Performance of Corrosion Inhibiting Admixtures in a Marine Environment

Ian N. Robertson
Craig Newton
and
Many, many students

Funding provided by:
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and HI-DOT Research Board, Harbors Division

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Kauai Hindu Temple
1000-year design life.
Project Timeline

• Initiated in 1998 by Craig Newtson
• Funded for 5 years by FHWA and Hi-DOT (‘98-’03)
• Phase I – Field study of existing piers
• Phase II – Laboratory study of corrosion inhibitors
• Newtson left for New Mexico State Univ. (2003)
• Additional funding for 5 year field deployment (‘04-’09)
• Phase III – Field study of promising inhibitors
• Phase II and III studies terminated in 2012
Project Objectives

- Phase I – Field testing at harbor piers to evaluate the effectiveness of corrosion-inhibiting measures used in Hawaii
- Phase II – Accelerated Laboratory testing to evaluate the effectiveness of proposed corrosion-inhibiting methods
- Phase III - Compare corrosion-inhibiting methods under field conditions
Phase I
Field Testing of Existing Piers

- Performed in 2000 by Craig Newton and Merioni Bola
Phase I - Conclusions

• Corrosion was identified on all piers
• Increased DCI dosage decreased corrosion activity
• Epoxy coated reinforcing bars appeared to effectively combat corrosion

Research Report UHM/CE/00-01
by Bola and Newtson
Available at:
www.cee.hawaii.edu
Corrosion Inhibitor Study

- Phase II: Accelerated Laboratory corrosion tests
- Phase III: Field Exposure specimens
- Field study results
- Conclusions
- Recommendations
Phase II - Laboratory Testing

- Accelerated Laboratory corrosion tests – modified ASTM G 109-92
- Evaluating various corrosion inhibiting measures
Typical ASTM G 109 Test Specimen

3% NaCl Solution
Specimen Variables

• **Water-Cementitious Material Ratio**
  0.35  0.40  0.45

• **Aggregates**
  Halawa and Kapaa

• **Paste Content**
  • Varied from 28% to 35%

• **Admixtures**
  • Control specimens with no admixtures
  • Specimens with each of 8 admixtures intended to inhibit corrosion

• **Reinforcing Steel**
  • Uncoated Grade 60 deformed bars
Admixtures

- DAREX Corrosion Inhibitor (DCI)
- Rheocrete CNI
- Rheocrete 222+
- FerroGard 901
- Xypex Admix C-2000
- Latex-Modifier
- Silica Fume
- Fly Ash
100 different concrete mixtures
656 Individual specimens
Test Procedures

• Material Properties
  • Compressive Strength
  • Elastic Modulus
  • Permeability
• Initial and Final Conditions
  • Chloride Concentration Analysis
  • pH
• Readings every wet/dry cycle
  • Corrosion Current
  • Half-Cell Potential
  • Linear Polarization Resistance
  • Concrete Resistivity
• Autopsy
  • Split specimen at top reinforcement
  • Record extent of corrosion
Specimen Autopsy

- Record exterior appearance
- Half-cell readings over top reinforcement
- Core center of specimen
- Slice and grind samples for chloride tests at 0.5”, 1”, 1.5” and 2” below top surface
- Split at top reinforcement
- Record extent of corrosion
- pH measurement at top steel
- Discard specimen
- Repeat – 656 times!
Laboratory Phase

- All specimens autopsied and recorded
- Two published reports
  - Kakuda, Robertson and Newtson (2005) UHM/CEE/05-04
  - Okunaga, Robertson and Newtson (2005) UHM/CEE/05-05
Laboratory Observations

• Low w/c ratio meant that many specimens took longer than expected to corrode
• Reinforcement protection admixtures:
  • DCI and CNI show effective protection
  • Rheocrete 222+ and FerroGard 901 show unreliable performance
• Decreased permeability admixtures:
  • Flyash and Silica Fume both effective
  • Xypex Admix C-2000 and Latex-Modifier performed poorly
Long-Term Field Monitoring

