ON SITE EVALUATION OF THE ELASTIC MODULUS OF CONCRETE

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ABSTRACT

A new experimental method for the on site determination of the elastic modulus of concrete is described. It is based on the pull-out test, which is commonly used for the estimate of concrete strength. The method consists in pulling out a metal insert embedded in the concrete mass and measuring the pulling force and the subsequent displacement of its point of application. In order to correctly detect the displacement and process the experimental data, it is needed to solve some technical problems such as:

- the control of the hole verticality: it is ensured by the use of three displacement transducers;
- the elimination of all phenomena of mutual sliding between the mechanical parts of the apparatus and between the insert and the concrete mass: it is achieved by performing an adequate number of loading - unloading cycles.

The stiffness value of the system is calculated through pull-out tests. The material deformability is then estimated through an appropriate correlation curve between stiffness and elastic modulus which has been worked out on the basis of finite elements simulations and experimental results.

The proposed method offers interesting possibilities of application for the characterization of existing structures at affordable costs.

1 INTRODUCTION

The need to estimate the elastic modulus of existing concrete structures is increasingly felt by designers and people who are involved in building repairs and maintenance. In fact, the widespread use of products for the restoration of damaged concrete members requires preliminary studies on compatibility between old and new materials, and therefore it becomes of great importance to ascertain their respective deformability characteristics. Moreover, the need of a viable method for the on site determination of the elastic modulus of concrete is due to the increasing attention devoted to serviceability conditions and hence to maximum deflections.

For new structures, the elastic modulus of concrete can be determined effectively by means of compressive tests on prism-shaped or cylinder-shaped specimens, while for existing structures the methods currently adopted often prove unsatisfactory: for example, the pulse wave tests are deeply influenced by humidity and testing conditions in general, as well as by the presence of surface discontinuities or reinforcing steel, while the compressive tests on core drilled specimens have the drawback that they must be performed in the laboratory, thus resulting in a higher cost.

The aim of this investigation is to develop a new method for the on site determination of the elastic modulus of concrete, which should be easy-to-perform, repeatable and accurate. The idea is to make use of the pull-out test [1 - 8], slightly modified in order to measure not only the pulling force but also the displacement of the extractor, and then to correlate the elastic modulus with the stiffness value of the extractor - concrete system. Several pull-out tests and standard tests on prism shaped specimens were performed; then a finite element simulation closely in keeping with actual testing conditions was made using various values of the elastic modulus as input data; finally a correlation linking the model stiffness to the Young's modulus of concrete was worked out on the basis of this simulation. Such a correlation was found to be in good agreement with the experimental data.

2 EXPERIMENTAL SETUP

2.1 Test specimens

Four types of concrete were examined in the course of the laboratory testing campaign. They differ form each other because of the cement proportions (which vary from 200 kg/m^3 to 300 kg/m^3) or the water/cement ratio (which is equal to 0,7 or 0,8), resulting in a strength spectrum that is fairly representative of the typical strength values of existing structures (see table 1).

The following test pieces were produced for each type of mix:

- No. 4 cubes, sized 16x16x16 cm^3 (for the compressive tests);
- No. 4 prisms, sized 16x16x50 cm^3 (for the elastic modulus tests and the pull-out tests).

They were water-cured for 28 days before testing.

In addition, 3 slabs (named I, II and III), having characteristics similar to those of mixes A, B, and C were used during the first experimental step (see par. 3.1).

Table 1 - Mix characteristics

Mix characteristics	Mix A	Mix B	Mix B1	Mix C
Cement Proportions	200 kg/m^3	250 kg/m^3	250 kg/m^3	300 kg/m^3
Type of cement	CEM I 42,5 R	CEM I 42,5 R	CEM I 42,5 R	CEM I 42,5 R
Cement density	3200 daN/m^3	3200 daN/m^3	3200 daN/m^3	3200 daN/m^3
Sand density (0 - 7)	2700 daN/m^3	2700 daN/m^3	2700 daN/m^3	2700 daN/m^3
Gravel density (7 – 15)	2600 daN/m^3	2600 daN/m^3	2600 daN/m^3	2600 daN/m^3
Sand proportion (by weight)	50%	50%	50%	50%
Gravel proportion (by weight)	50%	50%	50%	50%
Max. aggregate size	15 mm	15 mm	15 mm	15 mm
Water / cement ratio	0,7	0,7	0,8	0,7

2.2 Preliminary tests: determination of the cube strength and the elastic modulus

Four cubes sized 16x16x16 cm^3 for each type of mix were subjected to crushing tests in order to determine the average cube strength of the mixes according to UNI EN 12390-3 (see table 2).

