Concrete Strength Variability and Mix Design for Large Concrete Paving Projects

ACI 2021 Spring Convention
Special Session to Honor Dr. Shiraz Tayabji, P.E.
W. Charles Greer, Jr., P.E.
Known Shiraz since 1971

Graduate School – U of I
Colleagues – Same Firm
Projects --- Same Side & Opposite Sides of Fence
Technical Committees
Airfield Paving Projects

Over 2 Million cu yds
Contracts = 10,000 to 450,000 cu yds
Several Thousand Sets of Flexural Beam Tests
3 Major Considerations for Materials in Mix Design Process

**STRENGTH**

**Flexural – 3rd Point**
ASTM C 78

More cement >>>
more strength but also more shrinkage & cracking
3 Major Considerations for Materials in Mix Design Process

**WORKABILITY**

More water >>>
Reduce stiffness – 2 edge sword

More shrinkage & cracking
Slipform Paving >>> *self-policing*
3 Major Considerations for Materials in Mix Design Process

**DURABILITY -- Most critical issue**

Gradation, Geology, Particle Shape, Pyrite, ASR, F-T, D-Cracking
3 Major Considerations for Materials in Mix Design Process

STRENGTH

WORKABILITY

DURABILITY --- Most critical issue --- more critical than strength

Keep These Issues in Proper Balance --- But, Strength Is Major Factor in Payment
**Strength is What Engineers Specify and What Owners Base Pay On**

*What Strength is Required to Achieve 100% Pay?*

*What Strength Is Required in the Lab Mix Designs?*

*What Strength Is Required in the Field Mix Production?*

*Take a Look at the Past*
In the Beginning..........
With

Pavement Use
Subgrade Type
Gradation
Atterberg Limits
Drainage – good/poor
Frost – none/severe
Wheel Load

Concrete Thickness

Note:

For Concrete Thickness

Subgrade Impact = 1”
Pavement Use = 1” to 4”
In the Beginning........... What is missing?
--- Concrete Strength ---

Strength was specified in Standard Specifications for Construction - 1948
FAST FORWARD TO 1974
Fast Forward to 1974

Concrete Strength Now a Variable in Design

Concrete Flexural Strength
Factor of Safety
Subgrade Strength
K-value
Gear/Wheel Load
Fast Forward to 1974

Conc Flex = 650 vs 750 psi (F.S. = 2.0)
Subgrade, k = 100 pci
Dual Gear & GW = 100,000 lb

T = 12-1/4” vs 11-1/4”

Delta Conc Flex = 100 psi
Delta Concrete Thickness = 1”
Fast Forward to 1974

Concrete mixes based on

**Slump** 1/2” to 1-1/2” --- if vibrated

**Air Content** 3% to 7%

**Cement Content** Not less than 5.0 sacks per cu yd for air entrained

**Water Content** Not more than 5.5 gallons per sack of cement
(Areas of severe freeze-thaw)

**Flexural Strength --- 3rd Point Loading**

2 Beams for each 150 cu yds
Tested at 7 days and 28 days

Moving Average of 5 Consecutive 28-day tests

Equal to or greater than specified flexural strength

No more than 20% of beams tested at 28-days less than specified strength

Not clear where the 20% can be
Fast Forward to 1974

**Concrete Pavement Paid Based on**

**Thickness Deficiency**

- 0.00” to 0.20” = 100%
- 0.21” to 0.30” = 80%
- 0.31” to 0.40” = 72%
- 0.41” to 0.50” = 68%
- 0.51” to 0.75” = 57%
- 0.76” to 1.00” = 50%
- >1.00” = 0% if not removed and replaced (Engineer judgement)

No benefit for extra thickness

**Flexural Strength**

No clear penalty for low strength
Fast Forward to 1974

Concrete Pavement Paid Based on Strength and Thickness

Impact of Thickness on Required Strength (ATL Projects post 1974)

\[ FS_{\text{ADJ}} = FS_{\text{ACT}} \times \left( \frac{T_{\text{ACT}}}{T_{\text{DESIGN}}} \right)^2 \]

