MONITORING ELASTIC PROPERTIES OF CONCRETE SINCE VERY EARLY AGE BY MEANS OF CYCLIC LOADINGS, ULTRASONIC MEASUREMENTS, NATURAL RESONANT FREQUENCY OF COMPOSITE BEAM (EMM-ARM) AND WITH SMART AGGREGATES

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Keywords: Early age behaviour of concrete, Young’s modulus, round robin test, dynamic testing, ultrasonic measurements

Abstract: Early age cracking of structures often leads to aesthetic problems and service life reduction. Among the parameters involved in the stress build-up that causes this cracking process, the stiffness evolution is of major importance for models and numerical computations. This paper reports the use of six different techniques aimed for stiffness evolution assessment, applied on the same concrete mix, in a round robin experimental test within three laboratories. The observations are compared after having expressed the results at the same maturity. Some of the reported techniques provide original means for Young’s modulus monitoring of concrete at early age both for industrial and research applications. Two sets of results emerge. Ultrasonic measurements provide values of Young's modulus much higher than the values provided by the static or quasi static tests at the time of the concrete setting. This difference decreases as the concrete hardens.

1 INTRODUCTION

At early age, numerous parameters are involved in the cracking process of concrete structures. Service life, permeability or aesthetic are affected by these damages.

Before the setting time, important changes in volume may produce internal fractures mainly due to the relative movements between concrete and rebars. They can be avoided by adequate casting procedures and limiting the desiccation.

Assuming that concrete is properly cured in this early period and that no damage affects the structure, other volume changes appear after setting. They are mainly due to temperature changes, self desiccation and drying. In the case of restrained deformations, cracks can be induced depending on the competition between the stresses induced by these restrained deformations and the tensile strength of the material.

As stresses induced by restrained deformation are involved in the cracking process, the Young’s modulus evolution of concrete, since the earliest age, is of major importance both for modelling and numerical computation purposes. That is why, among our three laboratories, a round-robin experimental test has been performed. Six different techniques were applied on the same ordinary concrete in order to monitor the stiffness evolution since the earliest age:

- Classical loadings in the hardened state;
- Cyclic loadings with a recently developed equipment (BTJASPE) [1] and on cylinders removed from their mould just after the setting time;
- Cyclic loadings on a TSTM machine [2];

- A new method based on the natural resonant frequency of a composite beam (EMM-ARM) [3];
- Ultrasonic measurements [4] using classical equipment.
- Ultrasonic measurements using a new type of sensors (Smart aggregates or SMAGs) embedded in concrete [5].

The observations can be compared after having expressed the results at the same maturity (equivalent time method).

These techniques scan a wide variety of ways for monitoring the Young's modulus of concrete since the earliest age, for both industrial and research applications.

2 MIXING AND MATERIALS CHARACTERIZATION

The same material is used in the three laboratories. The mixture proportions are given in Table 1.

Table 1 - Mixture proportions of the concrete, w/c: 0.54.

Components	**Mass (kg /m^3)**
CEM I 52.5 N PMES CP2	340
Sand (Bernières 0/4)	739
Gravel (Bernières 8/22)	1072
Total water	184

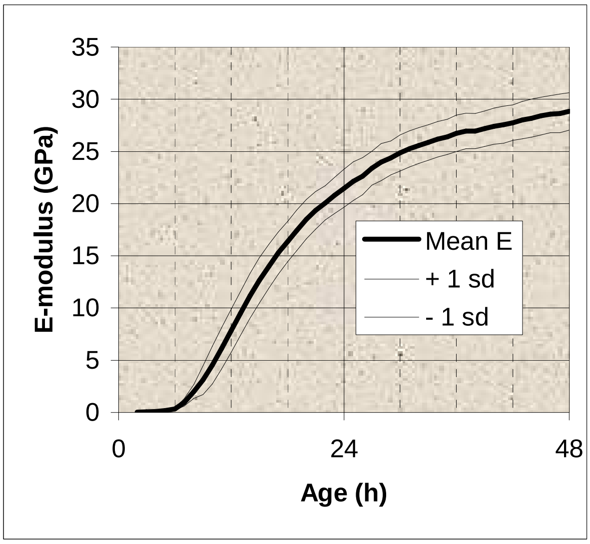

Figure 1: Scattering of the results with manual and mechanical mixing (± 1 standard deviation around the mean values of the 8 tests presented in section 3.2.

Fresh concrete was mixed mechanically or manually depending on the volume of the batch (from 2 litres to approx. 30 litres). Even though these differences can lead to scattered results, no significant effect was observed in the performed experiments. Indeed, a series of 8 tests performed with the techniques presented hereafter in section 3.2, led to a coefficient of variation of the E-modulus not greater than 13 % over a period ranging from the setting of the concrete to 48 hours (Figure 1).

The strength evolution in compression and in tension was characterized with classical tests from just after setting until 180 days. Such information was useful for quantifying the limits of the automatic loadings applied at early age in order to avoid any damage of the samples. The samples were cylinders (Ø 11 cm x 22 cm and Ø 16 cm x 32 cm). They were cured inside auto adhesive aluminium tape at 20ºC, and capped with sulphur mortar. Results are reported on Figure 2.