- 25 Field panels were placed at mean sea level at Pier 38 in Honolulu Harbor
- Selected most promising Phase II mixtures
- Included one panel with Kryton KIM
- Panels installed from July 2002 to June 2003
- Measurements to be taken annually for 7 years - supported by HDOT funding
Field Site
Oahu, Hawaii
Long-Term Field Specimen Design

- Reinf.
- 6" Thk Panel
- High Water
- Mean Sea Lvl
- Low Water

Dimensions:
- 6' Height
- 2' Width
- 2' Width

Panel thickness: 6"
Typical Field Panels
Field Specimen Tests

• Half-cell potential readings taken across top surface of panel - annually
• Panels removed from ocean every other year
• Chloride concentrations taken through cover concrete (away from the reinforcing steel)
• pH levels measured at level of reinforcing
Chloride Concentration Samples

2004 concrete sampling method
Chloride Concentration Samples

concrete sampling method
• Field Panel Sampling
  • Extract cores
  • Cut slices at various depths
  • Crush to powder
  • Test for chloride content
  • Test for pH level
Chloride Concentration Tests

- All chloride concentrations used the **Acid-Soluble** test method with a CL-2000 Chloride Field Test System (James Instruments, Inc.)

www.ndtjames.com
Chloride Concentration v.s. depth for Control w/ 0.40 w/c
Life-365 Prediction Software

Life-365™
Life-365 Service Life Prediction Model™
for Reinforced Concrete Exposed to Chlorides

Version 1.1

Life-365 Service Life Prediction Model and Life-365
are trademarks of the Silica Fume Association.
Used with permission
Life-365 Prediction Software

- Admixtures are limited for analysis:
  - Rheocrete CNI (used for DCI also as same calcium nitrite compositions)
  - Rheocrete 222+
  - Fly Ash
  - Silica Fume
  - Slag (not used for this research)
Life-365 Default Values

• The three main values focused on in this report include:

1. Diffusion coefficient, $D_{28}$ (m$^2$/s)
2. Diffusion decay index, $m$ (dimensionless)
3. Chloride threshold, $C_t$ (% mass concrete)
Chloride Concentrations with Life-365 Predictions

Panel 1 - Kapaa - Control (0.4 w/c)

Acid-soluble chloride (% by wt of concrete) vs. Depth (in.)

- Top (1.5 yrs)
- Middle (1.5 yrs)
- Bottom (1.6 yrs)
- Life-365 (1.5 yrs)
- Life-365 (1.5 yrs Adjusted)
Chloride Concentrations with Life-365 Predictions

- Default and adjusted input values for Control Panels 1 and 2

<table>
<thead>
<tr>
<th></th>
<th>Default values</th>
<th>Adjusted values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffusion coefficient</td>
<td>7.94E-12</td>
<td>5.50E-12</td>
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<tr>
<td>m</td>
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<td>0.38</td>
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<td>Corrosion threshold</td>
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</table>
Chloride Concentrations with Life-365 Predictions

Panel 1 - Kapaa - Control (0.4 w/c)

Acid-soluble chloride (% by wt of concrete) vs Depth (in.)

- Top (1.5 yrs)
- Middle (1.5 yrs)
- Bottom (1.6 yrs)
- Life-365 (1.5 yrs)
- Life-365 (1.5 yrs Adjusted)
Chloride Concentrations with Life-365 Predictions

Panel 1 - Kapaa - Control (0.4 w/c)

- Green line: Top (3.4 yrs)
- Blue line: Middle (3.4 yrs)
- Blue triangle: Bottom (3.4 yrs)
- Black dashed line: Life-365 (3.4 yrs)
- Red line: Life-365 (3.4 yrs Adjusted)
Chloride Concentrations with Life-365 Predictions

Panel 1 - Kapaa - Control (0.4 w/c)
Chloride Concentrations with Life-365 Predictions

Panel 2 - Halawa - Control (0.40 w/c)

Acid-soluble chloride (% by wt of concrete)

Depth (in.)

