Comprehensive Durability Modeling for Concrete Structures

Demystifying STADIUM®

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Webinar Summary

- Description of STADIUM®
- Using STADIUM® for new structures
- Using STADIUM® for existing structures
- Extending STADIUM® use to asset management
Who We Are
SIMCO is an engineering firm entirely dedicated to the durability and preservation of concrete structure.
• SIMCO is recognized for its integrated solutions that lead to the optimum design and maintenance of concrete structure.

• SIMCO assists owners and managers in the management of the complete lifecycle of their structure assets.
A Comprehensive Offer

SIMCO’s Unique Offer

Software Solutions

Engineering Services

Specialized Lab Services
Description of STADIUM®
Basic Principle

STADIUM® models the transport of chemical species in cementitious materials resulting from exchanges at the material/environment interface.
Main features

- Chloride, sulfate, carbonate ingress
- Temperature effects
- Moisture transport (wetting/drying cycles, capillary suction)
- Multiple chemical reactions
- Cement, fly ash, slag chemistry
- Time-dependent exposure conditions.
Main features

- Specific geometry of the structure
- Influence of local materials
- Influence of local exposure conditions
- Multiple degradation phenomena
- Rehabilitation analyses
STADIUM® Main Algorithm

Input parameters:
- Material properties
- Environment
- Geometry

The model is divided in 2 main modules:

- The transport module makes the species move during one time step,
- The chemistry module simulates the reactions between species in the pores and the hydrated paste.
The transport module accounts for the following:

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Notes:

- All equations are coupled to each other (e.g. temperature influences moisture and diffusion),
- The equations are solved using FEM,
- 1D and 2D versions are available.
STADIUM® – LAB Application

Characterization of concrete mixtures

Evaluation of transport properties – Input to STADIUM®

- Drying test
  - ASTM C1792
- Permeability
- Moisture isotherm

- Migration test
  - Modified ASTM C1202
- Tortuosity
- Diffusion coefficients
Additional features:

- Base species considered: OH\(^-\), Cl\(^-\), Na\(^+\), K\(^+\), Ca\(^{2+}\), Mg\(^{2+}\), SO\(_4\)^{2-}\), H\(_2\)SiO\(_4\)^{2-}\), Al(OH)\(_4\)^{−}\), Fe(OH)\(_4\)^{−}\), HCO\(_3\)^{−}\), NO\(_2\)^{−}\).

- Possibility of setting time-dependent boundary conditions (exposure solution, temperature, humidity) to better reproduce climate conditions.

- The model accounts for the effect of cement and SCM hydration on transport properties, e.g.: reduction of diffusion coefficients through time due to presence of fly ash.

- The model also accounts for the effect of pore volume variations from chemical reactions on transport properties (feedback effect).
STADIUM® – Exposure Conditions

Time-dependent boundary conditions:

Exposure to deicing salts during winter

After a one-year cycle, the model goes back to the beginning of the year. The cycle is repeated.
The chemistry module solves the thermodynamic equilibrium relationships between hydrated cement paste minerals and species in the pore solution:

- Excess of some species may lead to the formation of new minerals,
- Conversely, dissolution may occur when concentration levels of some species is low,
- The module handles the equilibrium of pure minerals (classical law of mass-action),
- The effect of temperature on chemistry is considered.
### STADIUM® – Chemistry Module

#### INPUT TO CHEMISTRY MODULE
- Mix composition
- Cement chemistry
- SCMs chemistry
- Chemistry database

#### CALCULATED PARAMETERS
- Hydrated cement paste composition
- Pore solution composition
Handling of chloride binding:

• Chloride binding mostly occurs as the result of chloride in the pore solution interacting with AFm phase (e.g. monosulfates).

• The reaction results in the formation of Friedel’s salt.

• Friedel’s salt equilibrium is modeled as a solid solution with AFm phases.

• A small portion of chloride binding also occurs due to physical binding with charged pore surfaces. The Langmuir-type model implemented in STADIUM is pH-dependent.
At the end of calculations, the model provides the following information:

- Space and time distribution of species concentrations,
- Space and time distribution of mineral contents,
- Space and time distribution of temperature and humidity,
- Analysis of the main variables to get: total calcium, sulfur and chloride content.
- Chloride content at specific depth to estimate the time to initiate corrosion for different rebar depths.
STADIUM IS NOT LIFE-365!