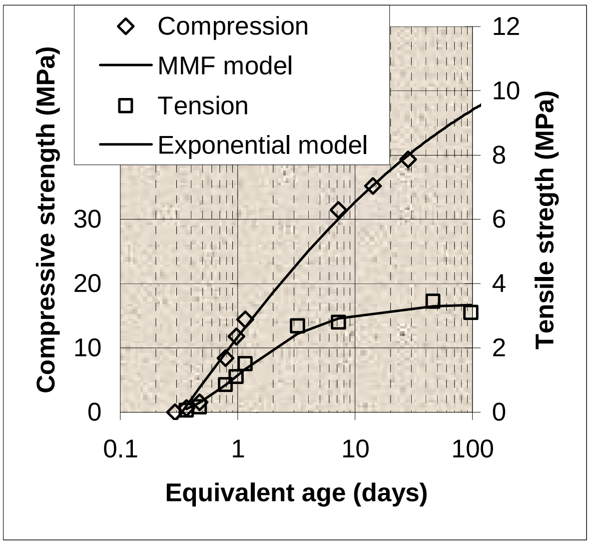

Figure 2: Compressive and tensile strengths.

For the sake of the calculations of the limits imposed during the automatic loadings (tests presented in sections 3.2 and 3.3), the best fitting were obtained by the following mathematical models. For the compressive strength, a MMF model [6] is used:

$$f_{cm}(t) = \frac{a\,b + c\,t_{eq}^{\ d}}{b + t_{eq}^{\ d}}$$

With t_{eq} in days, $f_{cm}(t)$ in MPa, a = -83.9, b = 0.56, c = 65.5 and d = 0.3.

Surely this model applies very well to the growth of bacteria populations but it has been chosen only for its mathematical accuracy.

The evolution of the tensile strength is modelled by an exponential model:

$$f_{ct,sp} = a\exp\left(-\frac{1}{t_{eq}}\right) - b$$

With t_{eq} in days, $f_{ct,\,sp}$ in MPa, a = 3.5 and b = 0.13

The activation energy, 32.2 kJ mol^{-1}, was also determined with calorimetric tests. This parameter allows calculations of an equivalent age (t_{eq}) [7], [8], [9] in order to compare our results.

3 STIFFNESS MONITORING: EXPERIMENTAL TECHNIQUES AND PROTOCOLS

3.1 Classical tests

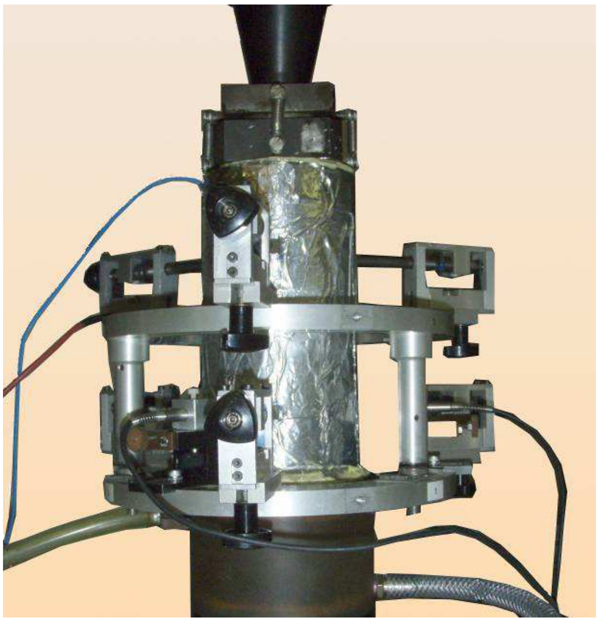

Figure 3: Extensometer and test setup for cyclic loadings on unconfined specimens. This setup was used to validate BTJASPE.

Classical tests, considered as reference, were performed at IFSTTAR on cylinders at different ages. The sample geometry was the same as the one used for strength measurements. The first tests were performed on samples 7 hours after casting. Strains were measured by extensometers (Figure 3), with results comparable to those of strain gauges [10].

For short term tests (<1 week), the cylinders are 11 cm in diameter and 22 cm in length. For longer term testing, cylinders are 16 cm in diameter and 32 cm in length. The protocol of loading consists in applying 4 cycles between 5 and 30 % of the strength measured on other cylinders (with the same geometry) just before the test [11]. The loading rate is set to 0.5 MPa/s

Classical tests were also performed on concrete cylinders (15 cm in diameter and 30 cm in length) at the University of Minho. The protocol of loading consists in applying 5 cycles between 0.8 MPa and 33 % of the strength at the age of testing. The loading rate was set to 0.3 MPa/s.

3.2 BTJASPE and cyclic loadings

A new testing device was designed at IFSTTAR [1], [12], [13], aimed at measuring automatically the evolution of the stiffness of a concrete cylinder in compression at early age (since the setting time up to a couple of days). It is placed between the crossheads of an automatic testing machine.

