A MINIATURIZED EARLY AGE CONCRETE STRENGTHENING AND HYDRATION MONITORING SYSTEM BASED ON PIEZOELECTRIC TRANSDUCERS

CONFERENCE PAPER · MAY 2013

DOI: 10.13140/2.1.4133.7126

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10th HSTAM International Congress on Mechanics

Chania, 25-27 May, 2013

A Miniaturized Early Age Concrete Strengthening and Hydration Monitoring System based on Piezoelectric Transducers.

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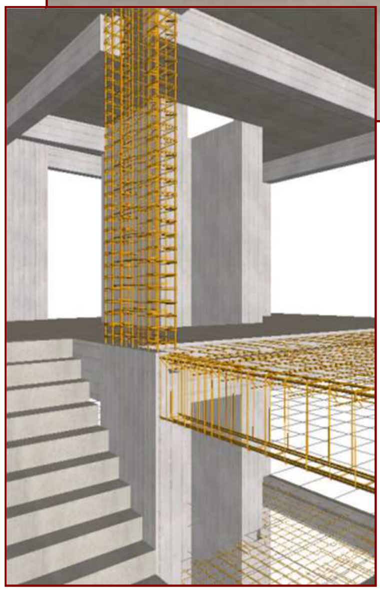
Outline of the presentation

1. Concrete Early Age Monitoring
2. Development of a wireless miniaturized impedance sensing system
3. Experimental set-up
4. Impedance signatures evaluation and interpretation
5. Results and discussions
6. Conclusions

1. Concrete Early Age Monitoring.



- The mechanical performance of concrete governs the global behavior of a concrete structure and because of that the investigation and observation of significant concrete properties is essential for their safety evaluation.
- Monitoring of concrete strength development and stiffness alteration at early age stages of curing, is an important aspect for total quality control and evaluation of structures fabrication procedure.

1. Concrete Early Age Monitoring.

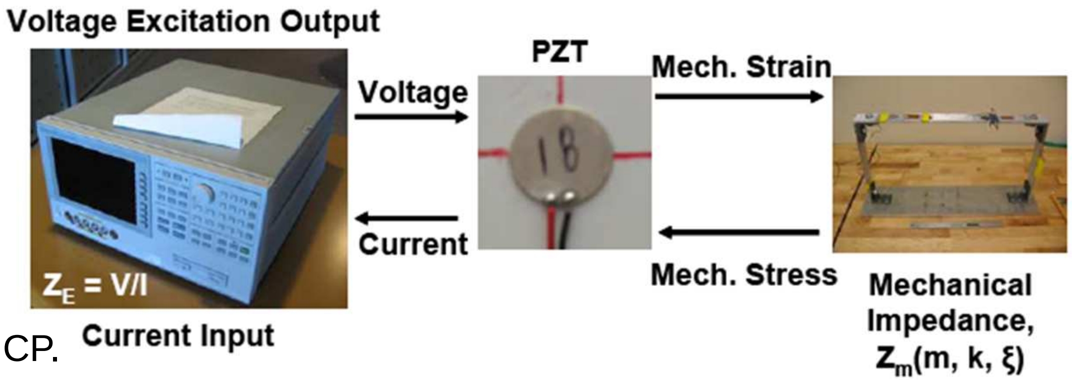
- In-situ control of structural integrity of concrete structures from the very early stages of construction throughout their life-time provides essential information for collapse and damage prevention.

- Various methods of non-destructive testing exploiting strength, stiffness and integrity sensitive feature of concrete have been presented and applied for in-situ monitoring of concrete structures.

2. Development of a wireless miniaturized impedance sensing system

2.1. Electro-mechanical impedance based early age monitoring.

The (E/M) impedance technique, uses piezoelectric materials, (e.g. Lead Zirconate Titanate-PZT), which exhibit the characteristic feature to **generate surface charge** in response to an applied **mechanical stress** and conversely, **undergo mechanical deformation** in response to an **applied electric field.**



2. Development of a wireless miniaturized impedance sensing system

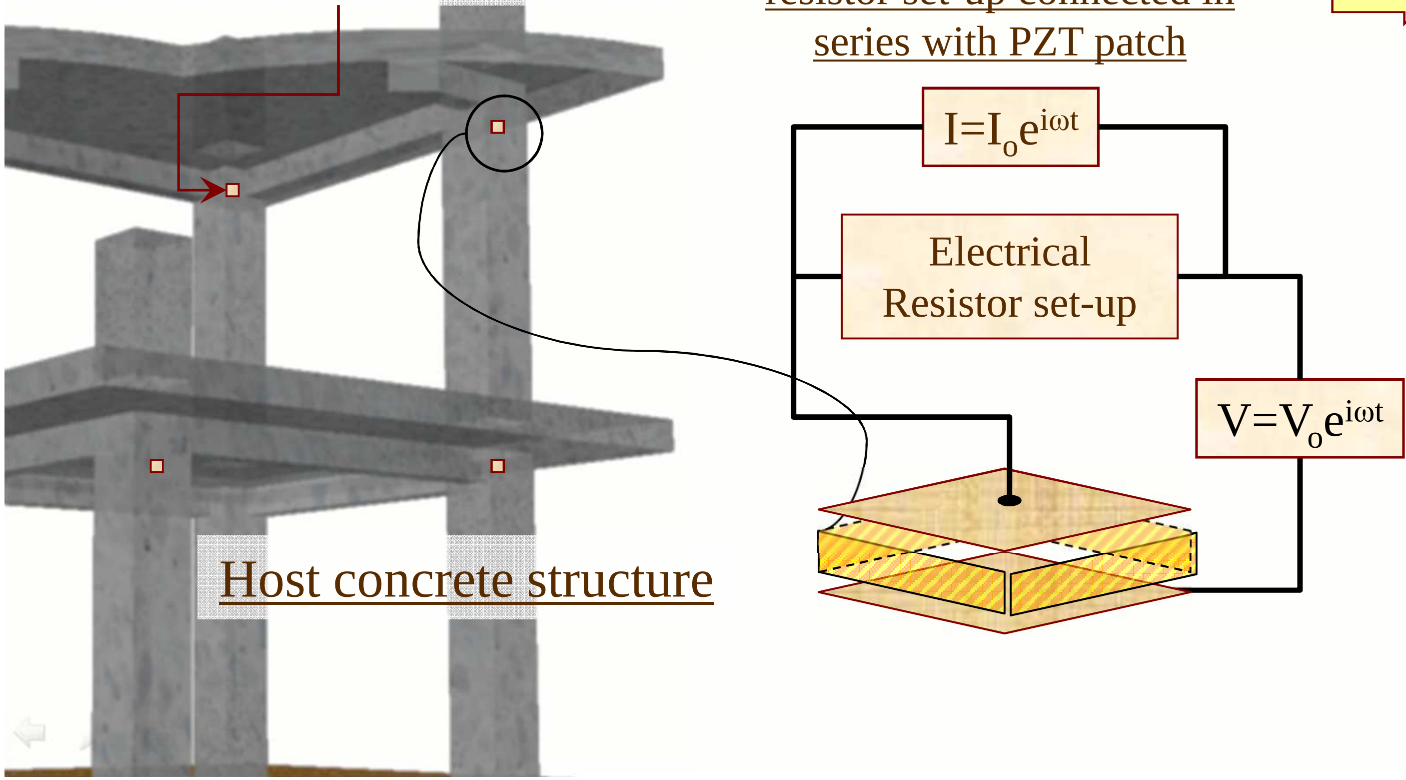
2.2. Electro-mechanical impedance signatures

