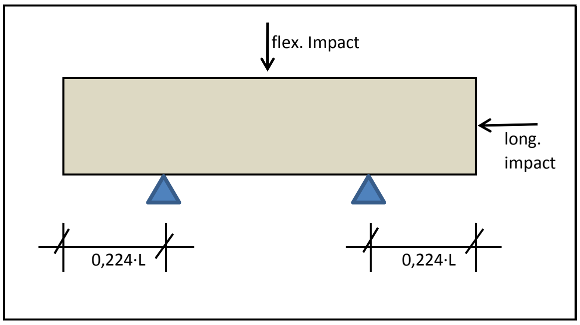


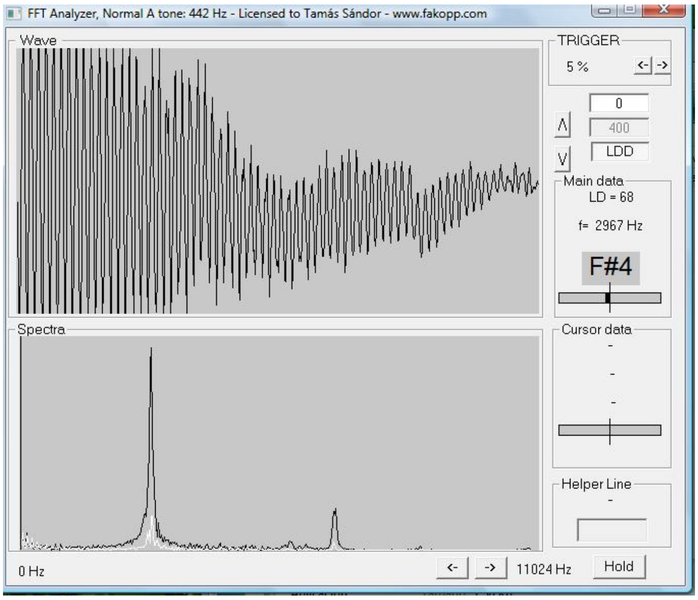
Fig. 2. Image of the support and impact zones

The holders being used are made of triangular prisma-shaped extrusioned polystyrene of 35 kg/m³ density and with sides of 3 cm. The samples are supported by the edges of this prism.

3. Signal register device. Non-contact signal transducers have been used in this study in order to prevent miscalculations caused by the flutters that could be generated by the slightest movement of the samples. Depending on the vibration frequency range of a given material, it will be necessary to choose a transducer able to correctly translate these frequencies. The transducers must be placed in the antinode points fixed in the standard.

4. Signal processing system and analysis software [4]. This is composed of: signal conditioner/amplifier, signal analyzer, display showing the frequency and the analysis of the obtained spectrum.

The image of the product we obtain is:



FFT Analyzer, Normal A tone: 442 Hz - Licensed to Tamás Sándor - www.fakopp.com

TRIGGER 5 %

Main data
LD = 68
f= 2967 Hz
F#4

Fig. 3. Screen image reproduction of the software used

From the value of the resonant frequency given in Hz, we can obtain the pulse velocity:

$$V = 2Lf$$

V = Velocity
L = test sample length (160 mm)
f = Resonant frequency

And using the density value, it is possible to calculate the MOE $_{long}$ value:

$$MOE_{long} = \rho v^2$$

ρ = density

The value we use as resonant frequency is the average value of six successive readings obtained with a maximum difference of 1% between them.

4.2. Flexural MOE (MOE$_{flex}$) by impact

Holding the specimens in the corresponding face to the bottom of the mould (face 1), and rotating them 90 degrees and holding in a lateral side of the mould (face 2), successive readings of the flexural resonant frequencies are made. Specifications described in standard [2] referring to the conditions of the holders, results calculations, etc., have been followed. It is considered a 0, 22 Poisson's ratio.

4.3. Longitudinal MOE (MOE_{us}) by ultrasound

A transmitting and receiving appliance of ultrasound C368 made by Matest, was used for this determination. This appliance has 55 kHz transceiver feelers.