The cylindrical sample (Ø 100 x 200 mm) is cast and remains in a 1 mm thick stainless steel mould (Ø 100 x 254 mm) as shown in Figure 4.

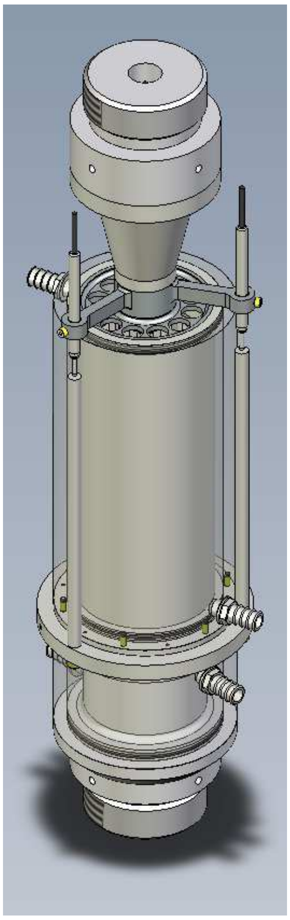

Figure 4: BTJASPE associated to the upper and lower bearings.

Circulation of water around the mould allows controlling the specimen's temperature and thus properly masters its maturity. Once the concrete has been placed, the loading is applied by means of a steel piston guided inside the upper part of the mould. Fixed to this piston, three arms support three LVDT measuring the longitudinal deformations of the sample. These measurements include strains of the sample but also strains resulting from the deformation of the steel piston and of the base of the rig. Finite element calculations performed during the design process of the test setup allowed taking these artefacts into account in the expression of the results [1].

An upper conical bearing includes a system delicately detecting, during the first step, the contact with the sample even if the concrete is still in its fresh state. When the contact is detected, the control of the test is ensured by measuring the mean value of the displacements delivered by the 3 LVDT around the sample. Then, the loading of the sample is ensured at a constant displacement rate. This control allows starting the tests soon after casting.

A lower bearing supports BTJASPE. It is surrounded by a cylindrical vessel where a circulation of water allows removing the heat coming from the piston of the testing machine.

In order to check the accuracy of this test setup, other tests using similar cyclic loadings were performed on concrete cylinders removed from their cardboard mould just after the concrete setting (detected by ultrasonic measurement). The sample is capped with sulphur mortar, equipped with an extensometer and placed between the upper and the lower bearings used for BTJASPE (Figure 3). A ball joint is placed between the upper face of the sample and the upper bearing. In that case, the sample is not confined inside a stainless steel mould thus the results are more reliable and they were considered as validation tests for BTJASPE study (called VTB).

3.3 TSTM

Since 2006, a revisited Temperature Stress Testing Machine (TSTM) has been under development in the laboratory of civil engineering at the ULB for testing concrete since setting, under free and restraint conditions [2][14]. The machine is equipped with a double walled mould allowing a thermal regulation and, in particular, ensuring isothermal curing conditions (Figure 5).

A new methodology was developed for the monitoring of the Young's modulus. The test is controlled at a constant loading rate, thanks to the software "DION®" (Walter & Bai).

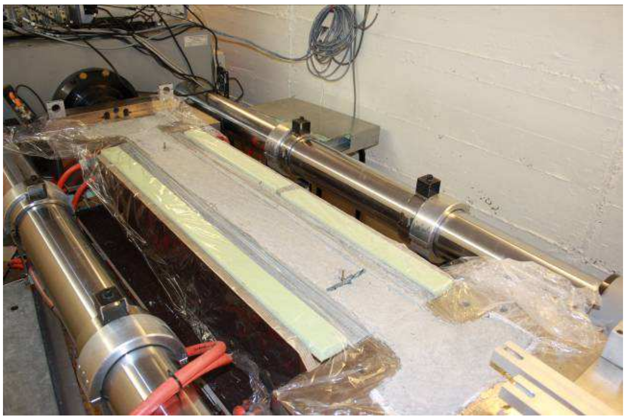

Figure 5: TSTM equipment for cyclic loadings.

The test begins shortly after the final setting time of the concrete [15]. This time is determined by a device, presented later, called FreshCon.

For each cycle of loading, the moving end of the testing machine is controlled by the force sensor, up to 20 % of the compressive strength at the age of testing. The sample is then unloaded till a null force. Recordings are taken during the cycles. The Young's modulus is computed from measurements taken in concrete in the straight part of the sample during each loading and unloading cycle. These displacement measurements can then be directly used to compute the Young's modulus. The duration of each cycle was approximately 60 minutes. The relation between the stresses and the deformations is quasi linear during the loading. In order to keep the strictly linear zone of the *stress/strain* curve, the Young's modulus is calculated between 30 and 80% of the maximum load reached in each cycle.