Piezoelectric sensor/actuator bonded to host structure

Electrical current measuring through an properly designed resistor set-up connected in series with PZT patch

$$Z_{electo\text{-}mech} = V_o / I_o$$

Electo-mechanical impedance calculation



Stimulation Harmonic voltage applied at PZT patch electrodes

2. Development of a wireless miniaturized impedance sensing system

2.2. Electro-mechanical impedance signatures

- Electro-mechanical impedance:

Z=Resistance + iReactance or,

$$Z=R_s+iX_s$$

- Impedance "signatures" of a structure (in frequency domain) contain vital information of the structural parameters, **stiffness**, **damping** & **mass**.
- The **Basic statement** of the present technique, is that concrete strength and stiffness development level, correspond to a **unique pattern** of the sharp peaks generated in the impedance vs. frequency plots.

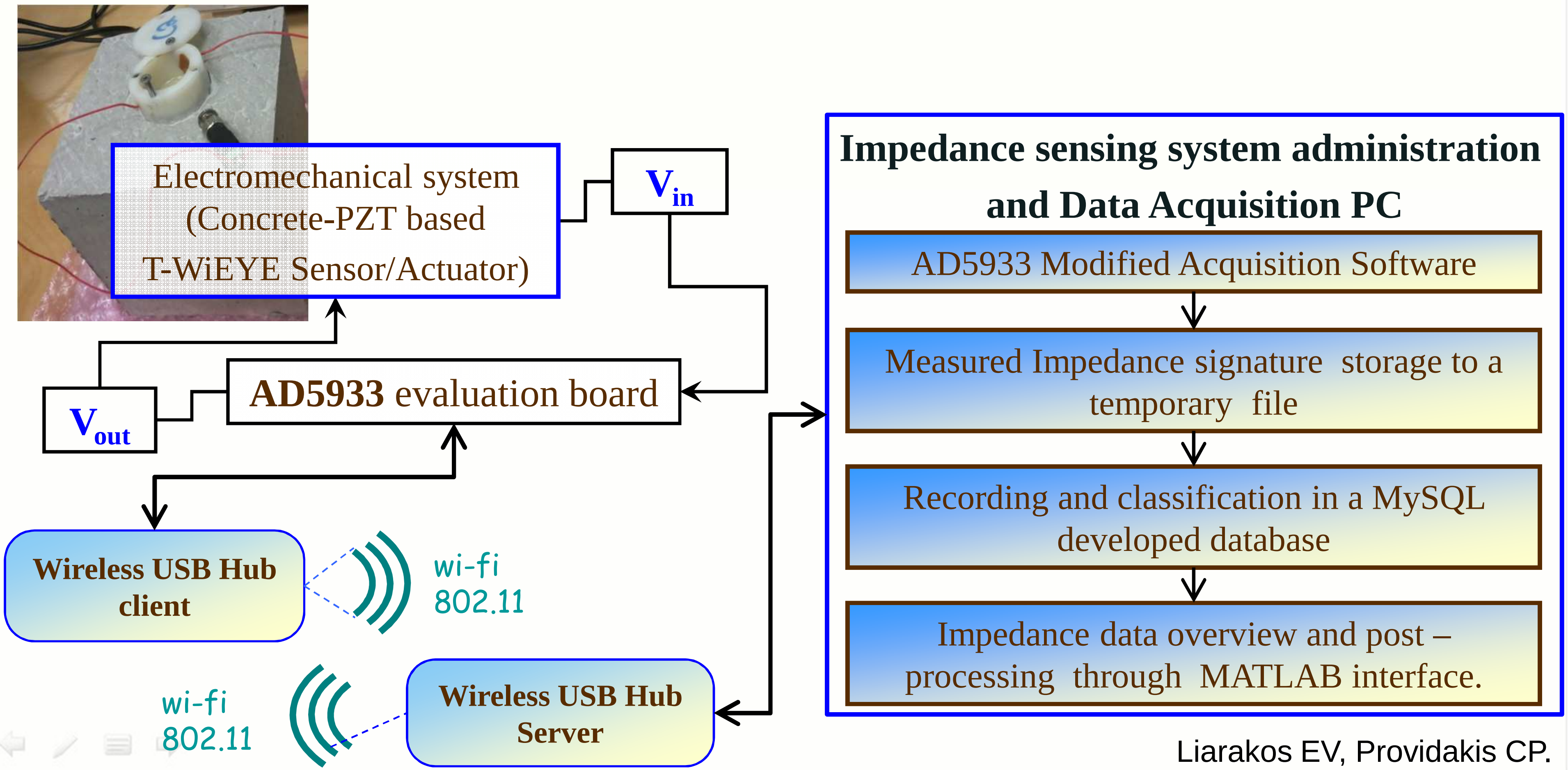
2. Development of a wireless miniaturized impedance sensing system

2.3. T-WiEYE impedance sensing system

In order to monitoring efficiently early-age concrete hardening process, a **T**eflon based **Wi**reless integrat**E**d monitoring s**Y**st**E**m (T-WiEYE) was developed. This system provides **measurement accuracy**, data **extraction** and **overview** in **real time** reclaiming **wireless technology**, easy carrying and fitting to a wide variety of structures geometries and has **much lower cost** than classical impedance analyzing systems.

