Service Life Prediction of Cracked Reinforced Concrete Structures subjected to Chloride Attack and Carbonation

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H.-W. Song

Professor
School of Civil and Environmental Engineering
Yonsei Univ., Seoul 120-749, KOREA
Introduction

**Durability concept**
- Durability concept and strategy
- Performance-based durability design
- Scheme of service life prediction

**Models for service life prediction**
- Early-age cracks in concrete
- Chloride diffusion-penetration model
- $CO_2$ carbonation model
- Steel corrosion model
  - Electric corrosion cell model
  - Oxygen diffusion model
- Corrosion cracking model

**Examples for Service life prediction**

**Conclusion**
Recently, severe deteriorations in concrete structures, such as bridges, buildings etc., has been criticized in major mass media in Korea: “Korea is Republic of Concrete”.

인정시 서울 수도권 쓰래기 매립지
에의 건설폐기물을 가득 싣은 15,6
트리 위편 면자 길을 잇기이며 하루 8해
여대여 줄을 서서 들어온다. 쓰래기
중장어로 생활쓰래기는 크게 줄었지만
콘크리트 건설폐기물은 지난해
수도권 매립지 전체 반입 쓰래기의
53%를 차지했을 정도로 많게 늘고
있다.

대한민국 언론은 건설폐기물 중장
시키는 온전에 따라 집계 부속 콘크리트
기구가 선도적으로 빛나고 있다. 기술적
환경의 개발성 ((Environment) 상황은 “재활
용 강화를 일정 비율의 부담으로 사용
모로 해야 하는데 건설재료부-환경
부 등 부재로 이념으로 이뤄지지 않고
있다”고 말했다.

이제의 ‘콘크리트 공화국’이라는
임으로도 계속될 전망이다.

Recently, severe deteriorations in concrete structures, such as bridges, buildings etc., has been criticized in major mass media in Korea: “Korea is Republic of Concrete”.
Recently, spalling of concrete from concrete structures, such as bridges, tunnels, etc., has become a big problem criticized in mass media in Japan.
Deterioration in Concrete Structures

- Shrinkage cracks
- Alkali aggregate reaction
- Thermal cracks
- Water drainage
- Sulphate attack
- Reinforcement corrosion
Corrosion of PC strands due to poor consolidation
Old and New Durability Concepts

Old Codes: AASHTO, EC2, BS
- Simple deemed-to-satisfy rules (deterministic)
- Experience based rules of thumb
- Poor environmental classification

Result
No relation between performance and service life (implicit 50 years)

New Codes: Performance-based design
- Degradation models
- Material parameters
- Detailing of environmental actions
- Statistical quantification (mean, standard deviation, distribution)
- Choice of service life

Result
Documented service life design, failure probability
Service Life of RC structures (ISO/WG 13823)

- **Time**
  - **t**<sub>start</sub>
  - **t**<sub>exp</sub>
  - **t**<sub>s</sub> = **t**<sub>start</sub> + **t**<sub>exp</sub>

- **Durability limit state**

- **Service life**
  - **t**<sub>s</sub> ≥ **t**<sub>d</sub>

- **Environmental Actions** (combination of rain, de-icing salts etc)

- **Transfer mechanism**

- **Degradation Agents** (moisture, Cl<sup>-</sup>, CO<sub>2</sub>, micro cracks etc)

- **Degradation mechanism**

- **Resistance mechanism (R)**

- **Damage or disfigurement mechanism (S<sub>lim</sub>)**
  - Yes
  - ULS: R ≥ S?
  - SLS: S ≤ S<sub>lim</sub>?
  - Yes
  - collapse
  - malfunction

- **Boundary conditions**
- **Mass transport analysis**
- **Corrosion of reinforcement**
- **Concrete crack**
- **Deterioration of concrete**

- **Structural analysis**

- **Durable Structure**

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Service life = durability limit + safety limit

\[ t_s = t_{\text{start}} + t_{\text{exposure}} \]

**Governing equations**

\[ \alpha_i \frac{\partial \theta}{\partial t} + \text{div} J_i - Q_i = 0 \]

- **Hydration computation**
  - Size, shape, mix proportions, initial and boundary conditions
  - Temperature, hydration level of each component

- **Microstructure computation**
  - Bi-model porosity distribution, interlayer porosity

- **Pore pressure computation**
  - Pore pressures, RH and moisture distribution

- **Chloride transport and equilibrium**
  - Dissolved and bound chloride concentration

- **Corrosion model**
  - Corrosion rate, amount of O₂ consumption

- **Ion equilibrium model**
  - Dissolved Oxygen transport and equilibrium

- **Carbon dioxide transport and equilibrium**
  - Gas and dissolved CO₂ concentration

- **Conservation Laws satisfied?**
  - yes
  - Corrosion rate, crack, tension stiffening factor
  - Continuum Mechanics

- **No**
  - Increment time, continue
  - Corrosion model
  - Tension stiffening factor: \( \alpha \)

  \[ \sigma_t = f_t \left( \frac{\epsilon_{\text{eff}}}{\epsilon_t} \right)^\alpha \]

**Performance degradation**

<table>
<thead>
<tr>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deformation compatibility, momentum conservation</td>
</tr>
<tr>
<td>Tension stiffening model</td>
</tr>
<tr>
<td>Max. Load</td>
</tr>
<tr>
<td>Deterioration increase</td>
</tr>
<tr>
<td>Time</td>
</tr>
<tr>
<td>Service-life decrease</td>
</tr>
</tbody>
</table>

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Schematic description of service life design

\[ t_s = t_{\text{start}} + t_{\text{exp}} \]

\[ t_D : \text{design service life} \]

\[ P \{\text{failure}\} \text{ at } t_D = P \{t_s \leq t_D\} \leq P_{\text{target}} \]

\[ P \{\text{failure}\} \text{ at } t_D = P \{R(t_D) \leq S(t_D) < 0\} < P_{\text{target}} \]
Durability Failure of Structure

\[ P_f = P(R - S \leq 0) \]