- \( FS_{\text{ADJ}} \) = Adjusted Flexural Strength
- \( FS_{\text{ACT}} \) = Actual Measured Flexural Strength
- \( T_{\text{ACT}} \) = Actual Thickness
- \( T_{\text{DESIGN}} \) = Design Thickness

For Actual Thickness = 16.5” and Design Thickness = 16”

Factor = 1.065  --- ~ 42 psi for FS = 650 psi

For Actual Thickness = 17.0” and Design Thickness = 16”

Factor = 1.129  --- ~ 84 psi for FS = 650 psi

Two edge sword if actual thickness is less than design thickness
FAST FORWARD TO 2018
See FAA --- AC 150/5370-10H --- Item P-501
“Standard Specifications for Construction of Airports”

**Concrete Pavement Paid Based on**

*Strength --- Lot Basis with 4 Sublots --- 90% Within Limits*

*Thickness*

*Grade*

*Profile Smoothness*

*Adjustments for Repairs*

*Adjustments for Grinding*
What Strength is Required in the Field to Achieve 100% Pay?

For any given Lot (~ 2000 cu yd), it depends on

Average 28-day flexural strength and standard deviation of the sublots

4 Sublots per Lot --- 1 sample per sublot (~ 500 cu yd)

2 test specimens per sample (i.e. per sublot --- also discard outliers per ASTM E 178)

Strength of Sublot is Average of the 2 test specimens

Strength of Lot is Average of the 4 Sublots --- also, standard deviation of the 4 Sublots
What Strength is Required in the Field to Achieve 100% Pay?

90% Within Limits or Greater

Percent Within Limits for Lot

Function of average flexural strength and standard deviation of the 4 sublots
Concrete Mix Design Process

**What Strength is Required to Achieve 100% Pay?**

*What Strength in the Lab Mix Designs?*

*Before Lab Designs………………*

*What Strength Is Needed in the Field Production?*
**Concrete Pavement Paid Based on**

*Strength --- Lot Basis with 4 Sublots --- 90% Within Limits*

*See Paragraph 501-8.1a*

12/21/2018

<table>
<thead>
<tr>
<th>Percentage of Materials Within Specification Limits (PWL)</th>
<th>Lot Pay Factor (Percent of Contract Unit Price)</th>
</tr>
</thead>
<tbody>
<tr>
<td>96 – 100</td>
<td>106</td>
</tr>
<tr>
<td>90 – 95</td>
<td>PWL + 10</td>
</tr>
<tr>
<td>75 – 90</td>
<td>0.5 PWL + 55</td>
</tr>
<tr>
<td>55 – 74</td>
<td>1.4 PWL – 12</td>
</tr>
<tr>
<td>Below 55</td>
<td>Reject¹</td>
</tr>
</tbody>
</table>

¹ Although it is theoretically possible to achieve a pay factor of 106% for each lot, actual payment in excess of 100% shall be subject to the total project payment limitation specified in paragraph 501-8.1.

² The lot shall be removed and replaced unless, after receipt of FAA concurrence, the Owner and Contractor agree in writing that the lot will remain; the lot paid at 50% of the contract unit price; and the total project payment limitation reduced by the amount withheld for that lot.
Fast Forward to 2018

Concrete Pavement Paid Based on
Strength --- Lot Basis with 4 Sublots --- 90% Within Limits

PAY FACTOR VERSUS PERCENT WITHIN LIMITS

THE WORLD’S GATHERING PLACE FOR ADVANCING CONCRETE
What Strength is Required in the Field to Achieve 100% Pay?

Go to Section 110

\[ Q_L = \frac{(X - L)}{S_N} \]

\[ X = \text{LOT AVERAGE (Average of Sublot Averages)} \]

\[ L = \text{LOWER SPECIFICATION LIMIT} \]

\[ S_N = \text{STANDARD DEVIATION OF SUBLOT AVERAGE VALUES} \]

Paragraph 501-6.6a indicates that the Lower Specification Limit is

93% of Strength in para 501-3.3

For Flexural Strength in Para 501-3.3 = 650 ---- Lower Specification Limit = 604.5
Fast Forward to 2018........