2. Development of a wireless miniaturized impedance sensing system

T-WiEYE impedance sensing system functionality diagram



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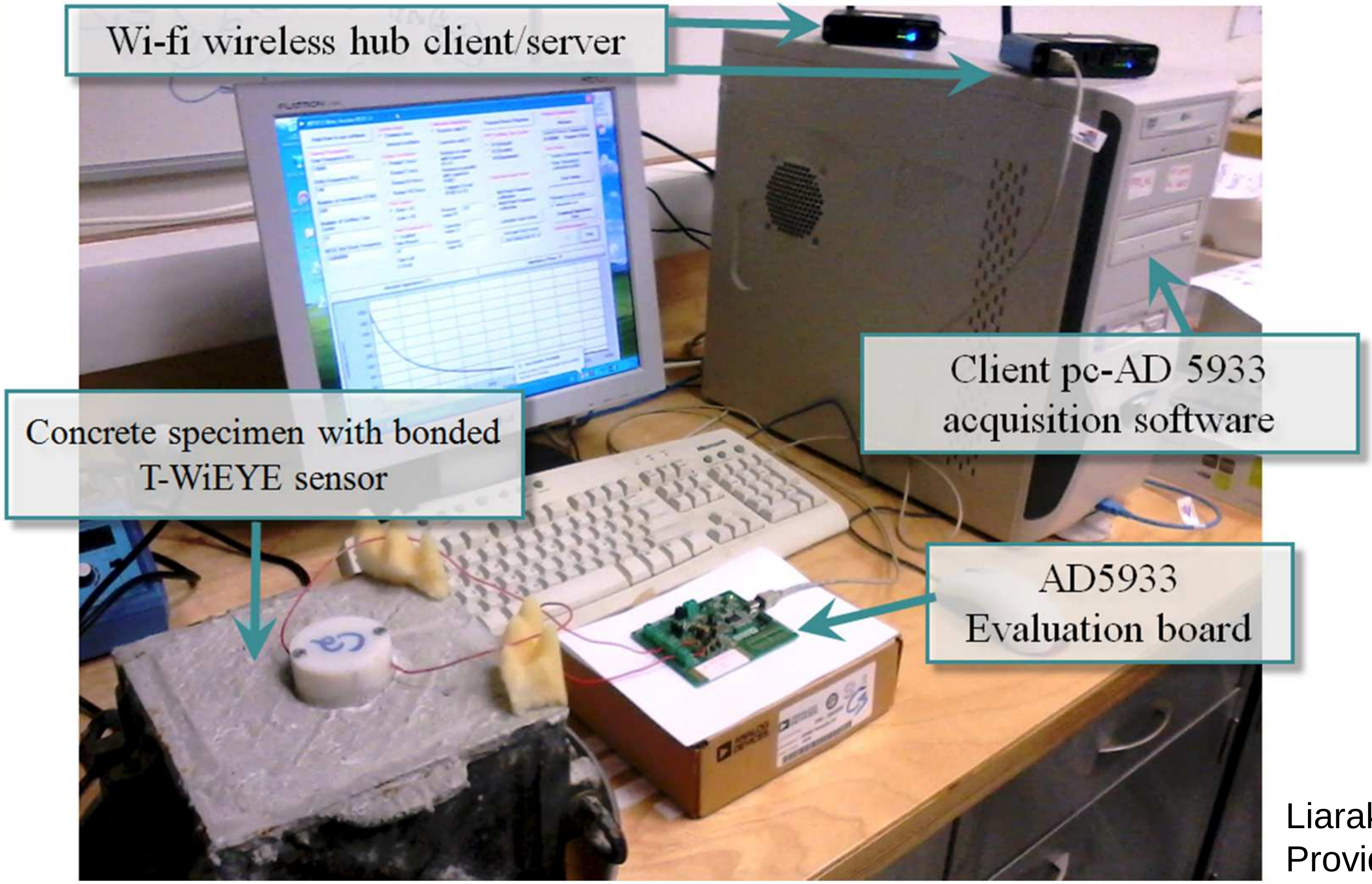
3. Experimental set-up

3.1. Lab Set-Up of Miniaturized impedance sensing system



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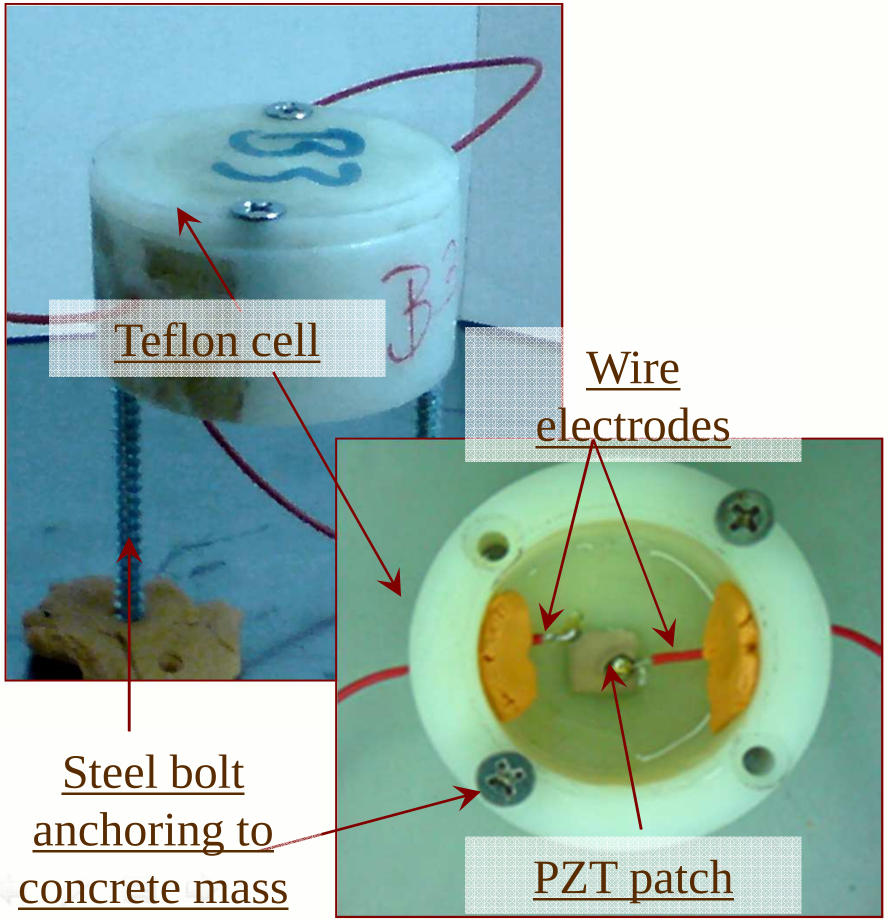
3. Experimental set-up

