CONSTRUCTION CYCLE 6 (CC-6) REVISITED

FATIGUE ANALYSIS
and
ECONOMIC and DESIGN IMPLICATIONS

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Presentation Outline

• Review CC-6 Construction

• Review Full Scale and Lab Testing Results

• Statistical Analysis of Laboratory Fatigue Tests

• Discuss Design and Economic Implications

Why?

• Anecdotal evidence suggested that:
  
  • High flexural strength concrete will cause embrittlement and decreased pavement life.
  
  • Concrete constructed on black base will perform better than concrete constructed on cement base; however, design procedure doesn’t differentiate.
Based on this:

- AC 150-5320-6E restricted 90-day design flexural strengths to < 700 psi.
- This implies 28-day average strengths of ~ 650 psi and lower limit of ~ 600 psi
- However 28-day strengths of 700 to 750+ psi are not unusual at many airports, e.g.:
  - ORD
  - JFK
  - IAD
  - NAPTF
CC-6 Objectives

• Investigate the relative effect of concrete flexural strength on performance:
  • Full scale tests
  • Lab fatigue tests

• Investigate the effect of cement stabilized vs. asphalt stabilized subbase on performance with full scale tests

• (Look at E to R correlations)
Three Concrete Mixes

- **Low Strength**
  - Imported Gravel
  - 460 lbs/cy Cement
  - 500 psi Target
  - 662 psi Actual

- **Medium Strength**
  - Local Crushed Stone (carbonate)
  - 500 lbs/cy Cement
  - 750 psi Target
  - 762 psi Actual

- **High Strength**
  - Same stone & gradation as Medium Strength
  - 680 lbs/cy Cement
  - 1000 psi Target
  - 1007 psi Actual
### Full Scale Test Results

<table>
<thead>
<tr>
<th>Test Item</th>
<th>Equivalent Passes @ 45 kips</th>
<th>Equivalent Passes @ 70 kips</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRS-1 North</td>
<td>9,108</td>
<td>63</td>
</tr>
<tr>
<td>MRS-1 South</td>
<td>7,834</td>
<td>54</td>
</tr>
<tr>
<td>MRS-2 North</td>
<td>577,393</td>
<td>1,855</td>
</tr>
<tr>
<td>MRS-2 South</td>
<td>572,096</td>
<td>1,838</td>
</tr>
<tr>
<td>MRS-3 North</td>
<td>9,909,051</td>
<td>4,696</td>
</tr>
<tr>
<td>MRS-3 South</td>
<td>11,175,129</td>
<td>5,296</td>
</tr>
</tbody>
</table>

North – AC Base          South – Econocrete Base

### Full Scale Test Results - Equiv 70k

![Graph showing concrete strength vs repetitions for MRS-3 North and South](image-url)
Concrete Laboratory

- Compressive Strength
- Split Tensile Strength
- Flexural Strength
- Concrete Beam Fatigue Testing
- Coefficient of Thermal Expansion

Laboratory Fatigue Results

<table>
<thead>
<tr>
<th>Test Item</th>
<th>Target Strength psi</th>
<th>28-Day Strength psi</th>
<th>Strength of Field-Cut Samples psi</th>
<th>Number of Cast Beams</th>
<th>Number of Cut Beams</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRS1</td>
<td>500</td>
<td>662</td>
<td>660</td>
<td>39</td>
<td>16</td>
</tr>
<tr>
<td>MRS2</td>
<td>750</td>
<td>763</td>
<td>749</td>
<td>0*</td>
<td>18</td>
</tr>
<tr>
<td>MRS3</td>
<td>1000</td>
<td>1007</td>
<td>932</td>
<td>0*</td>
<td>19</td>
</tr>
</tbody>
</table>

* Cast beams were not handled properly.

From Brill and Hao
MRS-1

Figure 2. Fatigue Test Results for MRS1 Cast Beams.

Figure 3. Fatigue Test Results for MRS1 Field-Cut Beams.

Field Cut Beams – MRS-2 & 3

Figure 4. Fatigue Test Results for MRS2 Field-Cut Beams.

Figure 5. Fatigue Test Results for MRS3 Field-Cut Beams.
The plots show scatter, as is to be expected for fatigue test results, but the trends appear to be similar.

A test was therefore made to estimate to what extent the combined test results can be represented by a common model.

The procedure given in Pindyck and Rubinfeld [5], section 5.3.3, was followed.

Null Hypothesis: the regressions for two sets of data are identical.