Reliability Index

\[ \beta = \frac{R_m - S_m}{\sqrt{\sigma_R^2 + \sigma_S^2}} \]

- \( R \): Durability resistance
- \( S \): Degradation agents

\[ R_S < 0 \quad \text{Failure} \]
\[ R_S > 0 \quad \text{Safe} \]
**Durability Design Strategy**

**Measures:**
- High quality and impermeable concrete
  - low chloride diffusivity (material)
  - sufficient concrete cover (design)
  - no early-aged cracks (construction)

**Performance evaluation tool**
- verification of 100 years service life
  - min cover
  - max. $D_{cl}$
Early-age cracks in concrete limit life span of concrete structures

- Temperature variation properties
- Shrinkage properties
- Strength and stiffness development properties

Microcracks

Degradation of long-term durability performance

Environment

Load

Drying

Hardening

Concrete
It is necessary to develop an analytical algorithm of steel corrosion, which considers pre-existing early-age crack and cover concrete quality, for accurate prediction of service life of cracked RC structures subjected to chloride attack or/and carbonation.
Scheme of Service Life Prediction

Exposure Condition
- Weather
- Temperature
- Relative Humidity
- Crack in Cover

Location of Structures ➔

Mixing Properties
- Cement
- Aggregate
- Water
- Blend

Cement: C_2S, C_3S, C_3A, C_4AF

Geometric Boundary
- Length
- Shape
- Boundary

Finite Element Method ➔

Early Age Behavior
- Heat Generation Analysis
- Hygro Migration Analysis

Micro Structure Development

CO₂ Carbonation model
- pH distribution
- Ca(OH)₂ & CaCO₃ distribution
- Carbonation depth

pH = 9, pH = 12

Chloride content, pH

Steel corrosion model
- Corrosion product amount (rust)
- Corrosion current density (corrosion rate)

Crack model
- Equivalent diffusion coefficient: D_{eq}
- Crack width

Chloride diffusion-penetration model
- Free chloride content
- Total chloride content

Chloride diffusion-penetration model

Steel corrosion model

Corrosion cracking and service life of RC structure
- Corrosion initiation
- Time to corrosion
- Time to corrosion cracking
- W_{crit} < W_{rust}

Initiation period
- Propagation period
- Acceleration period
- Deterioration period

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Governing equations for mass and energy conservation for service life prediction

\[
\alpha_i \cdot \frac{\partial (X_i)}{\partial t} + \text{div} J_i (X_i, \nabla X_i) - Q(X_i) = 0
\]

<table>
<thead>
<tr>
<th>Variables</th>
<th>Potential term</th>
<th>Flux term</th>
<th>Sink term</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_i$</td>
<td>$\rho c$ [Kcal/K·m³]</td>
<td>$- K_H \nabla T$ [Kcal/ m²·s]</td>
<td>$Q_H$ [Kcal/m³·s]</td>
</tr>
<tr>
<td>$T$</td>
<td>- Constant</td>
<td>- Constant</td>
<td>- Multi component heat of hydration model of cement</td>
</tr>
<tr>
<td>$P$</td>
<td>$\phi \frac{\partial S}{\partial P}$ [kg/Pa·m³]</td>
<td>$-(K_i + K_j) \nabla P$ [kg/ m²·s]</td>
<td>$- Q_{\text{hyd}} - \frac{\partial (\rho S \phi)}{\partial t}$ [kg/ m³·s]</td>
</tr>
<tr>
<td>$C_{ci}$</td>
<td>$\phi S$ [mol/l/mol·m³]</td>
<td>$- D_{ci} \nabla C_{ci}$ or $- D_{ci} \nabla C_{cl}$ [mol/ m²·s]</td>
<td>$Q_{ci}$ [mol/ m³·s]</td>
</tr>
<tr>
<td>$C_{co2}$</td>
<td>$\phi (1 - S) K_{co2} + \phi S$ [mol/l/mol·m³]</td>
<td>$- D_{co2} \nabla C_{co2}$ or $- D_{co2} \nabla C_{co2}$ [mol/ m²·s]</td>
<td>$Q_{co2}$ [mol/ m³·s]</td>
</tr>
<tr>
<td>$C_{o2}$</td>
<td>$\phi (1 - S) K_{o2} + \phi S$ [mol/l/mol·m³]</td>
<td>$- D_{o2} \nabla C_{o2}$ or $- D_{o2} \nabla C_{o2}$ [mol/ m²·s]</td>
<td>$Q_{o2}$ [mol/ m³·s]</td>
</tr>
</tbody>
</table>

- $\alpha_i$ - Mass and Knudsen diffusion in sound and/or cracked surface
- $\nabla$ - Random geometry of pores and Knudsen vapor diffusion
- $\rho$ - Temperature and porosity change dependent
- $\phi$ - Reactive chloride ion content due to binding capacity
- $S$ - Path dependent transport of mass
- $K$ - Temperature and porosity change dependent
- $Q$ - CO₂ consumption due to carbonation process
- $O_2$ - O₂ consumption due to corrosion process

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Equivalent diffusion coefficient for early-age cracks in concrete

Cracks in REV (Representative Elementary Volume) (Song, 2002)

- Capillary flux $J_{cp}$
- Crack flux $J_{cr}$

Average method

Flux of chloride ion

Flux of CO$_2$

Equivalent diffusivity

Area of solid: $A_s$

Area of crack: $A_{cr}$

Area of capillary pore: $A_{cp}$

Total area: $A_0$

Gas (H$_2$O, CO$_2$, O$_2$)

Liquid (H$_2$O, Cl$^-$, CO$_2$, O$_2$)

Normalized chloride diffusivity

Normalized CO$_2$ diffusivity

RCPT (Rapidly Chloride Penetration Test)

