NUMERICAL EVALUATION OF A TEFLON BASED PIEZOELECTRIC SENSOR EFFECTIVITY FOR THE MONITORING OF EARLY AGE CONCRETE STRENGTHENING

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Outline

1. Concrete Early Age Monitoring
2. Piezoelectric sensors – Electro Mechanical Admittance (EMA) method
3. Teflon (PTFE) based Piezoelectric Sensor (TPS)
4. Numerical evaluation of TPS in monitoring of early age concrete
5. Results and discussion
1. Early age monitoring of concrete

- Concrete strength and mechanical properties, such as Young Modulus, are developed several days after fabrication and casting of constructional members.

- Cement hydration procedure is responsible for the concrete strengthening and elastic behavior evolution and if is not completed properly final product will not compliance with standards.

Experimental monitoring of concrete strength by compression testing of cubic specimens (Applied Mechanics Lab, TUC, 2014)
1. Early age monitoring of concrete

- **Eurocode 2 (EC2)** defines that concrete quality is controlled by performing axial compression test using cubic or cylindrical specimens **28 days** after production.

- Monitoring of concrete strengthening procedure from the **very first stages**, e.g. 1st day or even 12 hours after casting, can **prevent possible failures** regarding **mechanical performance** and **integrity of concrete structures**.

- **Non Destructive Testing (NDT)** techniques that based on concrete dynamic behavior can provide timely and in-situ assessment of concrete mechanical properties.
  - Ultrasonic wave propagation (EN 12504-4 | ASTM C597)
  - Hydration heat monitoring, etc.
1. Non destructive testing of concrete

**Early Age Concrete monitoring and Piezoelectric Sensors**

- Monitoring of early age concrete (age<28 days) strengthening by embedding Teflon based Piezoelectric Sensors (TPS) inside concrete mass during fabrication.

- Piezoelectric sensors transform mechanical energy to electrical and vice versa.

- Evaluation of strengthening procedure via monitoring changes in Electro-Mechanical Admittance (EMA) and Electro-Mechanical Compliance (EMC) signatures.

- Present study deals with FEM modeling of TPS-Concrete electromechanical interaction and evaluation of proposed embedded piezoelectric sensor sensitivity regarding early age concrete Young Modulus changes.
2. Piezoelectric sensors – Electro Mechanical Admittance (EMA) method

Piezoelectric materials – Principles

• Mechanical energy to electrical and vise versa
• Piezoelectric phenomenon:
  ➢ Direct: Mechanical Stress \( (T, \text{Input}) \) \( \rightarrow \) Electric Voltage \( (V, \text{Output}) \)
  ➢ Reverse: Electric Voltage \( (\text{Input}) \) \( \rightarrow \) Mechanical Strain \( (S, \text{Output}) \)
• Ceramic materials | PZT: Lead Zirconate Titanate
2. Piezoelectric sensors – Electro Mechanical Admittance (EMA) method

Piezoelectric materials – Sensors/Actuators

- **Direct Piezoelectric Phenomenon**: Stress-Strain Sensors, Accelerometers etc.
- **Inverse Piezoelectric Phenomenon**: Vibration actuators, Stress waves actuators etc.
- **Electro-Mechanical Admittance Method.** Both sensor and actuator
  - Harmonic electric voltage stimulation $V_{in}$ (INPUT)
  - Electric current dynamic response $I_{out}$ (OUTPUT)
  - Admittance frequency response signatures

\[
Y = \frac{1}{Z} = \frac{Output}{Input} \frac{Electrical}{Electrical} \frac{Current}{Voltage} = \frac{F(I_{out})}{F(V_{in})} = G + iB
\]
2. Piezoelectric sensors – Electro Mechanical Admittance (EMA) method

Constitutive behavior – PZT patch

- Plain stress | Strain-Charge form
- In-plane electrical and mechanical isotropy ($d_{31}=d_{32}$)

\[
S_{11} = \left( T_{11} - v_{12} T_{22} \right) / \bar{Y}^E + d_{31} \left( V_3 / h \right)
\]

\[
S_{22} = \left( T_{22} - v_{12} T_{11} \right) / \bar{Y}^E + d_{32} \left( V_3 / h \right)
\]

\[
D_3 = d_{31} T_{11} + d_{32} T_{22} + \bar{\varepsilon}_{33} \left( V_3 / h \right)
\]

\[
Q_3 = \int_{A} D_3 dA
\]