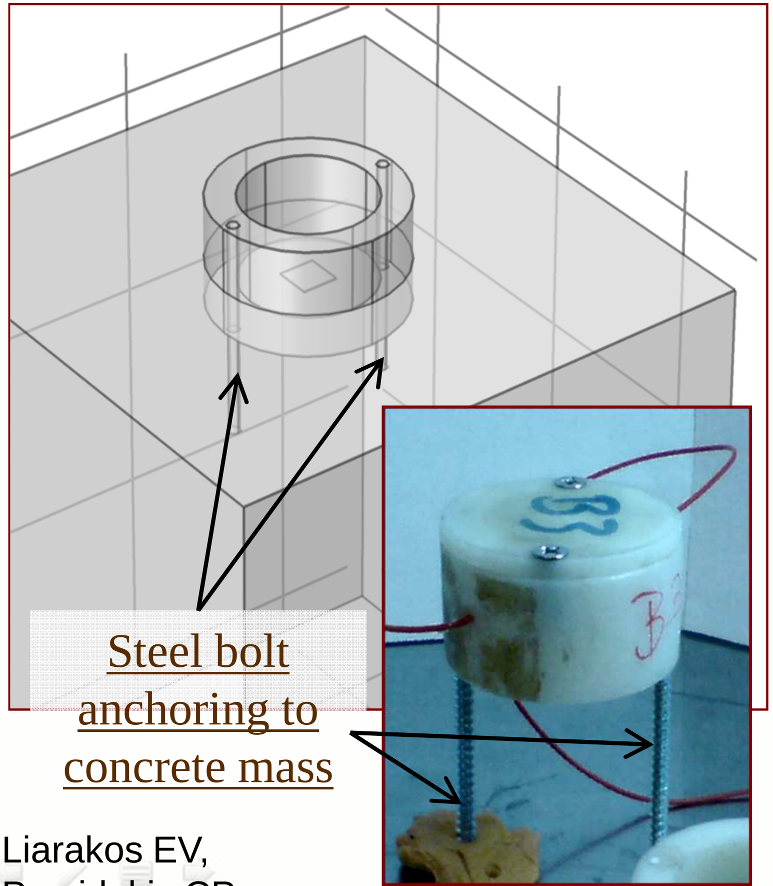
3.2. Teflon-based PZT sensor fabrication



- A properly designed cylinder Teflon cell is fabricated.
- A PZT patch of type PIC151 (PI Ceramics Co), size 10x10x0.2mm is bonded inside Teflon cell by a high stiffness epoxy glue.
- Wire electrodes are attached to PZT pole in order to connected and stimulated by AD5933 Eval. Board.

3. Experimental set-up

3.2. Teflon-based PZT sensor fabrication



- Steel bolts anchoring of T-WiEYE transducer provide robust bonding and improve the mechanical interaction between concrete mass and PZT sensor/actuator.
- Moreover steel bolts are helping to mechanical wave dispersion which are generated from PZT transducer and increase the effective depth.

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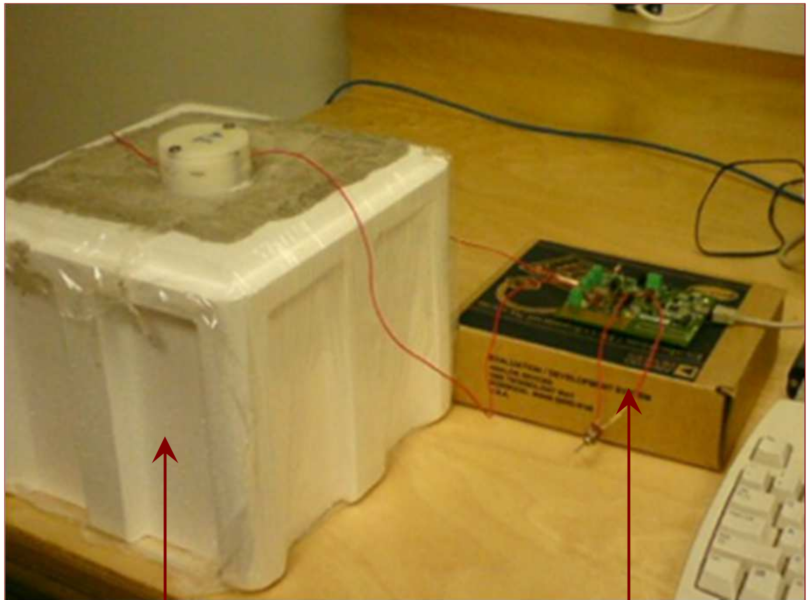
3. Experimental set-up

3.3. Experimental procedure identification



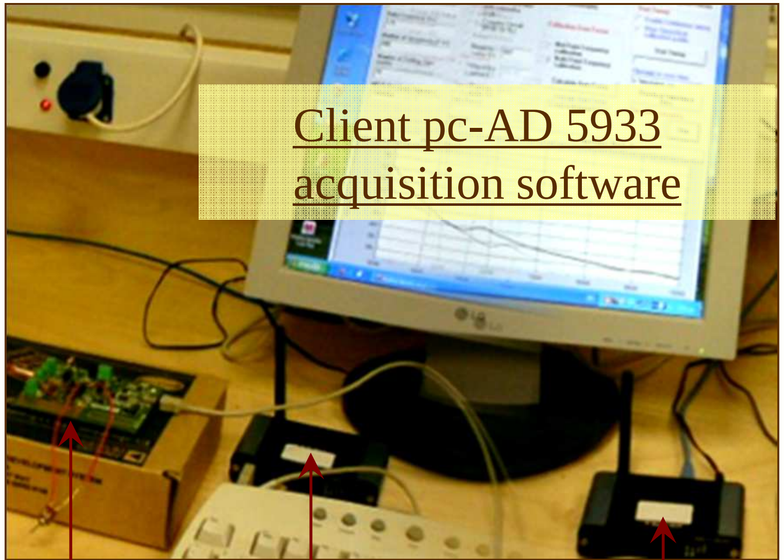
Concrete specimen with bonded T-WiEYE sensor

AD5933 Evaluation board

- Three cubic C20/25 concrete specimens, with dimensions 150x150x150mm are fabricated.
- Concrete mixture proportion: 1:0.62:1.36:1.35:2.76 (C:W:FA:MA:CA, ratio by mass of cement).
- T-WiEYE sensor are attached to concrete specimens immediately after specimens casting.

