University of Victoria | Graduate Studies

Notice of the Final Oral Examination for the Degree of Doctor of Philosophy

of

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"Multiscale Investigation and Resistivity-based Durability Modeling of EShC Containing Crystalline Admixtures"

Department of Civil Engineering

Tuesday, September 11, 2018
1:00 P.M.
Engineering / Computer Science Building
Room 468

Supervisory Committee:
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Abstract

World's infrastructure needs both sustainable and durable cementitious materials for implementation in new or existing structures. Annually, the repair of concrete structures deteriorated by water attack or water borne chemicals requires billions of dollars worldwide. Providing sustainable solutions, innovative materials and testing techniques that meet future construction needs, are the main challenges of construction industry to fabricate impermeable and durable concrete structures. It is well-known that concrete permeability is a good indicator of its expected durability until it remains uncracked. However, in various stages of its service life, different types of cracking in concrete can be developed due to exposure to different deterioration processes such as early plastic shrinkage or chloride-induced reinforcement corrosion. Although these cracks may not endanger concrete's structural performance from the mechanical point of view, they create a pathway for aggressive ions that can initiate degradation processes, lead to increase in concrete permeability and thus reduce its durability. Cracking in concrete might not be preventable, but its capability to naturally seal small cracks, named autogenous self-healing, provides an additional feature to manufacture more durable concrete structures. However, natural self-healing capability of concrete is limited and therefore it is typically omitted in the design of concrete structures. Hence, more attention has been recently paid to Engineered Self-healing Concrete (EShC) which is associated with artificially triggered healing mechanisms into the cementitious matrix by incorporating various substances such as crystalline products. EShC helps in reducing concrete permeability; thus, increasing its service-life and durability. Due to formation of needle-shaped pore-blocking crystals, Crystalline Admixtures (CA), as a candidate from the Permeability-Reducing Admixtures (PRA) category, can be implemented into concrete mixtures to fabricate EShC concretes. Crystalline waterproofing technology is not new, but still is unknown to many researchers, engineers, and construction industry professionals. The lack of knowledge of its microstructure and self-healing properties limits CA's proper usage in the construction industry. The techniques to assess the self-healing capability of mortar and concrete are not well-standardized yet. No research work has been done to address certain durability characteristics of this material (i.e. electrical resistivity or chloride diffusivity) especially when combined with Supplementary Cementitious Materials (SCM) and Portland Limestone Cement (PLC). Since the resistance of concrete against ions' penetration is a function of its permeability, it might be a straightforward and reliable parameter to rapidly evaluate concrete's durability during its intended service life. Hence, electrical resistivity measurement is considered as an indirect and alternative tool for other time-consuming permeability testing techniques to examine the CA's efficiency as it modifies the concrete's microstructure by crystals' deposition; thus, leads to permeability improvement.

In comparison to previous studies, on a larger scale, this thesis aims to systematically study the effects of CA on the microstructural features, self-healing properties and long-term durability and resistivity of cement-based materials and in addition, draw some comprehensive conclusions on the use of CA in new and repair applications. This study is divided into three major phases to propose all-inclusive work on using CA in construction industry. To satisfy the goals of each individual phase, a test matrix consisting of a series of four mixes with variables such as use of PLC or presence of CA in powder form is considered.

In order to address to the lack of research and industry knowledge discussed above, this PhD thesis includes the following phases: **Phase (I)** In this phase, the main focus is on the microstructural properties and the changes in the pore structure and chemical compositions of the cement phase of mortar mixes when treated with CA. These microstructural features are studied using Scanning Electron Microscope (SEM) and Scanning Transmission Electron Holography Microscope (STEHM). Moreover, physical and chemical characteristics of the hydration products are determined using image analysis and Energy Dispersive X-ray (EDX) Spectroscopy, respectively. **Phase (II)** This phase is allocated to macro-level investigation of durability characteristics such as chloride/water permeability and electrical resistivity of concrete structures containing CA and PLC cement. To non-destructively measure the chloride ion concentration in the field conditions, both changes in corrosion potential of rebars and concrete electrical resistivity in treated circular hollow-section steel reinforced columns exposed to simulated marine environment is monitored and compared over a 2-year period with control samples. In addition, laboratory-size concrete samples are studied to investigate the effects of CA presence on long-term resistivity, rapid chloride permeability, water permeability and chloride diffusivity of concrete. Later, a resistivity-based model is developed to predict long-term performance of concretes incorporating slag or metakaolin, studied in various environmental conditions. The long-term goal of this phase is to develop a standard design guideline and durability-based model. **Phase (III)** Using an innovative self-healing testing method [1], quantitative analysis of crack closure ability and self-healing potential of CA treated and control concretes with OPC or PLC cement is accomplished during this phase.

The obtained results from first phase showed that hydrated CA particle revealed fine, compact, homogenous morphology examined by STEHM and its diffraction pattern after water-activation indicated nearly amorphous structure, however, diffuse rings, an evidence for short-range structural order and sub-crystalline region, were observed which requires further investigation. The SEM micrographs taken from specimen's fractured surface showed formation of pore-blocking crystals for all treated mixes while similar spots in un-treated sections were left uncovered. Although needle-shaped crystals were observed in the treated mortar specimens, but not all of them had shapes and chemical compositions other than ettringite (well-known to

form needle-like crystals). Using backscatter SEM images and EDX spectrums, examination of polished mortar sections with and without CA also showed typical hydration phases, forming in the control system.

Results from phase II showed that concretes treated with CA had almost 50% lower water penetration depth and thus smaller permeability coefficient when compared with the virgin OPC or PLC concretes. According to salt ponding test results, the use of CA helped in enhancing the resistance to chloride penetration compared to control concrete. This improvement increases with increasing in concrete age. Strong linear relationship between Surface Resistivity (SR) and Bulk Resistivity (BR) data was observed which indicates that these test methods can be used interchangeably. The presence of SCM in concrete indicated considerable increase in both SR and BR compared to control concrete. Concretes incorporating slag or metakaolin have tendency to react more slowly (or rapidly in MK case), consume calcium hydroxide over time, form more CSH gel, densify internal matrix, and also reduce OH- in the pores' solution; thus, increase concrete electrical resistivity. For laboratory specimens, environmental conditions such as temperature variation and degree of water saturation indicated considerable effects on electrical resistivity measurements. As temperature or water content of concrete decreases, its electrical resistivity greatly increases by more than 2-3 times from reference environmental condition. This is mostly because of variation or accessibility in electron mobility. Experimental results from field investigation showed that electrical resistivity readings were highly influenced by the presence of rebar and concrete moisture conditions. In addition, concrete cover thickness and CA addition into cementitious matrix had a negligible effect on its resistivity.

In the last phase, the self-healing test results showed that addition of CA into mix led to higher rate of healing and full crack closure when compared to reference concrete. An empirical equation that relates water flow to the crack width was also proposed in this phase.