3.4 EMM-ARM

The EMM-ARM acronym stands for "Elasticity Modulus Measurement through Ambient Response Method". EMM-ARM has been initially devised by Azenha *et al.* [3] for continuous and quantitative assessment of concrete E-modulus since the fresh state. Subsequently, the technique has been extended to applications in cement paste [16] and cement stabilized soils [17]. The EMM-ARM is a variant to classical resonant frequency methods to determine stiffness properties in concrete cylinders [18], with two fundamental differences: (i) the specimen remains inside the mould throughout the entire testing procedure; (ii) the modal identification technique relies on 'output-only' techniques, thus not requiring explicit excitation of the specimen.

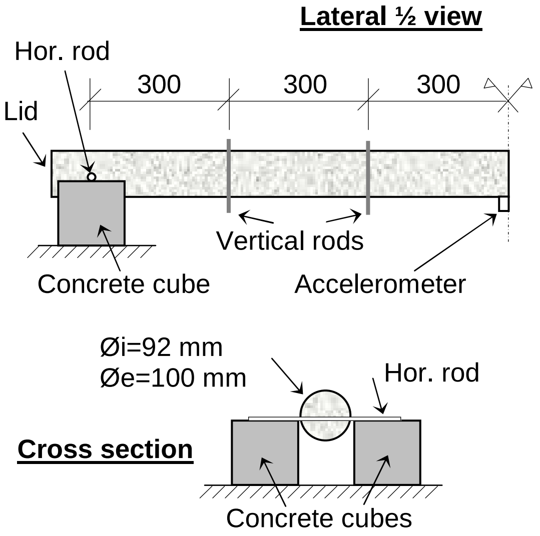

Figure 6: EMM-ARM acrylic mould. Units: mm.

To explain the procedure of EMM-ARM testing and analysis, the originally devised method for concrete is described. Fresh concrete is poured into a 2m long acrylic mould with an external/internal diameter of 100/92mm (Figure 6). After casting concrete inside the mould, lids are fixed at both extremities and the composite element is placed under simply supported conditions with 1.8 m span. An accelerometer is placed at mid-span, recording accelerations at a sampling rate of 200 Hz. From this point onwards, the test does not require any more human intervention, as all measurement tasks are automatic and the excitation provided by ambient vibrations is usually enough for adequate modal identification.

The modal identification process involves processing the accelerometer records with Fourier Transforms, together with windowing and averaging techniques that are explained in detailed in reference [3]. Such data processing allows obtaining the response spectrum of the composite beam. If the ambient vibrations are considered to behave as a white noise on average (i.e. equal energy content in all frequencies), the response spectrum of the beam should have peaks in correspondence to the resonant frequencies of the beam. It is therefore relatively easy to identify the first flexural resonant frequency of the composite beam, as its relevance in the spectrum is usually quite high. Because of the increasing stiffness of the concrete inside the acrylic tube, the overall stiffness of the composite beam increases along time, and so does its corresponding flexural resonant frequency. Based on the continuous evolution of the flexural resonant frequency, it is possible to infer the E-modulus of the tested concrete with basis on the dynamic equations of motion. The detailed explanation of all the equations adopted for such purpose, including the effect of the accelerometer's weight, is provided elsewhere [3]. However, the explanation for the case of a simply supported beam under uniformly distributed mass is much simpler to understand, and almost yields the same results, since the accelerometer's weight is frequently very small. Therefore for illustration purposes, the process of determination of concrete E-modulus for a simply supported beam with span L and subjected to uniformly distributed self-weight m, is shown. The flexural stiffness of the composite beam EI (E standing for the E-modulus and I for the second moment of area of the composite cross-section) can be estimated with basis on the measured resonant frequency through the following equation [19]:

$$EI = 4 \cdot m \cdot L^4 \cdot \left(f / \pi \right)^2$$

Based on the known values of acrylic E-modulus (E_a) and inertia of the acrylic tube and concrete (I_a and I_c), it is possible to estimate the E-modulus of concrete (E_c) through the simple relationship:

$$EI = E_c \cdot I_c + E_a \cdot I_a$$

The above equations are implemented into computer algorithms and allow EMM-ARM to provide continuous real-time information on the E-modulus of the tested material.

The experimental program at the University of Minho involved the casting of one specimen in an acrylic composite beam, under controlled environmental temperature of 19.2 ± 0.5 ºC. Nonetheless, the temperature inside the specimen was monitored to allow for maturity corrections.

3.5 Classical ultrasonic measurements

On this concrete, two classical techniques of ultrasonic measurements were performed. The ultrasonic measurements were performed with the Freshcon device (Figure 7) developed at the University of Stuttgart giving the ultrasonic pulse velocity (UPV) of waves traversing a concrete sample [20].

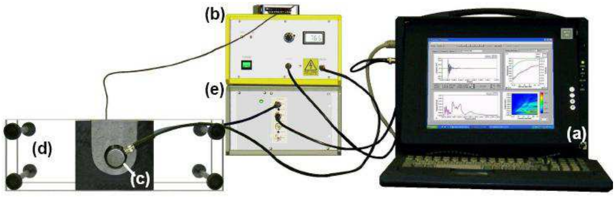

Figure 7 : FreshCon System.

