CONSTRUCTION CYCLE 6 (CC-6) REVISITED

FATIGUE ANALYSIS
and
ECONOMIC and DESIGN IMPLICATIONS

Roy D. McQueen, P.E.
roy@roydmcqueen.com
Gordon F. Hayhoe, PhD.
hayhoeg@verizon.net

1st Eastern Region Airports Conference - 1976

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?

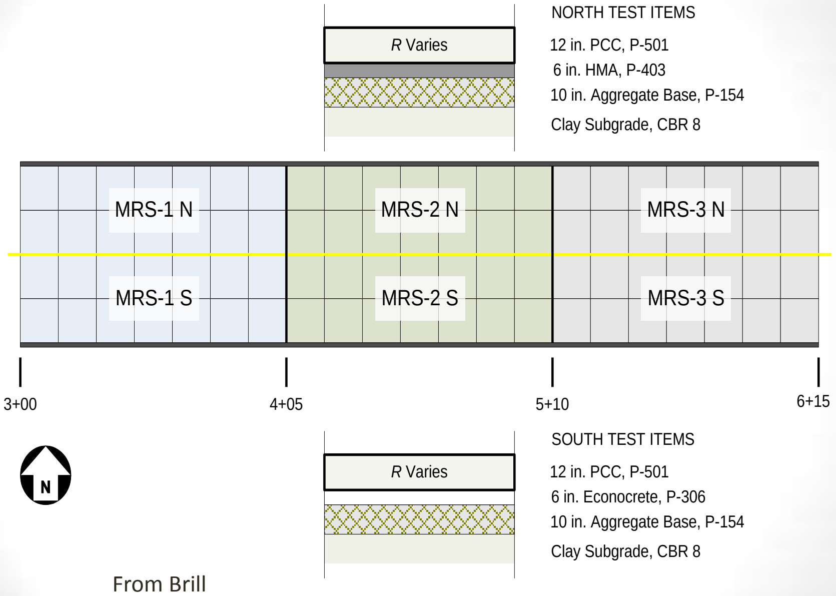
- Anecdotal evidence suggested that:
    - High flexural strength concrete will cause embrittlement and decreased pavement life.
    - Concrete constructed on black base will perform better than concrete constructed on cement base; however, design procedure doesn’t differentiate.

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)



NORTH TEST ITEMS

12 in. PCC, P-501
6 in. HMA, P-403
10 in. Aggregate Base, P-154
Clay Subgrade, CBR 8

SOUTH TEST ITEMS

12 in. PCC, P-501
6 in. Econocrete, P-306
10 in. Aggregate Base, P-154
Clay Subgrade, CBR 8

From Brill

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

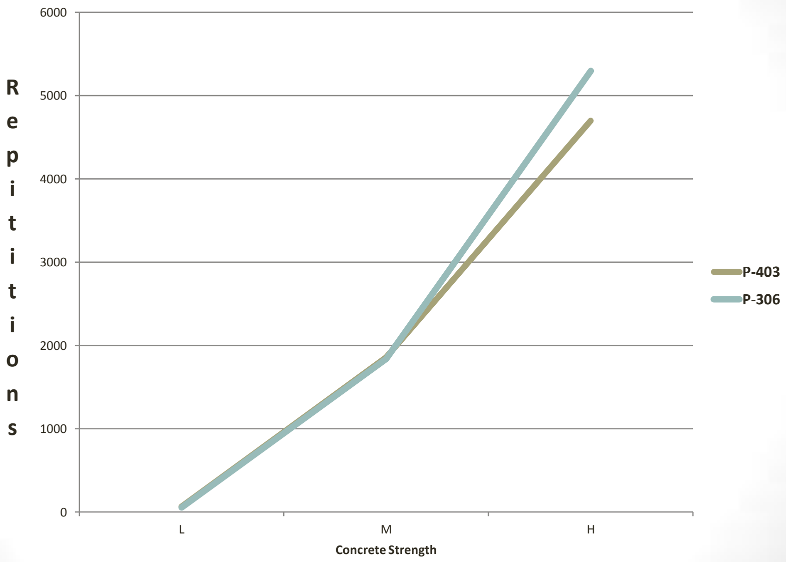
Full Scale Test Results

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

North – AC Base

South – Econocrete Base

Full Scale Test Results - Equiv 70k



Concrete Laboratory

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

Laboratory Fatigue Results

Test Item	Target Strength psi	28-Day Strength psi	Strength of Field-Cut Samples psi	Number of Cast Beams	Number of Cut Beams
MRS1	500	662	660	39	16
MRS2	750	763	749	0*	18
MRS3	1000	1007	932	0*	19

* Cast beams were not handled properly.

