JOINT TRANSPORTATION RESEARCH PROGRAM

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Determining the Optimal Traffic Opening Timing Through an In-Situ NDT Method for Concrete Early Age Properties

Introduction

Developing a reliable in-situ testing method to determine the real-time strength of concrete for optimal traffic opening time is a critical need for INDOT, due to fast-pace construction schedules that often exposes concrete pavements to substantial loading conditions even in its early age. Current methods for determining traffic opening times are inefficient and expensive, which often causes construction delays or cost overruns. The conventionally used testing methods, compressive test and flexural test, are very time consuming. Furthermore, the curing conditions of the tested specimens are quite different from field conditions. To address this critical need, the Purdue team has developed an in-situ nondestructive testing (NDT) method that PROVIDEs an accurate measurement of concrete strength at early age using the electromechanical impedance (EMI) method coupled with piezoelectric sensors (PZT).

Based on direct and indirect effects piezoelectric materials can act both as a transducer and a receiver to capture the properties change of host structures of which it is attached to. Previous literature has indicated that a piezoelectric sensor coupled with EMI technique can be a promising method to monitor the concrete properties change at the laboratory scale. However, none of the existing research has used the EMI signature to study the mechanical properties, particularly the development of elastic modulus and compressive strength for the cementitious materials in field conditions, especially at its very early age (4–8 hours). Moreover, the effect of different mix designs on the reliability of EMI methods have not been investigated in the existing literature.

In this project, the Purdue team developed an implementable EMI sensing method using a polymer-coated piezoelectric sensor. The team has also developed associated data processing software and a user-friendly graphic interface. Thousands of specimens were tested systematically with various mixes in the laboratory. A data processing method and the reliable sensing index were developed for monitoring the compressive strength gain of concrete. COMSOL Multiphysics model was employed to understand the fundamental mechanism of an EMI sensing technology. The finite element model (FEM) indicated that the EMI spectra shifting with the stiffness growth of concrete agreed with the experimental results. Notably, the team conducted several trial implementations on highway construction projects (I-70, I-74, and I-465) to monitor the strength development of concrete pavement. In summary, the EMI sensing system proposed in this study appears to be an accurate NDT method for testing in-place strength of concrete, particularly at the early age. The data gathered from this research enables INDOT engineers to make an informed decision on the optimal traffic opening time of concrete pavement after construction.

Findings

In this project, the feasibility of using EMI sensing technology for monitoring the compressive strength gain of concrete was systematically studied. Extensive experiments with multi-physics modeling were conducted on various samples ranging from cement paste, mortar, and concrete with various design mixes to field tests on the interstate highway projects. Computer modeling work was performed to assist the experimental studies. The findings of the work are detailed as follows:

- In the cement paste experiments, three different mixes were conducted using ordinary Portland cement (OPC), fly ash (FA), and silica fume (SF). More than 50 specimens were tested. The results suggested that the EMI data processed using the Root Mean Square Deviation (RMSD) statistical model has a high correlation with the compressive strength of cement paste samples from the 3rd to 28th day. The correlation coefficient (R2) of the RMSD index is higher than 0.9.
- The EMI sensing models constructed through the finite element method indicated that the EMI spectra, such as conductance and admittance signatures, would shift with

the increase of elastic modulus of concrete. The possible effective sensing range of the piezoelectric sensor obtained from modeling is around 5.5 inches in diameter.

- Through the extensive data analysis, the optimal frequency range of EMI spectra lies between 100 k to 400 kHz, which shows high correlation between compressive strength test results with EMI-RMSD index. It has been found that the R^2 values for compressive strength versus RMSD index are higher than 0.93 for all mortar samples with different water-to-cement ratios (W/C) and two types of cement (I and III), and the R^2 value is above 0.91 for elastic modulus versus RMSD index. It is important to point out that the R^2 value is 0.92 for all samples regardless of W/C, which implies that the EMI-RMSD index may be independent of the W/C.
- The ten most commonly used concrete mixtures at INDOT were tested using both EMI and compressive testing methods according to ASTM C39. Over 300 cylindrical concrete specimens were fabricated and tested. The regression results indicated that the correlation coefficient between the EMI sensing index and compressive strength of all mixes is higher than 0.90.
- The concrete slab test was also conducted and served as a pilot study to evaluate the feasibility of using the EMI sensing method for monitoring real-time compressive strength of concrete pavement on jobsites. The regression analysis was employed to evaluate the correlation between the index and mechanical strength. The obtained R^2 is 0.97, which indicates the sensing results have a high correlation with the compressive strength of concrete. The linear function was built using the regression model to estimate the real-time strength of concrete pavement at early age.
- Field tests were conducted on three interstates in Indiana, including interstate highway I-70, I-74, and I-465. Among the field tests, I-70 and I-465 are concrete patching projects and I-74 is the concrete paving project. Almost a hundred sensors were embedded in the concrete pavement to monitor the real-time strength development from 1 hour to 3 days. All polyester coated sensors used in this project performed well during the harsh construction process.
- For the one-day compressive strength of concrete pavement, the EMI sensing method has obtained higher results than compressive strength testing. This can be attributed to exothermic hydration reactions of mass concrete is higher than that of cylinder samples. However, more research needs to be conducted to validate the proposed hypothesis, due to the limited dataset obtained in this study.

Implementation

The goal of this project is to develop a reliable NDT method to monitor the real-time compressive strength gain of concrete pavement in order to determine the optimal traffic opening time. As the outcome of this project, the hardware and software of EMI technology, in conjunction with the operational manual, will be delivered to INDOT for potential field implementations.

- To protect the PZT sensors from harsh concrete construction and maintain its high sensitivity, the polyester-coated sensors are recommended to be embedded in concrete pavement for strength monitoring.
- The EMI signature interpreting software is built for data processing. The RMSD index is the most efficient statistical index to calculate the changes in stiffness and compressive strength of concrete over time.
- The optimal frequency range for EMI spectrum calculation is from 100 kHz to 400 kHz with a resolution of 5 kHz.The portable EMI sensing system is developed with data-processing software in this study, which is convenient for field implementation.

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