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.

THE WORLD'S GATHERING PLACE FOR ADVANCING CONCRETE

aci VIRTUAL CONCRETE CONVENTION

Known Shiraz since 1971

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

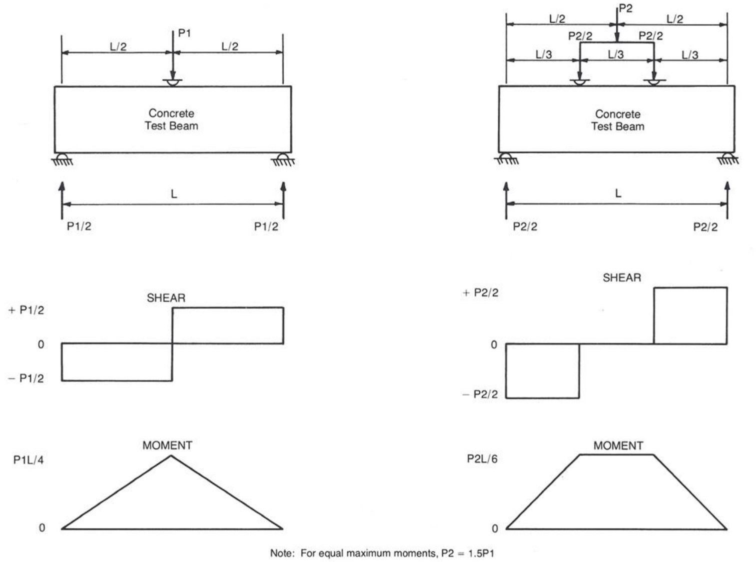
Airfield Paving Projects

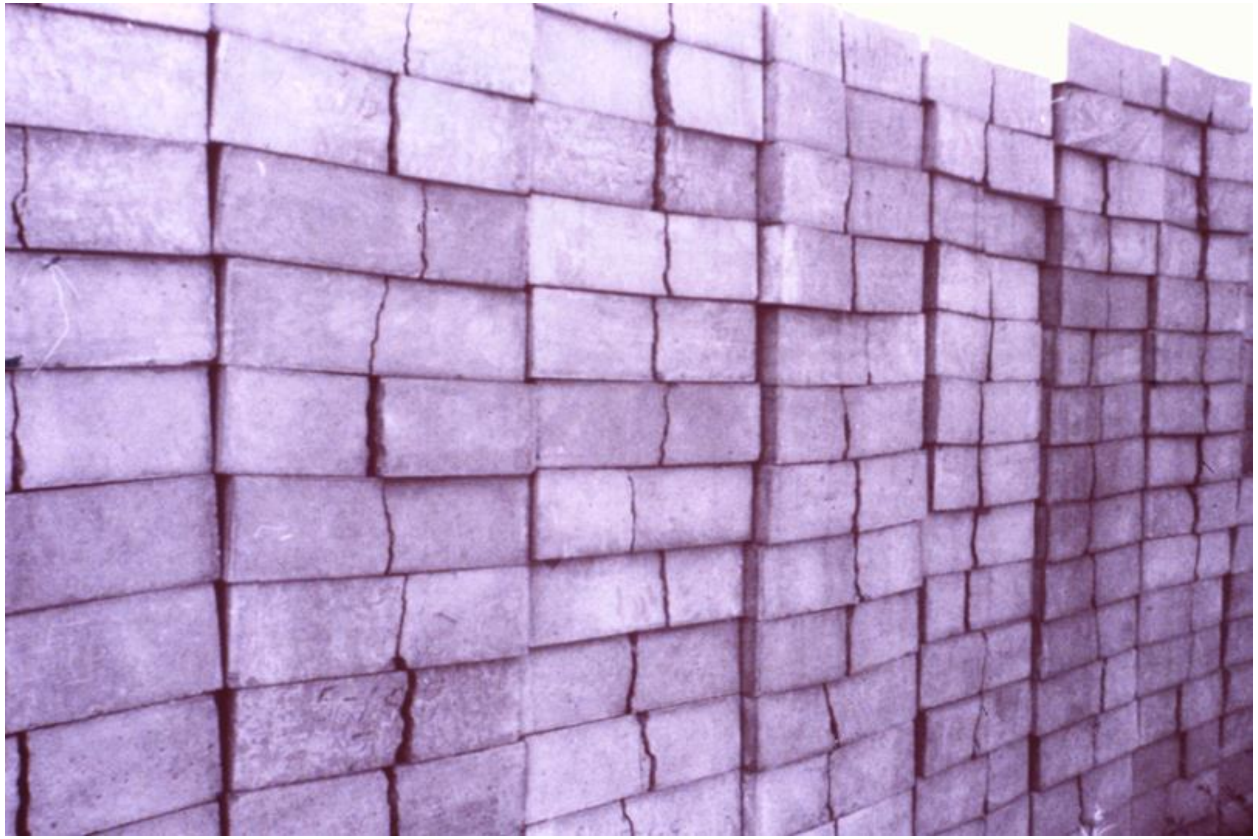
Over 2 Million cu yds
Contracts = 10,000 to 450,000 cu yds
Several Thousand Sets of Flexural Beam Tests

3 Major Considerations for Materials in Mix Design Process

STRENGTH

Flexural – 3rd Point
ASTM C 78

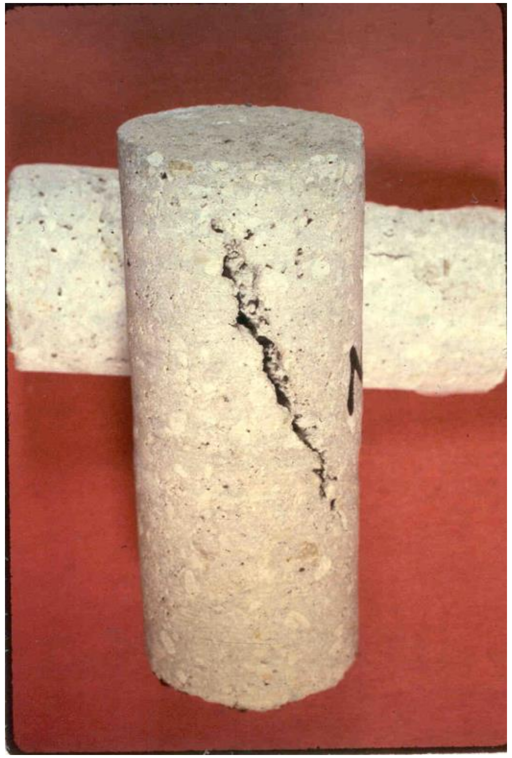


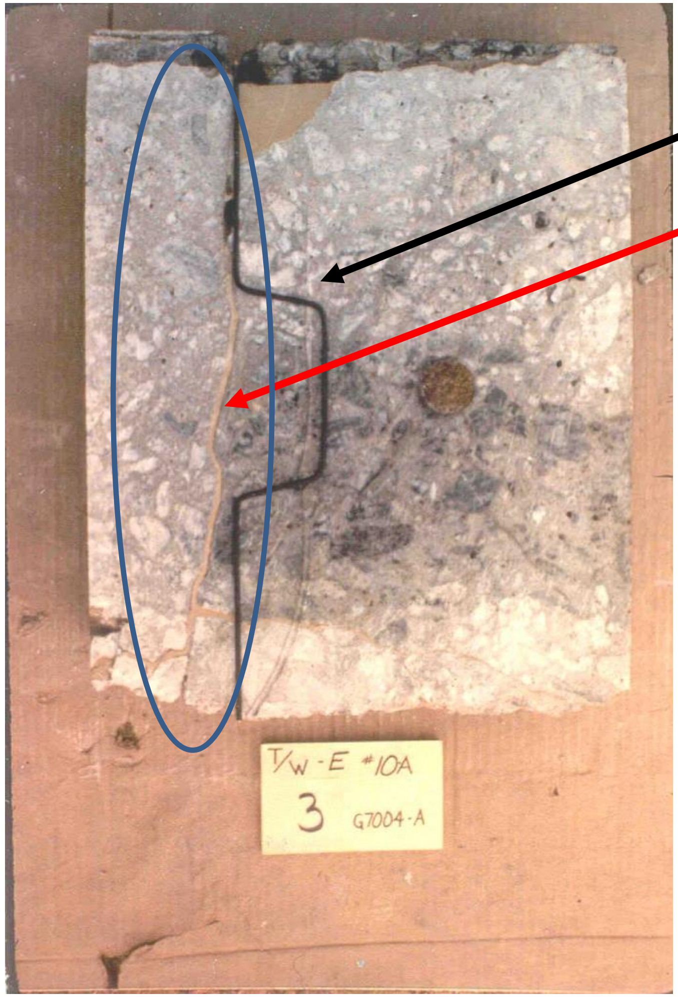


More cement >>>
more strength but also more shrinkage & cracking

3 Major Considerations for Materials in Mix Design Process

WORKABILITY





Design Keyway

Actual "Keyway"