From Brill and Hao

MRS-1

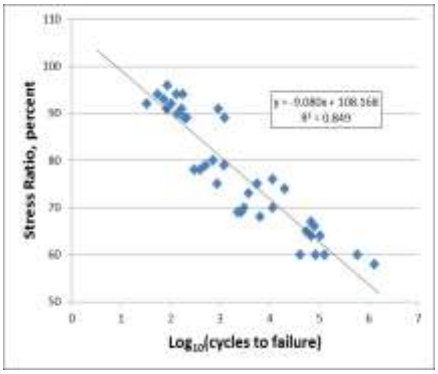


Figure 2. Fatigue Test Results for MRS1 **Cast Beams**.

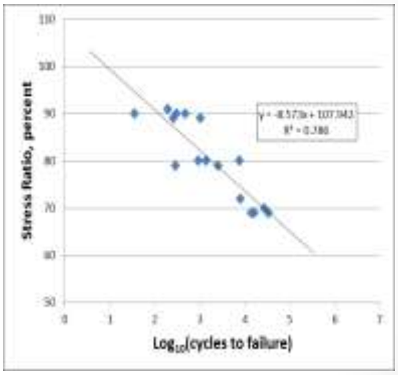


Figure 3. Fatigue Test Results for MRS1 **Field-Cut Beams**.

Field Cut Beams – MRS-2 & 3

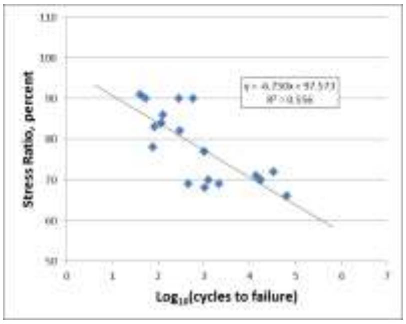


Figure 4. Fatigue Test Results for MRS2 Field-Cut Beams.

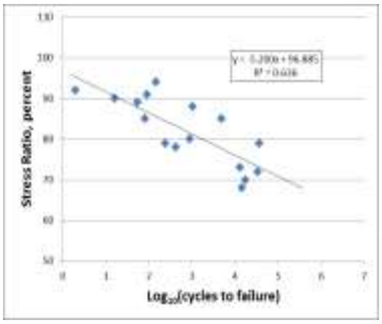


Figure 5. Fatigue Test Results for MRS3 Field-Cut Beams.

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.

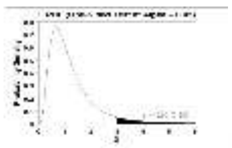
The procedure given in Pindyck and Rubinfeld [5], section 5.3.3, was followed.

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

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

Comparison	*K*	*N*	*M*	*N+M-2K*	*F(K, N+M-2K)*	*Alpha*
MRS1 Cut versus Cast	2	16	39	51	0.5892	0.5585
MRS1 Cut versus MRS2 Cut	2	16	18	30	3.7200	0.0360
MRS1 Cut versus MRS3 Cut	2	16	16	28	2.1223	0.1386
MRS2 Cut versus MRS3 Cut	2	18	16	30	2.1836	0.1302

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 psi/in
  - K = 200 psi/in
- **Flexural Strength**
  - 600 psi ≤ R ≤ 750 psi