3. Experimental set-up

3.3. Experimental procedure identification



Wi-fi wireless hub client/server

AD5933 Evaluation board

- Impedance signatures are acquired continuously every one hour from 3rd to 120th hour from casting.
- After 120th hour, signatures are acquired at the ages of 6, 7, 9, 11, 14, 17, 21, 24 and 28 days.
- Frequency sweep domain for each signature: 50-100kHz, with frequency step 180hz (278 measurement per data set).

3. Experimental set-up

3.3. Data extraction and visualization

- Each measured signature a) is send through wireless connection to central administration PC, b) stored to a temporary file and c) finally is recorded and classified to a MySQL developed database.
- Through a properly scripted MATLAB function and MySQL adds installation it is succeed the command transfer and administration of impedance measurements database to MATLAB interface. This provides the option of easy and quick impedance data post-processing.

4. Impedance signatures evaluation and interpretation

4.1. Concrete hardening sensitive features

- In present study the changes of collected impedance signatures during the curing period of concrete, reflects concrete's flexural modulus and strength development, respective to elapsed time from concrete casting.
- Moreover impedance signature alteration is caused from cement hydration procedure as concrete mass is hardening.
- Impedance signature changes are evaluated using well known from several studies statistical index and introducing two new indexes.

4. Impedance signatures evaluation and interpretation

4.2. Impedance signature changes evaluation tools

RMSD index express the **statistical deviation** of impedance signature values which refers to **an occasional structural integrity state,** from the values of an impedance signature which represents a **reference** integrity state. In present study as reference state R^0, is taken the real part of impedance signature at **3 hours** from concrete casting and as occasional state R^I, the real part of impedance signature which refers to a next concrete hardening state of curing process.

$$RMSD = 100 \times \sqrt{\frac{\sum_{j=1}^{N}\left(R_j^I - R_j^O\right)^2}{\sum_{j=1}^{N}\left(R_j^O\right)^2}}$$

$j=1:N$ where N the sweeping frequency points.

4. Impedance signatures evaluation and interpretation

4.2. Impedance signature changes evaluation tools

Besides deviation of impedance signature changes, an significant parameter which characterize the procedure of concrete hardening is the **rate of signature changes** through curing time. For this purpose the following rate sensitive indexes are introduced based on RMSD evolution.

- **RMSD Absolute Derivative**:

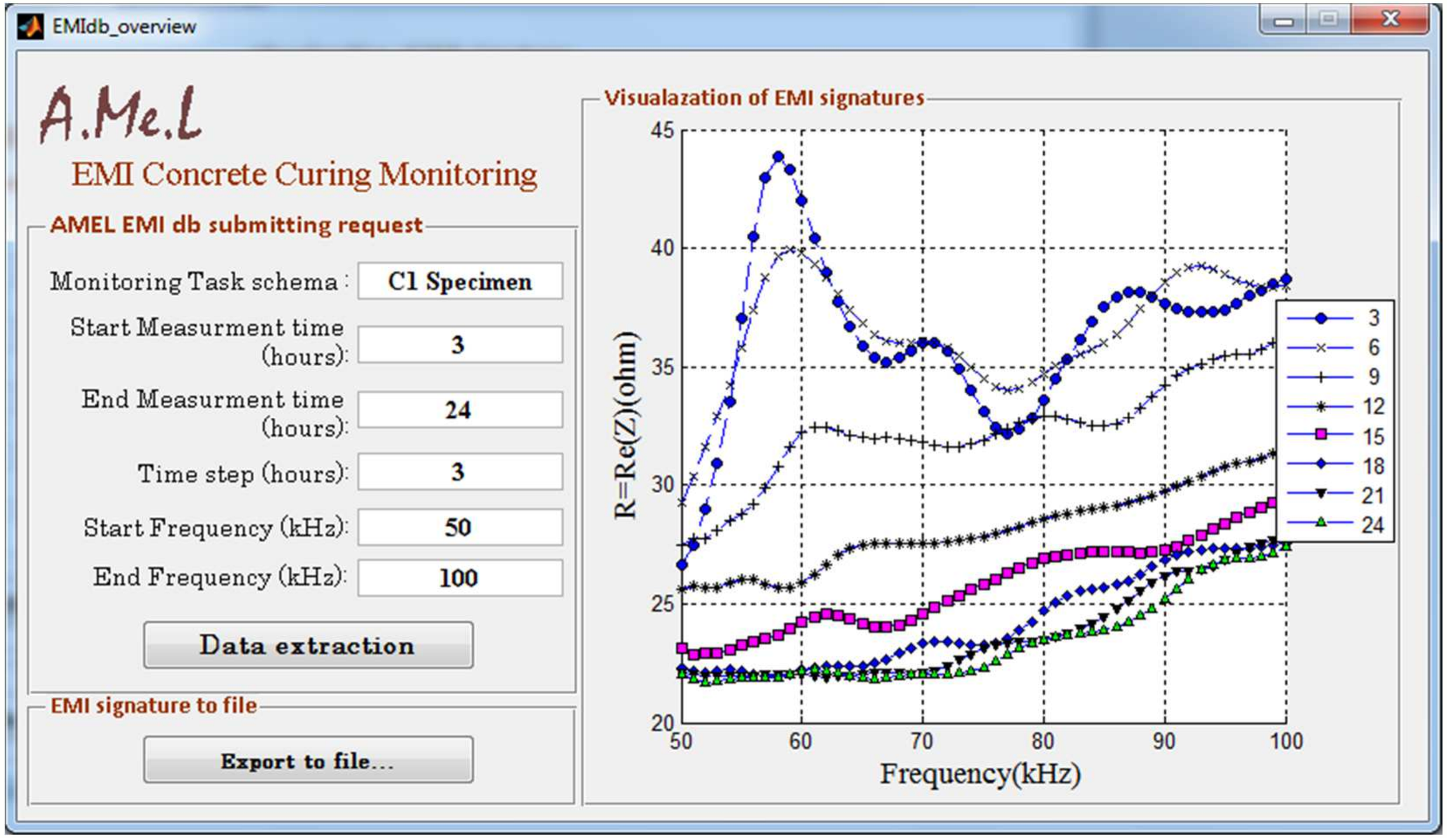
$$RMSD\_AD_n = \left|\frac{dRMSD_n}{dt_n}\right| = \left|\frac{RMSD_n - RMSD_{n-1}}{t_n - t_{n-1}}\right|$$