*By all accounts, Fick was a fine gentleman, just not for concrete.
In order to model chemical species transport in cementitious materials, you need to solve:

\[
\frac{\partial c^b_i}{\partial t} + \frac{\partial (wc_i)}{\partial t} - \text{div} \left( D_i \left( \frac{w z_i F}{RT} wc_i \text{grad}(\psi) + D_i wc_i \text{grad}(\ln \gamma_i) ight) + \frac{D_i c_i \ln(\gamma_i c_i)}{T} w \text{grad}(T) + c_i D_w \text{grad}(w) \right) = 0
\]
In order to get to Fick’s 2\textsuperscript{nd} law:

\[
\frac{\partial c}{\partial t} - \text{div} \left( D^* \text{grad}(c) \right) = 0
\]

You need to....
Back to basics

...neglect moisture transport coupling:

\[
\frac{\partial c_i}{\partial t} + \frac{\partial (wc_i)}{\partial t} - \text{div} \left( D_i w \, \text{grad}(c_i) + \frac{D_i z_i F}{RT} wc_i \, \text{grad}(\psi) + D_i wc_i \, \text{grad}(\ln \gamma_i) \right. \\
\left. + \frac{D_i c_i \ln(\gamma_i c_i)}{T} w \, \text{grad}(T) + c_i D_w \, \text{grad}(w) \right) = 0
\]
Back to basics

...neglect temperature effects:

\[
\frac{\partial c_i}{\partial t} + \frac{\partial (wc_i)}{\partial t} - \text{div} \left( D_i w \text{grad}(c_i) + \frac{D_i z_i F}{RT} wc_i \text{grad}(\psi) + D_i wc_i \text{grad}(\ln \gamma_i) \right. \\
+ \left. \frac{D_i c_i \ln(\gamma_i c_i)}{T} w \text{grad}(T) + c_i D_w \text{grad}(w) \right) = 0
\]
...neglect electrodiffusion coupling and chemical activity:

\[
\frac{\partial c_i}{\partial t} + \frac{\partial (w c_i)}{\partial t} - \text{div} \left( D_i w \text{ grad}(c_i) + \frac{D_i z_i F}{RT} u \times \text{ grad}(\psi) + D_i w c_i \times \text{ grad}(\ln \gamma_i) \right) + \frac{D_i c_i \ln(\gamma_i c_i)}{T} w \text{ grad}(T) + c_i D_w \times \text{ grad}(w) \right) = 0
\]
Back to basics

...and most of all, assume linear chloride binding:

\[
\frac{\partial c_i^b}{\partial t} + \frac{\partial (wc_i)}{\partial t} - \text{div} \left( D_i w \text{grad}(c_i) + \frac{D_i z_i F}{RT} \text{grad}(\psi) + D_i wc_i \text{grad}(\ln \gamma_i) \right)
+ \frac{D_i c_i \ln(w/c)}{T} w \text{grad}(T) + c_i D_w \text{grad}(w) \right) = 0
\]

Data show that chloride binding is always nonlinear!!
Using STADIUM® for new structures
Performance specifications

- Performance specification language is commonly incorporated in durability requirements for new concrete structures.
  - E.g.: 100-year service-life (time before major repairs)
- We are still in a transition phase: performance specifications are still mixed with prescription requirements.
  - E.g. RCPT values (1000 Coulombs)
- Long-term service-life often associated with corrosion initiation.
- Reliable modeling is needed to make a convincing case.
The U.S. Department of Defense recognizes STADIUM® as the only accurate numerical solution for the prediction of long-term behavior of reinforced concrete structures exposed to marine environments.

Since 2010, STADIUM® is specified in the Unified Facilities Guide Specifications (UFGS).

The service-life requirement is 75 years before major repairs, 65 years before corrosion initiation.