It has been measured the required time by the ultrasonic pulse to go through the test sample in longitudinal direction (160 mm)

The velocity of the longitudinal propagation of ultrasonic waves through the specimen (V_{us}) has been determined as:

$$V = L/t$$

t = time it takes the ultrasonic waves to go through the sample

Longitudinal MOE by ultrasound has been calculated with the expression:

$$MOE_{long} = \rho v^2$$

4.4. Static MOE by flexotraction

The procedure to determine static Young's modulus has been to manipulate specimens with strain gages and carry out flexural test by means of load increments until the signal stabilization of tensile strength and unital strain (* *). Linear regression in the initial zone of the graph (Figure 5) allows determining the Young's modulus.
With the purpose of facilitating a larger flexural zone, pure and constant, a proof loading system in two points has been used (Figure 4).

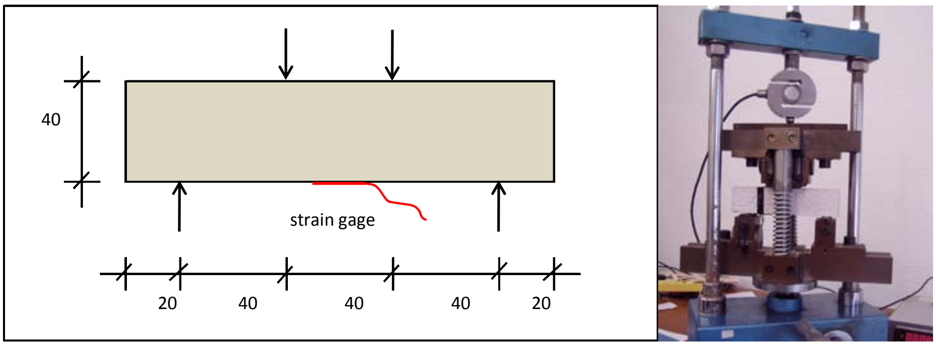


Fig. 4: Image of the load and supports working points

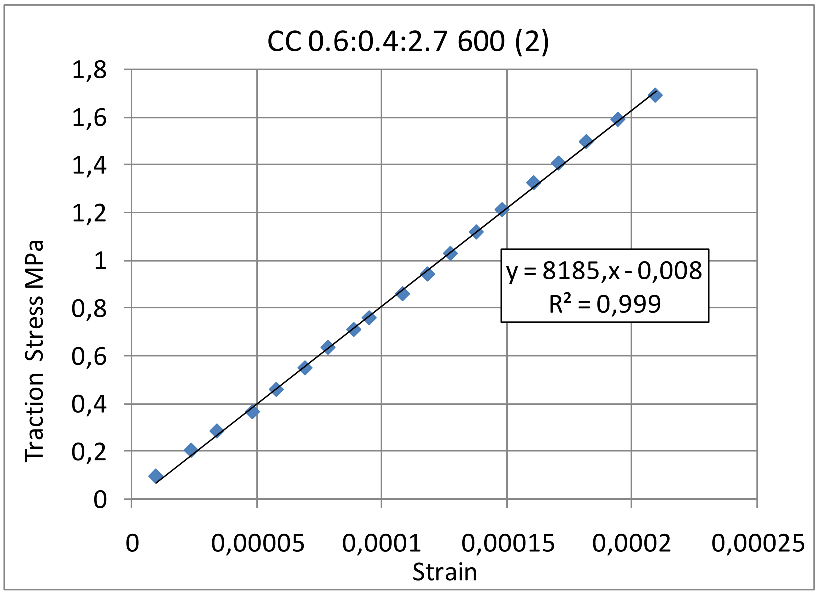


Fig. 5: Strain-traction stress graph in the linear-elastic zone

5. Experimental results and discussion

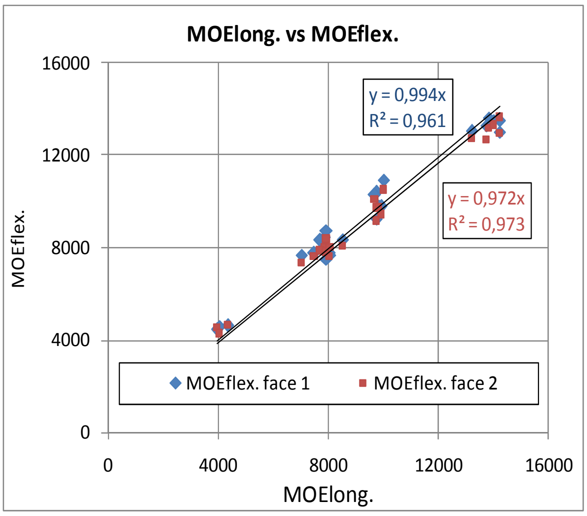
Table 2 represents the results of the non-destructive test for the MOE determination. Absolute errors for the MOE long and MOE flex determination have been omitted since only in one specimen the value exceeded 1%.

Values of the coefficients of variation expressed in % (C.V. %) of the results of each mixture, in general lower than 5%, prove the specimens' homogeneity and the reliability of the measurements.

Test		face 1	face 2	MOEflex. (MPa)			MOElong. (MPa)			MEAN MOE impact (long. & flex)			MOEus (MPa)		
NHL 3,5 1: 2,7-600	1	7656	7334	7495			7024			7259			8952		
	2	8346	8063	8205	C.V. %	4,7	8521	C.V. %	10,0	8363	C.V. %	7,3	10100	C.V. %	7,0
