ELECTRICAL BEHAVIOR OF PARTIALLY SATURATED CEMENT PASTE, MORTAR AND CONCRETE SUBJECTED TO RADIO FREQUENCY EXCITATION

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DEPARTMENT OF CIVIL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY DELHI

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THE THESIS HAS BEEN DEDICATED TO MY FAMILY

CERTIFICATE

This is to certify that the thesis entitled "**Electrical Behavior of Partially Saturated Cement Paste, Mortar and Concrete Subjected to Radio Frequency Excitation**" being submitted by **Mr. Gopinandan Dey** to the Indian Institute of Technology Delhi is a record of bonafide research work carried out by him under our supervision and guidance. The thesis work, in our opinion, has reached the standard, fulfilling the requirements for the award of **Doctor of Philosophy** degree.

The research report and results presented in this thesis have not been submitted, in part or full, to any University or Institute for the award of any degree or diploma.

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Abstract

Cement based materials (CBMs) are porous and constitute a significant portion of materials used in construction in the form of cement concrete, cement mortar or cement paste. The porous nature of CBMs facilitate moisture movement through the pores which also act as a conduit for aggressive chemicals. All degrading chemical reactions occur in the presence of moisture that may originate from a variety of sources such as rainwater, surface water or ground water. The transport property of the material and the susceptibility to the diffusion of aggressive chemicals are dependent on the degree of saturation (DoS) and for assessments of not only the gross DoS but information of its temporal variation and spatial distribution in the material are essential. This enables identification of the level of vulnerability of the material to a probable hazardous condition and planning for pre-emptive repair actions. The primary objective of this thesis is to estimate the DoS in CBM and its spatial variation by developing an inexpensive electrical impedance based non-destructive technique.

In this work, the CBM samples of 75 mm x 75 mm x 300 mm are considered which host embedded electrodes for multiple measurements along the sample length for determination of the spatial variation of the impedance as a function of the DoS. The AC voltage is applied at radio frequencies (RF) ranging from 100 kHz to 500 kHz; the reason being that low RF has higher penetration in the material due to its inverse relationship to the square root of frequency, thus able to generate information from larger depth. To generate simultaneous information corresponding to a band of frequencies, a pulse based input excitation is applied. To avoid the DC component and higher frequencies, the D-Lorentz waveform is chosen as the input waveform. The output signals are acquired in time domain in the oscilloscope and converted to frequency domain by performing FFT in the MATLAB environment. Subsequently, from the obtained FFT amplitudes at specific frequencies, the cumulative impedance between the source and at various measurement electrode positions along the length of the sample are calculated.

Two different approaches are considered to correlate DoS to the measured electrical parameters. One method is the **Voltage Ratio Method** in which the variation of the real and imaginary parts of output to input voltage ratio along the length of the sample is investigated with the DoS being homogenized along the sample through treatment in the climate chamber. It is observed that the plot between the real part and imaginary parts of the ratio vary linearly along the length for each DoS. The gradients of the lines are distinct for each DoS, thus the gradients

are used for estimation of the DoS for the homogenized sample. A second more general approach is developed which is named as the **Equivalent Circuit Method**, based on the linear variation of the cumulative real and imaginary parts of the impedance along the length for spatially homogenized DoS condition of the sample. The sample is discretized into parallel R-C circuit elements and empirical relationships between the bulk conductivity and the DoS are established for various levels of homogenized DoS during drying and wetting cycles of the CBM. The variation of the bulk relative permittivity for various frequencies is also explored and the values are found to be significantly higher than the value of the constituent ingredients. This enhanced value of relative permittivity is attributed to the Maxwell-Wagner (MW) effect in this frequency range.

For general situations, where the DoS is spatially variable in a CBM, a Tikhonov parameter and a Radial Basis Function (RBF) based inversion technique is developed that reconstructs the impedance profile along the length of the sample. The technique is observed to be robust with sparse measurement data. Further, using the empirical relationships derived from the equivalent circuit model, the impedance variation can be converted to spatial variation of the DoS. Thus, it demonstrates that DoS can be estimated from the knowledge of impedance or conductivity of the moist material. The methodology is validated by comparing the gross DoS of the sample estimated from DoS profile and gross DoS calculated from gravimetric measurement. The information obtained with this method related to DoS profile can provide preliminary data for assessment of transport property of the material which may be utilized for quality control and other important assessments of the CBM.