WPT (Water Permeability Test)

General durability test machine

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Chloride diffusion-penetration model

Governing equation of chloride transfer
\[
\frac{\partial}{\partial t} (S \phi C_{cl}) + S \phi (-D_{cl}) \nabla C_{cl} + q_i C_{cl} \cdot Q_{cl} = 0
\]

Sink term
Sink term modeling (Tang, 1996)

Reactive chloride ion contents in materials
\[
Q_{cl} = -C_{cl}^{n+1} - C_{cl}^{n} \cdot \frac{W_{pow}}{M_{Cl}} \cdot 10^{-2}
\]

Sink term in coupled deterioration analysis
\[
Q_{cl} = -\frac{C_{bound}^{n+1} - C_{bound}^{n}}{t_{n+1} - t_{n}} \cdot W_{used} \cdot 10^{-2}
\]

Where,
\[
Q_{cl}^{cb} = -\frac{C_{bound}^{n+1} - C_{bound}^{n}}{t_{n+1} - t_{n}} \cdot W_{used} \cdot 10^{-2}
\]

\(W_{used}\): consumption of cement components at carbonated area

Porosity
Saturation
D_{cl}
D_{eq_{cl}}
Free Chloride Contents

Early-age behavior
Pore structure formation

Potential term
Flux term
Sink term

Flux term

Equivalent diffusion coefficient of \(cl\)
permeability coefficient

\[
D^{eq_{cl}} = \left( \frac{D_{eq_{crack}} \phi^4 + D_{cl}}{8 \mu \eta \phi} \right)
\]

\[
k = \frac{10^{10} (1 - \phi) W_{tens}}{M_{Cl}^2} \frac{\partial}{\partial \phi} \frac{\partial}{\partial t}
\]
Analysis results for chloride attack

W/C : 42% , C = 380kg, 5 years aged

Beam Analysis (H:6cm, L: 28cm)

W/C 55% sound surface
W/C 55% cracked surface (0.1mm)
W/C 55% sound surface
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**Governing equation of CO₂ transfer**

\[
\frac{\partial}{\partial t} \left( \rho \phi (1 - S) \right) + \nabla \cdot ( \rho \phi (1 - S) \mathbf{v}) + \nabla \cdot ( \rho \phi D \nabla \phi) = 0
\]

- **Potential term**
- **Flux term**
- **Sink term**

\[
\text{CO}_2 \text{ flux } \quad J_{\text{CO}_2} = -D_{\text{eq}} \nabla \phi (1 - S) + D_{\text{eq}} \frac{\partial \phi}{\partial t}
\]

- Ion equilibrium

\[
\text{H}_2\text{O} + \text{CO}_2 \rightleftharpoons \text{H}_2\text{CO}_3
\]

- Molecular diffusion theorem

**Equivalent diffusion coefficient of CO₂ in cracked concrete:**

\[
D_{\text{eq}} = D_{\text{eq}} + \alpha \frac{\Delta \rho}{\rho}
\]

**Density of CO₂:**

\[
\rho_{\text{CO}_2} = \frac{M_{\text{CO}_2}}{R T}
\]

**Henry constant:**

\[
K_h = \frac{M_{\text{CO}_2}}{H_{\text{CO}_2}}
\]

**Ideal gas equation:**

\[
H_{\text{CO}_2} = \frac{H_{\text{CO}_2}}{1 + \frac{H_{\text{CO}_2}}{2M_{\text{CO}_2}}}
\]

- Equivalent diffusion coefficient of dissolved CO₂ in pores:

\[
D_{\text{eq}} = \alpha \frac{\Delta \rho}{\rho} (1 - S)
\]
**Analysis results for carbonation**

- **W/C 55% , CO₂ 10% , 1800 days after**

  - **(a) pH and CO₂ concentration distribution**
  - **(b) Ca(OH)₂ and CaCO₃ distribution**
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Alkali aggregate reaction, Chemical decomposition of hydrated cement
Freeze-thaw damage Temperature gradients Humidity gradients
Abrasions and Chemical Attack

Constituents:
- Reinforcing steel corrosion
- Abrasion and Chemical Attack
- Alkali aggregate reaction, Chemical decomposition of hydrated cement

Submerged concrete
Concrete at atmospheric zone
Concrete at splash and tidal zone

Oxygen supplying condition:
- High tide: Increasing of $i_{corr}$
- Low tide: Decreasing of $i_{corr}$
- Insufficient oxygen
- Sufficient oxygen

Electric corrosion cell model:
- Limit Current Density
- Oxygen concentration polarization

Steel corrosion model:
- Corrosion cracking
Computational flow of steel corrosion model

- Moisture transport
- Hydration heat analysis
- Early-age behavior analysis
- Salt attack analysis
- Carbonation analysis
- Micro structure
- Pore pressure
- Pore saturation
- Free chloride content
- pH in concrete
- Porosity and saturation

Corrosion Analysis Models

- Electric corrosion cell Model
  - Tafel method analysis
    (Splash zone)
- Oxygen diffusion Model
  - Formulation of $O_2$ diffusion
    (Submerged zone)

Prediction of life time in RC structures
Consideration of early age cracks for steel corrosion model

**Chloride Ion Penetration Analysis**

Equivalent Diffusion Coefficient

\[ D_{eq} = \left( \frac{D_{crack}}{R_s^2} + D_{cl} \right) \]

\[ D_{crack} = 2099 \text{ m}^2 \text{ s}^{-1} \]

**Oxygen Diffusion Analysis**

Equivalent Diffusion Coefficient

\[ D_{crack} = D_0^d \]

\[ D_{eq} = \frac{1}{L_4} \left( L_1 \cdot 0.5 L_4 (D_{g0} K_0 + D_{w0}) \right) + 0.5 L_4 D_0^d \]