More water >>>

Reduce stiffness – 2 edge sword

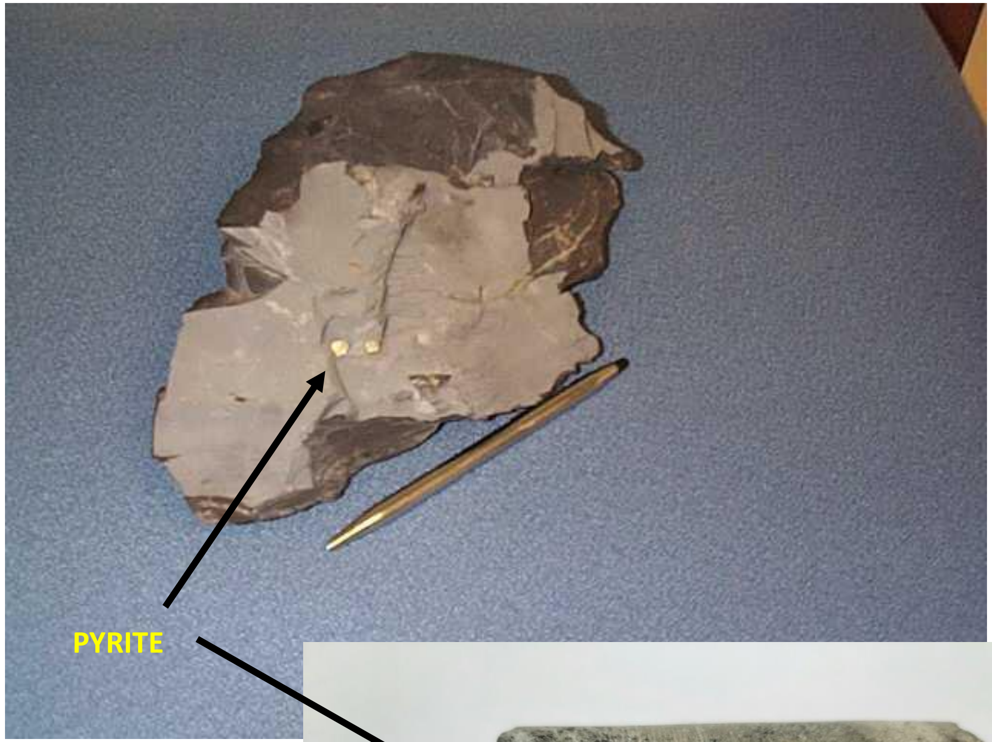
More shrinkage & cracking

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

Mix Design Process…………

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…………

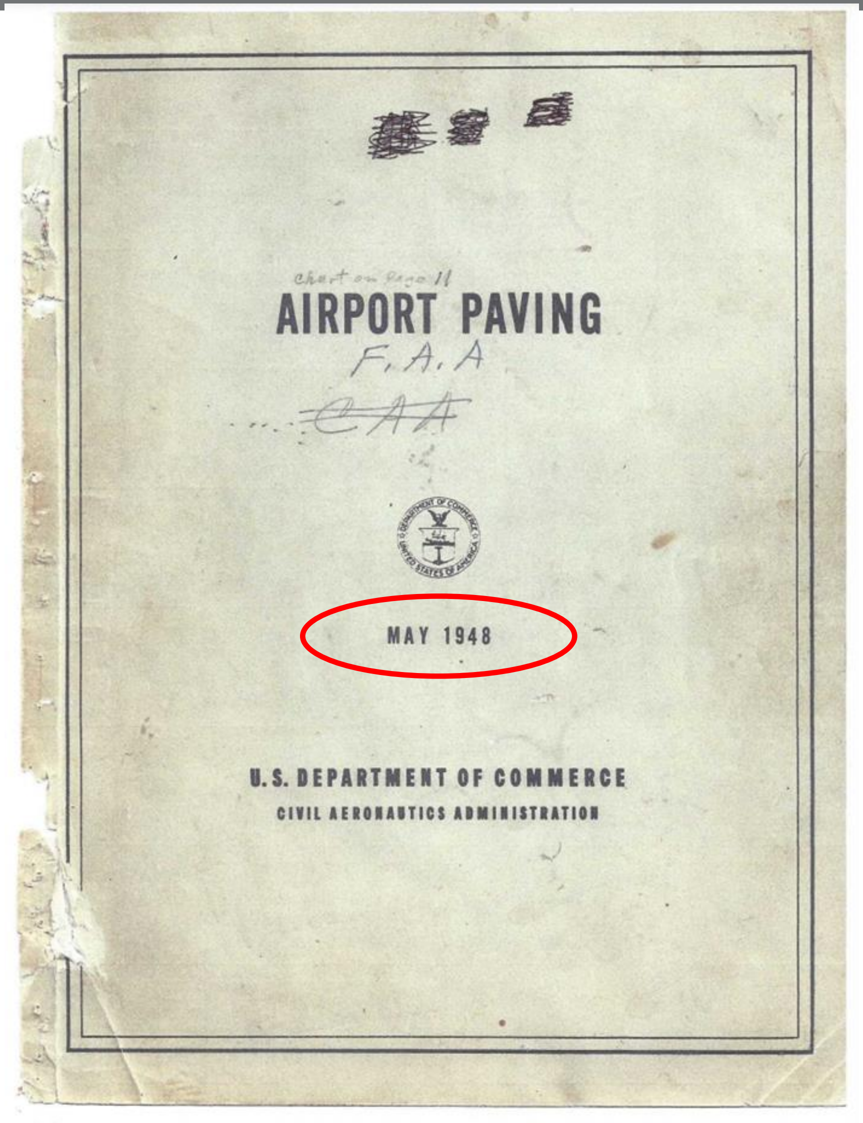


chart on page 11

AIRPORT PAVING

F.A.A

~~CAA~~

MAY 1948

U.S. DEPARTMENT OF COMMERCE

CIVIL AERONAUTICS ADMINISTRATION

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”

