Abstract of Dissertation

論文の内容の要旨

title of dissertation

Modeling of Steel Corrosion in Reinforced Concrete Coupled with Mass and Energy Transport in Porous Media and its Verification

（細孔組織中の熱・物質移動との連成を考慮した
コンクリート内部の鋼材腐食モデルの開発とその検証）

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This dissertation proposes a new concept in corrosion modeling approach which is based on the existing scientific corrosion laws and is also verified by experimentation. An enhanced simulation tool has been developed for the coupled effects of mass and energy transport through porous media of reinforced concrete using cutting edge corrosion modeling techniques. A comprehensive enhancement of finite element model for predicting the rate of steel corrosion in concrete structures under the effect of various environmental actions is developed. Deep investigations were concluded for the effects of various environmental actions namely, chloride, temperature, oxygen, carbonation and moisture on corrosion of reinforcing steel in concrete through extensive experimentation and the environmental variables that have been overlooked in the past research works were further explored and understood properly.

A semi-empirical-theoretical approach was adopted for modeling. The enhanced corrosion model being in close agreement with the experiment results predicts the corrosion rate and potential of steel in concrete for the mass and energy transport through porous media with good accuracy and precision. Influential parameters on prediction of corrosion in RC structures involving the severe environmental loadings are experimentally determined and numerically discussed through parametric study. Appropriate parameters for material modeling of corrosion on the basis of present computational scheme are successfully identified.

Chloride induced corrosion model is enhanced by revising chloride-tafel parameters and re-defining boundary conditions with more clear and conceptual physical meanings. The temperature induced corrosion model was extended from normal constant temperature to variable temperature environmental conditions. For this purpose a detailed and most appropriate numerical methodology has been developed for the application of Arrhenius Law within the frame structure

of Tafel's Law based on activation energy calculations. This semi-empirical-analytical calculation methodology is rather new and has not been adopted so far in the previous research works. Yet, it is interesting to note here that the overall Arrhenius plot method used for parameter identification is in accordance to what has been done in the past. The model being in close agreement with the experiment results predicts the corrosion rate and potential for the effect of temperature with good accuracy and precision.

This research also aims at investigation of the influence of coupled effect of limited oxygen and moisture diffusion on the corrosion process of RC structures under various defined conditions qualitatively as well as quantitatively for which the previous research data is limited. A series of experiments was conducted in this research to deal with the coupled effect of oxygen and moisture on corrosion. Altogether, 100 so-called "concrete corrosion cells", i. e. reinforced concrete specimens with locally separated as well as fused together anode-cathode steel bars and different concrete compositions (W/C, concrete cover and chloride concentration) as well as four different environmental conditions (air dry, submerged, 95% R.H and alternating wetting-drying) have been used for the laboratory tests. The experimental measurements consist of oxygen consumption rate, cathodic current density, half-cell potential and gravimetric corrosion mass loss. The following facts and figures were obtained from the experiment results.

The diffusion of oxygen is a vital limiting factor for corrosion only when the concrete is either submerged under water or is in high relative humidity environment. It was found that concrete cover does not affect the penetration of oxygen in normal dry air conditions. In case of wetting/drying cyclic exposure conditions, the experiment results are variable case by case and depend on the relative relation between the concrete cover and wetting drying cycle duration. The half-cell potential values for specimens submerged under water and having low to medium chloride concentration rise suddenly on the negative side after the specimens are submerged and then falls gradually until it gets constant but still remains much higher than the air dry value. Therefore, it can be said that the underwater potential measurements are not the true representative values of corrosion and should be re-calibrated using the experiment results of this dissertation. Using the experiment results (half-cell potential, gravimetric corrosion mass loss, macro-cell corrosion current and oxygen consumption rate) and a simplified equivalent electro-chemical oxygen diffusion controlled model, it was possible to calculate the influence of oxygen on the corrosion rate of the reinforcement under defined conditions. The modeling task has been incorporated by the use of concrete durability model 'DuCOM' developed by our research group at The University of Tokyo as a finite element computational approach on which the corrosion based reinforced concrete performance and quality at early age and throughout the life of concrete structure is being examined in both space and time domains for the effect W/C, concrete cover, chloride concentration, temperature, carbonation and various environmental humidity conditions. In this thermodynamic approach, reinforced concrete is treated as a composite material consisting of growing micro-scale pores in geometry, which governs basic mechanical and physical features of concrete with respect to long-term durability. On this line, the electro-chemical modeling of concrete forms the fundamental core of the theoretical approach to achieve both the scientific knowledge and engineering simulations of altering materials.

The experimental half-cell potential values of corroding rebars in concrete fluctuate with the time and depth of carbonation due to increase in resistivity and reduction in the electrolytic conductivity. The carbonation induced corrosion model can predict the behavior of corrosion for air dry relative humidity conditions. The model also shows fair qualitative simulation for various pH levels.

Summarizing the all above it can be concluded that in this dissertation, chloride induced corrosion model is enhanced, temperature induced corrosion model is developed, carbonation induced corrosion model is verified and modeling for the effect of oxygen on corrosion is investigated for authenticity by carrying out very original multi-variable experiments exploring maximum possible scenarios.