$S_{jj}, T_{jj}, j=1:3$ : Strain and Stress (Pa) Tensors

$v_{12}$ : Poisson ratio | $Y^E$: Young Modulus

$n_{pz}$ : PZT Mechanical Loss Factor

$d_{31}, d_{32}$ : Piezoelectric Coefficients (C/N)

$D_3, Q_3$: Electrical Displacement (C/m²) and Charge (C)

$\varepsilon_{33}$: Relative Dielectric Permittivity

$\delta$: Dielectric Loss Factor, $\varepsilon_0=8.854\text{e-12 (F/m)}$
2. Piezoelectric sensors – Electro Mechanical Admittance (EMA) method

**Electro-Mechanical Admittance (EMA) response**

- Assuming harmonic voltage excitation: \( V_3 = \overline{V}_3 e^{i\omega t} \)

\[
Y_3 = \frac{I_3}{V_3} = i\omega \frac{\overline{Y}^E d_{31}}{1 - \nu} \left( \frac{1}{\overline{V}_3} \int A S_1^s dA \right) + i\omega C_{33} \left( 1 - \frac{2}{1 - \nu} \kappa_{31}^2 \right)
\]

- First invariant of strain tensor: \( I_1^s = S_{11} + S_{22} \)
- Static Capacitance: \( C_{33} = \varepsilon_{33} A / h \)
- Piezoelectric Coupling Coefficient: \( \kappa_{31}^2 = d_{31}^2 Y^E / \varepsilon_{33} \)

![Diagram of piezoelectric coupling](image)

- Free PZT: \( I_3 = V_R / R = dQ_3 / dt \)
- PZT bonded on a host structure: \( I_3 = V_R / R \)
2. Piezoelectric sensors – Electro Mechanical Admittance (EMA) method

Electro-Mechanical Admittance (EMA) response

- Numerical simulation. PZT 5H type, \( l=10\)mm, \( h=0.2\)mm

[Graphs showing conductance and susceptance responses for free and embedded PZT.]

Host structure and embedding interface resonant peaks
2. Piezoelectric sensors – Electro Mechanical Admittance (EMA) method

Electro-Mechanical Compliance (EMC)

- Transfer function: Input Voltage – Output PZT Surficial Deformation $S_A | H$ (Cm/N)

$$H(\omega) = H_R + iH_I = \frac{\bar{S}_A}{\bar{V}_3} = \frac{\int \bar{I}^S dA_{pzt}}{\bar{V}_3} = \frac{1 - \nu}{\bar{Y}E d_{31}} \left[ \frac{Y_3}{i\omega} - C_{33} \left( 1 - \frac{2}{1 - \nu} \kappa_{31}^2 \right) \right]$$

- Elimination of dielectric response influence-trend that obscure in several cases structural vibration features.
- EMC express structural dynamic response both of PZT and host structure.
- More sensitive to host structure mechanical parameters changes (change of internal geometry-crack, Young Modulus etc.)
2. Piezoelectric sensors – Electro Mechanical Admittance (EMA) method

**Electro-Mechanical Admittance and Compliance**

- Numerical simulation. PZT 5H type, l=10mm, h=0.2mm
- EMC: Peak-shape signature is imaginary part
- EMC: Essential dynamic features **amplification** (Resonant frequency peaks emerged especially in low frequencies)
3. Teflon (PTFE) based Piezoelectric Sensor (TPS)

Early Age Concrete Monitoring - Embedded PZT sensors

- Embedded sensors contribute to the effective monitoring of concrete as they act like smart aggregates.
- Attached into concrete mass during fabrication. Monitoring of concrete response from the early stage of strengthening and hydration.
- A 5H type PZT, 10x10x0.2mm patch is bonded via epoxy inside a properly designed Teflon (PTFE).
- Protection from moisture and concrete strengthening loads.
3. Teflon (PTFE) based Piezoelectric Sensor (TPS)