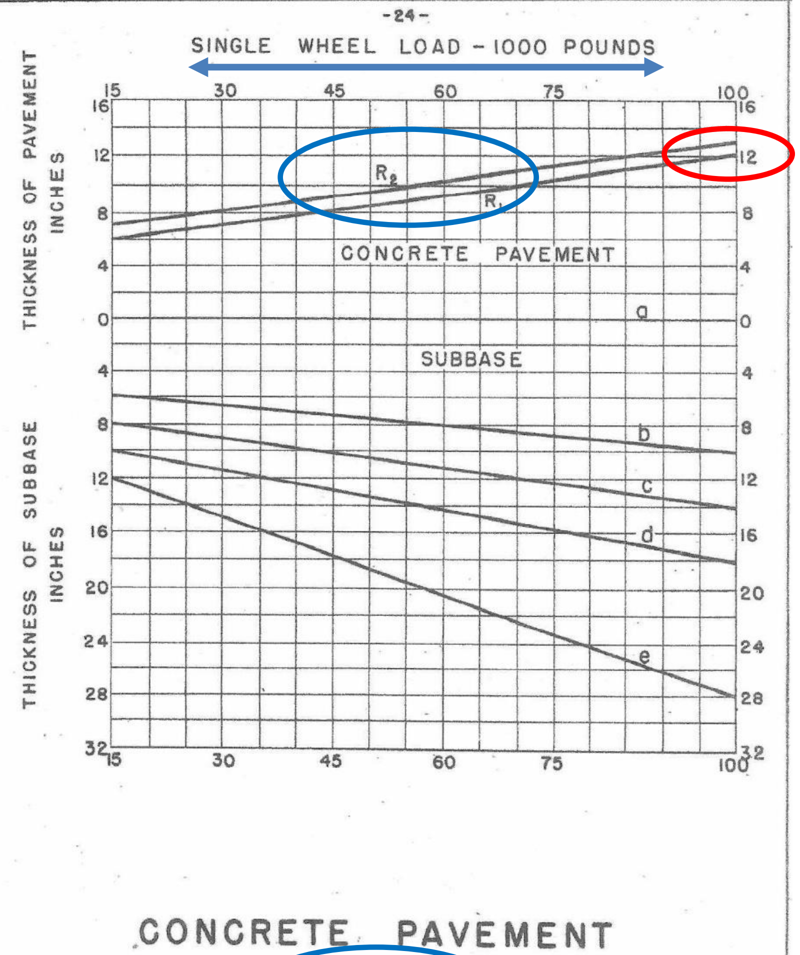


FIG. 4

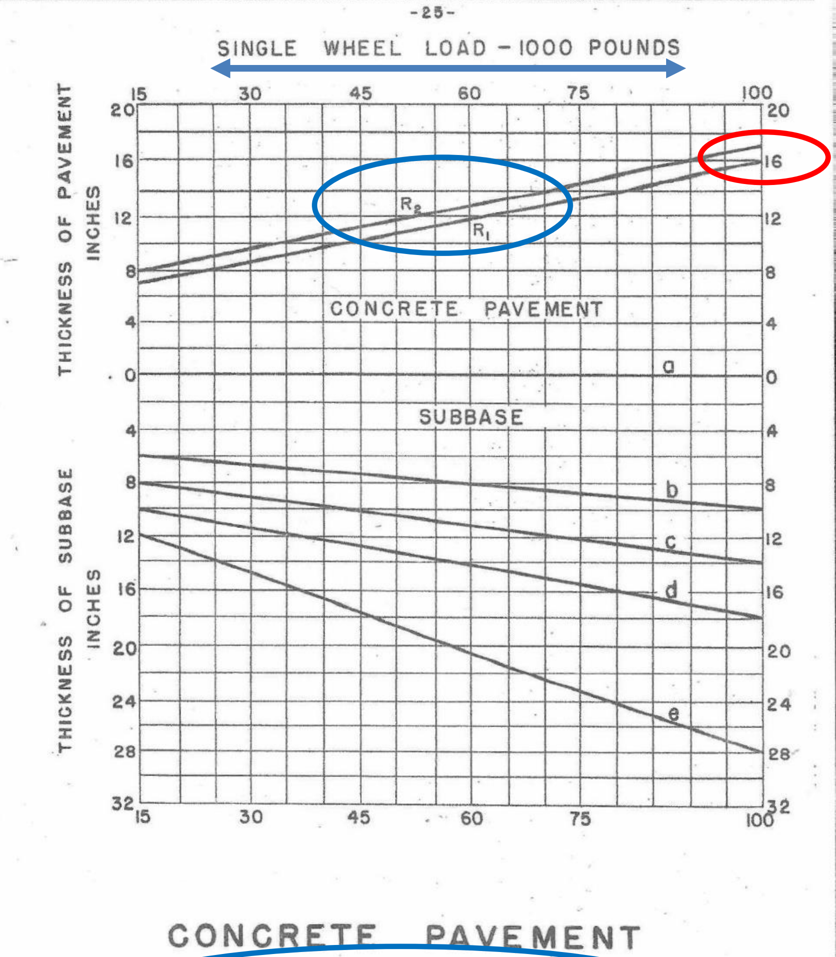
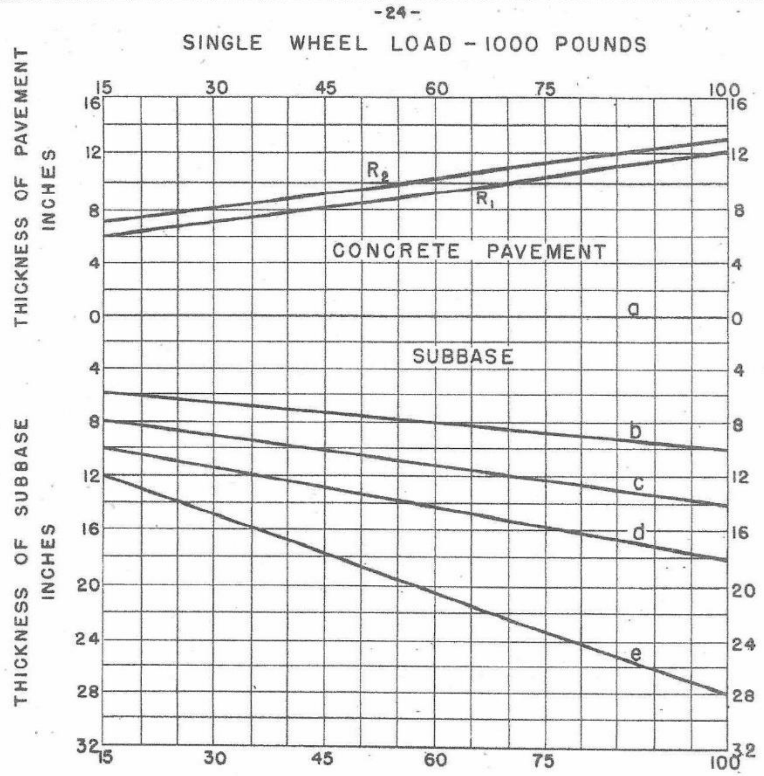


FIG. 5

In the Beginning………… What is missing?