सार

सीमेंट आधारित सामग्री (सीबीएम) छिद्रपूर्ण हैं और सीमेंट कंक्रीट, सीमेंट मोर्टार या सीमेंट पेस्ट के रूप में निर्माण में उपयोग की जाने वाली सामग्रियों का एक महत्वपूर्ण हिस्सा है। सीबीएम की झरझरा प्रकृति छिद्रों के माध्यम से नमी की आवाजाही की सुविधा देती है जो आक्रामक रसायनों के लिए एक नाली के रूप में भी काम करती है। सभी अपमानजनक रासायनिक प्रतिक्रियाएं नमी की उपस्थिति में होती हैं जो विभिन्न स्रोतों से उत्पन्न हो सकती हैं जैसे कि वर्षा जल, सतही जल या भूजल। सामग्री की परिवहन संपत्ति और आक्रामक रसायनों के प्रसार के लिए संवेदनशीलता, संतृप्ति (DoS) की डिग्री पर निर्भर है और न केवल सकल DoS के आकलन के लिए, बल्कि सामग्री में इसके लौकिक भिन्नता और स्थानिक वितरण की जानकारी आवश्यक है। यह संभावित खतरनाक स्थिति के लिए सामग्री की भेद्यता के स्तर की पहचान करने और पूर्व-खाली मरम्मत कार्यों के लिए योजना बनाने में सक्षम बनाता है। इस थीसिस का प्राथमिक उद्देश्य सीबीएम में DoS का अनुमान लगाना और एक सस्ती विद्युत प्रतिबाधा आधारित गैर-विनाशकारी तकनीक विकसित करके इसकी स्थानिक भिन्नता है।

इस काम में, 75 मिमी x 75 मिमी x 300 मिमी के सीबीएम नमूनों पर विचार किया जाता है, जो कि DoS के एक फ़ंक्शन के रूप में प्रतिबाधा के स्थानिक भिन्नता के निर्धारण के लिए नमूना लंबाई के साथ कई मापों के लिए एम्बेडेड इलेक्ट्रोड की मेजबानी करता है। एसी वोल्टेज 100 kHz से 500 kHz तक के रेडियो आवृत्तियों (RF) पर लगाया जाता है; कारण यह है कि निम्न RF आवृति के वर्गमूल से इसके विपरीत संबंध के कारण सामग्री में उच्च पैठ रखता है, इस प्रकार यह बड़ी गहराई तक जानकारी उत्पन्न करने में सक्षम है। आवृत्तियों के एक बैंड के साथ एक साथ सूचना उत्पन्न करने के लिए, एक पल्स आधारित इनपुट उत्तेजना लागू की जाती है। डीसी घटक और उच्च आवृत्तियों से बचने के लिए, डी-लोरेंत्ज़ तरंग को इनपुट तरंग के रूप में चुना जाता है। आउटपुट सिग्नल ऑसिलोस्कोप में समय डोमेन में प्राप्त किए जाते हैं और MATLAB वातावरण में FFT प्रदर्शन करके आवृत्ति डोमेन में परिवर्तित होते हैं। इसके बाद, विशिष्ट आवृत्तियों पर प्राप्त एफएफटी आयामों से, स्रोत के बीच और नमूना की लंबाई के साथ विभिन्न माप इलेक्ट्रोड पदों पर संचयी प्रतिबाधा की गणना की जाती है।

दो अलग-अलग दृष्टिकोणों को मापा विद्युत मापदंडों के लिए DoS को सहसंबंधित माना जाता है। एक विधि वोल्टेज अनुपात विधि है जिसमें नमूना की लंबाई के साथ आउटपुट वोल्टेज के अनुपात में वास्तविक और काल्पनिक भागों की भिन्नता की जांच की जाती है, जिसमें DoS को जलवायु कक्ष में उपचार के माध्यम से नमूने के साथ समरूप किया जाता है। यह देखा गया है कि अनुपात के वास्तविक भाग और काल्पनिक भागों के बीच का भूखंड प्रत्येक DoS की लंबाई के साथ रैखिक रूप से भिन्न होता है। लाइनों के ग्रेडिएंट प्रत्येक DoS के लिए अलग होते हैं, इस प्रकार ग्रेडिएंट्स

Homogenized नमूने के लिए DoS के अनुमान के लिए उपयोग किया जाता है। एक और अधिक सामान्य दृष्टिकोण विकसित किया गया है जिसे नमूना के स्थानिक रूप से समरूपित DoS स्थिति के लिए लंबाई के साथ प्रतिबाधा के संचयी वास्तविक और काल्पनिक भागों के रैखिक भिन्नता के आधार पर समतुल्य सर्किट विधि के रूप में नामित किया गया है। नमूना को समानांतर आर-सी सर्किट तत्वों और बल्क चालकता के बीच अनुभवजन्य संबंधों में विवेकाधीन किया जाता है और CBM के सूखने और गीला होने के दौरान DoS को विभिन्न स्तर के समरूप डीओएस के लिए स्थापित किया जाता है। विभिन्न आवृत्तियों के लिए थोक सापेक्ष पारगम्यता की भिन्नता का भी पता लगाया जाता है और मूल्यों को घटक अवयवों के मूल्य से काफी अधिक