- Top (1.4 yrs)
- Middle (1.4 yrs)
- Bottom (1.7 yrs)
- Life-365 (1.4 yrs)
- Life-365 (1.4 yrs Adjusted)
Chloride Concentrations with Life-365 Predictions

Panel 2 - Halawa - Control (0.40 w/c)

- Top (3.4 yrs)
- Middle (3.4 yrs)
- Bottom (3.4 yrs)
- Life-365 (3.4 yrs)
- Life-365 (3.4 yrs Adjusted)
Chloride Concentrations with Life-365 Predictions

Panel 2 - Halawa - Control (0.40 w/c)

Acid-soluble chloride (% by wt of concrete)

Depth (in.)
Chloride Concentrations with Life-365 Predictions

- Default and adjusted input values for Control Panel 7

<table>
<thead>
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Chloride Concentrations with Life-365 Predictions

![Graph showing chloride concentrations with Life-365 predictions for Panel 7 - Kapaa - Control (0.35 w/c). The graph illustrates the acid-soluble chloride (% by wt of concrete) versus depth (in.) with different markers representing top, middle, and bottom layers along with Life-365 predictions.]
Chloride Concentrations with Life-365 Predictions

Panel 7 - Kapaa - Control (0.35 w/c)
Chloride Concentrations with Life-365 Predictions

Panel 7 - Kapaa - Control (0.35 w/c)
Chloride Concentrations with Life-365 Predictions

- Default and adjusted input values for DCI Panels

<table>
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<td>Diffusion coefficient</td>
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<td>m</td>
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<td>Corrosion threshold</td>
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</table>
Chloride Concentrations with Life-365 Predictions

Panel 3 - Kapaa - DCI (2 gal/yd$^3$)

- Top (3.4 yrs)
- Middle (3.4 yrs)
- Bottom (3.4 yrs)
- Life-365 (3.4 yrs)
- Life-365 (3.4 yrs Adjusted)
Chloride Concentrations with Life-365 Predictions

Panel 4 - Halawa - DCI (2 gal/yd³)

Acid-soluble chloride (% by wt of concrete)

Depth (in.)
Chloride Concentrations with Life-365 Predictions

- Default and adjusted input values for CNI Panels

<table>
<thead>
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<th>Adjusted values</th>
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<td>m</td>
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<td>Corrosion threshold</td>
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<td>0.05</td>
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</tbody>
</table>
Chloride Concentrations with Life-365 Predictions

Panel 5A - Kapaa - CNI (4 gal/yd$^3$)

- Top (4.7 yrs)
- Middle (4.7 yrs)
- Bottom (4.7 yrs)
- Life-365 (4.7 yrs)
- Life-365 (4.7 yrs Adjusted)
Chloride Concentrations with Life-365 Predictions

Panel 6 - Kapaa - CNI (2 gal/yd³)

Acid-soluble chloride (% by wt of concrete)

Depth (in.)

- Top (5.3 yrs)
- Middle (5.3 yrs)
- Bottom (5.3 yrs)
- Life-365 (5.3 yrs)
- Life-365 (5.3 yrs Adjusted)
Chloride Concentrations with Life-365 Predictions

- Default and adjusted input values for Rheocrete 222+ Panels

<table>
<thead>
<tr>
<th></th>
<th>Default values</th>
<th>Adjusted values</th>
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<td>Corrosion threshold</td>
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</tbody>
</table>
Chloride Concentrations with Life-365 Predictions

Panel 16 - Kapaa - Rheocrete 222+ (1 gal/yd³)

Acid-soluble chloride (% by wt of concrete)

Depth (in.)

Top (3.3 yrs)
Middle (3.3 yrs)
Bottom (3.3 yrs)
Life-365 (3.3 yrs)
Life-365 (3.3 yrs Adjusted)
Chloride Concentrations with Life-365 Predictions

Panel 17 - Halawa - Rheocrete 222+ (1 gal/yd$^3$)

- Top (3.3 yrs)
- Middle (3.3 yrs)
- Bottom (3.3 yrs)
- Life-365 (3.3 yrs)
- Life-365 (3.3 yrs Adjusted)
Chloride Concentrations with Life-365 Predictions

- Default and adjusted input values for Fly Ash Panels

<table>
<thead>
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<th>Adjusted values</th>
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Chloride Concentrations with Life-365 Predictions

Panel 11 - Kapaa - Fly Ash (15%)

Acid-soluble chloride (% by wt of concrete) vs. Depth (in.)