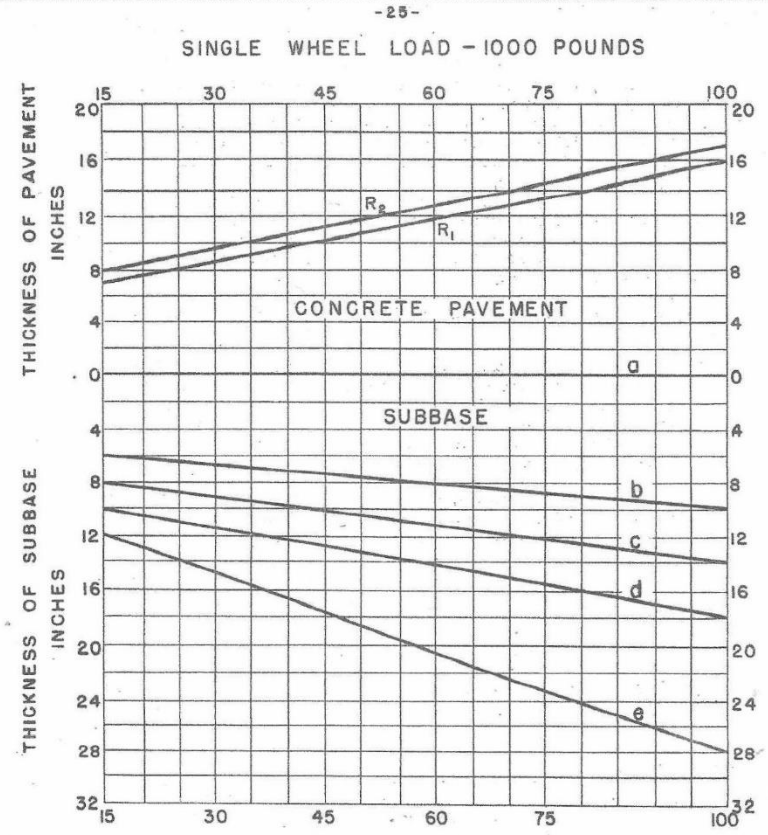
--- Concrete Strength ---



CONCRETE PAVEMENT

RUNWAYS

FIG. 4



CONCRETE PAVEMENT

TAXIWAYS, APRONS & RUNWAY ENDS

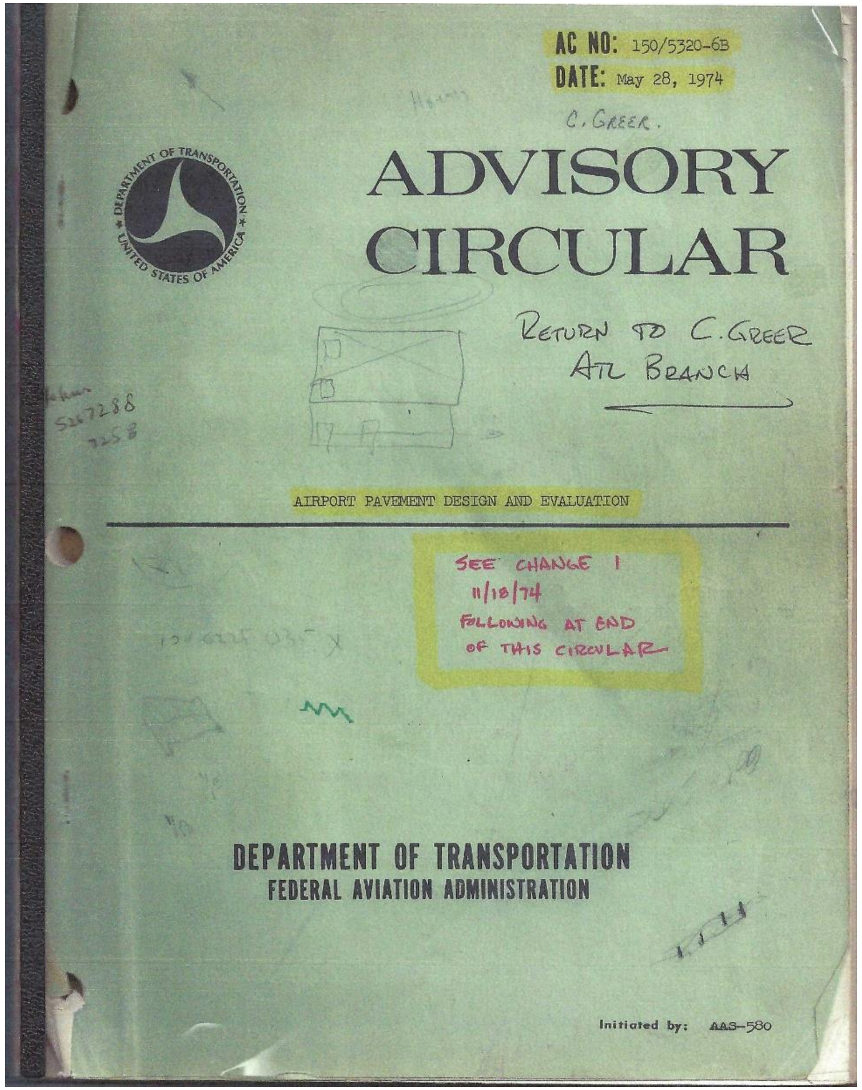
FIG. 5

Strength was specified in
Standard Specifications for Construction - 1948

FAST FORWARD TO 1974

Fast Forward to 1974…………

1974 Pavement Design Manual



Fast Forward to 1974…………
Concrete Strength Now a Variable in Design

Concrete Flexural Strength
- ***Factor of Safety***

Subgrade Strength
- ***K-value***

Gear/Wheel Load

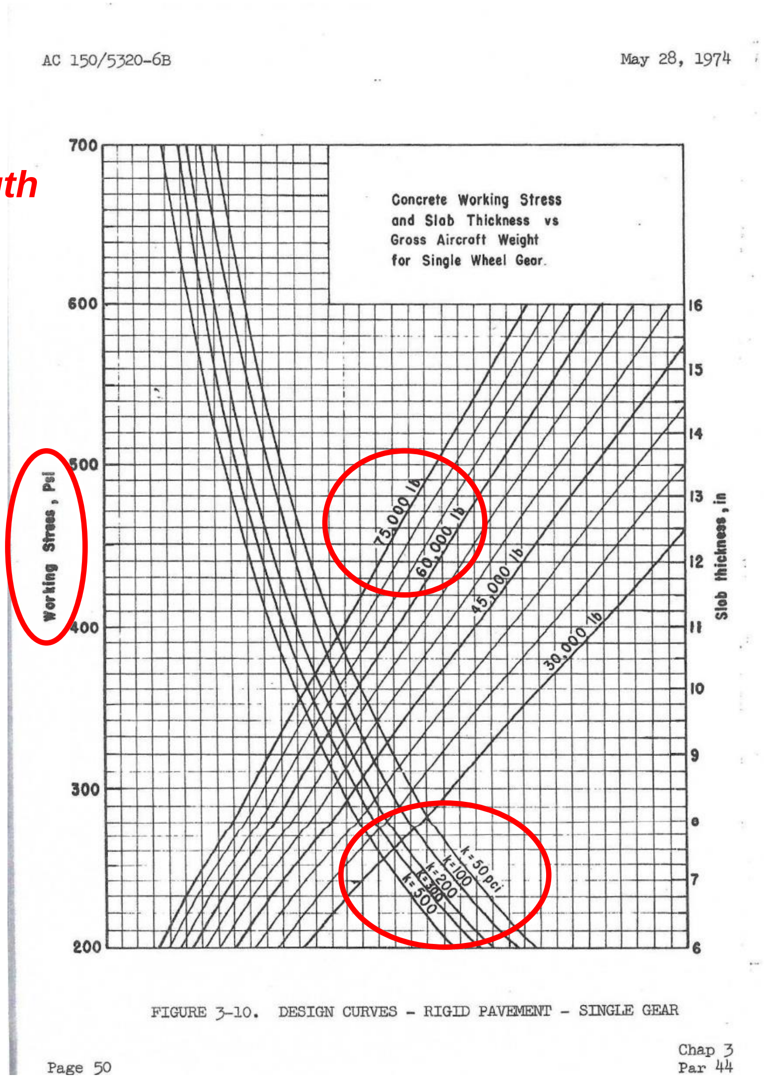


FIGURE 3-10. DESIGN CURVES - RIGID PAVEMENT - SINGLE GEAR

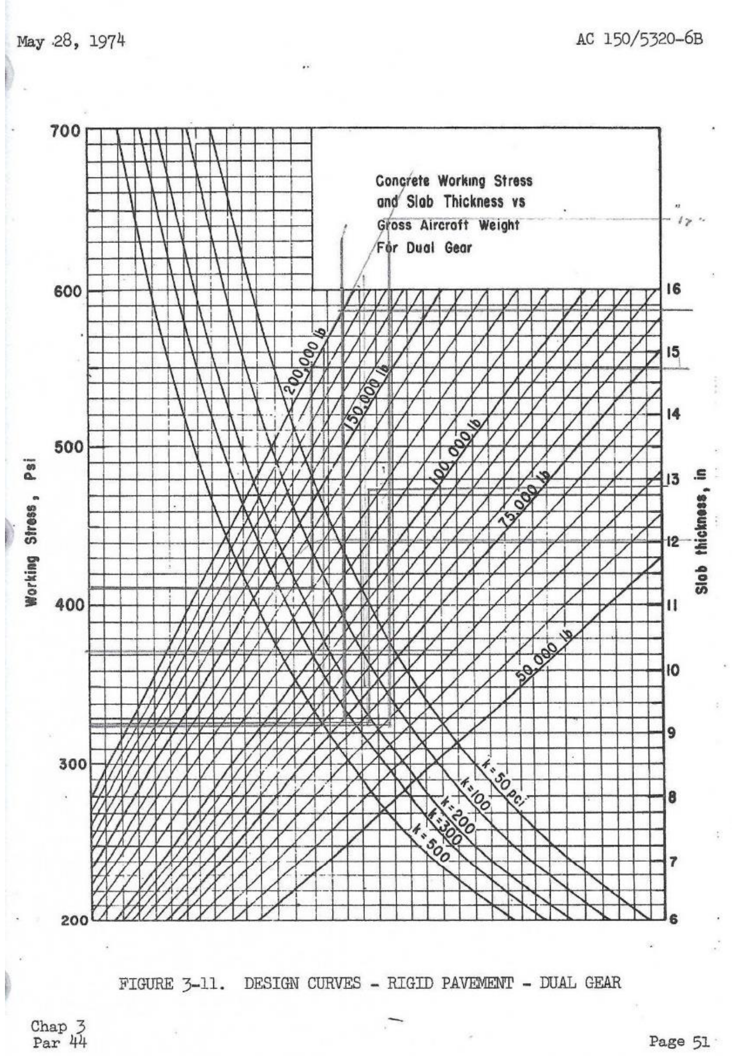


FIGURE 3-11. DESIGN CURVES - RIGID PAVEMENT - DUAL GEAR

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"