Concrete Early Age Monitoring – TPS Embedding

- Fixing of steel bolt on Teflon casing for robust anchoring of TPS in concrete mass.
- Anchoring is improving the mechanical conductivity between TPS and concrete’s mass.
- Mechanical conductivity. The ability of an interface between different materials to allow the transmission of mechanical energy, via waves, with the lower possible energy losses.
4. Numerical evaluation of TPS in monitoring of early age concrete

Finite element problem formulation

- Matrix Equation of motion: \[ \mathbf{M} \ddot{\mathbf{u}} + \mathbf{K}_u \mathbf{u} + \mathbf{K}_{uv} \mathbf{V} = \mathbf{f} \]
- Matrix Equation of electric charge: \[ \mathbf{K}_{Vu} \mathbf{u} + \mathbf{K}_{VV} \mathbf{V} = \mathbf{q} \]
- Tetrahedral solid element. 3 displacement and 1 electric charge degrees of freedom in every node

\( \mathbf{M} \): Mass matrix \((3N \times 3N)\), \( N \): Number of nodes
\( \mathbf{K}_u \): Mechanical stiffness matrix \((3N \times 3N)\)
\( \mathbf{K}_{uv} \): Voltage-Force EM stiffness matrix \((3N \times N)\)
\( \mathbf{K}_{Vu} \): Displacement-Charge EM stiffness matrix \((N \times 3N)\)
\( \mathbf{u} \): Nodal Displacement vector \((3N \times 1)\)
\( \mathbf{f} \): Nodal force vector \((3N \times 1)\)
\( \mathbf{V} \): Nodal Voltage vector \((N \times 1)\)
\( \mathbf{q} \): Nodal Electric charge vector \((N \times 1)\)
4. Numerical evaluation of TPS in monitoring of early age concrete

**Frequency domain analysis**

- Harmonic voltage excitation: \( V = \overline{V} e^{i\omega t} \)
- No external loading: \( f = 0 \)
- Harmonic displacement and charge response: \( u = U e^{i\omega t} \), \( q = Q e^{i\omega t} \)
- Electro-Mechanical Admittance matrix equation:

\[
Y = i\omega \left( K_V - K_{Vu} \left( K_u - \omega^2 M \right)^{-1} K_{uV} \right)
\]

- \( Y \): Admittance \((N \times N)\) matrix.
4. Numerical evaluation of TPS in monitoring of early age concrete

Finite element model – Discretization

- **Comsol FEM** analysis. ½ Symmetry Geometry model
- 42719 tetrahedral elements
- Minimum element size: 1mm (close to PZT dimensions)
- Max element size: 20 mm (close to coarse aggregate size)

![Diagram of PZT, Steel bolts, Teflon, and Epoxy]
4. Numerical evaluation of TPS in monitoring of early age concrete

**Finite element model – Boundary conditions**

- Frequency response analysis.
  - 10-60 kHz, step 220 Hz
  - 60-160 kHz, step 400 Hz
- 1 V, Voltage stimulation of PZT patch.
- Symmetry boundary conditions.
- PZT – Linear Elastic materials interfaces: Continuity of displacement field.

PZT up surface: Electric voltage stimulation
PZT Lower surface: Grounded

19/30
4. Numerical evaluation of TPS in monitoring of early age concrete

Finite element model – Material properties

- Piezoelectric material: PZT
- Linear elastic isotropic materials: Teflon, Epoxy, Steel, Concrete

<table>
<thead>
<tr>
<th>Property</th>
<th>PZT 5H</th>
<th>Epoxy</th>
<th>Teflon (PTFE)</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density $\rho$ (kg/m$^3$)</td>
<td>7800</td>
<td>1800</td>
<td>2160</td>
<td>7850</td>
</tr>
<tr>
<td>In-plane Young Modulus $Y^E$ (GPa)</td>
<td>66.7</td>
<td>4</td>
<td>0.5</td>
<td>205</td>
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<tr>
<td>Normal Young Modulus $Y^E_p$ (GPa)</td>
<td>52.6</td>
<td>4</td>
<td>0.5</td>
<td>205</td>
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<tr>
<td>Poisson Ratio $\nu$</td>
<td>0.34</td>
<td>0.3</td>
<td>0.3</td>
<td>0.28</td>
</tr>
<tr>
<td>Piezoelectric coefficient $d_{31} = d_{32} \mid d_{33}$ (C/N) x1e-12</td>
<td>-210</td>
<td>500</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Relative electrical permittivity $\varepsilon_{11} = \varepsilon_{22} \mid \varepsilon_{33}$</td>
<td>1980</td>
<td>2400</td>
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<td>-</td>
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<tr>
<td>Mechanical Loss Factor $n$</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.005</td>
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<tr>
<td>Electrical Loss Factor $\delta$</td>
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<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
4. Numerical evaluation of TPS in monitoring of early age concrete