What Strength is Required in the Field to Achieve 100% Pay?

Go to Section 110

\[ Q_L = \frac{(X - L)}{S_N} \]

\[ X = (Q_L \times S_N) + L \]

BIG QUESTION—— WHAT IS VALUE OF S_N ?

Look at Past Contractor Production

What Is a Best Estimate of S_N
Fast Forward to 2018............

What Strength is Required in the Field to Achieve 100% Pay?

What Is a Best Estimate of $S_N$?

Large Projects

On-site Central Mix Plants

On-site Stockpiles & Storage

May Be New Material Combinations (Little or No History)

Look at Past Contractor Production on other Projects

Look at Industry Data
Fast Forward to 2018

What Strength is Required in the Field to Achieve 100% Pay?

\[ X = (1.20 \times S_N) + L \]

BIG QUESTION --- WHAT IS VALUE OF \( S_N \)?

Look at Past Contractor Production

What \( S_N \) Are We Looking for?

\( S_N \) of the Lots

Overall \( S_N \) (single beam tests) = ~ 20 – 80 psi

Most 40 – 60 psi, use 60 psi

Overall \( S_N \) (2 beam sublots) = \(
\frac{60}{(2)^{1/2}} \) = ~ 42 psi

Overall \( S_N \) (4 subplot Lots) = \(
\frac{42}{(4)^{1/2}} \) = ~ 21 psi
For a Lot to Receive 100% (i.e. 90% Within Limits)

Lot Average $\Rightarrow L + (1.2 \times 42)$

Lot Average $\Rightarrow (604.5 + 50.4) \Rightarrow 655$

What Average of All Lots Is Needed for All Lots to Receive 100% Payment?

i.e. --- All Lots $\Rightarrow 655$
Fast Forward to 2018…………

What Strength is Required in the Field For All Lots to Receive 100% Payment?

Average of All Lots $\Rightarrow (655) + 3 \times [S_{\text{ALL-LOTS}}]

Average of All Lots $\Rightarrow (655) + 3 \times [21]

Average of All Lots $\Rightarrow ~718

Thus, Concrete in the Field Requires an Overall Lot Average $\Rightarrow ~720$

Now --- What Strength Is Required in the Lab Mix Designs?

How Much Strength If Any Will be Lost from the Lab to the Field?

Past Experience Indicates $\Rightarrow$ One Standard Deviation of Field Tests

Lab Average Strength $\Rightarrow 720 + 21 = ~740$
Fast Forward to 2018………..

Lab Mix Design Process

Prepare Mixes for Strength vs Cement Content Curve

_in Lab at 3-4 cement contents_

Plot Strength versus Cement Content

 曲线看起来如预期………

Increased cement yields increased strength

However, that is not always the case…………….
Prepare Strength vs Cement Content Curve

in Lab at 3-4 cement contents

Sometimes………………

If One Batch per Cement Content

Strength Sometimes Can Drop at Higher Cement Content

How Can This Be?

It is known as Material and Test Procedure Variability
Lab Mix Design Process for Flexural Strength

Typical to Prepare Strength vs Cement Content Curve

in Lab at 3-4 cement contents

However --- Need to Consider Variability in Strength
**Fast Forward to 2018********

**Lab Mix Design Process**

**Variability**

*If You Prepare Multiple Batches of Mix at each Cement Content, You Will Get a Range of Average Strengths of the Batches*

**Limited Special Case Study**

**Two Batches at Each of Two Cement Contents**

**Tested all Beams at 28 Days**

<table>
<thead>
<tr>
<th>CEMENT FACTOR 1</th>
<th>CEMENT FACTOR 2</th>
<th>FLEXURAL STRENGTH AT 28 DAYS (PSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BATCH 1</td>
<td>BATCH 2</td>
<td>BATCH 1</td>
</tr>
<tr>
<td>635</td>
<td>630</td>
<td>710</td>
</tr>
<tr>
<td>645</td>
<td>680</td>
<td>756</td>
</tr>
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<td>725</td>
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</tbody>
</table>