	3	7752	7614	7683	Media	7794	7488	Media	7678	7585	Media	7736	8975	Media	9342
NHL 3,5 1: 4-600	1	4450	4547	4498			3958			4228			5941		
	2	4612	4624	4618	C.V. %	2,1	4342	C.V. %	4,9	4480	C.V. %	3,3	5944	C.V. %	0,5
	3	4584	4272	4428	Media	4515	4037	Media	4112	4233	Media	4314	5997	Media	5961
NHL 3,5 1: 2,7-3600	1	10392	9723	10057			9742			9900			12366		
	2	10279	10090	10184	C.V. %	3,4	9674	C.V. %	1,8	9929	C.V. %	2,6	13001	C.V. %	2,5
	3	10934	10509	10722	Media	10321	10010	Media	9809	10366	Media	10065	12701	Media	12689
NHL 3,5 1: 4-3600	1	8423	8004	8214			7876			8045			10591		
	2	8741	8373	8557	C.V. %	2,9	7928	C.V. %	1,5	8242	C.V. %	2,2	10927	C.V. %	2,8
	3	8316	7862	8089	Media	8287	7702	Media	7835	7896	Media	8061	10344	Media	10620
CC 1: 2,7-600	1	9791	9736	9763			9848			9806			12197		
	2	9781	9450	9615	C.V. %	3,0	9913	C.V. %	0,8	9764	C.V. %	1,8	11991	C.V. %	2,3
	3	9255	9164	9209	Media	9529	9755	Media	9839	9482	Media	9684	11644	Media	11944
CC 1: 4-600	1	7771	7604	7687			8040			7864			10119		
	2	7510	7821	7665	C.V. %	1,1	7928	C.V. %	0,9	7796	C.V. %	0,9	10423	C.V. %	1,8
	3	7657	7994	7825	Media	7726	8064	Media	8011	7945	Media	7868	10457	Media	10333
CC 1: 2,7-3600	1	13511	12943	13227			14225			13726			16465		
	2	12987	13647	13317	C.V. %	1,3	14212	C.V. %	2,0	13765	C.V. %	1,6	16710	C.V. %	3,2
	3	13303	12672	12988	Media	13177	13739	Media	14059	13363	Media	13618	15713	Media	16296
CC 1: 4-3600	1	13630	13164	13397			13814			13606			19063		
	2	13493	13310	13402	C.V. %	2,2	13999	C.V. %	3,0	13700	C.V. %	2,6	18774	C.V. %	4,7
	3	13038	12742	12890	Media	13230	13219	Media	13677	13055	Media	13453	17434	Media	18424

Table 2. Results of several MOE

The result of the correlation between MOE long and MOE flex is shown in Figure 6, where the accuracy and correlation between both types of determinations are evident.