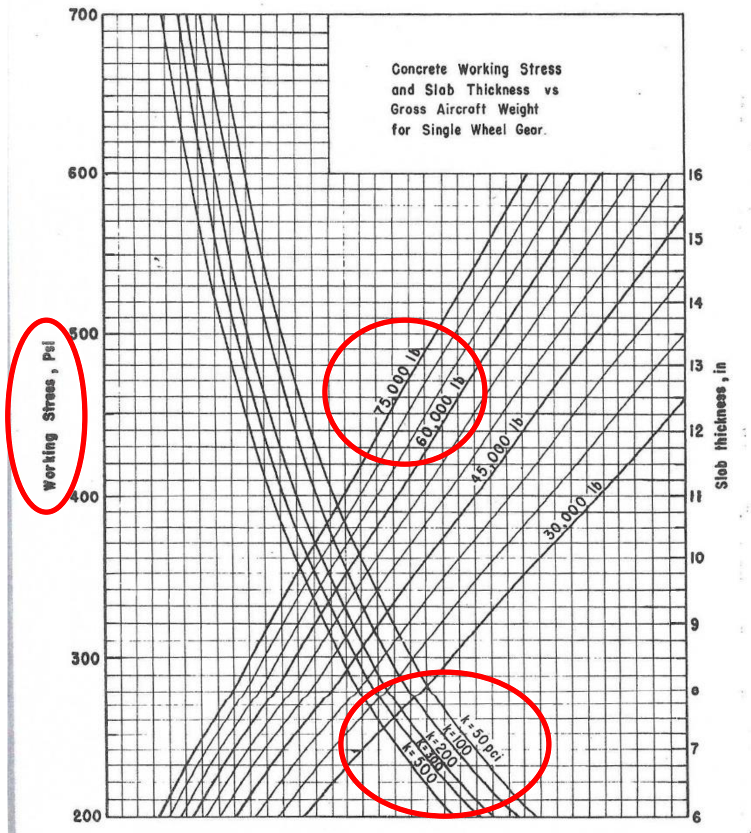


FIGURE 3-10. DESIGN CURVES - RIGID PAVEMENT - SINGLE GEAR

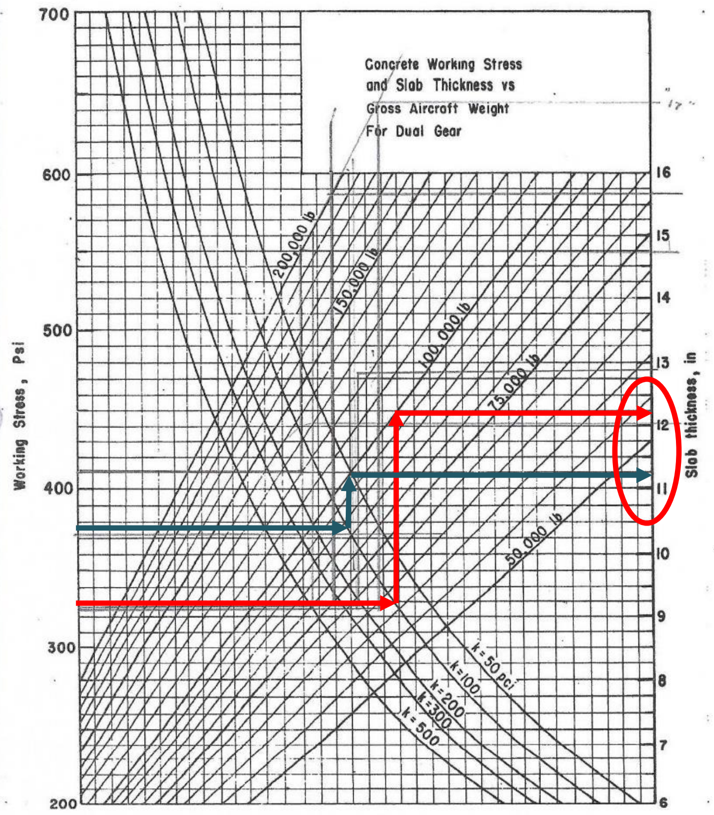


FIGURE 3-11. DESIGN CURVES - RIGID PAVEMENT - DUAL GEAR

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

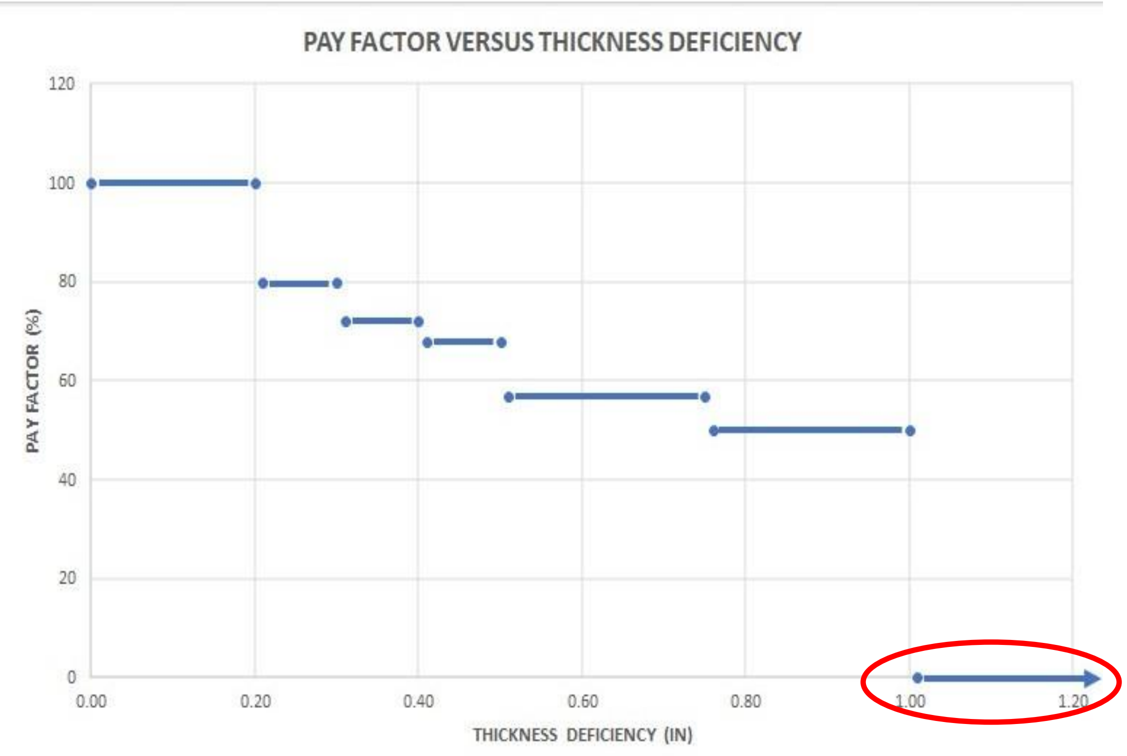
Fast Forward to 1974…………

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

VIRTUAL CONCRETE CONVENTION

Fast Forward to 1974…………

Concrete Pavement Paid Based on Strength and Thickness

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

$$FS_{ADJ} = FS_{ACT} \times (T_{ACT}/T_{DESIGN})^2$$

FS_{ADJ} = Adjusted Flexural Strength

FS_{ACT} = Actual Measured Flexural Strength

T_{ACT} = Actual Thickness

T_{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

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*

Fast Forward to 2018…………

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

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

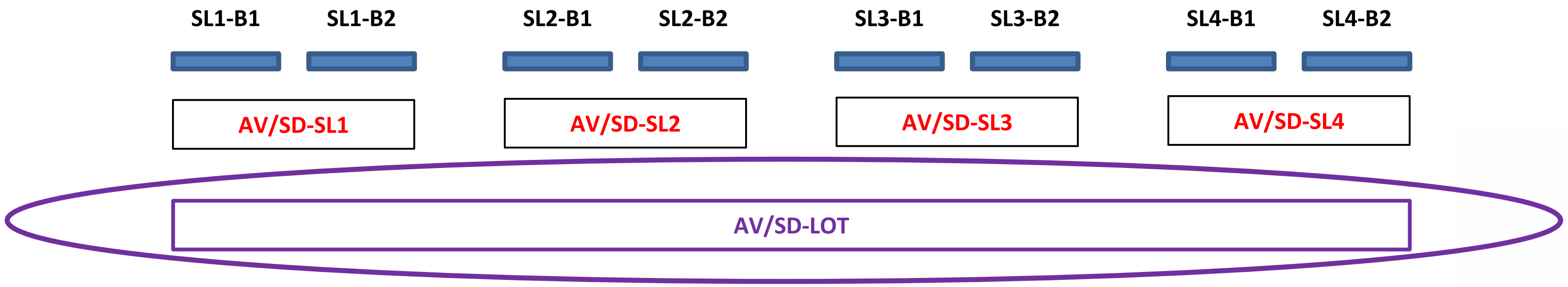
Average 28-day flexural strength and standard deviation of the sublots

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



Fast Forward to 2018…………

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?

Fast Forward to 2018…………

Concrete Pavement Paid Based on

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

See Paragraph 501-8.1a

Price Adjustment Schedule[1]

Percentage of Materials Within Specification Limits (PWL)	Lot Pay Factor (Percent of Contract Unit Price)
96 – 100	106
90 – 95	PWL + 10
75 – 90	0.5 PWL + 55
55 – 74	1.4 PWL – 12
Below 55	Reject[2]