**Chloride Thresholds**

Free Chloride Contents

Exposure Conditions

Splash Zone

Submersed Structure

**O_2**: Sufficient

O_2**: Sufficient

O_2**: Insufficient

**Electric corrosion cell model**

Free Chloride Contents

Changing Anode Tafel Slope

Increasing Corrosion Current Density

**Oxygen diffusion model**

Consumption Dissolved O_2

O_2 Supply is Insufficient

Generation of Concentration Slope

I_{corr} is Limit Current Density

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Electric corrosion cell model

**Chloride Thresholds**

<table>
<thead>
<tr>
<th>Condition of Steel</th>
<th>Passive</th>
<th>Passive Layer is Destroying</th>
<th>No Passive Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Chloride Thresholds</td>
<td>1.2 kg/m³ (KCI, JCI specification)</td>
<td>2.4 kg/m³ (Hausmann, 1969)</td>
<td>[c] = ( \frac{1.2}{\text{cement weight}}(1 - \alpha_{\text{fixed}}) )</td>
</tr>
<tr>
<td>Free Chloride Thresholds</td>
<td>Corrosion Start</td>
<td>[c] = ( \frac{2.4}{\text{cement weight}}(1 - \alpha_{\text{fixed}}) )</td>
<td>No Passive Layers</td>
</tr>
</tbody>
</table>

**Corrosion Potential**

*SHE* Activation Overcharge (Standard Hydrogen Electrode)

- Anode: \( E_{\text{corr}} = E_{\text{Fe}} + \eta^a \)
- Cathode: \( E_{\text{corr}} = E_{\text{O}_2} + \eta^c \)
- Corrosion Current Density: \( i_{\text{corr}} = i_a = i_c \)
**Corrosion stage vs corrosion current density**

**Stage 1**
- Passive Condition
- $C^+ < 1.2 \text{ kg/m}^3$
- Anode Tafel Slope = $\infty$
- Cathode Tafel Slope = $2\beta$

**Stage 2**
- Passive Layer is Destroying
- $1.2 \text{ kg/m}^3 \text{ (KCl) } < C^+ < 2.4 \text{ kg/m}^3$
- Anode Tafel Slope
  \[
  \beta = \frac{0.059 ([cl^-]_s - [cl^-]_i)}{[cl^-] - [cl^-]_i}
  \]

**Stage 3**
- No Passive Layer
- $C^+ = 2.4 \text{ kg/m}^3 \text{ (Hausmann, 1969)}$
- Not increase $i_{corr}$

### Condition of the passive layers

<table>
<thead>
<tr>
<th>Condition of the passive layers</th>
<th>Corrosion current density ($A/m^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exist</td>
<td>$\log i_{corr} = \log i_{o_r}$</td>
</tr>
</tbody>
</table>
| Being destroyed               | $\log i_{corr} = \frac{0.998 - 0.06pH - 0.059\log i_{o_r} + \beta \log i_{o_r}}{\beta + 0.059}$ \[
  \beta = \frac{0.059 ([cl^-]_s - [cl^-]_i)}{[cl^-] - [cl^-]_i}
  \] [ $cl^-$ ] : free chloride content(% wt of cement) at the stage [ $cl^-_i$ ] : free chloride content(% wt of cement) for the stage of corrosion initiation [ $cl^-_s$ ] : free chloride content(% wt of cement) for the stage of no passive layers |
| No exist                      | $\log i_{corr} = 8.458 - 0.508pH + 0.5\log i_{o_r} + 0.5\log i_{o_r}$ |
Consideration of early age cracks for oxygen diffusion model

- $\rho_{gO_2} = \frac{M_{O_2}}{RT} \cdot H_{O_2} \cdot \rho_{dO_2} = K_{O_2} \cdot \rho_{dO_2}$
- $J_{O_2} = -(D_{gO_2} \cdot K_{O_2} + D_{dO_2}) \nabla \rho_{dO_2}$
- $Q_{O_2} = -\phi S \frac{M_{O_2} i_{corr}}{z_{O_2} F} \frac{A_{bar}}{V_{elem}}$

\[
\frac{\partial}{\partial t} \left\{ \phi \left[ (1-S) \cdot \rho_{gO_2} + S \cdot \rho_{dO_2} \right] \right\} + \text{div}(J_{O_2}) - Q_{O_2} = 0
\]
**Oxygen Diffusion Model**

**Governing equation of oxygen diffusion**

\[
\frac{\partial}{\partial t} \left\{ \phi (1 - S) \cdot \rho_{gO_2} + S \cdot \rho_{dO_2} \right\} + \text{div}(J_{O_2}) - Q_{O_2} = 0
\]

**Potential term**

\[
\rho_{gO_2} = \frac{M_{O_2}}{RT} \cdot H_{O_2} \cdot \rho_{dO_2} = K_O \cdot \rho_{dO_2}
\]

\[
K_O = \frac{M_{O_2}}{RT} \cdot \frac{1}{n_{H_2O}} \cdot H_{O_2}
\]

**Flux term**

**Diffusion coefficient of gaseous O\(_2\) in pores**:

\[
D_{gO_2} = \frac{\phi \cdot D_{O_2}'}{\Omega} \cdot \frac{(1 - S)^4}{1 + \frac{l_m}{2(r_m - r_a)}}
\]

**Diffusion coefficient of dissolved O\(_2\) in pores**:

\[
D_{dO_2} = \frac{\phi \cdot S^4 \cdot D_{O_2}'}{\Omega}
\]

**Equivalent coefficient of O\(_2\) in cracked concrete**

\[
J_{O_2}^\text{total} = \frac{1}{I_A} \left\{ \left[ (L_1 - 0.5L_4)(D_{gO_2} K_{O_2} + D_{dO_2}) + 0.5L_4 D_{O_2}' \right] \rho_{dO_2} \right\}
\]

