Enhancements of ICON Software: Environmental Condition Modeling and Design Implementation

David A. Lange.
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Concrete Structures Under Drying Condition

Concrete Slab on Base with Perfect Contact - Engineers’ Design

Drying Causes Volume Change in Concrete Material

Volume Change Alters Structural Configuration
Concrete Structures Under Drying Condition

Volume Instability:
Volume Change in Concrete Structures in Absence of External Loading Changes

Consequence of Volume Instability:
- Causes Undesired Stress
- Alters Structural Boundary Condition
- Reduces Pre-stress in PC’s tendons
- Causes Cracks in Highly Restrained Structures

How to Overcome?
Engineers predict degree of problem and incorporate into their design
Concrete Structures Under Drying Condition

What do we need for the PREDICTION?

- Material Model
- Material Properties
- FEA Tool
- Internal RH & Temperature
- Geometry & BC of Structure
Outline:

- ICON Software
- Material Test
- NAPTF Single Slab Curling Simulation
- Using ICON for Slab Curling Study
- Future Directions
ICON: 3D FEA Code for Concrete Structures Under Drying Condition
ICON (Illinois CONcrete):
- 3D Finite Element Analysis Code
- Material Aging of Concrete
- Time Dependent Environmental Excitations (RH & Temperature)

MATERIAL:

- CR: Creep → Solidification Material Theory
- SH: Shrinkage → Hygrothermal Response
- T: Thermal Dilation → Simple Linear Model

INSTANTANEOUS RESPONSE → Linear Elasticity

ELEMENTS:
- Solid & Interface Elements
Newton-Raphson Method was employed for solving Non-linearity in Interface Element

$k_n^+ = 1 \text{ psi}$

$k_n^- = 1e12 \text{ psi}$
Step-by-Step Method for Time Dependent Analysis

At time = \( t_0 \):
- Material Properties are FIXED
- \( \sigma_0, \Delta \varepsilon_{HT}, \Delta \varepsilon_T \) are KNOWNS

During Time Step:
- Linearly varying stress assumption
- Static analysis with KNOWNS
- Compute \( \Delta \varepsilon_{TOTAL}, \Delta \varepsilon_{EL}, \Delta \varepsilon_{CR}, \Delta \sigma \)

At time = \( t_0 + \Delta t \):
- Update Deformations & Stress
- Update Material Properties
Material Test
Instantaneous Response
→ Age Dependent Young’s Modulus

\[
\frac{E(t_a)}{E_{28}} = \left( \frac{t_a}{a_E + b_E t_a} \right)^{0.5}
\]

\[
a_E = 0.45
\]

\[
b_E = 15
\]

\[
E_{28} = 4 \times 10^6 \text{ psi}
\]

NOTE: High Volume Fly Ash Concrete
(60% of cement was replaced)
Creep

→ Laboratory Test Setup for Creep

**Creep in Compression**

- Load Bearing Plate
- Load Cell
- Cylinder Specimen
- Ball bearing
- Spring
- Embedment Type Strain Gauge

**Creep in Tensile**

- Hooked End
- Lever
- Circular Rod
- Prism Specimen
- End plate (bonded with epoxy)
- Weight

Embedment Type Strain Gauge

Texas Measurement Inc., Part# PMFL-60-2LT
Creep

**Creep in Tension**

\[ \text{Creep in Tension} \approx 5 \times \text{Creep in Compression} \]

**Stress applied to Creep Specimen**

<table>
<thead>
<tr>
<th>Age (day)</th>
<th>Compressive (psi)</th>
<th>Tensile (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>140</td>
<td>20</td>
</tr>
<tr>
<td>14</td>
<td>350</td>
<td>44</td>
</tr>
<tr>
<td>30</td>
<td>500</td>
<td>73</td>
</tr>
</tbody>
</table>

**Stress/ Strength ratio at the loading age = 10\sim 15\%**

**NOTE:** Specific Creep = Creep Strain Divided by Applied Stress
Shrinkage

→ Drying Shrinkage Measurement

**Embedment Type Strain Gauge**

Texas Measurement Inc., Part# PMFL-60-2LT

**Prism Specimen with Embedment Type Strain Gauge**

Drying Surface

Embedment Type Strain Gauge

**Top view**

3"

**Front View**

1.8"

2.4"

1.8"

Shrinkage strain (in./in. x 10^-6)

NAPTF material is High Volume Flyash Concrete (60% of cement was replaced)
Shrinkage → Laboratory Test for Internal RH

RH Prove & Digital Sensor

- Plastic Tube
- GoreTex Cap
- Sensirion SHT75 RH sensor

RH Sensor locations

RH reduction in prism (drying at age of 28d)

- 0.25"
- 0.5"
- 0.75"
- 1.5"

Age (day)

0 14 28 42 56 70 84 98 112 126 140

RH (%) 100 90 80 70 60 50

Front View
NAPTF Single Slab Curling Simulation
Moisture Curling of NAPTF Single Slab

NAPTF Single Slab

Vertical LVDT  Clip Gauge
Moisture Curling of NAPTF Single Slab

1/4 Model of NAPTF Single Slab

Solid elements (Solidifying material)
RH, T measured at NAPTF

Symm.

