ABSTRACT

Current material testing methods for concrete can neither meet the fast pace of construction projects, nor reflect the realistic mechanical property of the in-place concrete. The specifications (ASTM C39) require cylinder break testing for the quality assurance (QA) of concrete; however, this process involves several steps such as sample preparation, transportation, curing, and breaking, which is inefficient and inaccurate. The curing condition of concrete cylinder samples is distinct from the realistic curing condition of in-place concrete, and results in the discrepancy between the cylinder strength versus the in-place strength.

Stress wave based nondestructive evaluation (NDE) has been applied to address this challenge. Among other methods, the electro-mechanical impedance (EMI) method is distinct because of its practical convenience. For example, EMI method uses a piezoelectric element as both the actuator and the sensor, so there is no need to switch the hardware between transmitting and receiving mode; the data collection device sweeps through a broadband frequency range and collects abundant frequency domain data in a few seconds; the piezoelectric sensor is simpler in structure and more affordable compared with commercial ultrasonic probes.

Existing EMI studies have made decent advances in civil engineering area, such as the monitoring of curing of cementitious material, the monitoring of corrosion of steels, and the monitoring of structural damage. Most of these studies use statistical metrics to register the change of EMI spectrum, then correlate such change with target variables. However, the limitation of these statistical methods is that they are difficult to generalize among sensors and materials. Although the reference states are subtracted or divided from the current states, the simple arithmetic operation is not enough to eliminate the variance introduced by sensors and materials.

In this research, a novel acoustic sensor with a wave-guide is made to induce the local volumetric resonance of concrete material. The sensor is embedded in fresh concrete and monitors the in-place elastic modulus and strength development of the concrete. The resonant peak of EMI spectrum of the sensor is governed by the concrete material in the proximate area of the sensor. The sensor itself does not affect the position of resonant peak.

This research covers theoretical demonstration, sensor design and prototyping, remote testing systems, experimental study, and machine learning. Current work demonstrated the sensor successfully produced the resonant peaks those are related to concrete curing process ($R^2 = 0.86$ for lab testing and $R^2 = 0.64$ for field testing); however, the sensitivity ($S \cong 1.00$ Hz/psi) of the resonant frequency is not sufficient for practical application.

Machine learning algorithms were employed to map the EMI spectra to concrete strength profile. Several existing architectures were explored and evaluated. A novel machine learning scheme was proposed and successfully improved the accuracy of prediction. The algorithm is also able to handle real-time data with decent generalization among diverse concrete mixtures.

The integration test for the sensing system, including the sensor, the data collection device, the data pipeline, and the trained machine learning models, was performed in field testing in eight States. The average mean absolute percentage error (MAPE) of the field prediction results is 23.04%.

The knowledge produced during this study further advanced the application of EMI sensors in the NDE of concrete material. The EMI resonator tailored for local structural resonance is reported in this study for the first time. The EMI data processing algorithm using machine learning that is generalizable among various concrete mixtures is employed in this study for the first time. This study would be helpful for the real-world application of EMI technique in the NDE of concrete and other phase changing materials.