**Sink term**

**The rate of O\(_2\) consumption**

\[
Q_{O_2} = -\phi S \cdot \frac{M_{O_2} \cdot i_{\text{corr}}}{z_{O_2} \cdot F} \cdot \frac{A_{\text{bar}}}{V_{\text{elem}}}
\]

**Corrosion rate in concrete**

\[
R_{\text{corr}} = \phi S \cdot \frac{M_{Fe} \cdot i_{\text{corr}}}{z_{Fe} \cdot F}
\]

**Faraday’s law**

\[
\phi = I_A \cdot \frac{z_{Fe} \cdot F}{A_{\text{bar}}}
\]
Loss of performance due to steel corrosion

- **Initiation period**
- **Propagation period**
- **Acceleration period**
- **Deterioration period**

Loss of performance related to corrosion of steel

- Corrosion initiation
- Time to corrosion cracking

Time to corrosion cracking

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Analysis results for steel corrosion tendency

- **Splash zone structure**
  - Graph showing corona current density ($I_{corr}$) over years for different chloride concentrations (45%, 55%, 65%).

- **Submerged zone structure**
  - Graph showing corona current density ($I_{corr}$) over years for different chloride concentrations (45%, 55%, 65%).

- **Visualization of steel analysis**
  - Image showing steel surface and corrosion propagation with color-coded regions indicating different stages of corrosion.
Corrosion cracking model

Deformation of steel

Thickness of corrosion product induced corrosion cracking

\[ d_s = B[2 \alpha_p (1 - \nu_t) - K^2 (1 - 2 \nu_t) - 1]q_e \]

Critical corrosion amounts

\[ W_{\text{crit}} = \pi D \frac{\rho_{st} \rho_{net}}{\rho_{st} - K \rho_{st}} \left( d_0 + d_s \right) \]

Critical corrosion amounts

Deformation of steel

- a. Corrosion initiated
  - Corrosion initiation
  - Internal pressure generate
- b. Free expansion
- c. Stress initiated
- d. Concrete cracking

Corrosion cracking process (Liu, 1996)

<table>
<thead>
<tr>
<th>cover (cm)</th>
<th>2</th>
<th>3</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yokozeki (1997)</td>
<td>1.1</td>
<td>1.8</td>
<td>3.1</td>
</tr>
<tr>
<td>Morikawa (1987)</td>
<td>2.3</td>
<td>3.1</td>
<td>3.7</td>
</tr>
<tr>
<td>This study</td>
<td>1.4</td>
<td>2.0</td>
<td>3.2</td>
</tr>
</tbody>
</table>

\( f_{ck} = 320 \text{ kgf/cm}^2, \) steel diameter : 16mm
Example for service life prediction of RC which does not considered the concept of service life

- Underground RC tunnel
  - Cover depth = 5 cm
  - CO₂ = 670 ppm
  - Chloride concentration = 0.35~0.50 mol/L
  - Relative humidity = 70~100 %
  - Temperature = 20 °C

- Tunnel inside = atmospheric zone
- Marine atmosphere
- Splash zone
- Submerged zone
- Chloride in sea water
- Ground water
- Sea water

Mix proportions

<table>
<thead>
<tr>
<th>Water/Cement Ratio (%)</th>
<th>45</th>
<th>55</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ordinary Portland Cement (kg/m³)</td>
<td>365</td>
<td>291</td>
</tr>
<tr>
<td>Cement Composition</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C₂A</td>
<td>10.4</td>
<td>10.4</td>
</tr>
<tr>
<td>C₃S</td>
<td>47.2</td>
<td>47.2</td>
</tr>
<tr>
<td>C₄AF</td>
<td>9.4</td>
<td>9.4</td>
</tr>
<tr>
<td>C₂S</td>
<td>27</td>
<td>27</td>
</tr>
<tr>
<td>Mono Sulfate</td>
<td>3.9</td>
<td>3.9</td>
</tr>
<tr>
<td>Coarse Aggregate (kg/m³)</td>
<td>1102</td>
<td>1078</td>
</tr>
<tr>
<td>Sand Aggregate (kg/m³)</td>
<td>735</td>
<td>812</td>
</tr>
</tbody>
</table>

Environmental conditions

<table>
<thead>
<tr>
<th>W/C</th>
<th>pH</th>
<th>External chloride concentration (mol/L)</th>
<th>Relative humidity (%)</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>45, 55</td>
<td>9~11</td>
<td>0.35</td>
<td>70</td>
<td>20</td>
</tr>
<tr>
<td>45, 55</td>
<td>10~11</td>
<td>0.5</td>
<td>100</td>
<td>20</td>
</tr>
</tbody>
</table>
Analysis at Splash Zone (cover = 5cm)

- Critical $\rho' = 1.2 \text{ kg/m}^3$
- Corrosion initiation
- Critical $W_{corr}$ at 5cm cover

- $W/C = 45\%$
- $W/C = 55\%$

- $f_{ck} = 240 \text{ kgf/cm}^2$, steel diameter: 32mm
Analysis at Submerged Zone (cover = 5cm)

- Decreasing of $i_{corr}$ for insufficient oxygen
- Corrosion does not propagate
- Reduction of crack effect by poor quality of concrete

W/C = 45%

- $f_c = 240$ kgf/cm², steel diameter: 32mm
Quality of cover concrete
(W/C = 45% vs. W/C = 55%)

- **Splash zone**
  - Chloride content (kg/m²)
    - 45%
    - 55%
  - Year

- **Submerged zone**
  - Chloride content (kg/m²)
    - 45%
    - 55%
  - Year

- **Steel**
  - Diameter: 32mm
  - f_{ck} = 240 kpsi
  - Concrete Materials, Mechanics & Engineering Lab., Yonsei Univ.
Corrosion rate with different pH