Similarly, three prisms sized 16x16x50 cm^3 per mix were used to determine the elastic modulus according to UNI EN 13412 (see table 2).

Table 2 - Average values of cube strength and elastic modulus

Mix	Failure stress (°) [MPa]	Elastic modulus (°°) [MPa]
A	20,64	24˙662
B1	11,52	18˙471
B	20,77	25˙177
C	18,84	22˙654
	(°) average value of four tests	(°°) average value of three tests

2.3 Pull-out tests

The prism shaped specimens previously used to determine the elastic modulus were later subjected to pull-out tests. On the whole, between 15-18 extractions were performed on each type of mix.

The insert used is commonly available on the market and consisted of a mechanical block that is embedded in the concrete mass through geometric type expansion. Its anchor length is equal to 40 mm and the drill diameter is equal to 14 mm (see fig. 1).

The testing apparatus consisted of an electric-hydraulic system for the gradual pull-out of the insert and for the continuous measurement of both the load applied and the displacement of the extractor. By means of a manual pump, the oil in the hydraulic circuit is pressurised thus activating a hydraulic jack; the latter applies the pulling force to the extractor (which connects the insert to the jack itself) reacting against a bearing ring with internal diameter measuring 70 mm; at the same time, a digital system for data amplification, conditioning and acquisition records the electrical signals received from a pressure cell and three inductive bridge transducers connected to the extractor. The latter have a nominal stroke of ± 10mm with a precision class of 0,1%.

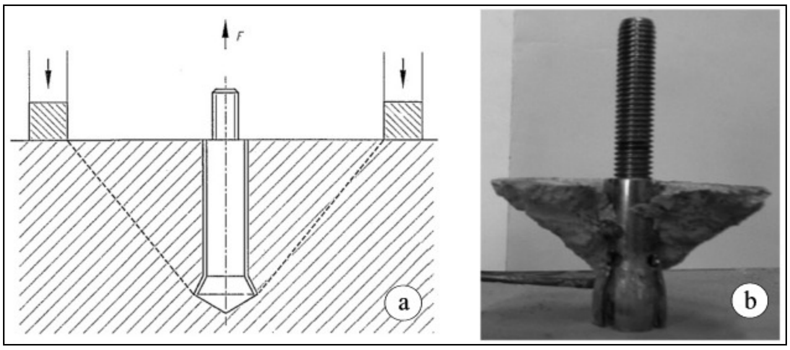

Fig. 1 - Outline of the geometric configuration (a) and detail of the insert after the extraction (b)

The choice of the number and the arrangement of the displacement transducers was made based on the following considerations: as for their position, a FEM analysis preliminarily made revealed that the geometric configuration and the loads considered are such that the effects due to the application of the pulling force are negligible at a distance of 150 mm from the axis of the extractor and therefore the displacement transducers were placed in this position; as for their number, it was determined in order to correctly identify a plane in a Cartesian reference system and consequently the displacement of the extractor with respect to the undisturbed concrete surface results from the intersection between such a plane and the vertical axis identified by the extractor itself.

3 TEST RESULTS AND DISCUSSION

3.1 First experimental step

Through eight preliminary extractions (two per mix) the pull-out failure strength was determined.

In order to obtain a load vs. displacement curve suitable for the determination of the actual stiffness of the system, it is necessary to perform a certain number of loading - unloading cycles during each test, so as to eliminate all phenomena of mutual sliding between the elements of the structure which might distort the displacement measurements.