The sample thickness is 4.7 cm. Two samples are cast inside two similar containers: one for P-waves measurements and one for S-waves measurements. Samples are placed in a thermally regulated chamber and their temperatures are measured continuously during the test. Detailed information about this method can be found in [21].

The P-waves (V_P) and S-waves (V_S) velocity can be used to compute the dynamic E-modulus (E_{dyn}) and Poisson's ratio (ν_{dyn}) through the following equations, where ρ is the concrete density [22]:

$$\nu_{dyn} = \frac{1 - 2(V_S^2 / V_P^2)}{2 - 2(V_S^2 / V_P^2)}$$

$$E_{dyn} = V_P^2 \ \rho \ \frac{(1 + \nu_{dyn}) \ (1 - 2\nu_{dyn})}{(1 - \nu_{dyn})}$$

BTPULS is another device used in the study which remained, in the 90's, at the step of prototype [23]. It allows measuring the velocity of P-waves traversing standard cylinders remaining in their cardboard mould. The wave is emitted at the bottom and received at the top of the cylinder. Coupling is ensured by sonographic gel, between the emitter and the sample, while oil is used on the other side [4] to fill the gap between the sample and the receiver. Although performances are lower than FreshCon (the detection begins to be effective only during the setting time and the temporal resolution is only 1 µs), their mutual results are comparable.

3.6 Smart aggregates

The first smart aggregates (SMAG) were developed at the University of Houston [24]. They consist in piezoelectric sensors which can be embedded inside a concrete element and, as for a classical ultrasonic method, continuously monitor the P-waves evolution throughout the setting process. They are of great interest since they do not present the same limitations as the Freshcon system. In the latter, the fixed design of the mould which only allows varying the temperature during the tests does not allow applying specific hygral and/or mechanical boundary conditions on the concrete sample.

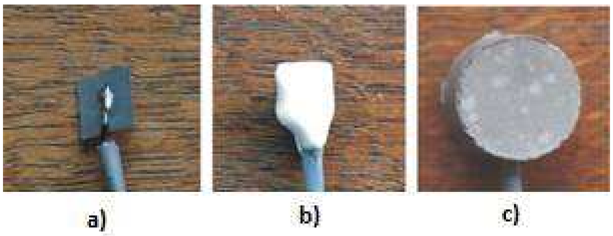

Figure 8: Principle of SMAGs: a) Piezoelectric patch, b) Patch with waterproof coating, c) SMAGs **[24]**.

The SMAGs can easily be integrated in structural elements on the construction sites, and the concrete properties can then be assessed at any given time. These properties are then obtained on a sample that followed the exact same curing and boundary conditions as the structure itself.

A SMAG consists in a flat piezoelectric patch which is wrapped in a waterproof coating and embedded in a small cube or cylinder made of mortar (Figure 8). The SMAGs used in this study have been designed and fabricated in the laboratory of civil engineering at ULB-BATir. Technical details and results of these specific SMAGs can be found in [5].

In order to test the feasibility of measurements of the P-wave velocity in concrete at early age using SMAGs, a prismatic mould, containing a pair of SMAGS with a distance d=5.6cm, has been prepared. The results have been compared to the FreshCon in [5], [25].

4 RESULTS AND DISCUSSIONS

4.1 Classical extensometry

Measurements of the modulus of elasticity were performed by means of classical extensometry in two laboratories (Table 2).

Table 2 – Classic Young's modulus measurement.

U Minho		IFSTTAR	
Days	GPa	Days	GPa
2.78	34.66	0.36	2.72
6.80	36.1	0.47	7.32
14.11	36.6	0.79	18.76
27.98	38.59	0.97	22.86
		1.16	26.14
		7.23	36.41
		14.23	37.43
		28.23	39.66
		90.23	39.62

As loading protocols are very similar, these results are mixed in order to obtain a single description of the evolution of the Young's modulus by these classical means.

For the sake of the analysis of our results, the following mathematical model is proposed (figure 9):

$$E(t) = \frac{a}{t^p} + b$$

where E(t) is expressed in GPa, t in days, $a = -16.4$, $b = 39.75$ and $p=0.84$.

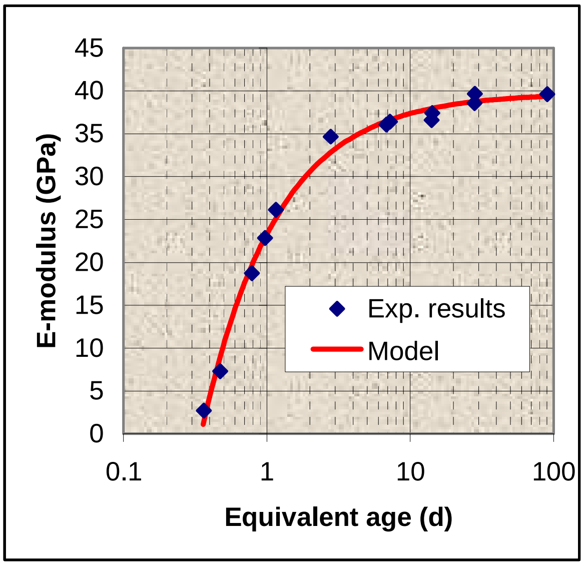

Figure 9: Evolution of the E-modulus obtained with classical methods. A model is adjusted to these data.

