

A Multiphysics Digital Twin for 2D Chloride Transport Modeling in Cement-based Coastal Structures

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Abstract

Climate change is intensifying the physical and chemical loads on coastal and hydraulic concrete infrastructure, as more frequent wetting-drying, freeze-thaw, and temperature cycles interact with chloride ingress to accelerate reinforcement corrosion and structural degradation. Existing durability models often treat moisture transport, heat transfer, and ion diffusion as separate or weakly coupled processes, and are rarely formulated in a way that generalizes across the wide range of concrete and other cement-based porous materials used in practice. This study presents TransChlor, a multiphysics digital twin model for chloride ingress in cement-based materials, whose current module implements a two-dimensional (2D) coupled transport formulation for heat, moisture, and chloride ions within the material cross-section. The model is built on a general porous-media formulation, coupling transport equations with a hydration-dependent description of pore structure and ionic binding, so that it can be applied across ordinary and advanced concretes, mortars, and other cement-based mixtures without reformulating the underlying physics. The 2D formulation captures boundary effects, cracks, and geometric heterogeneities that one-dimensional models cannot resolve, and is calibrated and validated against laboratory exposure tests and long-term field monitoring data from coastal and hydraulic structures. Building on this 2D physics-based core, a digital twin architecture assimilates sensor and inspection data in near real time, allowing the model to be continuously updated and used for probabilistic remaining-service-life estimation and maintenance planning. Preliminary simulations show that the 2D coupled transport module captures localized chloride accumulation patterns around geometric discontinuities that simplified 1D approaches tend to miss, particularly under alternating marine exposure conditions. The digital twin prototype further demonstrates the feasibility of linking this 2D transport model with monitoring data streams for adaptive durability assessment across different cement-based material formulations. These results support the development of predictive, data-informed tools for the design, monitoring, and life-cycle management of coastal and hydraulic infrastructure built with concrete and other porous cementitious materials.

Keywords

Transchlor, Digital Twin, 2D Chloride Transport, Cement-based Materials, Multiphysics Modeling, Coastal Infrastructure, Durability