### Results of the F-test of Fatigue Beam Sample Data Sets

<table>
<thead>
<tr>
<th>Comparison</th>
<th>$K$</th>
<th>$N$</th>
<th>$M$</th>
<th>$N+M-2K$</th>
<th>$F(K, N+M-2K)$</th>
<th>$Alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRS1 Cut versus Cast</td>
<td>2</td>
<td>16</td>
<td>39</td>
<td>51</td>
<td>0.5892</td>
<td>0.5585</td>
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<tr>
<td>MRS1 Cut versus MRS2 Cut</td>
<td>2</td>
<td>16</td>
<td>18</td>
<td>30</td>
<td>3.7200</td>
<td>0.0360</td>
</tr>
<tr>
<td>MRS1 Cut versus MRS3 Cut</td>
<td>2</td>
<td>16</td>
<td>16</td>
<td>28</td>
<td>2.1223</td>
<td>0.1386</td>
</tr>
<tr>
<td>MRS2 Cut versus MRS3 Cut</td>
<td>2</td>
<td>18</td>
<td>16</td>
<td>30</td>
<td>2.1836</td>
<td>0.1302</td>
</tr>
</tbody>
</table>

Where:
- $K$ = number of restrictions (number of coefficients in each regression).
- $N$ = number of samples in the first set of data.
- $M$ = number of samples in the second set of data.
- $N+M-2K$ = number of degrees of freedom.
- $F(K, N+M-2K)$ = $F$-statistic ($X$ in the figure).
- $Alpha$ = significance level for the indicated value of the $F$-statistic.

From Hayhoe
Fatigue Test Conclusions

• For MRS1:
  • the fatigue results from the field-cut samples and the cast samples can both be represented by the same regression equation to a high level of confidence.
  • This indicates that, when properly cured and stored, cast beam samples provide a very good estimate of the fatigue strength of in-place concrete.

• For MRS1 vs. MRS3 field-cut samples and MRS2 vs. MRS3, a single regression equation can be used at a reasonably high level of confidence. Not so with MRS1 vs. MRS2 field cut.

• Although a single regression equation is not evident from the data, the trends are the same and consistent with full scale tests.

Summary Of CC-6 Findings

• Rigid pavement performance is strongly correlated to flexural strength, both from the full scale and laboratory tests.

• There were no major differences in the performance of rigid pavements on concrete and asphalt stabilized bases.

• Commonly used correlations of concrete elastic modulus from flexural strength, \( E = f(R) \) are not reliable.

• Laboratory fatigue results suggest that the fatigue strength increases in proportionately with flexural strength.

• Embrittlement of concrete is more a function of cement content and SCM than flexural strength.
Application of Findings

- Design Thickness
- Cost Savings

Design Implications

- Results indicate that the limitations on design strength contained in FAA Advisory Circulars 150/5320-6E can be relaxed provided cement contents are reasonable.

- From the CC-6 mixes a maximum cement content and not flexural strength should be considered for inclusion in P-501.

- Also suggests that materials investigations should be part of the design & specification development processes.
Design Sensitivity

- **Traffic:**
  - Heavy
  - Light

- **Subgrade:**
  - $k = 100 \text{ psi/in}$
  - $K = 200 \text{ psi/in}$

- **Flexural Strength**
  - $600 \text{ psi} \leq R \leq 750 \text{ psi}$

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# Heavy Traffic Mix – Major Hub

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>Gross Wt. lps</th>
<th>Annual Departures</th>
<th>% Annual Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A380-800</td>
<td>1,239,000</td>
<td>148</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>A310-200</td>
<td>315,041</td>
<td>889</td>
<td>0.00</td>
</tr>
<tr>
<td>3</td>
<td>B737-800</td>
<td>174,700</td>
<td>1,066</td>
<td>0.00</td>
</tr>
<tr>
<td>4</td>
<td>B747-8 Freighter (Preliminary)</td>
<td>978,000</td>
<td>296</td>
<td>0.00</td>
</tr>
<tr>
<td>5</td>
<td>B777-300 Baseline</td>
<td>662,000</td>
<td>667</td>
<td>0.00</td>
</tr>
<tr>
<td>6</td>
<td>A340-500 std</td>
<td>813,947</td>
<td>1,111</td>
<td>0.00</td>
</tr>
<tr>
<td>7</td>
<td>A340-500 std Belly</td>
<td>813,947</td>
<td>1,111</td>
<td>0.00</td>
</tr>
</tbody>
</table>

# Light Traffic Mix – Regional

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>Gross Wt. lps</th>
<th>Annual Departures</th>
<th>% Annual Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>B757-200</td>
<td>250,000</td>
<td>100</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>A320-100</td>
<td>150,000</td>
<td>500</td>
<td>0.00</td>
</tr>
<tr>
<td>3</td>
<td>B737-500</td>
<td>134,000</td>
<td>1,200</td>
<td>0.00</td>
</tr>
<tr>
<td>4</td>
<td>Fokker F100</td>
<td>100,000</td>
<td>1,200</td>
<td>0.00</td>
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</table>
Variations Thickness Flexural Strength