This function is accepted as the reference for the comparisons between the different methods.

4.2 BTJASPE Results

Eight tests with cyclic loadings were performed, 4 with BTJASPE and 4 validation tests on samples removed from the mould after the setting (VTB). All these results are plotted in Figure 10.

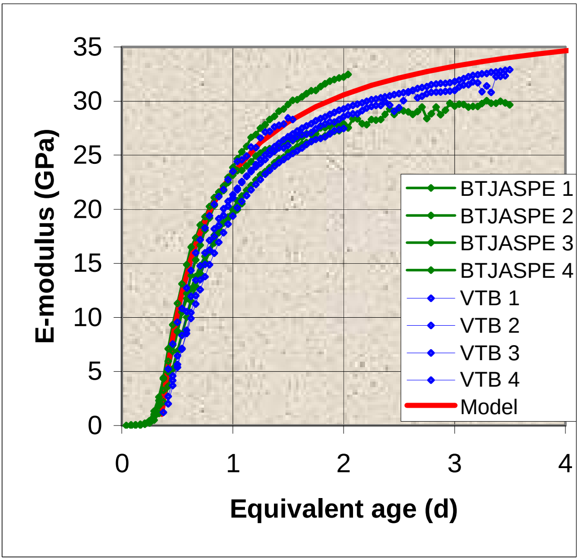

Figure 10: Determination of the Young's moduli with BTJASPE and cyclic loadings on unconfined specimens (validation tests).

It can be observed that these data are in good agreement, both between themselves and also when compared to classical measurements.

If the setting period is defined between the time when the Young's modulus starts to become different from a null value to the time when the evolution reaches a quasi straight line, we can observe that setting periods determined with BTJASPE are in a very narrow range (6 to 8 hours). The range is wider if the validation tests are included in the analysis. For these tests, the initial temperatures are in a range between 18 to 22 °C. In BTJASPE, the temperature is rapidly equal to 20 °C while, for the validation tests in the dormant period, it follows the room temperature. That is why, even if the results are expressed in equivalent time, concrete setting periods are more scattered for the validation tests (the equivalent time calculation is less reliable in the dormant period). A setting time can, after BTJASPE results, be fixed at 7 hours.

4.3 TSTM

Figure 11 shows the E-modulus evolution for one sample in the TSTM device, where a very good agreement with the model of the classical tests can be observed.

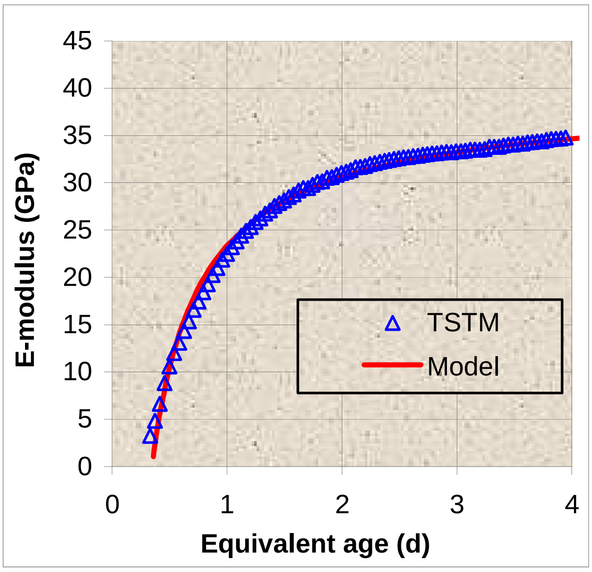

Figure 11: Young's Modulus with TSTM compared to reference model.

4.4 EMM-ARM Results

The test results for the EMM-ARM beam, together with the E-modulus obtained from classical testing (model), are shown in figure 12. Results before and after setting are separated depending on a liquid or a solid behaviour of the material.

The coherence between classical testing and EMM-ARM is quite satisfactory at all ages of testing, confirming the feasibility of this technique to evaluate quasi-static E-moduli.

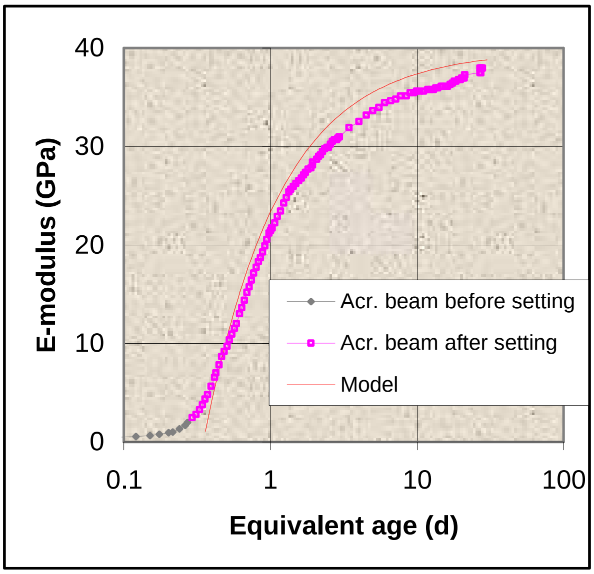

Figure 12: Young's Modulus with EMM-ARM and classical testing.