Heavy Traffic Mix – Major Hub

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

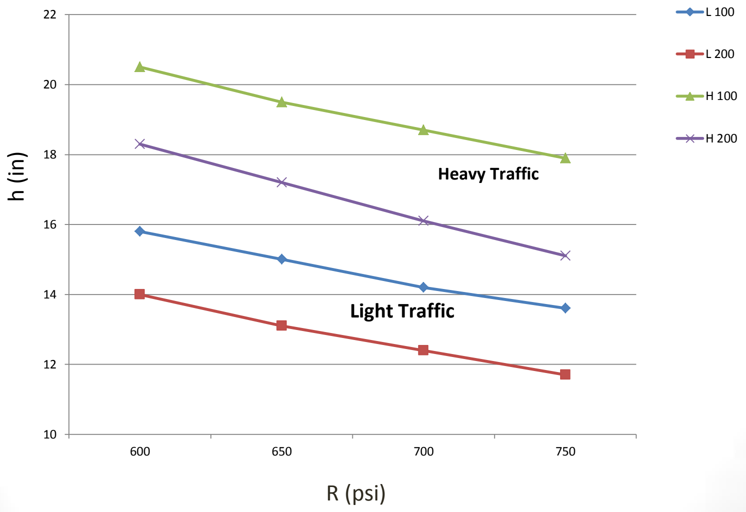
Light Traffic Mix - Regional

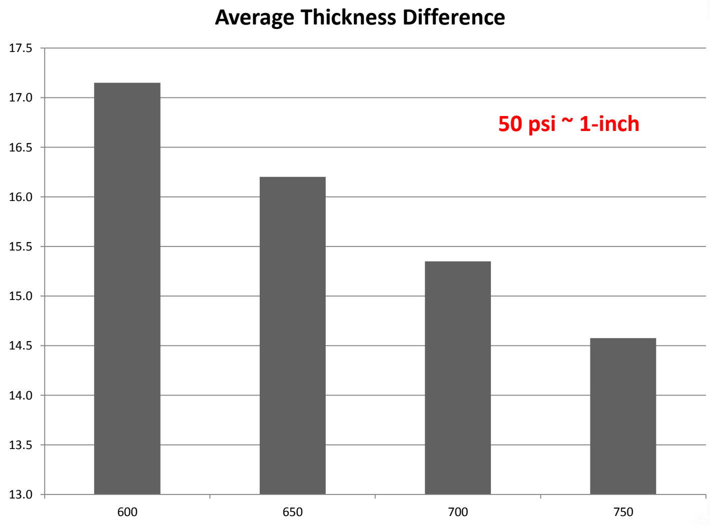
No.	Name	Gross Wt. lbs	Annual Departures	% Annual Growth
1	B757-200	250,000	100	0.00
2	A320-100	150,000	500	0.00
3	B737-500	134,000	1,200	0.00
4	Fokker F100	100,000	1,200	0.00

Variations Thickness Flexural Strength

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

Thickness vs. Flexural Strength




Average Thickness Difference

50 psi ~ 1-inch

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)

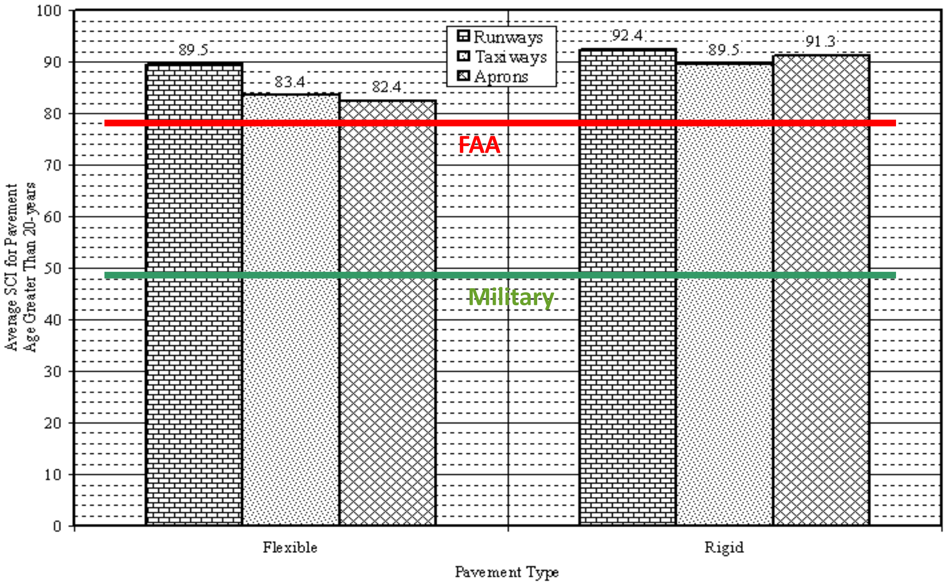
- **Assume:**
  - 75 psi/in R, or 1.5-inch reduction in slab thickness
  - Substitute cement base for asphalt base
- **Revised Section:**
  - Heavy: 16.5-in PCC / 6-in CTB ………. $108.00 / sy
  - Light: 10.5 -in PCC / 6-in CTB ………. $ 65.00 / sy
- **Savings:**
  - 15% for Heavy
  - 23% for Light
  - **15% 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