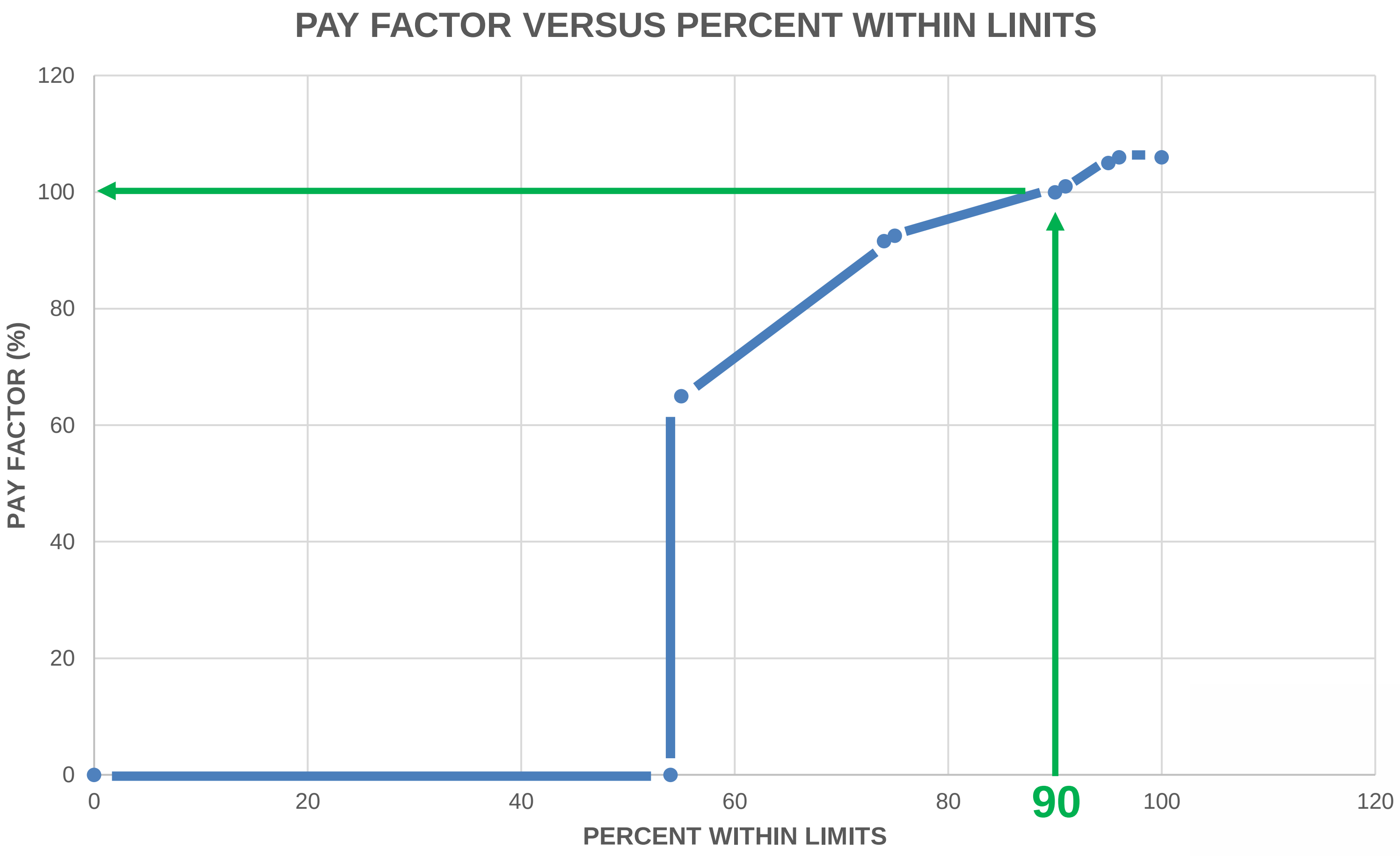
[1] Although it is theoretically possible to achieve a pay factor of 106% for each lot, actual payment in excess of 100% shall be subject to the total project payment limitation specified in paragraph 501-8.1.

[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



Fast Forward to 2018…………

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

Go to Section 110

$$Q_L = (X - L) / S_N$$

X = LOT AVERAGE (Average of Sublot Averages)

L = LOWER SPECIFICATION LIMIT

S_N = 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

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

Go to Section 110

$Q_L = (X – L) / S_N$

$X = (Q_L * S_N) + L$

$X = (1.20 * S_N) + L$

BIG QUESTION ---
WHAT IS VALUE OF S_N?

Look at Past Contractor Production

What Is a Best Estimate of S_N

Table 1. Table for Estimating Percent of Lot Within Limits (PWL)

Percent Within Limits (P_L and P_U)	Positive Values of Q (Q_L and Q_U)							
	n=3	n=4	n=5	n=6	n=7	n=8	n=9	n=10
99	1.1541	1.4700	1.6714	1.8008	1.8888	1.9520	1.9994	2.0362
98	1.1524	1.4400	1.6016	1.6982	1.7612	1.8053	1.8379	1.8630
97	1.1496	1.4100	1.5427	1.6181	1.6661	1.6993	1.7235	1.7420
96	1.1456	1.3800	1.4897	1.5497	1.5871	1.6127	1.6313	1.6454
95	1.1405	1.3500	1.4407	1.4887	1.5181	1.5381	1.5525	1.5635
94	1.1342	1.3200	1.3946	1.4329	1.4561	1.4717	1.4829	1.4914
93	1.1269	1.2900	1.3508	1.3810	1.3991	1.4112	1.4199	1.4265
92	1.1184	1.2600	1.3088	1.3323	1.3461	1.3554	1.3620	1.3670
91	1.1089	1.2300	1.2683	1.2860	1.2964	1.3032	1.3081	1.3118
90	1.0982	1.2000	1.2290	1.2419	1.2492	1.2541	1.2576	1.2602
89	1.0864	1.1700	1.1909	1.1995	1.2043	1.2075	1.2098	1.2115
88	1.0736	1.1400	1.1537	1.1587	1.1613	1.1630	1.1643	1.1653
87	1.0597	1.1100	1.1173	1.1192	1.1199	1.1204	1.1208	1.1212
86	1.0448	1.0800	1.0817	1.0808	1.0800	1.0794	1.0791	1.0789
85	1.0288	1.0500	1.0467	1.0435	1.0413	1.0399	1.0389	1.0382
84	1.0119	1.0200	1.0124	1.0071	1.0037	1.0015	1.0000	0.9990
83	0.9939	0.9900	0.9785	0.9715	0.9671	0.9643	0.9624	0.9610
82	0.9749	0.9600	0.9452	0.9367	0.9315	0.9281	0.9258	0.9241
81	0.9550	0.9300	0.9123	0.9025	0.8966	0.8928	0.8901	0.8882
80	0.9342	0.9000	0.8799	0.8690	0.8625	0.8583	0.8554	0.8533
79	0.9124	0.8700	0.8478	0.8360	0.8291	0.8245	0.8214	0.8192
78	0.8897	0.8400	0.8160	0.8036	0.7962	0.7915	0.7882	0.7858
77	0.8662	0.8100	0.7846	0.7716	0.7640	0.7590	0.7556	0.7531
76	0.8417	0.7800	0.7535	0.7401	0.7322	0.7271	0.7236	0.7211
75	0.8165	0.7500	0.7226	0.7089	0.7009	0.6958	0.6922	0.6896
74	0.7904	0.7200	0.6921	0.6781	0.6701	0.6649	0.6613	0.6587
73	0.7636	0.6900	0.6617	0.6477	0.6396	0.6344	0.6308	0.6282
72	0.7360	0.6600	0.6316	0.6176	0.6095	0.6044	0.6008	0.5982
71	0.7077	0.6300	0.6016	0.5878	0.5798	0.5747	0.5712	0.5686
70	0.6787	0.6000	0.5719	0.5582	0.5504	0.5454	0.5419	0.5394
69	0.6490	0.5700	0.5423	0.5290	0.5213	0.5164	0.5130	0.5105
68	0.6187	0.5400	0.5129	0.4999	0.4924	0.4877	0.4844	0.4820
67	0.5878	0.5100	0.4836	0.4710	0.4638	0.4592	0.4560	0.4537
66	0.5563	0.4800	0.4545	0.4424	0.4355	0.4310	0.4280	0.4257
65	0.5242	0.4500	0.4255	0.4139	0.4073	0.4030	0.4001	0.3980
64	0.4916	0.4200	0.3967	0.3856	0.3793	0.3753	0.3725	0.3705
63	0.4586	0.3900	0.3679	0.3575	0.3515	0.3477	0.3451	0.3432
62	0.4251	0.3600	0.3392	0.3295	0.3239	0.3203	0.3179	0.3161
61	0.3911	0.3300	0.3107	0.3016	0.2964	0.2931	0.2908	0.2892
60	0.3568	0.3000	0.2822	0.2738	0.2691	0.2660	0.2639	0.2624
59	0.3222	0.2700	0.2537	0.2461	0.2418	0.2391	0.2372	0.2358
58	0.2872	0.2400	0.2254	0.2186	0.2147	0.2122	0.2105	0.2093
57	0.2519	0.2100	0.1971	0.1911	0.1877	0.1855	0.1840	0.1829
56	0.2164	0.1800	0.1688	0.1636	0.1607	0.1588	0.1575	0.1566
55	0.1806	0.1500	0.1406	0.1363	0.1338	0.1322	0.1312	0.1304
54	0.1447	0.1200	0.1125	0.1090	0.1070	0.1057	0.1049	0.1042
53	0.1087	0.0900	0.0843	0.0817	0.0802	0.0793	0.0786	0.0781
52	0.0725	0.0600	0.0562	0.0544	0.0534	0.0528	0.0524	0.0521
51	0.0363	0.0300	0.0281	0.0272	0.0267	0.0264	0.0262	0.0260
50	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Item C-110 Method of Estimating Percentage of Material Within Specification Limits (PWL) 85

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?

$X = (1.20 * S_N) + L$

BIG QUESTION --- WHAT IS VALUE OF S_N ?

Look at Past Contractor Production

What S_N Are We Looking for?