- Top (5.3 yrs)
- Middle (5.3 yrs)
- Bottom (5.3 yrs)
- Life-365 (5.3 yrs)
- Life-365 (5.3 yrs Adjusted)
Chloride Concentrations with Life-365 Predictions

Panel 12 - Halawa - Fly Ash (15%)
Chloride Concentrations with Life-365 Predictions

- Default and adjusted input values for Silica Fume Panels

<table>
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</table>
Chloride Concentrations with Life-365 Predictions

Panel 8 - Kapaa - Silica Fume (5%)

Acid-soluble chloride (% by wt of concrete) vs. Depth (in.)

- Top (5.2 yrs)
- Middle (5.2 yrs)
- Bottom (5.2 yrs)
- Life-365 (5.2 yrs)
- Life-365 (5.2 yrs Adjusted)
Chloride Concentrations with Life-365 Predictions

Panel 10 - Kapaa - Silica Fume (5%)

Acid-soluble chloride (% by wt of concrete) vs. Depth (in.)

- Top (2.9 yrs)
- Middle (2.9 yrs)
- Bottom (2.9 yrs)
- Life-365 (2.9 yrs)
- Life-365 (2.9 yrs Adjusted)
Half-cell Potential Tests

• Half-cell potential tests were performed to evaluate corrosion conditions within each field panel.

<table>
<thead>
<tr>
<th>Measured Potential (mV)</th>
<th>Statistical risk of corrosion occurring</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; -350</td>
<td>&gt;90%</td>
</tr>
<tr>
<td>Between -350 and -200</td>
<td>50%</td>
</tr>
<tr>
<td>&gt; -200</td>
<td>&lt;10%</td>
</tr>
</tbody>
</table>

Reference electrode = Copper Sulfate Electrode (CSE)
Testing Half-cell Potential

Panel #5: Kapaa 0.40 w/c with 2 gal/cuyd CNI

Panel #1: Kapaa Control with 0.4 w/c ratio

Access hole for electrical connection to reinforcement

Stainless Steel Cables

High Water

Mean Sea Lvl

Low Water

Distance from top of panel (cm)

Average Half Cell (-0.001mV)

Probability of corrosion:

> 90%

50%

< 10%

2.0 years
3.4 years
4.1 years
4.5 years
5.2 years
5.6 years
7.0 years
8.6 years

Crack Observed
Final Autopsy of Field Panels
Panel 2: Halawa Control with 0.40 w/c ratio

Panel #2: Halawa Control with 0.40 w/c ratio

Distance from top of panel (cm)

Average Half Cell (-0.001mV)

Probability of corrosion.

Rust Observed

< 10%

> 90%

50%
Panel 2: Halawa Control with 0.40 w/c ratio
Panel 2: Halawa Control with 0.40 w/c ratio
Panel 2: Halawa Control with 0.40 w/c ratio
Panel 2: Halawa Control with 0.40 w/c ratio
Panel 7: Kapaa Control - 0.35 w/cm

Half-Cell Potential at Various Years

Half-Cell potential at 9.6 years

Panel #7: Kapaa Control with 0.35 w/c ratio

Distance from top of panel (cm)

Probability of corrosion.