Criteria for Corrosion (Broomfield, 1997)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Corrosion Current Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive Condition</td>
<td>$I_{\text{corr}} &lt; 0.001 \text{ A/m}^2$</td>
</tr>
<tr>
<td>Low to Moderate Corrosion</td>
<td>$0.001 &lt; I_{\text{corr}} &lt; 0.005 \text{ A/m}^2$</td>
</tr>
<tr>
<td>Moderate to High Corrosion</td>
<td>$0.005 &lt; I_{\text{corr}} &lt; 0.01 \text{ A/m}^2$</td>
</tr>
<tr>
<td>High Corrosion</td>
<td>$I_{\text{corr}} &gt; 0.01 \text{ A/m}^2$</td>
</tr>
</tbody>
</table>

High pH (12) Does not increase to high corrosion rate
Comparison of different prediction methods

**Graph: Chloride content (% of concrete weight) vs. Cover depth (mm)**

- **Life365**
- **Experiment**
- **Fick Law**
- **This study**

**Table:**

<table>
<thead>
<tr>
<th>Penetration mechanism</th>
<th>Fick's law</th>
<th>Life 365</th>
<th>This study</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fixed</strong> $D_{cl}$</td>
<td>$1 \times 10^{-12}$ m$^2$/s</td>
<td>$D_{28} = 1 \times 10^{-12}(206-240/T)$</td>
<td>$D_{cl} = 1 \times 10^{-12}$ m$^2$/s</td>
</tr>
<tr>
<td>Time effect</td>
<td>$D(t) = D_{ref} \left( \frac{t}{t_{ref}} \right)^m$</td>
<td>$D(t) = D_{ref} \left( \frac{t}{t_{ref}} \right)^m$</td>
<td>$D(t) = D_{ref} \left( \frac{t}{t_{ref}} \right)^m$</td>
</tr>
<tr>
<td>Temperature effect</td>
<td>$D(T) = D_{ref} \exp \left[ \frac{U}{R} \left( \frac{1}{T_{ref}} - \frac{1}{T} \right) \right]$</td>
<td>$D(T) = D_{ref} \exp \left[ \frac{U}{R} \left( \frac{1}{T_{ref}} - \frac{1}{T} \right) \right]$</td>
<td>$D(T) = D_{ref} \exp \left[ \frac{U}{R} \left( \frac{1}{T_{ref}} - \frac{1}{T} \right) \right]$</td>
</tr>
<tr>
<td>Humidity effect</td>
<td>$D(h) = D_{ref} \left( \frac{1-(1-h)^4}{(1-h)^4} \right)$</td>
<td>$D(h) = D_{ref} \left( \frac{1-(1-h)^4}{(1-h)^4} \right)$</td>
<td>$D(h) = D_{ref} \left( \frac{1-(1-h)^4}{(1-h)^4} \right)$</td>
</tr>
</tbody>
</table>
## Durability strategy using different mix proportion

<table>
<thead>
<tr>
<th>Items</th>
<th>W/ C (%)</th>
<th>W</th>
<th>Binder</th>
<th>Unit weight (kg/m³)</th>
<th>B X (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OPC 45%</td>
<td>45</td>
<td>164</td>
<td>365</td>
<td>735</td>
<td>1102</td>
</tr>
<tr>
<td>OPC 55%</td>
<td>55</td>
<td>160</td>
<td>291</td>
<td>812</td>
<td>1078</td>
</tr>
</tbody>
</table>

### Change of mix proportion for design chloride diffusion coefficient using Slag with lower W/C

| W/ B 40% Slag 30%        | 40       | 160 | 280    | 120 | 785 | 972 | 0.75 | 0.013 |

<table>
<thead>
<tr>
<th>Envir.</th>
<th>Splash zone</th>
<th>Submerged zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/C</td>
<td>45</td>
<td>55</td>
</tr>
<tr>
<td>$T_{w/o\ crack}$</td>
<td>10.9</td>
<td>5.5</td>
</tr>
<tr>
<td>$T_{w/o\ crack}$</td>
<td>6.8</td>
<td>3.5</td>
</tr>
</tbody>
</table>

- Increasing of cover depth
- Increasing of pH in pore solution
- Increasing of cover concrete quality

- Decreasing of $D_{cl}$
- Decreasing of W/C
- Decreasing of external $c^+$ concentration

### Increased service life of RC structures
Service life analysis for RC at splash zone (1)

- Critical chloride content = 1.2 kg/m³ (KCl, JCI)

- No crack:
  - W/C = 40%, Slag 30%
  - Crack width = 0.1mm
  - Corrosion does not occur!!

- Crack width = 0.3mm
  - Service life
Service life analysis for RC at splash zone (2)

Corrosion initiation with 0.1mm crack = service life for chloride attack

Corrosion cracking = service life for chloride attack

Critical corrosion amounts

Cracking time

Corrosion initiation

Corrosion cracking
Service life analysis for RC at submerged zone (1)

Critical chloride content = 1.2 kg/m³ (KCl, JCl)

- No crack
- Crack width = 0.1mm
- Crack width = 0.3mm

W/C = 40%, Slag 30%

Corrosion does not occur!!
Service life analysis for RC at submerged zone (2)

Decreasing of $i_{corr}$ for insufficient oxygen

Corrosion initiation with 0.1mm crack = service life for chloride attack

Corrosion initiation with 0.3mm crack = service life for chloride attack

Critical corrosion amounts

Corrosion does not propagate

Corrosion cracking does not occur!!