4.5 Comparison between ultrasonic measurements

The results obtained, for the same concrete, with the SMAGs are compared to the results obtained with the classical FreshCon system with a U-shaped mould and the BTPULS system. Results are plotted on Figure 13.
Freshcon seems to give different results, in the first part of the curve, but these results occur before the setting.

The relative error sharply decreases after setting. From 24 hours onward, the curves are almost superimposed.

With the FreshCon system, P-waves and S-waves were simultaneously measured on the same concrete with dedicated FreshCon containers, what allows an accurate computation of the E modulus as shown on Figure 14 (curve # 3). In the case where no S-waves measurements is possible, taking a constant value of ν_{dyn} in the equation for the computation of E_{dyn} leads to substantial errors, especially at early age. However, in order to evaluate the relevance of the Smart Aggregates method compared to usual UPV measurements, a constant Poisson's ratio of 0.3 has been considered.

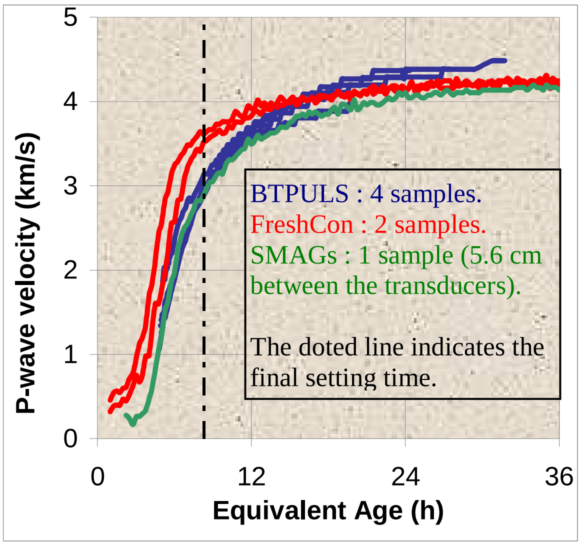

Figure 13: Comparison of the measured *P*-wave velocities using BTPULS, FreshCon and the SMAGs.

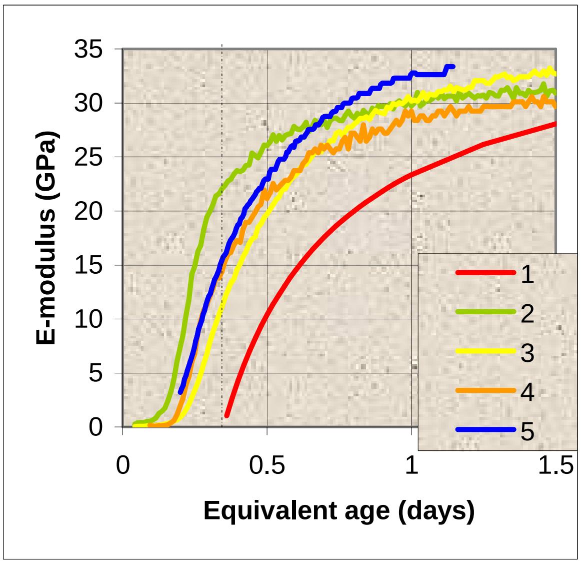

Figure 14. Comparison of the calculated dynamic E-modulus. Doted lines mark the age of 8 h.

1. Model for static classical tests
2. FreshCon data assuming a constant ν
3. FreshCon data assuming a variable ν
4. Smart Aggregates
5. BTPULS.

Despite differences before the setting time, Figure 14 shows a good agreement between all the techniques.

The discrepancies before the setting time (8.3 h) can be due to different air content in the different moulds. Furthermore, different techniques are used for placing the concrete in the moulds. The "SMAGs samples" are placed on a vibrating table which the energy is less effective due to the high weight of the sample. Vibrating needles are used for the other techniques. Indeed, it is known that a strong dependency of the early age P-waves velocity to the air content of the mix exists. In aired mixes, the initial velocity is around 250m/s, whereas for de-aired mixes, initial values close to 1500m/s can be observed.

In addition, ultrasonic results are compared (Figure 14) to classical E-modulus measures. It is well known that dynamic E-modulus (E_{dyn}) is higher than static E-modulus (E_{stat}). Furthermore, it has been observed [13], for this concrete, that the ratio E_{dyn} / E_{stat} decreases from a value equal to about 13 to a value close to 1 between the setting time and 24 h. It is then obvious that comparisons between dynamic and static measurements of E-modulus at early age cannot be achieved without taking these effects into account.

Despite the fact that the ultrasonic recordings seem to be earlier than the static ones, the setting times deduced from the two techniques are not so different. Indeed, a technique proposed by [26] indicates a setting time equal to 8.3 h which is, here, close to the setting times obtained with classical tests (8 h) or BTJASPE (7 h).