- **RMSD-R**:

$$RMSD\_R(t_n) = \frac{\sum_{k=1}^{n} dRMSD_k}{\sum_{k=1}^{n} dt_k}$$

5. Result and discussions

5.1. Impedance real part signatures from 3 to 24 hours from concrete casting for specimen C1.



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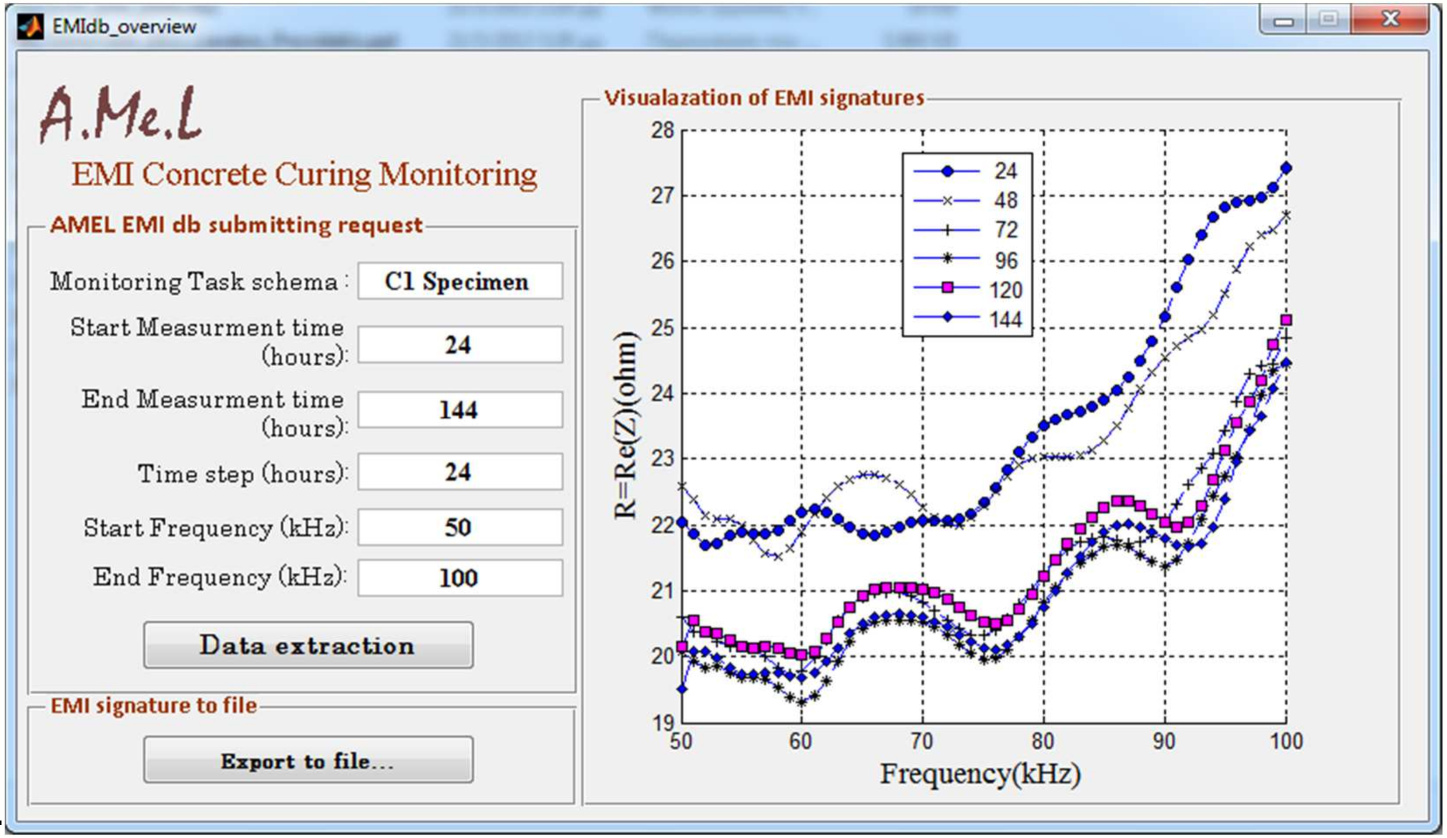
5. Result and discussions

5.1. Impedance real part signatures from 24 to 144 hours from concrete casting for specimen C1.



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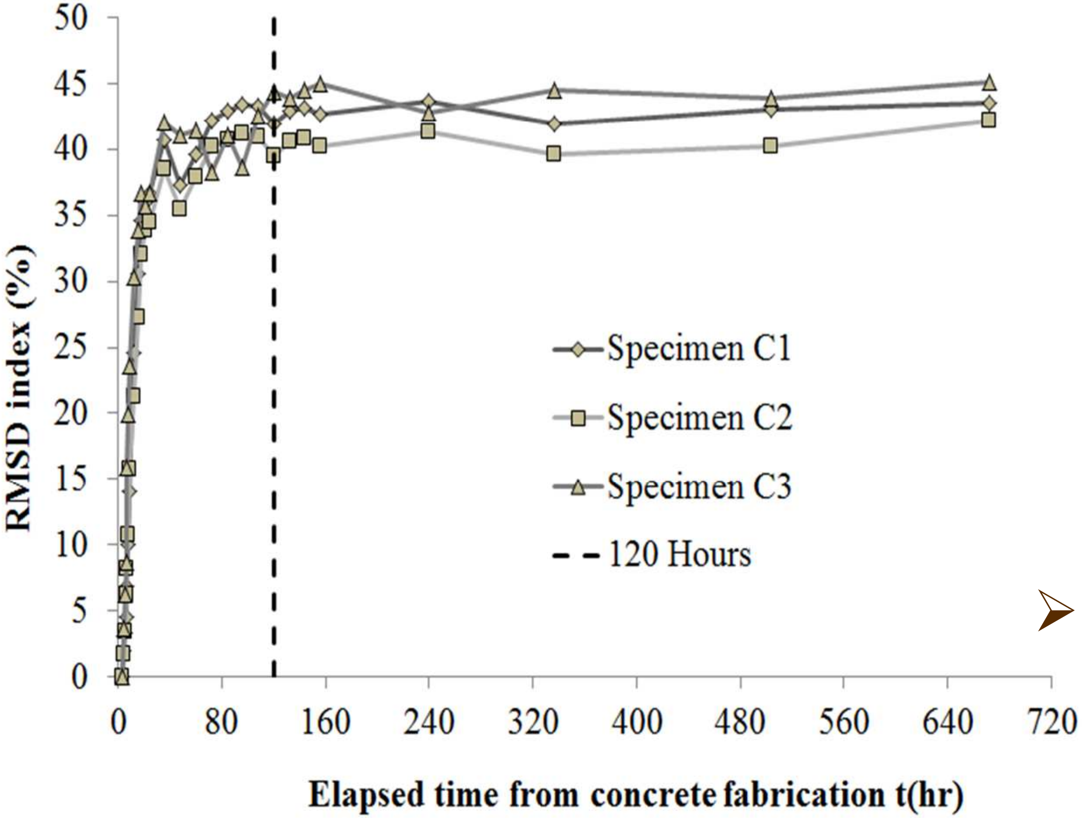
5. Result and discussions