US Navy, USACE, USAF, NASA
UFGS Methodology

Characterization of lab mixes

Mix selection: service-life requirements

Production: QA/QC
UFGS Methodology

SIMCO’s test methods are part of the UFGS protocol:

- Volume of permeable voids (porosity): ASTM C642
- Diffusion coefficients: modified ASTM C1202 (migration test)
- Moisture permeability: ASTM C1792 (drying test)
Example – mix qualification

**MIX A**
- 0.35 w/b
- 20% Fly Ash Type C
- $D_{Cl} (28d): 2.44e^{-12} \text{ m}^2/\text{s}$

**MIX B**
- 0.35 w/b
- 35% GGBFS
- $D_{Cl} (28d): 1.70e^{-12} \text{ m}^2/\text{s}$

**ADDITIONAL INFO**
- Location: Norfolk, VA (Temp., RH)
- Salinity: 34 ppt
- Tidal zone
- Rebar depth: 4 in. (100 mm)

Exposure: Sealed surface, no mass transfer
Example – mix qualification

![Graph showing chloride content at rebar (ppm dry mass) over time (years). The graph compares MIX A and MIX B. The corrosion threshold is indicated by a dashed line. At 40 years, MIX A reaches the corrosion threshold, while at 65 years, MIX B reaches it.](image-url)
Introduction of variability language

- Lab testing: 3 or more batches
- Calculation of tolerance limit: max expected diffusion coefficient
- Value that will not be surpassed in more than 1 in 10 batches at 90% confidence level
- This value must clear durability requirements
Calculation of critical value

- Max value of diffusion coefficient that allows reaching durability requirements
- Used for QA/QC validation
Using STADIUM® for existing structures
Existing structures

Similar test protocol

- Data obtained from cores instead of lab cylinders.
- Additional benefit: chloride profiles can be measured.
- Missing information: mix proportions, cement chemistry.
- Petrographic analyses can provide some missing information.
Concrete Characterization

**TEST SERIES**
- Absorption test (ASTM C642)
- Migration test (ASTM C1202 mod.)
- Drying test (ASTM C1792)
- Chloride profiles (ASTM C1152)
- Petrographic analysis

**MODELING PARAMETERS**
- Volume of permeable voids (porosity)
- Diffusion coefficients (tortuosity)
- Water permeability, moisture isotherm
- Chloride load (exposure cond.)
- Mixture composition
Simulation procedure

Concrete characterization

Verification of current contamination level

Prediction of future behavior
Case study

Bridge in Southern Florida
Case study

Analysis of the central section:

- No signs of corrosion could be observed in the middle span.
- The objective was to estimate the time to corrosion in that part of the structure.
- The bridge was 26 years-old at the time of the study.
Case study

Modeling of current conditions:
Case study

Remaining service-life – Time to corrosion initiation

- Current age of the structure: 10 years
- Corrosion initiation: Present Concrete Age - 28 years
- Rebar depth: 2 in.
- Critical Threshold for Black Steel (Modified G109)
Case study

Extension of service-life

- No Repair
- Sealer
- Overlay
- Patch Repair

**Chloride content at rebar**

- Chloride content (%) vs. Time (years)
  - Time: 0, 10, 20, 30, 40, 50 years
  - Chloride content: 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07

The graph shows the chloride content at rebar over time for different repair methods.
Case study

Extension of service-life

- No sealer
- Applied once
  - Every 10 years
- Every 6 years
Past Repairs

CI Profile History

- Points measured (2013)
- Numerical simulation
- Corrosion initiation threshold

Year: 1957
Past Repairs

CI Profile History

- Points measured (2013)
- Numerical simulation
- Corrosion initiation threshold

Original Concrete

Year: 1994
Past Repairs

CI Profile History

- Points measured (2013)
- Numerical simulation
- Corrosion initiation threshold

Year: 1995
Extending STADIUM® use to asset management
Asset management

Extend single structure protocol to clusters of concrete elements

- Prioritize intervention.
- Plan intervention.
- Optimize maintenance operations.
- Optimize costs.
Asset Management – PoR experience
Asset Management – PoR experience

KMS - Kademuren Modellering Systeem

Degradation Analysis per Zone and Element
Evaluate Degradation with STADIUM®

For each Zone/Element combination
Select the most critical Zone/Element combination

Schedule Next Inspection
Close Monitoring Required
Repair

Critical Year (Trigger/Intervention)
Maintenance Proposal

Post Treatment Analysis
THANK YOU!

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