4.6 Comparison between static techniques

In addition to these differences between static and dynamic results, a more detailed analysis of the differences between static or quasi-static tests can be performed.

It can be observed (Figure 15), over the 36 first hours, that the width of the bunch of curves decreases from, approximately, 7 GPa at the setting time to 2 GPa at 36 hours. After 36 h till 100 hours it remains in this range. EMM-ARM stays in this range till approximately one month. Presumably this very early range would be much lower if the setting times were grouped over a shorter period of time.

The question then arises to know why our different techniques induce these differences in the setting times. The mixing techniques, the temperature histories and the amplitude of loadings could be at the origin of these discrepancies.

Different techniques of mixing were used. It is well known that flocs are present in the cement powder. A relationship exists between the mixing energy and the deflocculation. Knowing that the properties of the concrete depend on the fineness of the cement, round robin tests should be performed with strictly similar protocols. From a practical point of view, this goal was, for our 3 laboratories, like a holly grail. Indeed, a great amount of constituents should be provided in each laboratory, the volumes of the batches should be the same, the same lot of cement should be used, the same mixers should be used and the same temperature histories should be applied. In the case of our study, we were not able to implement these protocols. Instead, we decided to show the feasibility of our techniques at the cost of a greater dispersion of our results. This point should be improved for future studies.

It is known that the setting time is influenced by the temperature history during the dormant period. This observation could explain a part of the discrepancies observed between the different techniques. BTJASPE and TSTM are well adapted for this kind of problem because the temperatures can be kept constant. The use of the equivalent time method doesn’t give absolutely accurate results. Nevertheless, for the EMM-ARM and ultrasonic methods, the use of the equivalent time method associated with a control of the room temperature, gives sufficiently good results when the temperature histories are measured.

In these first tests, the amplitude of the loading could have an influence on the measured evolution of the Young's modulus. For EMM-ARM, the deformations are reduced at minimal values and this question does not arise. For the tests performed with the TSTM, 20 % of the compressive strength was applied, thus, theoretically, there should be no damage. For BTJASPE, 250 micro-strain were applied. There could be doubts concerning the possibility of damage to the sample. No systematic analysis was performed but the latter technique showed similar results compared to classical measurements. Nevertheless, future tests should be performed by taking into account the evolution of the compressive strength.

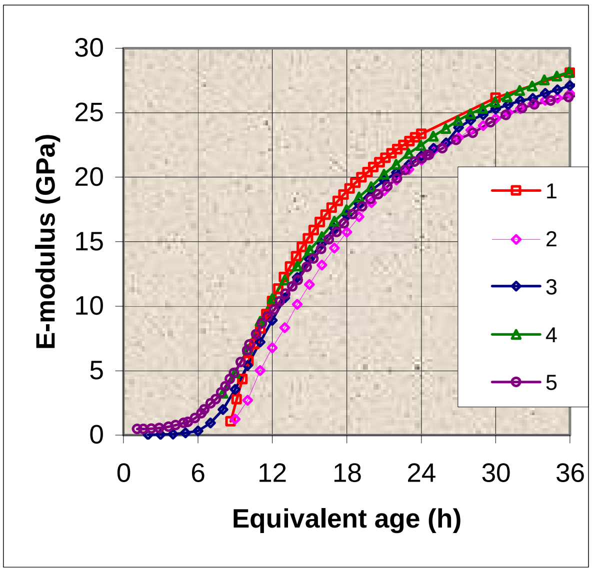

Figure 15: Comparison between the E-modulus measured by the static and quasi static methods:

1. Model for static classical tests
2. Mean E-mod. of 4 validation tests for BTJASPE
3. Mean E-mod., 4 BTJASPE
4. TSTM
5. EMM-ARM, Acrylic beam

5 CONCLUSIONS

Different automatic techniques aimed at measuring changes in the stiffness of a concrete at early age were used in three different laboratories. They can be grouped in static and ultrasonic methods.

The first ones give responses similar to classical measurements. These classical measurements consist in performing the test after having removed the samples from their mould just after the setting time. Despite the fact that the samples are very fragile, the concrete begins to harden at the end of the working day thus, automatic methods are almost obligatory. Two methods are based on the use of laboratory testing machine (TSTM, BTJASPE) while the third method (EMM-ARM) is well adapted for laboratory testing and in field. Their mutual performances are in good agreement. Some improvements concerning the protocols of mixing and loading have to be worked on.

The ultrasonic measurements are also automatic methods and they are good candidates for the monitoring of the stiffness of the concrete at very early age. Two classical techniques (FreshCon, BTPULS) are compared to a newly developed technique (SMAGs). Their results show a clear effect of the loading rate on the E modulus calculation compared to values obtained with static tests. A transition between the results of ultrasonic techniques and static ones is not yet clearly accessible. This transition seems to be depending on the water content of the concrete and thus, at very early age, the degree of hydration [13] but models should be found to promote the use of ultrasonic techniques applied to the monitoring of the concrete stiffness at very early age.

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