The loading interval within which to perform the stabilization cycles and the number of cycles were determined through preliminary pull-out tests made on three concrete slabs (named I, II and III) whose characteristics were similar to those of mixes A, B, B1 and C. Three loading ranges were defined as a function of the pull-out failure strength, 15%-35%, 20%-40%, 30%-50%: they are deliberately low in order to avoid the onset of microcracking phenomena that would affect the material characteristics. Subsequently, on each slab and for each loading range four tests consisting in 10 loading - unloading cycles were performed and the evolution of the strain difference per cycle was analyzed: it was found that the system tends to stabilize quite rapidly and after 5 cycles the damping is on average 70%-80%, which was considered satisfactory. Besides, at the fifth cycle, the damping is more marked for loading ranges of 20%-40% and 30%-50%. Based on the foregoing results, it was decided to perform 5 loading - unloading cycles in a loading range of 20%-50%.

3.2 Second experimental step

The pull-out tests thus set up were then performed on mixes A, B, B1, C and the subsequent load vs. displacement curves were plotted (see fig. 2). The experimental stiffness values $K_{test,\ i}$ (i = 1 to 5), i.e. the values of the slopes of the curve in each cycle, were calculated at the reloading stage and it was decided to assume as representative value the one obtained for the fifth cycle (K_{test} = $K_{test,\ 5}$), by analogy with the procedure adopted in standard elastic modulus tests. Finally, the average value of the experimental stiffnes, ($\overline{K}_{test}$), was calculated for each type of mix.

The stiffness value obtained from the tests includes the elongation of the extractor stem connecting the insert to the hydraulic jack. Accordingly, it proves necessary to correct the stiffness value obtained to take into account the stiffness associated with the connecting stem, K_{stem}, through the formula:

$$\overline{K}_{net} = \frac{\overline{K}_{test} \cdot K_{stem}}{K_{stem} - \overline{K}_{test}}$$

whose simple demonstration is omitted.

The stiffness associated with the connecting stem, K_{stem}, was determined through a FEM analysis, while the stiffness of the other components of the testing apparatus can be assumed to be infinite.

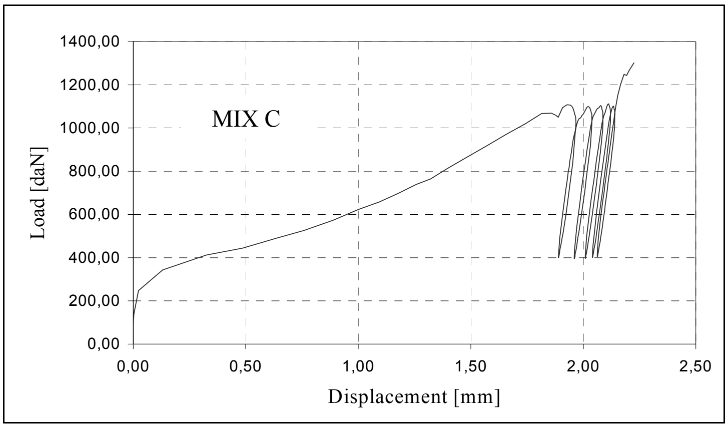

Fig. 2 - Typical load vs. displacement curve obtained through pull-out tests (mix C)

4 FEM SIMULATION

The pull-out test was simulated through a finite elements code with the aim of evaluating the relation existing between the elastic modulus of concrete and the stiffness of the material itself in the conditions of pull-out tests.

Consistently with actual testing conditions, the model adopted was axisymmetric and the analysis chosen was linear elastic because the pulling force applied in order to calculate the experimental stiffness is a small percentage of the pull-out failure strength (20%-50%). Moreover, the system was assumed to be continuous because the mutual sliding between the insert and the concrete mass could be considered completely exhausted at the end of the stabilisation cycles.