Rust Observed

< 10%

> 90%

< 10%
Panel 7: Kapaa Control - 0.35 w/cm

Visual Observation

Rust on Front Edge
Panel 7: Kapaa Control - 0.35 w/cm

Visual Observation – Reinforcing Steel

Panel #7
Kapaa Control 0.35 w/c

LEGEND:
+ - HALF-CELL LEAD CONNECTION
Panel 7: Kapaa Control - 0.35 w/cm

Visual Observation of Panel 7 Top Layer Top Surface Reinforcing Steel
Panel 4: Halawa 0.40 w/cm with 10 l/m³ DCI

Half-Cell Potential Various Years

Half-Cell potential at 9.7 years
Panel 4: Halawa 0.40 w/cm with 10 l/m³ DCI

Visual Observation

Crack and Rust at Front edge of Panel 4
Panel 4: Halawa 0.40 w/cm with 10 l/m³ DCI

Visual Observation – Reinforcing Steel
Panel 4: Halawa 0.40 w/cm with 10 l/m³ DCI

Visual Observation of Panel 4 Top Layer Top Surface Reinforcing Steel
Panel 5A: Kapaa 0.40 w/c ratio w/ 20 l/m³ CNI
Panel 5A: Kapaa 0.40 w/c ratio w/ 20 l/m³ CNI
Panel 15: Kapaa 0.40 w/c; 5 l/m³ Rheocrete

Panel #15: Kapaa 0.40 w/c with Rheocrete 222+ at 5 l/m³ (1 gal/cuyd)

Distance from top of panel (cm)

Average Half Cell ( - 0.001mV).

Probability of corrosion.

< 10%

50%

> 90%

Rust Observed
Panel 15: Kapaa 0.40 w/c; 5 l/m³ Rheocrete
Panel 18: Halawa 0.40 w/c; 15 l/m³ Ferrogard

Panel #18: Halawa 0.40 w/c with Ferrogard at 15 l/m³ (3 gal/cuyd)

Distance from top of panel (cm)

Average Half Cell (−0.001mV)

Rust Observed

Probability of corrosion.

< 10%

50%

> 90%

2.0 years
3.4 years
4.1 years
4.5 years
5.2 years
5.6 years
7.0 years
9.7 years

Panel 18: Halawa 0.40 w/c; 15 l/m³ Ferrogard
Panel 18: Halawa 0.40 w/c; 15 l/m³ Ferrogard
Panel 14: Kapaa 0.40 w/c; 5% Latex Modifier

Panel #14: Kapaa 0.40 w/c with 5% Latex Modifier

- Average Half Cell (\(-0.001 \text{mV}\))
- Distance from top of panel (cm)
- Probability of corrosion:
  - < 10%
  - 50%
  - > 90%

<table>
<thead>
<tr>
<th>Distance from top of panel (cm)</th>
<th>19</th>
<th>42</th>
<th>65</th>
<th>88</th>
<th>110</th>
<th>133</th>
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<tbody>
<tr>
<td>Rust Observed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Probability of corrosion</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
Panel 14: Kapaa 0.40 w/c; 5% Latex Modifier
Panel 21: Kapaa 0.40 w/c; 2% Xypex

Panel #21: Kapaa 0.40 w/c with 2% Xypex

Average Half Cell (-0.001mV)

Distance from top of panel (cm)

Rust Observed after 7 years

Probability of corrosion.
Panel 21: Kapaa 0.40 w/c; 2% Xypex
Panel 22: Kapaa 0.40 w/c; 2% Kryton KIM

Panel #22: Kapaa 0.40 w/c with 2% Kryton KIM

- Distance from top of panel (cm)
- Average Half Cell (\(-0.001\text{mV}\))
- Probability of corrosion.

Crack Observed
Panel 22: Kapaa 0.40 w/c; 2% Kryton KIM
Panel 22:
Kapaa 0.40 w/c; 2% Kryton KIM
Panel 13: Halawa (0.36 w/cm) 15% Fly Ash

Half-Cell Potential Various Years

Half-Cell potential at 9.6 years
Panel #8: Kapaa 0.36 w/c with 5% Silica Fume (Master Builders)

Average Half Cell ( -0.001mV).

Distance from top of panel (cm)

Rust Observed

Probability of corrosion.