<table>
<thead>
<tr>
<th>Flex. Str. (psi)</th>
<th>k value (psi/in)</th>
<th>Traffic Condition</th>
<th>Slab h (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>100</td>
<td>Heavy</td>
<td>20.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Light</td>
<td>15.8</td>
</tr>
<tr>
<td>200</td>
<td></td>
<td>Heavy</td>
<td>18.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Light</td>
<td>14.0</td>
</tr>
<tr>
<td>650</td>
<td>100</td>
<td>Heavy</td>
<td>19.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Light</td>
<td>15.0</td>
</tr>
<tr>
<td>200</td>
<td></td>
<td>Heavy</td>
<td>17.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Light</td>
<td>13.1</td>
</tr>
<tr>
<td>700</td>
<td>100</td>
<td>Heavy</td>
<td>18.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Light</td>
<td>14.2</td>
</tr>
<tr>
<td>200</td>
<td></td>
<td>Heavy</td>
<td>16.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Light</td>
<td>12.4</td>
</tr>
<tr>
<td>750</td>
<td>100</td>
<td>Heavy</td>
<td>17.9</td>
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<tr>
<td></td>
<td></td>
<td>Light</td>
<td>13.6</td>
</tr>
<tr>
<td>200</td>
<td></td>
<td>Heavy</td>
<td>15.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Light</td>
<td>11.7</td>
</tr>
</tbody>
</table>

Thickness vs. Flexural Strength

![Graph showing variations in thickness and flexural strength with traffic condition as a factor](image-url)
Cost Implications (1)

- **Pavement Costs**
  - P-501 concrete cost = $200 per cubic yard, or approximately $5.50 per sy per inch.
  - P-403 asphalt base cost = $75 per ton, or approximately $26.00/sy for 6 inches.
  - P-304 cement treated base cost = $100 per cy or approximately $16.50/sy for 6 inches.

- **Baseline:**
  - Heavy: 18-in PCC / 6-in AC base .......... $126.00 / sy
  - Light: 12-in PCC / 6-in AC base .......... $ 93.50 / sy
Cost Implications (2)

• Assume:
  • 75 psi/in R, or 1.5-inch reduction in slab thickness
  • Substitute cement base for asphalt base

• Revised Section:
  • Heavy: 16.5-in PCC / 6-in CTB .......... $108.00 / sy
  • Light: 10.5-in PCC / 6-in CTB .......... $ 65.00 / sy

• Savings:
  • 15% for Heavy
  • 23% for Light
  • 15% to 20% cost savings is reasonable cost savings if the results of CC-6 are implemented

• Sustainability

Other Factors To Consider

• Conservatism in Design – how much is enough?

• Top Down Cracking

• Materials Evaluation During Design
FAA vs. Military Terminal Conditions
re: DOT/FAA/AR-04/46

Average PCI for Pavements Over 20-years
re: DOT/FAA/AR-04/46
Rigid Pavement Design

CRITICAL LOAD CONDITION ASSUMPTIONS
Maximum stress at pavement edge
25% Load Transfer to adjacent slab

Bottom Up Cracking Governs

Warping, Curling and Top Down Cracking
Slab Size Traditionally To Control Top Down Cracking

Granular Subbase

<table>
<thead>
<tr>
<th>Slab t (in)</th>
<th>Slab Size (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>12.5</td>
</tr>
<tr>
<td>7-9</td>
<td>15</td>
</tr>
<tr>
<td>9-12</td>
<td>20</td>
</tr>
<tr>
<td>&gt;12</td>
<td>25</td>
</tr>
</tbody>
</table>

Stabilized Base

$L / L < 5$

\[ l = \left( \frac{Eh^3}{12(1-u^2)k} \right)^{1/4} \]

(From AC 150/5320-6E)

Top Down Cracking

As slab thickness decreases, top down cracking risk increases
Materials Investigation During Design

- Establish Cement Content - Flexural Strength Relationship
  - Records Research
  - Contractor Interviews
  - Highway Departments
  - Trial Batches

- Establish 28-day vs. 90-day strength relationship

- Perform Sensitivity Analysis of \( h = f(R) \)

- Select realistic 28-day strength for P-501
Conclusions

• Implementation of NAPTF research can result in significant cost savings for rigid pavements.

• Limitations on flexural strength in AC 150/5320-6E should be re-evaluated.

• Consider revising P-501 with limitation on cement content and not flexural strength.

• Since design procedures do not directly differentiate between ASB and CTB, costs should govern in the selection.

Suggestions for Further Work

• Further laboratory fatigue testing and re-analysis of data

• Extend design procedure to include top down cracking for light load pavements

• Laboratory fatigue tests should be extended to develop recommendations for maximum cement content

• Incorporate the CC-6 findings into 40 year life study. Are we already constructing 40 year life rigid pavements when actual R exceeds design R?
Questions?