5.2. RMSD index evolution respective to elapsed from concrete casting time.



- The **first 80 hours** RMSD increased rapidly and **from 80 to 120 hours is stabilized** around a constant value approximately equal to **43% (SE:0.23)**, **40% (SE:0.32)** and **44% (SE:0.26)** for specimens C1, C2 and C3 respectively.
- RMSD remaining around these values until the **end of curing period** (28 days).

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5. Result and discussions

5.3. Concrete stiffness evolution respective to Eurocode EC2 pattern .

EuroCode EC2 predict that early age concrete Young's Modulus evolution during curing process is described from formula:

$$E_{cm}(t) = E_{cm}^{28}\{\beta_{cc}(t)\}^{0.3} : (GPa), \quad \beta_{cc} = \exp\left\{s\left(1 - \sqrt{\frac{672}{t}}\right)\right\}$$

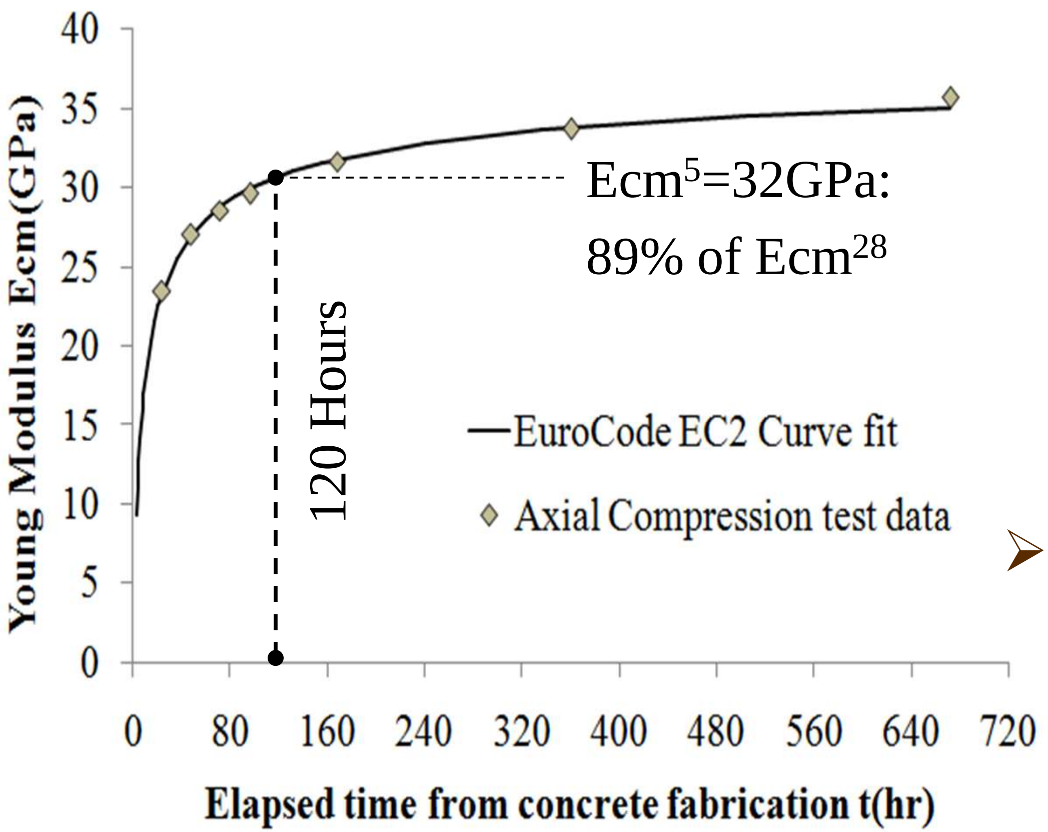
Where: $\boldsymbol{E_{cm}^{28}}$ (GPa) the 28 days age concrete's Young Modulus

t(hr) the elapsed time from concrete fabrication

s a dimensionless coefficient which varies from 0.2 to 0.38 and corresponds to cement type (R ,N and S) types.

5. Result and discussions

5.3. Concrete stiffness evolution respective to Eurocode EC2 pattern .



- Along with non-destructive in-situ process of concrete curing monitoring, a series of compression test have be done in order to directly evaluated the strength and flexural modulus development.
- On Young's modulus experimental values the EC2 model is fitted for *s=0.317* and Ecm^{28} =36GPa