RH & Temperature Measured at NAPTF

Material Properties Measured at UIUC

Constant RH, T

Material Properties

Measured at UIUC
Moisture Curling of NAPTF Single Slab

Drying Scenario #1:
RH Measured at NAPTF

Lift-off Displacement

Drying Scenario #1: Decreased with Daily Fluctuation

Labels are Depth of RH sensors from Drying Surface

Lift-off at Corner of Slab
Moisture Curling of NAPTF Single Slab

Drying Scenario #2: Monotonic Decrease

Lift-off Prediction with Drying Scenario #2

Drying Scenario #2: Monotonic Decrease of RH

Lift-off at Corner of Slab

Labels are Depth of RH sensors from Drying Surface

IUCAT

CENTER OF EXCELLENCE FOR AIRPORT TECHNOLOGY
Using ICON to Learn about Slab Curling
Using ICON to Learn about Slab Curling

Parameters of interest:

- Material Parameters
- Slab Size & Thickness
- Base Stiffness
- Base Material Type

All simulations were conducted with the same condition of NAPTF single slab EXCEPT the parameters of interest
Sensitivity of Moisture Curling to Material Parameters

**VARIABLE:** Material Properties of Slab

+/- 25% Variation of Material Response:

- Young’s Modulus
- Hygrothermal Strain
- Creep
- CTD
Sensitivity of Moisture Curling to Material Parameters

Moisture Curling of Slab is Very Sensitive to Hygrothermal Strain Response

**Peak Lift-off Displacement vs. Material Properties**

- **Elastic Modulus**
- **Hygrothermal Strain Response**
- **Creep**
- **CTD**

**Peak Stress vs. Material Properties**

- **Elastic Modulus**
- **Hygrothermal Strain Response**
- **Creep**
- **CTD**

**Peak Lift-off Displacement**

**Peak Stress**
Effect of Slab Size on Slab Curling

**VARIABLE:** Slab Size (L)

Variation of Slab Size:

- 12.5 ft x 12.5 ft
- 15.0 ft x 15.0 ft
- 17.5 ft x 17.5 ft
- 20.0 ft x 20.0 ft
Effect of Slab Size on Slab Curling

Lift-off Displacement is Sensitive to Slab Size, Assuming Stiff Base

- Peak Lift-off Disp. for Different Salb Size (L)
- Peak Stress for Different Slab Size (L)

Graphs showing the relationship between slab size and lift-off displacement and peak stress.
Slab Thickness Effect on Slab Curling

**VARIABLE:** Slab Thickness (D)

**Variation of Slab Size:**
- 11 in.
- 12 in.
- 13 in.
- 14 in.
Slab curling is not very sensitive to slab thickness, Assuming Stiff Base

**Peak Lift-off Displacement**

- RH$_{p6} = RH$_{p5}

**Peak Stress**

- RH$_{p6} = RH$_{p5}
Base Stiffness Effect on Slab Curling

**VARIABLE: Base Stiffness** ($E_b$)

Variation of Base Stiffness

- $4 \times 10^6$ psi
- $4 \times 10^5$ psi
- $4 \times 10^4$ psi
- $4 \times 10^3$ psi
Base Stiffness Effect on Slab Curling

Stress is Sensitive to Base Stiffness Change

Peak Lift-off Displacement

Peak Stress

Soft Base Reduces Stress on Slab. WHY?
Base Stiffness Effect on Slab Curling

Soft Base Reduces Stress on Slab. WHY?

\[ E_b = 4 \times 10^3 \text{ psi} \]

\[ E_b = 4 \times 10^6 \text{ psi} \]

Then, Soft Base Material is the SOLUTION?
Base Stiffness Effect on Slab Curling

Soft Base is Not the Solution!
Role of Viscoelastic Base in Slab Curling

HMAC Base Reduces Stress on Slab

- Viscoelastic Base

**Graph:**
- Peak Stress for Different Base Stiffness ($E_b$)
- Max. Principle Stress (psi)

- EL
- HMAC

Stress Reduction due to Creep in HMAC base (~12.5%)
Future Directions
Future Directions

Field Validation for Slab Curling using ICON simulation

• ATREL
  - Prof. Jeff Roesler (UIUC)

• Atlanta Hartsfield International Airport
  - Prof. Kim Kurtis (GaTech), Quintin Watkins (Atlanta Airport)

• O’Hare International Airport
  - Prof. David Lange (UIUC), Yi-Shi Liu (UIUC)
Future Directions

Environmental Condition Modeling

- Current ICON uses measured internal RH & Temperature as INPUTS
- Environmental Conditions from Weather Database
  - Moisture & Heat Diffusion Analysis
  - Provide ICON internal RH & Temperature
- ICON as Design Tool for Pavement with Environmental Conditions
Using ICON to generate test cases for curled slabs that will be used as initial conditions for the loading analysis

The test cases will be selected to provide a rich database representing common materials and environmental conditions

The test cases will be selected to provide some extreme conditions that drive significantly high curling