**Range Within Batch = 50 – 90 psi --- yet SD = 21 – 30 psi (CV = 3-4%)**

**Range of Low 3 Average to High 3 Average in Given Batch**

42 to 68 psi
Prepare Strength vs Cement Content Curve

in Lab at 3-4 cement contents

Variability

If You Prepare Multiple Batches of Mix at each Cement Content,
You Will Get a Range of Average Strengths of the Batches

Average Strength Tends to Increase with Increased Cement

However,

If One Batch per Cement Content

Strength Sometimes Can Drop at Higher Cement Content

How Can This Be?
Prepare Strength vs Cement Content Curve

in Lab at 3-4 cement contents

Variability

If You Prepare Multiple Batches of Mix at each Cement Content, You Will Get a Range of Average Strengths of the Batches.

Average Strength Tends to Increase with Increased Cement Content.

However,

If One Batch per Cement Content, You Will Not Always Get the Average

Strength Sometimes Can “Drop” at Higher Cement Content.
Fast Forward to 2018

Lab Mix Design Process

Lab Mix Design Process for Flexural Strength

Typical to Prepare Strength vs Cement Content Curve

in Lab at 3-4 cement contents

If you have one batch per cement content, Consider performing regression analysis of strength vs cement Then, establish a lower bound for the regression at 95% confidence

Or, Prepare Multiple Batches for Each Cement Content and Perform regression and lower bound analysis

Or, Better yet Prepare multiple batches of selected mix at the plant on multiple days And prepare test beams and test at various ages and analyze results...
Sometimes Flexural Strength Issues Just Tie You Up in Knots…

General Considerations

IPRF Study 2010 --- Precision of Flexural Tests

- Single operator std dev = 50 psi - 2 tests from same batch by same operator could differ by 140 psi

- Multi lab std dev = 70 psi - tests by 2 labs on same batch could differ by 200 psi

ASTM C 78 – 2018 --- Precision of Flexural Tests

- Single operator std dev = 37 psi - 2 tests from same batch by same operator could differ by 104 psi

- Multi lab coeff var = 6.9% - tests by 2 labs on same batch could differ by 19.3% of the average (125 psi at 650 psi)

Problem --- within test variability is in same range as contractor overall production variability for single test samples (40 – 60 psi)
Sometimes Flexural Strength Issues Just Tie You Up in Knots…

In 40+ years, if concrete pavement has the following:

- Designed by a good engineer
- Constructed by a good contractor with good quality control on mixing and placing process
- Tested by a good agency with good to excellent procedures

I have not seen it fail due to strength --- it is almost always workability and/or durability issues
Future of Mixes

Performance Engineered Mixes (PEM)

Control Thermal Movements --- Coefficient of Thermal Expansion (CTE)

Control Shrinkage --- Nuclear Industry Limits Drying Shrinkage to 0.04% or Less (0.48” per 100’)

Move to Better Tests for Alkali Silica Reactivity (ASR) Assessments

Vibrating Kelly Ball to Assess Workability

Better Control of Air Content (1% Increase in Air Content Can Lower Strength 5% -- Impact on Freeze-Thaw)

Use Maturity Testing of In-place Concrete for Acceptance and Payment for Strength

(Why Wait 28 Days on a Test with a Precision of 100+ psi?????????)
Sometimes Flexural Strength Issues Just Tie You Up in Knots…

So, do not get tied up in knots over Strength, it is not the issue –

Workability and Durability are key

If you have Workability and Durability, You will have sufficient Strength

Millions of $$$ in Strength Penalties

Yet Pavements Perform Well and Beyond Their Design Lives
Sometimes Flexural Strength Issues Just Tie You Up in Knots…

Other Issues

Location of Samples

Age Effects

Test Beams Are Not In-place Pavement

QUESTIONS?