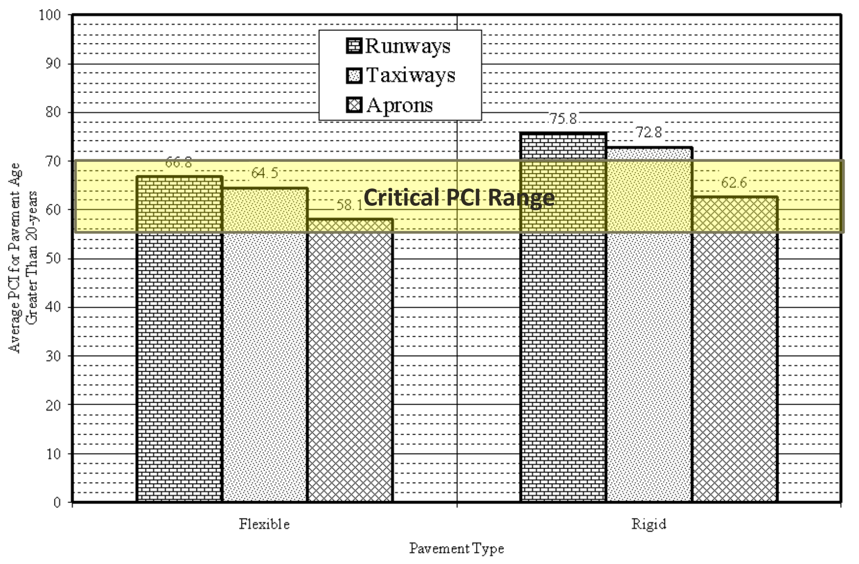
FAA vs. Military Terminal Conditions

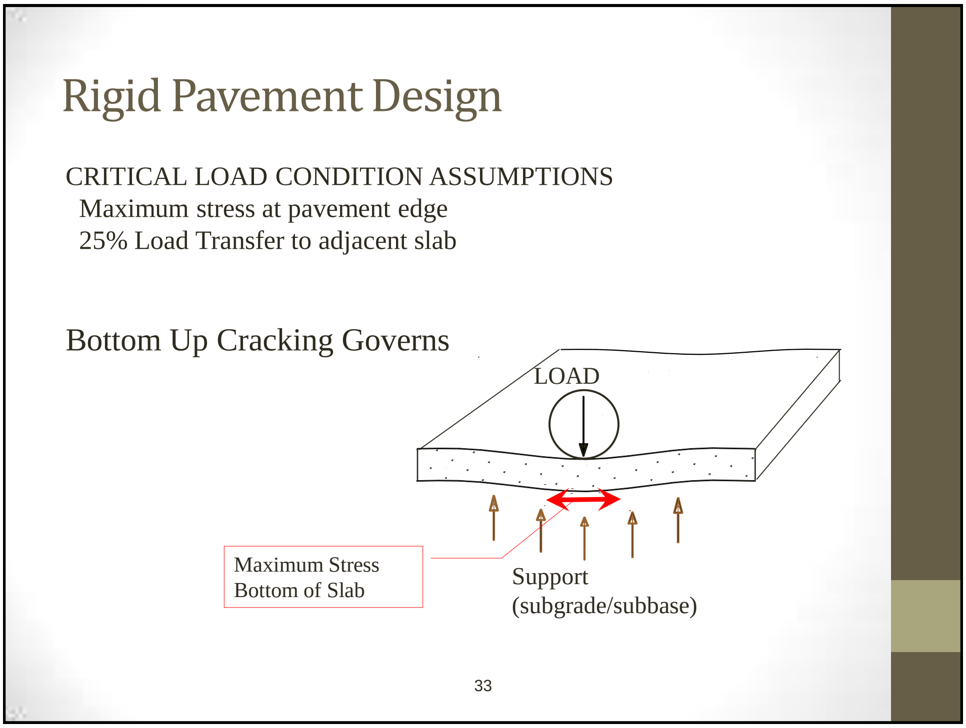
re: DOT/FAA/AR-04/46



Average PCI for Pavements Over 20-years

re: DOT/FAA/AR-04/46

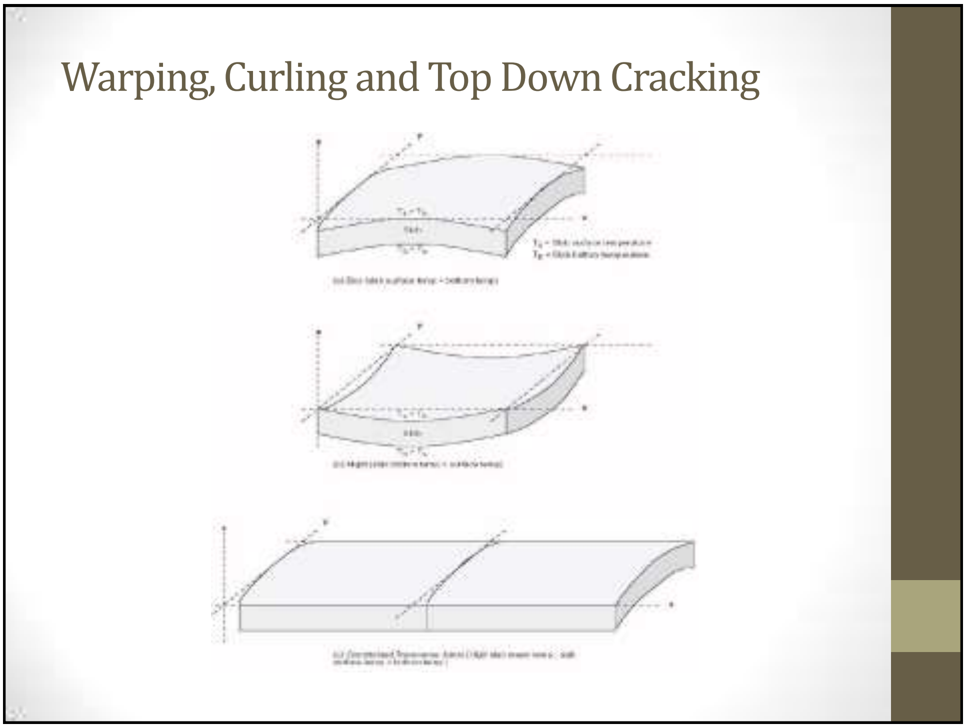




Rigid Pavement Design

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

Slab t (in)	Slab Size (ft)
6	12.5
7-9	15
9-12	20
>12	25