< 10%

50%

> 90%
Panel 8: Kapaa 0.36 w/c; 5% Silica Fume
Panel 9: Kapaa 0.36 w/c; 5% Silica Fume

Panel #9: Kapaa 0.36 w/c with 5% Silica Fume (Master Builders)

Distance from top of panel (cm)

Average Half Cell (-0.001mV)

Rust Observed

Probability of corrosion.

< 10%

50%

> 90%

1.1 years
2.4 years
3.2 years
3.6 years
4.3 years
4.8 years
6.2 years
8.7 years
Panel 9: Kapaa 0.36 w/c; 5% Silica Fume
Reinforcing Steel Mass Loss

Field Panel (Number and Admixture)

- P2-Control: 0.40 w/c
- P7-Control: 0.35 w/c
- P4-DCI: 10l/m³
- P3A-DCI: 20l/m³
- P5-CNI: 10l/m³
- P6-CNI: 10l/m³
- P5A-CNI: 20l/m³
- P15, P17 & P17A
- Rheocrete: 5l/m³
- P18, P19 & P20
- P14-Latex Modifier
- P21-Xypex
- P22-Kryton Kim
- P8, p9 & p10
- 5% Silica Fume
- P11, P12 & P13
- 15% Fly Ash
Reinforcing Steel Mass Loss

Field Panel (Number and Admixture)

- P2-Control: 0.40 w/c
- P7-Control: 0.35 w/c
- P4-DCI: 10/l/m³
- P3A-DCI: 20/l/m³
- P5-CNI: 10/l/m³
- P6-CNI: 10/l/m³
- P5A-CNI: 20/l/m³
- P15, P17 & P17A Rheocrete: 5/l/m³
- P18, P19 & P20
- P14-Latex Modifier
- P21-Xypex
- P22-Kryton Kim
- P8, P9 & P10
- 5% Silica Fume
- P11, P12 & P13
- 15% Fly Ash

Mass Loss (%)
Reinforcing Steel Mass Loss

Field Panel (Number and Admixture)

Mass Loss (%)
Conclusions
Based on field specimens

• Control panel with w/c ratio of 0.35 performed better than control panels with w/c ratio of 0.40
• DCI and CNI both appear effective at 20 ℓ/m³ dosage. Results for 10 ℓ/m³ dosage not reliable.
• Rheocrete 222+ and FerroGard 901 provide varying performance results.
• Latex-modifier and Xypex Admix C-2000, showed poor performance.
Conclusions
Based on field specimens

- Panel with Kryton KIM showed minor corrosion and low half-cell readings after 9 years.
- Panels with 5% silica fume replacement showed inconsistent results – possibly due to inadequate distribution of silica fume during mixing.
- Panels with 15% fly ash replacement showed good performance after 9 years.
Recommendations

• Use low w/c ratio mixtures

• Include fly ash replacement at 15% or greater

• Include DCI or CNI corrosion inhibitor at 20 l/m³ or greater

• Possibly add Kryton KIM for additional protection
Kauai Hindu Temple
1000-year design life.
Final Design

• Use high Fly Ash concrete
• Use low cement and water content
• Use superplasticizers to increase slump
• Add superplasticizer, NOT WATER, at site
• All of the above reduce concrete shrinkage
• Monitor internal temperature of concrete to prevent thermal cracking
• Wet cure for 7 days or more
• Design for 3000psi concrete after 90 days
Application of burlap and moisture
Wet burlap covered with plastic sheet
### Table 4 — Average compressive strength of concrete cylinders, MPa (psi)

<table>
<thead>
<tr>
<th>Test age</th>
<th>Lower slab</th>
<th>Upper slab</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 days</td>
<td>6.0 (870)</td>
<td>7.3 (1065)</td>
</tr>
<tr>
<td>7 days</td>
<td>9.0 (1300)</td>
<td>10.9 (1580)</td>
</tr>
<tr>
<td>28 days</td>
<td>14.8 (2145)</td>
<td>17.5 (2540)</td>
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<tr>
<td>90 days</td>
<td>23.1 (3350)</td>
<td>27.6 (4000)</td>
</tr>
</tbody>
</table>
Any Questions?