Concrete Materials, Mechanics & Engineering Lab., Yonsei Univ.
# Summary for service life

<table>
<thead>
<tr>
<th></th>
<th>Splash zone</th>
<th>Submerged zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/C</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>W/C</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>$T_{w/o\ crack}$</td>
<td>10.9</td>
<td>6.8</td>
</tr>
<tr>
<td>$T_{w/o\ crack}$</td>
<td>5.5</td>
<td>3.5</td>
</tr>
<tr>
<td>$T_{w/\ crack}$</td>
<td>6.03</td>
<td>-</td>
</tr>
<tr>
<td>$T_{w/\ crack}$</td>
<td>5.5</td>
<td>-</td>
</tr>
<tr>
<td>W/B</td>
<td>W/B=40%, Slag=30%</td>
<td>W/B=40%, Slag=30%</td>
</tr>
<tr>
<td>$T_{w/o\ crack}$</td>
<td>Over 100 yrs</td>
<td>Over 100 yrs</td>
</tr>
<tr>
<td>$T_{w/\ crack}$</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Need to control cracking in early age!!

<table>
<thead>
<tr>
<th></th>
<th>Splash zone</th>
<th>Submerged zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crack width</td>
<td>0.1mm</td>
<td>0.3mm</td>
</tr>
<tr>
<td>$T_{service}$</td>
<td>65 yrs</td>
<td>2.5 yrs</td>
</tr>
<tr>
<td>$T_{service}$</td>
<td>59.8 yrs</td>
<td>1.5 yrs</td>
</tr>
</tbody>
</table>
Carbonation analysis of liner concrete at tunnel

(a) Carbonation depth simulation

(b) Distribution of pH at 100 years

(c) Distribution of Ca(OH)$_2$ and CaCO$_3$

(d) Contour of carbonation depth at 100 years
Chloride attack in carbonated concrete (1)

- Chloride distribution at carbonated area (Tuutti, 1982)

![Diagram showing chlorides in concrete](image)

- Decreasing of porosity

- Carbonation initiation and propagation

- Chloride ion in pore

- Fixed chloride ion (Friedel)

- Porosity

- W/C 37% - 28 days
- W/C 37% - 180 days, RH 65%
- W/C 37% - fully carbonated

- Decreasing of porosity

- Chloride content (CaCl2/cement, %)

- Pore radius (10^-6 m)

- Front of carbonation

- Carbonation depth

- Cover depth (mm)
Chloride attack in carbonated concrete (2)

**Graphs and Data:**

- **Only chloride attack**
  - Chloride content (kg/m³) vs. Year
  - Chloride content (kg/m³) vs. Cover depth (cm)

- **Coupled deterioration analysis**
  - Chloride content (kg/m³) vs. Year
  - Chloride content (kg/m³) vs. Cover depth (cm)

- **Graphs show:**
  - 5 years
  - 45 years
  - 100 years

**Key Points:**

- **Deterioration analysis** includes both free chloride and bound chloride.
- The graphs illustrate the progression of chloride content over time and depth.
Service life prediction of RC structures
-an example of Busan-Geoje Fixed Link project in Korea

- Design life: 100 years.
- Nominal end of service life: corrosion initiation
- Level of Reliability: 90% (β = 1.3)

Environmental conditions

<table>
<thead>
<tr>
<th>Type of zones</th>
<th>Chloride concentration (mol/l)</th>
<th>CO₂ concentration (ppm)</th>
<th>Temperature (°C)</th>
<th>Relative humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Submerged</td>
<td>0.51</td>
<td>-</td>
<td>15.3</td>
<td>100</td>
</tr>
<tr>
<td>Splash</td>
<td>0.51</td>
<td>-</td>
<td>15.3</td>
<td>82.6</td>
</tr>
<tr>
<td>Atmospheric</td>
<td>0.19</td>
<td>-</td>
<td>15.3</td>
<td>65.3</td>
</tr>
<tr>
<td>Tunnel inside</td>
<td>-</td>
<td>670</td>
<td>20.0</td>
<td>65.3</td>
</tr>
</tbody>
</table>
Possible mix proportions

<table>
<thead>
<tr>
<th>Area</th>
<th>W/B</th>
<th>W (kg/m³)</th>
<th>Binder (kg/m³)</th>
<th>S (kg/m³)</th>
<th>G (kg/m³)</th>
<th>Admixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bridge Structures</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>0.350</td>
<td>140</td>
<td>160</td>
<td>160</td>
<td>80</td>
<td>751</td>
</tr>
<tr>
<td>B2</td>
<td>0.375</td>
<td>142</td>
<td>184</td>
<td>184</td>
<td>11.4</td>
<td>797</td>
</tr>
<tr>
<td>B3</td>
<td>0.375</td>
<td>142</td>
<td>152</td>
<td>152</td>
<td>-</td>
<td>76</td>
</tr>
<tr>
<td>B4</td>
<td>0.375</td>
<td>143</td>
<td>143</td>
<td>143</td>
<td>-</td>
<td>72</td>
</tr>
<tr>
<td>Submerged Tunnel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td>0.350</td>
<td>140</td>
<td>180</td>
<td>180</td>
<td>-</td>
<td>40</td>
</tr>
<tr>
<td>T2</td>
<td>0.350</td>
<td>140</td>
<td>160</td>
<td>160</td>
<td>-</td>
<td>80</td>
</tr>
<tr>
<td>T3</td>
<td>0.375</td>
<td>142</td>
<td>170</td>
<td>170</td>
<td>-</td>
<td>38</td>
</tr>
<tr>
<td>T4</td>
<td>0.375</td>
<td>142</td>
<td>152</td>
<td>152</td>
<td>-</td>
<td>76</td>
</tr>
</tbody>
</table>

Specific gravity
- Coarse aggregate: 2.64
- Sand: 2.58
- Cement: 3.16
- Slag: 2.89
- Fly ash: 2.19
- Silica fume: 2.21

Air content: 4.0%

Possible mix proportions

| Admixture | SP: 0.65~2.0% | AE: 0.014~0.023% |
Analysis result at atmospheric zone

**[Atmospheric - B1]**

- **Chloride content (kg/m³)**
- **Concrete cover (mm)**
- **Exposed time (year)**

**Critical Cl⁻ content**

Concrete cover = 50mm

**Service life**

**[Atmospheric - B2]**

- **Chloride content (kg/m³)**
- **Concrete cover (mm)**
- **Exposed time (year)**