पाया जाता है। इस क्रमिक सीमा में मैक्सवेल-वैगनर (MW) प्रभाव के लिए सापेक्ष पारगम्यता के इस संवर्धित मूल्य को जिम्मेदार ठहराया गया है।

सामान्य परिस्थितियों के लिए, जहां CS में DoS स्थानिक रूप से परिवर्तनशील होता है, एक Tikhonov पैरामीटर और एक रेडियल बेसिस फ़ंक्शन (RBF) आधारित इनवर्जन तकनीक विकसित की जाती है जो नमूना की लंबाई के साथ प्रतिबाधा प्रोफ़ाइल को फिर से संगठित करती है। तकनीक को विरल माप डेटा के साथ मजबूत होने के लिए मनाया जाता है। इसके अलावा, समतुल्य सर्किट मॉडल से प्राप्त अनुभवजन्य संबंधों का उपयोग करते हुए, प्रतिबाधा भिन्नता को DoS की स्थानिक भिन्नता में परिवर्तित किया जा सकता है। इस प्रकार, यह दर्शाता है कि DoS को नम सामग्री के प्रतिबाधा या चालकता के ज्ञान से अनुमानित किया जा सकता है। DoS प्रोफ़ाइल से अनुमानित नमूने के सकल DoS की तुलना करके और Gravimetric माप से गणना की सकल DoS द्वारा कार्यप्रणाली को मान्य किया गया है। DoS प्रोफ़ाइल से संबंधित इस पद्धति से प्राप्त जानकारी सामग्री की परिवहन संपत्ति के मूल्यांकन के लिए प्रारंभिक डेटा प्रदान कर सकती है, जिसका उपयोग गुणवत्ता नियंत्रण और CBM के अन्य महत्वपूर्ण आकलन के लिए किया जा सकता है।

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List of Symbols

Symbol	Description
L_k	Length of the specimen from source to kth electrode
R_e	Resistance of the external resistor
S_w	Degree of saturation
V_e	Voltage drop across external resistor
V_{in}	Input voltage
V_k	Output voltage at kth electrode
V_r^i	Imaginary part of output to input voltage
V_r^r	Real part of output to input voltage
Z^i	Imaginary Part of cumulative impedance
Z_{int}^1	Interfacial impedance in source end
Z_{int}^2	Interfacial impedance in far end
Z_{int}^{i1}	Imaginary part of interfacial impedance in source end
Z_{int}^{i2}	Imaginary part of interfacial impedance in far end
Z_{int}^{r1}	Real part of interfacial impedance in source end
Z_{int}^{r2}	Real part of interfacial impedance in far end
Z_k	Cumulative impedance upto kth electrode
Z_k^i	Imaginary part of cumulative impedance upto kth electrode
Z_k^r	Real part of cumulative impedance upto kth electrode
Z^r	Real part of cumulative impedance
c_m	Velocity of electromagnetic wave in the material

m_d	Weight of dry sample
m_i	Weight of sample in any intermediate saturation level
m_s	Weight of saturated sample
z^i	Imaginary part of impedance per unit length
z^r	Real part of impedance per unit length
ε^*	Complex permittivity
ε_0	Vacuum permittivity
ε_m	Relative permittivity of the material
ε_r	Bulk relative permittivity
μ^*	Complex magnetic permeability
μ_r	Relative magnetic permeability
ρ_0	Resistivity of the pore solution
σ^*	Complex conductivity
σ_t	Total bulk conductivity
σ_w	Pore water conductivity
$\emptyset$	Porosity of the material
A	Cross sectional area of specimen
C	Capacitance
F	Formation factor
I	Current
L	Length of the specimen
R	Resistance
WA	Water absorption coefficient
c	Velocity of electromagnetic wave in free space

l	Length of waveguide
s	Shape parameter
t	Travel time of electromagnetic wave
α	Connectivity of pores
β	Angular parameter for determination of DoS
ε	Bulk permittivity
λ	Tikhonov regularization parameter
μ	Support point of radial basis function
ρ	Bulk resistivity
σ	Bulk conductivity
φ	Radial basis function
ω	Angular frequency

List of Acronyms

Acronym	Definition
AC	Alternating Current
CBM	Cement Based Material
DC	Direct Current
DoS	Degree of (Moisture) Saturation
ECM	Equivalent Circuit Method
FFT	Fast Fourier Transform
GA	Gaussian
GPR	Ground Penetrating Radar
IMQ	Inverse Muliquadric
kHz	kilo Hertz
KVL	Kirchhoff's Voltage Law
MHz	Mega Hertz
M-W	Maxwell-Wagner
NMR	Nuclear Magnetic Resonance
RBF	Radial Basis Function
RF	Radio Frequency
RH	Relative Humidity
TDR	Time Domain Reflectometry
VRM	Voltage Ratio Method
w/c	Water to Cement Ratio