EVALUATION OF STRENGTH CHARACTERISTICS OF MORTAR AND CONCRETE DURING CURING USING EMI AND SURFACE WAVE PROPAGATION TECHNIQUES

NELLY BINTI MAJAIN

**FACULTY OF ENGINEERING
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NELLY BINTI MAJAIN

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2016

DECLARATION

I hereby declare that the material in this thesis is my own except for quotations, excerpts, equations, summaries and references, which have been duly acknowledged.

26 January 2016

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Nelly Binti Majain
MK 1211008T

CERTIFICATION

NAME : **NELLY BINTI MAJAIN**

MATRIC NO. : **MK 1211008T**

TITLE : **EVALUATION OF STRENGTH CHARACTERISTICS OF MORTAR AND CONCRETE DURING CURING USING EMI AND SURFACE WAVE PROPAGATION TECHNIQUES**

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DECLARED BY

1. MAIN SUPERVISOR
Assoc. Prof. Dr. Willey Liew Yun Hsien Signature

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2. CO-SUPERVISOR
Dr. Lim Yee Yan ______________________

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Nelly Majain
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ABSTRACT

Concrete is a non-homogenous material with complex microstructure, consisting of water, cement, aggregates and other suitable materials. During concreting of concrete structures, heat will be released due to the hydration process between cement and water. At this stage, curing process is crucial and it needs to be monitored so that the concrete will be able to achieve the desired strength and becomes durable. Due to the complexity of concrete microstructure, the evaluations for concrete curing and strength monitoring are difficult and have moved at a slower pace. However, in recent years the advancements of piezoelectric materials such as Lead Zirconate Titanate (PZT) have attracted interest among researchers to develop new non-destructive evaluation methods to investigate the performance of concrete. The key advantage of using PZT is that it can be placed anywhere even in remote and inaccessible locations as both actuator and sensor to monitor concrete structures. The electromechanical impedance (EMI) and surface wave propagation techniques employing PZT transducer have been developed by researchers as a non-destructive approaches for evaluating concrete. The main objective of this thesis is to evaluate the strength characteristics of mortar and concrete during curing using the EMI and surface wave propagation techniques. In order to achieve this, the research begins with conducting parametric study on free vibration of PZT transducer in the application of EMI technique. The work continues with experimental investigation to study the feasibility of using the EMI and surface wave propagation techniques employing PZT transducer for evaluation of strength characteristics of mortar and concrete during curing. The PZT transducers were attached to the mortar and concrete specimens through surface bonding and embedded methods. The results showed that by using the EMI and surface wave propagation techniques employing the PZT transducer, the duration of concrete setting and curing can be determined. Also, a good correlation between the concrete dynamic modulus of elasticity with compressive strength has been achieved by using the surface wave propagation method. For these reasons, the EMI and surface wave propagation techniques can be a useful tools to ensure the safety and quality of concrete structures during construction and service.

ABSTRAK

PENILAIAN CIRI-CIRI KEKUATAN MORTAR DAN KONKRIT SEMASA PENGAWETAN MENGGUNAKAN TEKNIK EMI DAN PERAMBATAN GELOMBANG PERMUKAAN

Konkrit merupakan bahan yang tidak homogen dengan mikrostruktur yang kompleks dan yang terdiri daripada air, simen, agregat dan bahan-bahan lain yang sesuai. Semasa kerja menuang konkrit dalam pembinaan struktur konkrit, haba akan dibebaskan melalui proses penghidratan di antara simen dan air. Pada peringkat ini, proses pengawetan adalah penting dan ia perlu dipantau supaya konkrit akan dapat mencapai kekuatan yang dikehendaki dan menjadi tahan lama. Oleh kerana konkrit mempunyai mikrostruktur yang kompleks, penilaian untuk pengawetan konkrit dan pemantauan kekuatan adalah sukar dan bergerak dengan kadar perlahan. Walau bagaimanapun, beberapa tahun kebelakangan ini, kemajuan bahan-bahan piezoelektrik seperti 'Lead Zirconate Titanate' (PZT) telah menarik minat kalangan penyelidik untuk membina teknik-teknik penilaian ujian tanpa musnah yang baru bagi mengkaji prestasi konkrit. Kelebihan utama menggunakan PZT ialah ia boleh diletakkan dimana-mana walaupun di tempat yang jauh dan lokasi yang tidak dapat diakses sebagai aktuator (penggerak) dan sensor (pengesan) untuk mengawasi struktur konkrit. Teknik elektromekanikal impedans (EMI) dan perambatan gelombang permukaan menggunakan transduser PZT telah dibangunkan oleh para penyelidik sebagai pendekatan tanpa musnah untuk penilaian konkrit. Objektif utama tesis ini adalah untuk membuat penilaian terhadap ciri-ciri kekuatan mortar dan konkrit semasa pengawetan menggunakan teknik-teknik EMI dan perambatan gelombang permukaan. Bagi mencapai objektif ini, penyelidikan ini bermula dengan menjalankan kajian parametrik terhadap getaran bebas transduser PZT dalam penggunaan teknik EMI. Penyelidikan diteruskan dengan kajian eksperimen untuk mengkaji kemungkinan menggunakan teknik EMI dan perambatan gelombang permukaan menggunakan PZT transduser untuk penilaian ciri-ciri kekuatan mortar dan konkrit semasa pengawetan. Transduser PZT diletakkan ke atas spesimen mortar dan konkrit melalui ikatan permukaan dan kaedah terbenam. Hasil kajian ini menunjukkan bahawa dengan menggunakan teknik EMI dan perambatan gelombang permukaan menggunakan transduser PZT, tempoh penetapan konkrit dan pengawetan boleh ditentukan. Selain itu, korelasi yang baik antara modulus dinamik keanjalan konkrit dengan kekuatan mampatan telah dicapai menggunakan kaedah perambatan gelombang permukaan. Oleh sebab itu, teknik EMI dan perambatan gelombang permukaan boleh menjadi kaedah yang berguna untuk memastikan keselamatan dan kualiti struktur konkrit semasa pembinaan dan perkhidmatan.