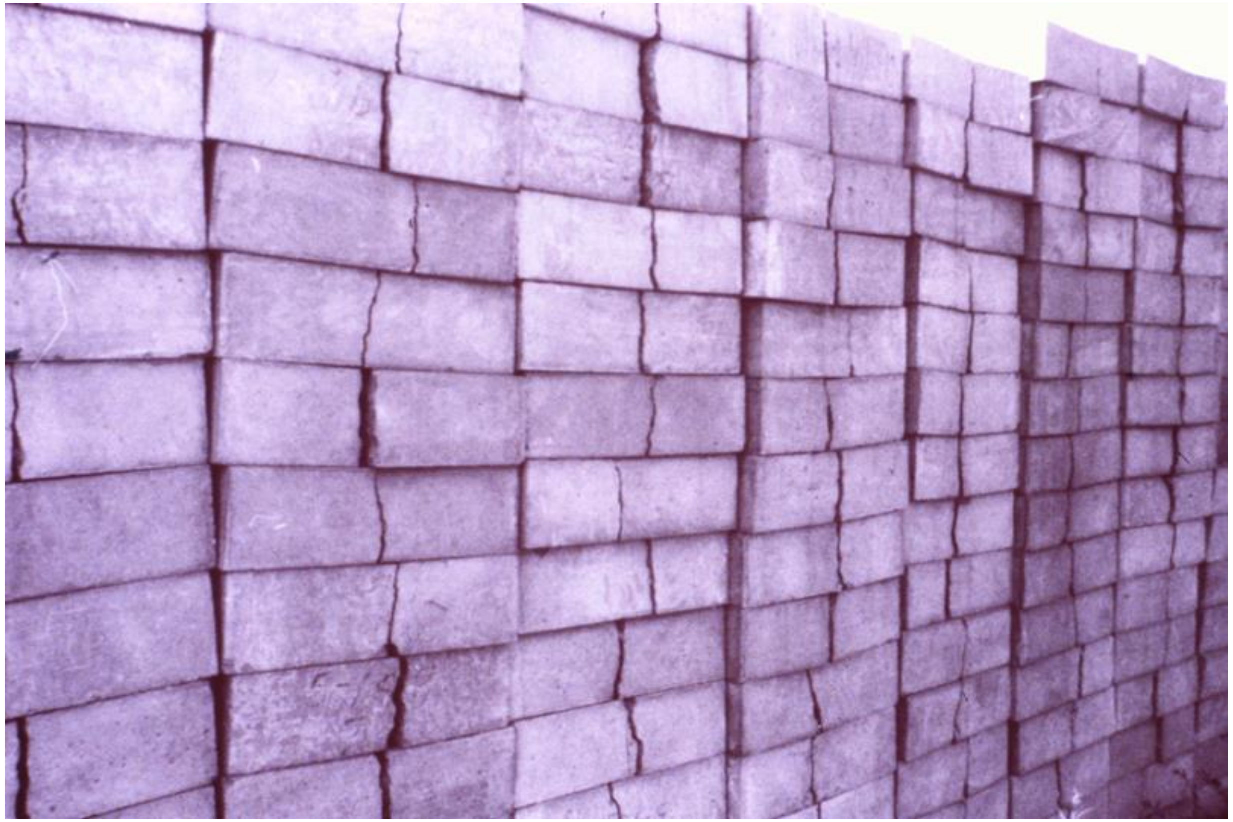
S_N of the Lots

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

Most 40 – 60 psi, use 60 psi

Overall S_N (2 beam sublots) = 60 / (2)^1/2 = ~ 42 psi

Overall S_N (4 sublot Lots) = 42 / (4)^1/2 = ~ 21 psi



Fast Forward to 2018…………

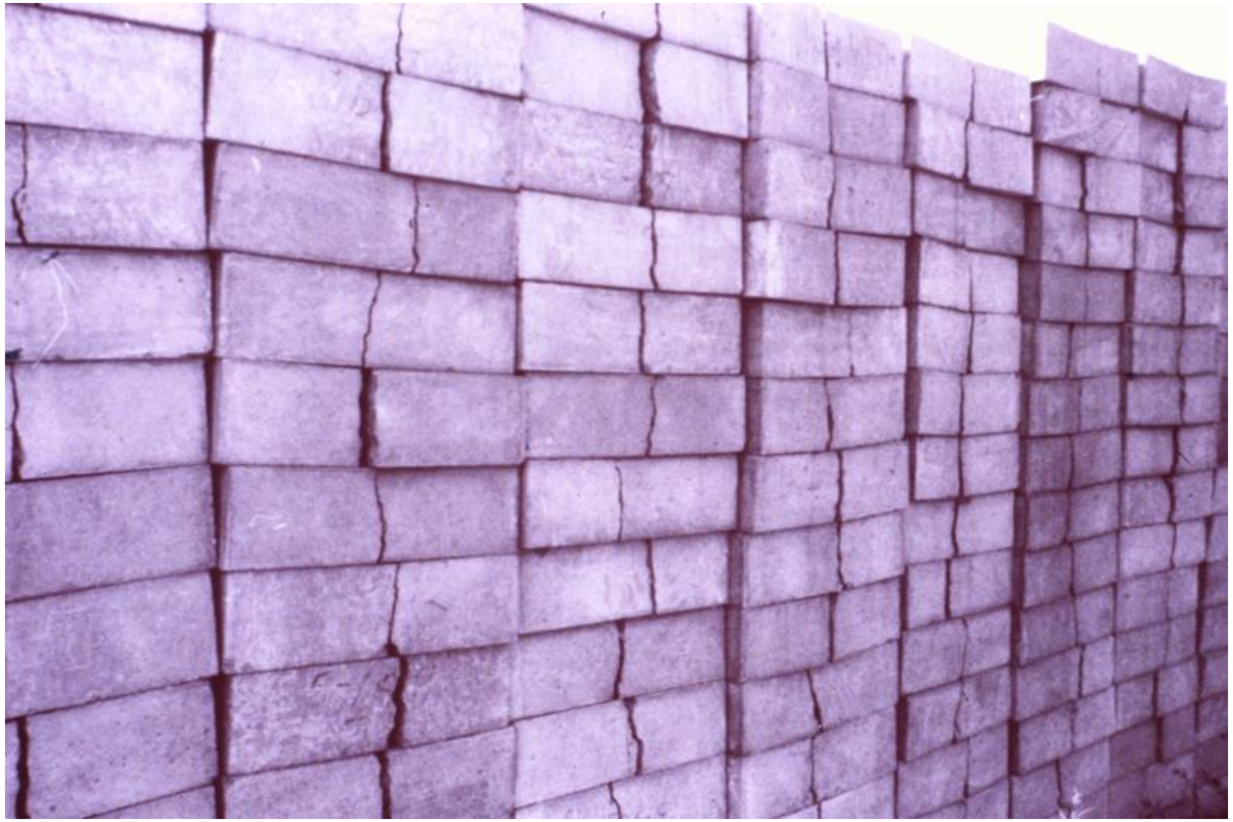
For a Lot to Receive 100% (i.e. 90% Within Limits)

*Lot Average =/> L + (1.2 * 42)*

Lot Average =/> (604.5 + 50.4) =/> 655

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

i.e. --- All Lots =/> 655



Fast Forward to 2018…………

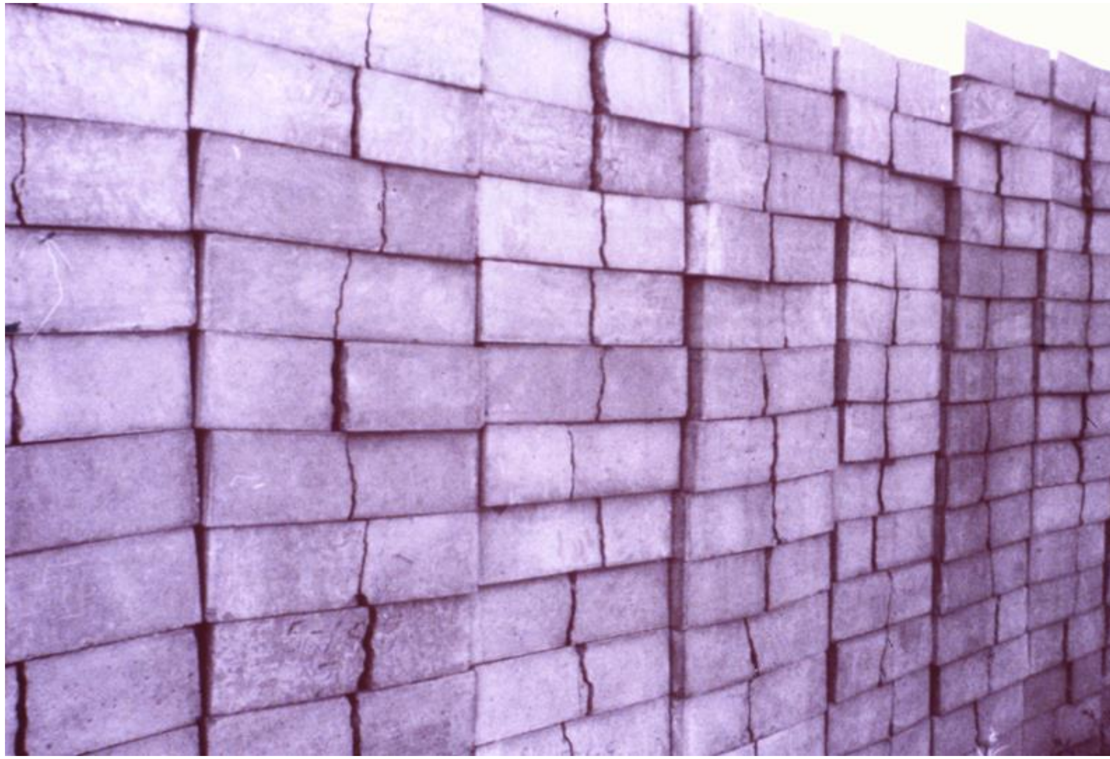
What Strength is Required in the Field For All Lots to Receive 100% Payment?