Finite element model – Concrete material model

- **C 20/25** concrete (\(\rho=2400 \text{ kg/m}^3\), \(\nu=0.2\), \(n=0.06\))
- **Eurocode 2** (EC2) Early age Young modulus evolution

\[
E_{cm}(t) = E_{cm}^{28} \left[ \exp \left( s \left( 1 - \sqrt{\frac{28}{t}} \right) \right) \right]^{\frac{1}{3}}
\]

\(E_{cm}^{28}\) (GPa): 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. Results and discussion

FEM analysis Results

- **Conductance $G_3$ and EMC imaginary part $H_I$ signatures:** $10$-$60$KHz
- Conductance is calculated via surficial integration on upper PZT terminal.

$$Y_3 = \frac{i\omega Q_3}{V_3} = \frac{i\omega}{A} \int \overline{D_3} dA$$
5. Results and discussion

FEM analysis Results

- 28 days age displacement modes in resonant frequencies: 10-60Khz
5. Results and discussion

FEM analysis Results

- Conductance $G_3$ and EMC imaginary part $H_I$ signatures: 60-160Khz
5. Results and discussion

FEM analysis Results

- 28 days age displacement modes in resonant frequencies: 60-160Khz
5. Results and discussion

Evaluation of signatures changes

• **Inverse Root Mean Square Deviation** \( IRMSD \) index applied to \( H_I \) signatures.

• As reference signature is taken EMC response of 28 days age concrete, \( H_I^{28} \)

• IRMSD is calculated for different frequency ranges of FEM calculated signatures.

\[
IRMSD = \sqrt{\sum_{j=1}^{M} \left( H_{I,j}^{28} \right)^2} \div \left( \sum_{j=1}^{M} \left( H_{I,j} - H_{I,j}^{28} \right)^2 + \sum_{j=1}^{M} \left( H_{I,j}^{28} \right)^2 \right)
\]

\( N \): Number of investigated signature part values.
5. Results and discussion

Evaluation of signatures changes

- Correlation of $IRMSD$ values with Young modulus, using a TPS acquired reference EMC signature in frequency range 27-37 kHz, that correspond to the dynamic response of a 28 days age concrete of specific quality (EC2: C16/20, C20/25, C30/37 etc.)

$$\lambda = \frac{E_{est}(t)}{IRMSD_{27-38kHz}} = a \ln(t) + b$$
5. Results and discussion

Conclusions

• An embeddable to concrete mass piezoelectric sensor, termed as TPS, has been designed based on the adhering of a 5H type PZT patch inside a properly fabricated Teflon casing.

• TPS aims to the monitoring of early age concrete by screening changes to the Electro-Mechanical Compliance (EMC) frequency response signatures.

• EMC signatures achieve to uncover essential structural dynamic features (resonance peaks) in frequency range 10-60 kHz, that are obscured in Electro-Mechanical Admittance (EMA) signatures because of PZT strong dielectric response.
5. Results and discussion

Conclusions

• Finite element modeling of electromechanical interaction between TPS and concrete reveals that TPS response is sensitive to concrete young modulus changes in frequencies between 20 and 37 kHz and in neighborhood of 55 kHz. It is mentioned that classic ultrasonic methods operates in 48 to 54 kHz range.

• In frequency range between 60 and 160 kHz significant EMC signatures changes are emerged in frequencies 108 and 137 kHz but they are not so intense to establish a reliable monitoring criterion.

• IRMSD index evolution as function of concrete age approach the pattern of EC2 Young Modulus model, approving that TPS device after an efficient calibration can be useful to Early Age Concrete strengthening monitoring.
Thank you very much for your attention

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