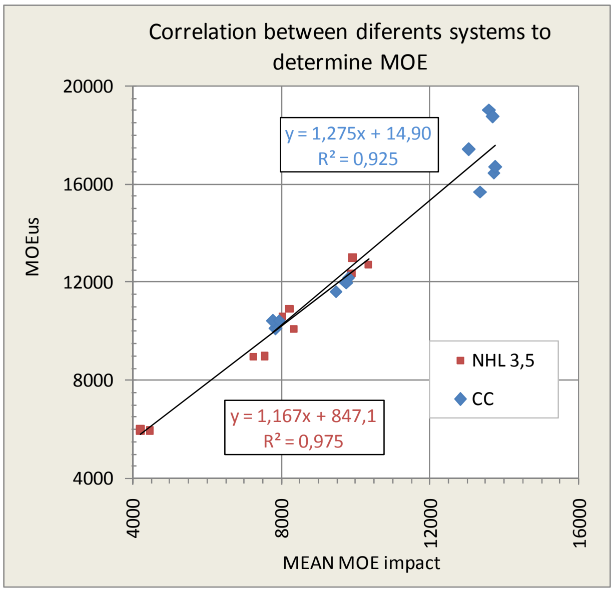


Fig. 6. Correlation between MOE long and MOEflex.

Fig. 7. Correlation between MOE impact and MOEus.

Figure 7 compares the results obtained by impact (average MOE long and MOE flex) with those determined by the velocity at which ultrasonic waves propagate. The correlation is excellent (R²of 0,97 and 0,92) although the values obtained by ultrasound are clearly higher (16 and 27%) than the impact ones.

Results corresponding to the determinations of the elasticity modulus by static flexure (E flex) and stress values of the flexotraction and compression tests are shown in table 3. Coefficients of variation values of the results of each mixture are clearly higher than the previous ones. As for the Young modulus, variability fluctuates between 5 and 18%.

Test		E bending			Traction stress Mpa			Compresion Stress MPa		
NHL 3,5 1: 2,7-600	1	7354			1,34			5,4		
	2	10055	C.V. %	15,6	1,37	C.V. %	1,5	6,7	C.V. %	15,5
	3	8590	Media	8666	1,33	Media	1,35	5,1	Media	5,71
NHL 3,5 1: 4-600	1	4684			0,78			2,6		
	2	4894	C.V. %	7,3	0,83	C.V. %	6,0	2,8	C.V. %	3,9
	3	5392	Media	4990	0,88	Media	0,83	2,6	Media	2,64
NHL 3,5 1: 2,7-3600	1	10765			1,9			6,0		
	2	9167	C.V. %	8,0	1,75	C.V. %	4,4	6,3	C.V. %	3,4
	3	10038	Media	9990	1,78	Media	1,81	5,8	Media	6,04
NHL 3,5 1: 4-3600	1	8480			1,09			4,6		
	2	7702	C.V. %	5,2	1,12	C.V. %	5,3	4,1	C.V. %	6,6
	3	8405	Media	8196	1,01	Media	1,07	4,2	Media	4,28
CC 1: 2,7-600	1	10526			2,57			10,5		
	2	8185	C.V. %	14,7	2,13	C.V. %	9,4	10,5	C.V. %	3,0
	3	8290	Media	9000	2,39	Media	2,36	10,0	Media	10,33
CC 1: 4-600	1	8914			1,97			7,7		
	2	10767	C.V. %	10,9	2,32	C.V. %	8,2	8,0	C.V. %	6,2
	3	9020	Media	9567	2,13	Media	2,14	7,1	Media	7,60
CC 1: 2,7-3600	1	12425			2,10			12,0		
	2		C.V. %	5,5	2,11	C.V. %	5,5	13,4	C.V. %	7,3
	3	13428	Media	12927	2,31	Media	2,17	11,6	Media	12,34
CC 1: 4-3600	1	15468			2,88			12,1		
	2	12040	C.V. %	17,6	2,51	C.V. %	10,4	10,9	C.V. %	6,9
	3	11174	Media	12894	2,36	Media	2,58	10,7	Media	11,24

Table 3. Results of E_{flex} and flexotraction and compression strength.