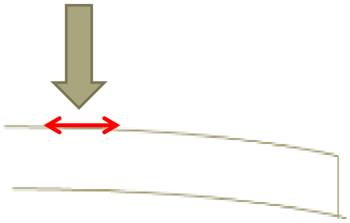
Stabilized Base

$L / \ell < 5$

$\ell = ((Eh^3)/(12(1-u^2)k)^{\wedge 1/4}$

(From AC 150/5320-6E)

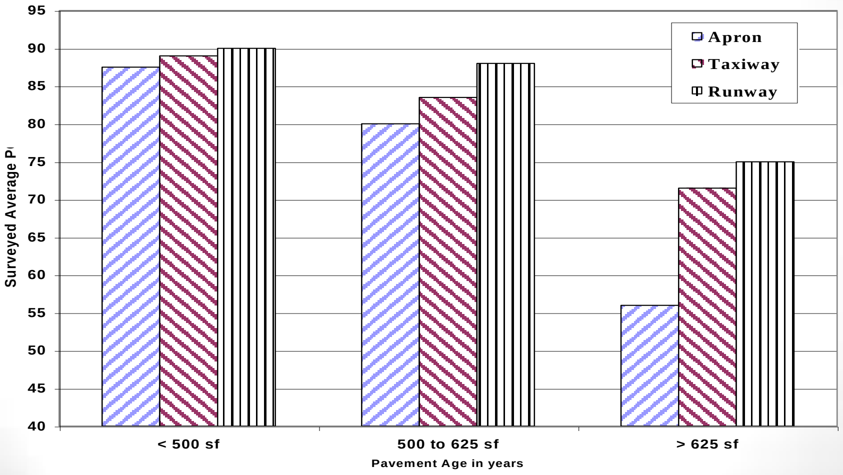
Top Down Cracking



As slab thickness decreases, top down cracking risk increases

PCI$_{AVG}$ OF 0 to 30 YEAR PCC PAVEMENTS GROUPED BY SIZE

re: DOT/FAA/AR-04/46



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?