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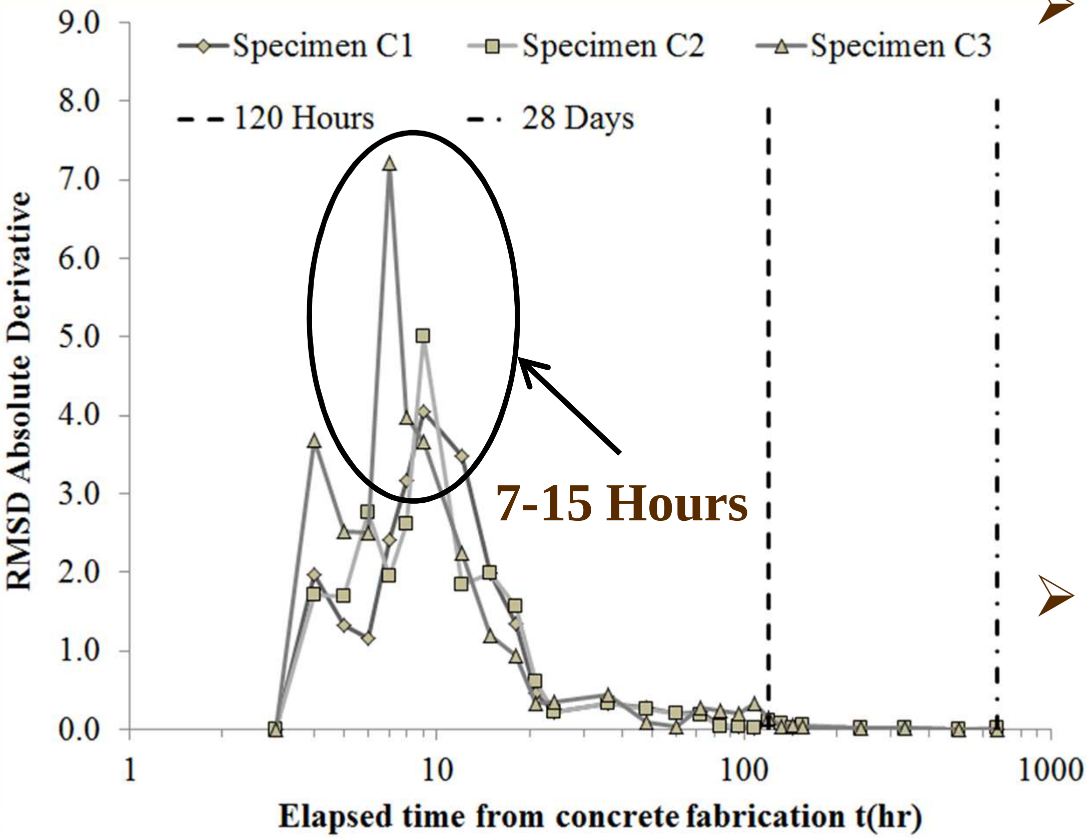
5. Result and discussions

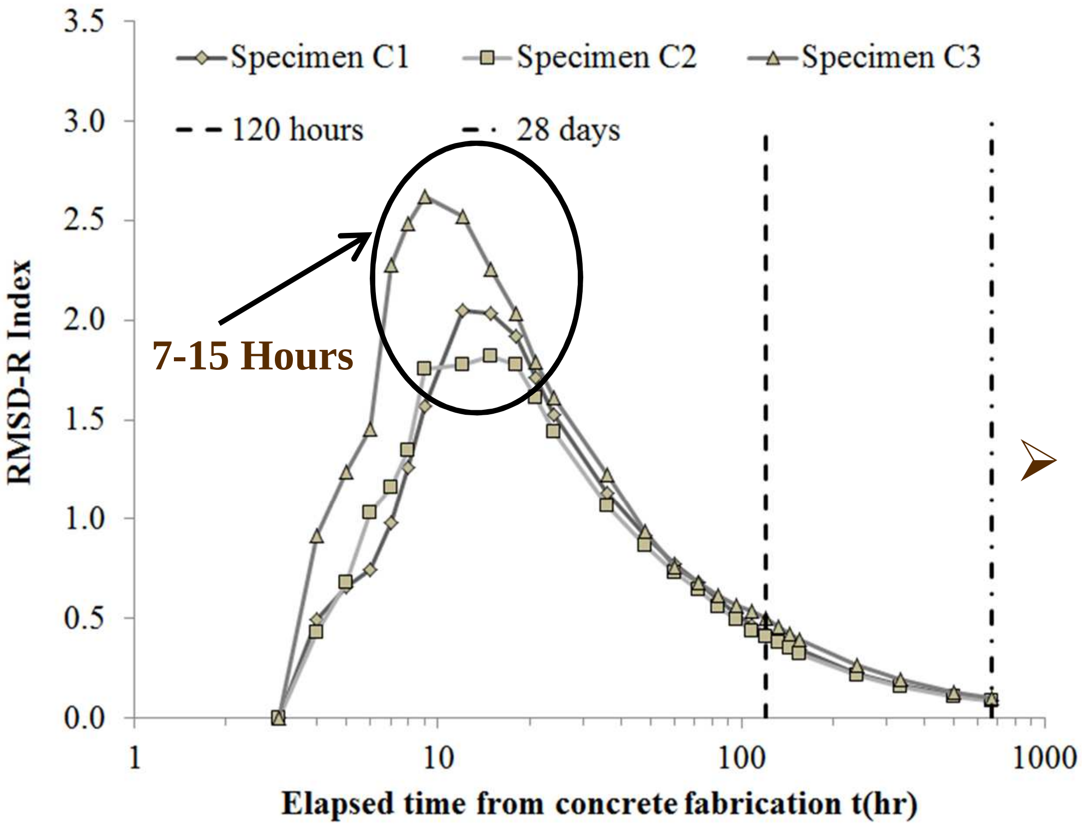
5.4. RMSD Absolute Derivative index evolution during concrete curing time



- RMSD-AD index is suddenly increase **between 3 and 7-8 hours**, appears a **peak** value between **8-12 hours** and after **15 hours** starts to decrease rapidly, depicting the cement hydration procedure.
- After 120 hours and until 28 days remain very low and constant.

5. Result and discussions

5.5. RMSD-R index Evaluation



- Approximately the same behavior is observed and from RMSD-R index which also is suddenly increase **between 3 and 7-8 hours** and appears a **peak** value between **8-12 hours**.
- Moreover RMSD-R index provide a normalized expression of RMSD changes rate, allowing a better observation of peak region.

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6. Conclusions

- A miniaturized integrated impedance measurement system has been developed, adopting wireless technology and providing the options of quick and efficient storage, classification and post-procession of measured impedance data employing MySQL and MATLAB design tools.
- An innovative PZT-TEFLON (PTFE) based sensor/actuator has been constructed upgrading the capability of concrete hardening monitoring from the very early stages of curing process.
- Three cubic C20/25 concrete specimens are investigated and impedance measurements are evaluated using RMSD, RMSD-AD and RMSD indexes.

6. Conclusions

➢ From RMSD index evolution observation during concrete curing period it is concluded that **after 120 hours** impedance signatures appear no significant changes. Combining this fact with concrete flexural modulus development estimation from EC2 proposed formula it can be stated that approximately 120 hours(5 days) from fabrication concrete has obtain adequate durability.

➢ Finally indexes RMSD-AD and RMSD-R declares that **first 8 to 15 hours** of concrete curing is a critical period for properly cement hydration procedure evolution.

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Co- financed by Greece and the European Union

NSRF 2007-2013
EUROPEAN SOCIAL FUND

This research has been co-financed by the European Union (European Social Fund – ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF) - Research Funding Program: Heracleitus II. Investing in knowledge society through the European Social Fund.