**[Atmospheric - B3]**

- **Chloride content (kg/m³)**
- **Concrete cover (mm)**
- **Exposed time (year)**
Analysis result at atmospheric (2)

[Atmospheric - B4]

- Concrete cover = 50mm
- Critical Cl\(^-\) content
- Service life

[Atmospheric - T1]

- Concrete cover = 75mm
- Critical Cl\(^-\) content
- Service life

[Atmospheric - T3]

- Concrete cover = 75mm
- Critical Cl\(^-\) content
- Service life
Analysis result at submerged zone (1)

[Submerged zone - B1]

Concrete cover (mm) vs Chloride content (kg/m³)

Concrete cover = 75mm

Critical Cl⁻ content

[Submerged zone - B2]

Cover depth (mm) vs Chloride content (kg/m³)

[Submerged zone - B3]

Concrete cover (mm) vs Chloride content (kg/m³)

Critical Cl⁻ content

Service life
Analysis result at submerged zone (2)

[Submerged zone - B4]

[Submerged zone - T1]

[Submerged zone - T3]

Concrete cover (mm)

Chloride content (kg/m³)

Exposed time (year)

Concrete cover = 75mm

Critical Cl⁻ content

Critical Cl⁻ content

Critical Cl⁻ content

Concrete cover = 75mm

Concrete cover = 75mm

Concrete cover = 75mm

Service life

Service life

Service life

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Analysis result at splash zone

[ Splash zone - B1 ]

[ Splash zone - B2 ]

[ Splash zone - B3 ]

[ Splash zone - B4 ]

Concrete cover = 75mm

Critical Cl⁻ content

Service life
## Summary of chloride attack analysis results

<table>
<thead>
<tr>
<th>Area</th>
<th>Structures</th>
<th>Mix Type</th>
<th>Service Life (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Atmospheric Zone</strong></td>
<td>Bridge (Piers &amp; Pylons)</td>
<td>A-B-1</td>
<td>212</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A-B-2</td>
<td>162</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A-B-3</td>
<td>168</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A-B-4</td>
<td>132</td>
</tr>
<tr>
<td></td>
<td>Immersed tunnel (inside)</td>
<td>A-T-1</td>
<td>167</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A-T-2</td>
<td>212</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A-T-3</td>
<td>178</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A-T-4</td>
<td>168</td>
</tr>
<tr>
<td><strong>Submerged Zone</strong></td>
<td>Caissons (external)</td>
<td>S-B-1</td>
<td>188</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S-B-2</td>
<td>165</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S-B-3</td>
<td>184</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S-B-4</td>
<td>171</td>
</tr>
<tr>
<td></td>
<td>Immersed tunnel (outside)</td>
<td>S-T-1</td>
<td>152</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S-T-2</td>
<td>188</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S-T-3</td>
<td>143</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S-T-4</td>
<td>184</td>
</tr>
<tr>
<td><strong>Tidal and Splash Zone</strong></td>
<td>Pylons, Piers &amp; Caissons</td>
<td>T-B-1</td>
<td>180</td>
</tr>
<tr>
<td></td>
<td></td>
<td>T-B-2</td>
<td>175</td>
</tr>
<tr>
<td></td>
<td></td>
<td>T-B-3</td>
<td>193</td>
</tr>
<tr>
<td></td>
<td></td>
<td>T-B-4</td>
<td>176</td>
</tr>
</tbody>
</table>

Satisfy the required service life for chloride attack
Analysis result for carbonation (1)

[ Carbonation at tunnel inside - T1 ]

- Cover depth = 75 mm

[ Carbonation at tunnel inside - T2 ]

Concrete cover (mm)
**Analysis result for carbonation (2)**

**[Carbonation at tunnel inside - T3]**

- **Carbonation depth (mm)** vs **Exposed time (year)**
- **Cover depth = 75 mm**

**[Carbonation at tunnel inside - T4]**

- **Carbonation depth (mm)** vs **Exposed time (year)**

**pH** vs **Concrete cover (mm)**

- **pH**
- **Ca(OH)\(_2\)**

**Ca(OH)\(_2\) (kg/m\(^3\))** vs **Concrete cover (mm)**

- **pH**
- **Ca(OH)\(_2\)**
### Summary of carbonation analysis results

<table>
<thead>
<tr>
<th>Mix</th>
<th>Carbonation depth after 100 yrs (mm)</th>
<th>Service life for carbonation (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>9.2</td>
<td>Over 300</td>
</tr>
<tr>
<td>T2</td>
<td>25</td>
<td>Over 250</td>
</tr>
<tr>
<td>T3</td>
<td>10</td>
<td>Over 300</td>
</tr>
<tr>
<td>T4</td>
<td>33</td>
<td>Over 250</td>
</tr>
</tbody>
</table>

![Graph showing carbonation depth over time](image)

- **Cover depth = 75mm**
- **Satisfy the required service life for carbonation**
Conclusion

- Concepts for durability design and strategy along with performance based service life prediction in current RC design codes are presented.

- A scheme of coupled deterioration analysis using chloride penetration model and a carbonation model which consider the early-age behaviour and time-space dependent diffusivity of concrete as well as cracks inside concrete are proposed.

- In order to predict the service life of cracked concrete structures by both chloride attacks and carbonation, a microscopic steel corrosion model is also proposed and implemented into a finite element analysis program.
  - electric corrosion cell model: $\text{cl}^-$, $\text{pH}$
  - oxygen diffusion model: supplied $O_2$

- The service life of RC structures become shortens significantly with increased crack width, increased W/ C, and decreased pH of pore water (i.e. carbonation).

- Optimum concrete mix proportions which make RC structures to possess the design service life can be obtained using this performance tool.
Thank you for your kind attention!

song@yonsei.ac.kr