From the comparative analysis of all the results, we can highlight the high correlation between flexural Young's modulus and MOE by impact and ultrasound ($R^2$of 0.94 and 0,92) (Figure 8).
Linear relations between both methods can be established in the cases we have studied; they follow the expressions:

$$\text{MOE impact} = 1{,}17 \cdot E - 1800$$
$$\text{MOE ultrasound} = 1{,}46 \cdot E - 2000$$

E given in MPa

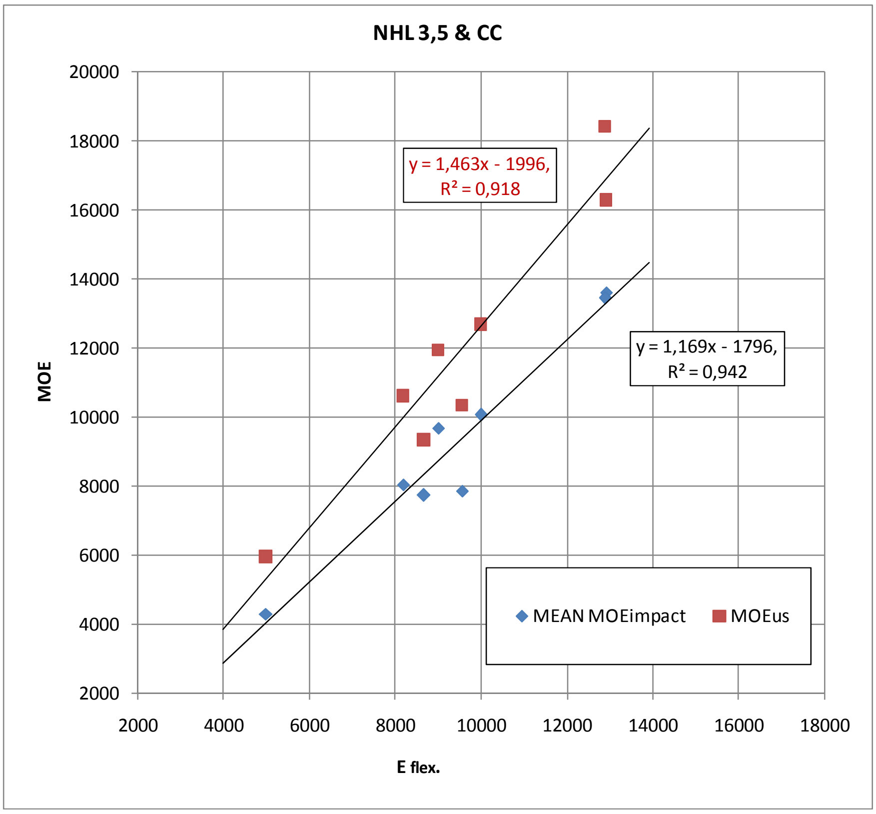


Fig. 8. Relation between MOE and Eflex

6. Conclusions

The measurement method of the dynamic Young's modulus by impulse excitation by vibration is extraordinary simple to use. When applied to mortars, it can be obtained results able to correlate with the other dynamic system studied (MOE by ultrasound) and with the determination of the static Young's modulus from the flexotraction test.
Standardized specimens RI.LEM 4x4x16 used in the ordinary mechanical tests are suitable to measure the dynamic modulus of elasticity.

The simplicity of the procedure and the reliability of the measures, as well as the low cost of the equipment (laptop and microphone) suggest that it could have widespread applicability of this procedure as a control tool in mortar factories. In addition, the method allows classifying mortars with greater simplicity according to their strain capacity and not only to their mechanical resistance.

The simplicity of the procedure as well as its correlation to other measured variables, suggest that this can be a methodology widely applied in studies on the evolution of the physical characteristics of lime mortars, such as mechanical strengths, static Young's modulus, carbonation depth, etc.

The aim of this paper is to demonstrate the importance of using non-destructive dynamic tests for solving stability problems of engineering projects. The experimentally obtained Young's modulus in laboratory indicates than there is a correlation expressed in form of an analytical function that helps to determine the corresponding static modulus. The results have been achieved under simplified assumptions since the relation for Young's modulus calculation is valid only for homogeneous and isotropic media while lime mortar, in general, does not comply with this condition.

Acknowledgments

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