With these hypotheses, the equation that rules the system is expressed by the following well known formula:

$$\sigma = C\varepsilon \tag{1}$$

where (being $\tau_{xz} = \tau_{yz} = 0$ and $\gamma_{xz} = \gamma_{yz} = 0$ because of the axial symmetry):

$$\sigma = \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \\ \sigma_z \end{bmatrix} \qquad \varepsilon = \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \\ \varepsilon_z \end{bmatrix} \qquad C = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)} \begin{bmatrix} 1 & \frac{\nu}{1-\nu} & 0 & \frac{\nu}{1-\nu} \\ \frac{\nu}{1-\nu} & 1 & 0 & \frac{\nu}{1-\nu} \\ 0 & 0 & \frac{1-2\nu}{2(1-\nu)} & 0 \\ \frac{\nu}{1-\nu} & \frac{\nu}{1-\nu} & 0 & 1 \end{bmatrix} \tag{2}$$

Since the variation of the Poisson's ratio does not sensibly affect the results (both in terms of displacement and stress field), the value of $\nu = 0{,}2$ was used throughout the simulation, while the Young's modulus varied from 15˙000 MPa to 45˙000 MPa in steps of 2˙500 MPa: consequently, the stiffness values relating to the pull-out tests can be determined as a function of the elastic modulus, thus making it possible to study the relation existing between such quantities. It must be remarked that the spectrum of values considered for the Young's modulus is deliberately wide, because it should cover the extreme cases of very low quality concrete (due to inadequate casting, for example) and rock materials (which may be considered as concrete with very high elastic modulus, in the absence of rock discontinuities).

The results of the simulation show a good parabolic relation between pull-out stiffness and elastic modulus. The correlation curve obtained through the finite elements simulation is in good agreement with the experimental data, as shown in fig. 3, and therefore could be used for the estimate of the elastic modulus of concrete directly on site.

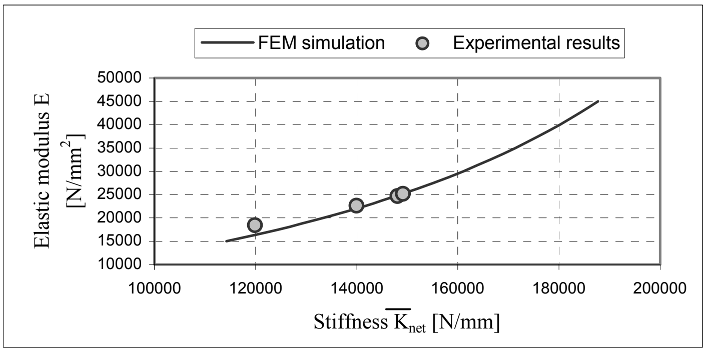

Fig. 3 - Test results and FEM curve

5 CONCLUSIONS

The primary goal of this investigation was to work out a method for the determination of the elastic modulus of concrete through pull-out tests with post-inserted blocks, to be able to propose the pull-out technique as a non-destructive procedure suitable for the estimate of the mechanical deformability of concrete in existing structures of any kind. The proposed testing procedure consists of the following steps:

1. Determining the pull-out strength through a preliminary test.
2. Completing five loading - unloading cycles within the loading range going from 20% to 50% of the pull-out strength.
3. Acquiring the data and plotting the complete load vs. displacement curve for the single tests.
4. Identifying the representative stiffness value as the one obtained for the fifth cycle.
5. Repeating the test a certain number of times in order to compensate for the variability in the results and considering the average stiffness value, conveniently corrected in order to take into account the stiffness of the extractor stem.
6. Using the correlation curve to estimate the elastic modulus: locating the point where the vertical straight line x = $\overline{K}_{net}$ intersects the correlation curve and reading the corresponding value of the Young's modulus on the ordinate axis.

The proposed method presents some advantages: it is "non destructive": it can be easily seen, in fact, that the damage caused to a structure is decidedly limited, can be readily repaired and will not give rise to a weak point in the structure; therefore it is suitable for assessing existing structures;

- it is simple to perform: the entire testing apparatus can be easily moved even to places that are hard to reach, and is sturdy enough for use at building sites, even underground;
- it is quite quick and inexpensive;
- it makes it possible to seek the point-by-point variations in the elastic modulus of the structure.

However, it needs further refinement and experimental validation, in the perspective to identify the possible factors of influence and optimise the number of tests to perform.

6 ACKNOWLEDGEMENTS

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