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LIST OF ABBREVIATION

ASTM	-	American Society for Testing and Materials
BS	-	British Standard
BS EN	-	British Standard European Norm
EMI	-	Electromechanical Impedance
IEEE	-	The Institute of Electrical and Electronics Engineers
MS	-	Malaysian Standard
NDE	-	Non-Destructive Evaluation
PVDF	-	Polyvinvylidene Fluoride
PWAS	-	Piezoelectric Wafer Active Sensors
PZT	-	Lead Zirconate Titanate
RMSD	-	Root Mean Square Deviation
SASW	-	Spectral Analysis of Surface Waves
SEF	-	Static Equivalent - Force
SHM	-	Structural Health Monitoring
SMA	-	Shape Memory Alloys
TOF	-	Time of Flight
UPV	-	Ultrasonic Pulse Velocity

LIST OF SYMBOLS

A_a	-	Cross sectional area of PZT patch
A	-	Constant mass matrix multiplier
b_a	-	Width of actuator
C	-	Electrical capacitance of PZT patch
d	-	Distance
d_{31}	-	Piezoelectric constant of PZT patch
d_c	-	Strain coefficient tensors (converse)
d_d	-	Strain coefficient tensors (direct)
$[d^c]$	-	Piezoelectric strain coefficient tensors (converse)
$[d^d]$	-	Piezoelectric strain coefficient tensors (direct)
δ	-	Electrical loss factor
D_3	-	Electric charge density on surface normal to axis 3 of PZT
D_i	-	Electric displacement
$[D]$	-	Electric displacement vector
E	-	Young's modulus of elasticity
E_3	-	Electric field applied along axis 3 of PZT patch
E_j	-	Applied external electric field
$[E]$	-	Applied external electric field vector
$\overline{\varepsilon_{33}}^T$	-	Complex dielectric constant at zero stress
$[\overline{\varepsilon^T}]$	-	Complex dielectric permittivity tensor
f	-	Frequency
g_{31}	-	Piezoelectric voltage constant
γ	-	Wave number
H(x(t))	-	Hilbert Transform
h	-	Thickness of PZT patch
h_a	-	Thickness of Actuator
i	-	Reference signature at different frequencies
j	-	Imaginary number
j	-	Amount of lag (in cross correlation)

k_{31}	-	Coupling factor
K_{str}	-	Dynamic Stiffness of Host Structure
K_{PZT}	-	Quasi-static stiffness of PZT patch
k	-	Wave number
l	-	Length of PZT patch
l_a	-	Length of Actuator
λ	-	Wavelength
ω	-	Angular frequency
φ	-	Admittance poles
ϕ	-	Displacement phase shift (phase angle)
η	-	Mechanical loss factor
$p_{12}(j)$	-	Cross Correlation
ρ	-	Density
R	-	Stiffness ratio
$R_{xy}(t)$	-	Cross Correlation of two signals x(t) and y(t)
s_{11}^{E}	-	Elastic constant along axis 1 at zero electric field
$[\overline{s^{E}}]$	-	Complex elastic compliance tensor
S_1	-	Strain of the PZT patch in direction 1
$[S]$	-	Strain tensor
t	-	Time
θ	-	Angular Coordinate
τ	-	Time step (Hilbert Transform)
T	-	Curie temperature
T_1	-	Stress applied in the direction 1
$[T]$	-	Stress tensor
V	-	Wave Velocity
V_P	-	P-wave Velocity
V_S	-	S-wave velocity
V_R	-	Rayleigh wave velocity
$V(t)$	-	Sinusoidal voltage applied
$\bar{V}$	-	Voltage applied (in complex notation)

v	-	Poisson ratio
v_a	-	Poisson ratio of actuator
w	-	Width of PZT patch
$X_1(n)$	-	Data sequence 1
$X_2(n)$	-	Date sequence 2
$x(t)$	-	Input signal
$\overline{Y}$	-	Complex electrical admittance
$\overline{Y_{11}^{E}}$	-	Complex Young's modulus of PZT patch along axis 1 at zero electric field
Z	-	Mechanical impedance of host structure
$Z_{i,1}$	-	Baseline admittance signatures at frequency interval *i*
$Z_{i,2}$	-	Admittance signatures at frequency interval, *i* with different temperature
Z_a	-	Mechanical impedance of actuator
$Z_{a,eff}$	-	Effective mechanical impedance of actuator
$Z_{s,eff}$	-	Effective mechanical impedance of host structure
Z_{axx}	-	Mechanical impedance of actuator in *x*-direction
Z_{ayy}	-	Mechanical impedance of actuator in *y*-direction
Z_{xx}	-	2-D Mechanical impedance of host structure in *x*-direction
Z_{yy}	-	2-D Mechanical impedance of host structure in *y*-direction
Z_{xy}	-	2-D Cross mechanical impedance of host structure in *y*-direction
Z_{yx}	-	2-D Cross mechanical impedance of host structure in *x*-direction

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