Average of All Lots =/> (655) + 3 * [$S_{N\text{-}ALL\text{-}LOTS}$]

Average of All Lots =/> (655) + 3 * [21]

Average of All Lots =/> ~ 718

Thus, Concrete in the Field Requires an Overall Lot Average = ~ 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 ~ One Standard Deviation of Field Tests

Lab Average Strength = 720 + 21 = ~740

Fast Forward to 2018…………
Lab Mix Design Process

Prepare Mixes for Strength vs Cement Content Curve

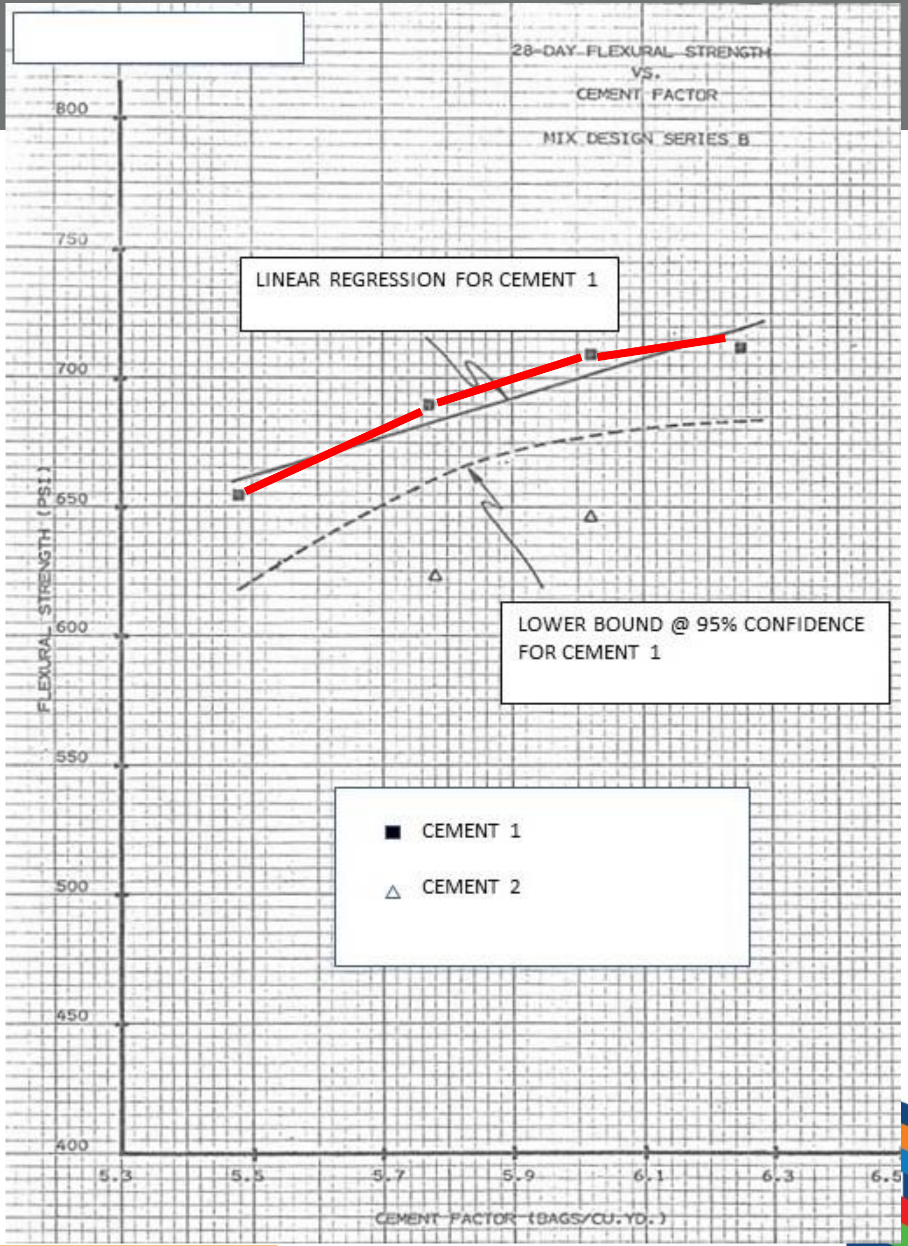
in Lab at 3-4 cement contents

Plot Strength versus Cement Content

Curve looks as expected…………

Increased cement yields increased strength

However, that is not always the case…………….



Fast Forward to 2018…………
Lab Mix Design Process

Prepare Strength vs Cement Content Curve

in Lab at 3-4 cement contents

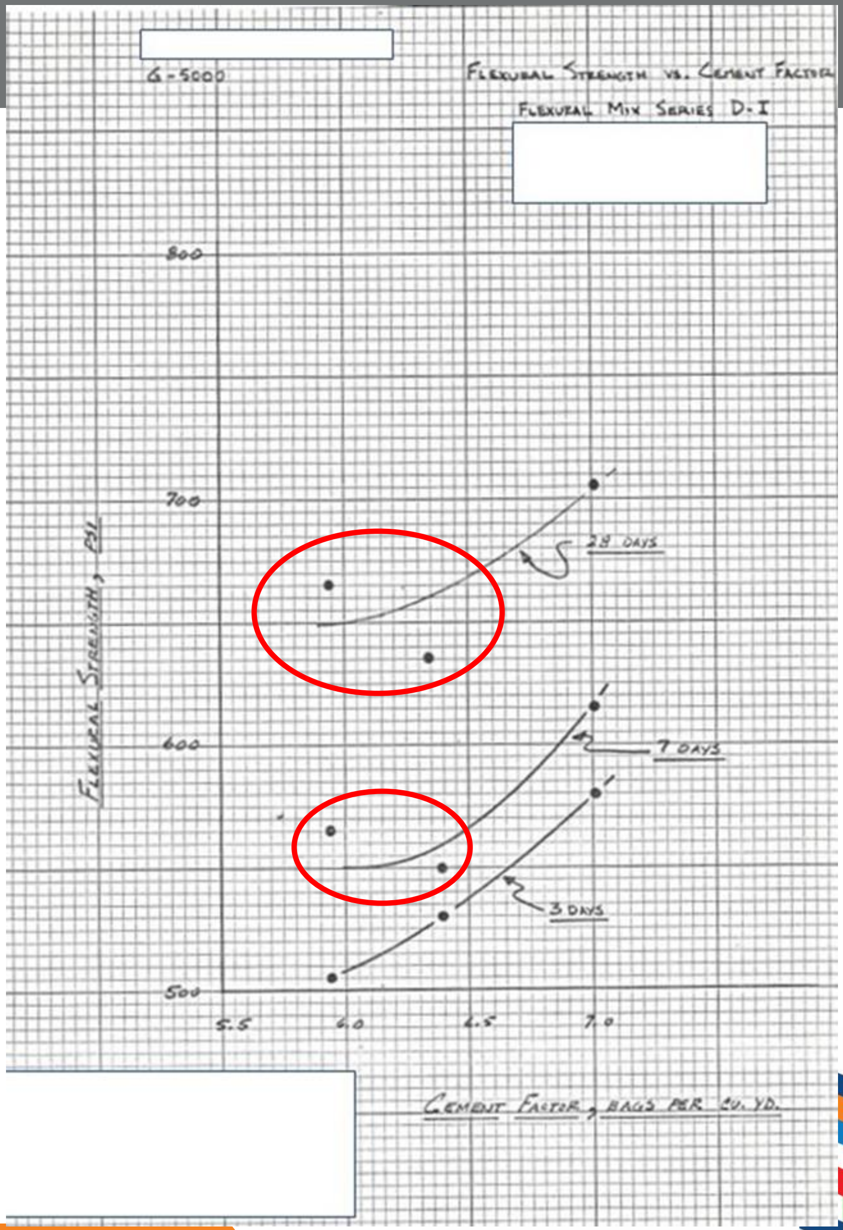
Sometimes…………….

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

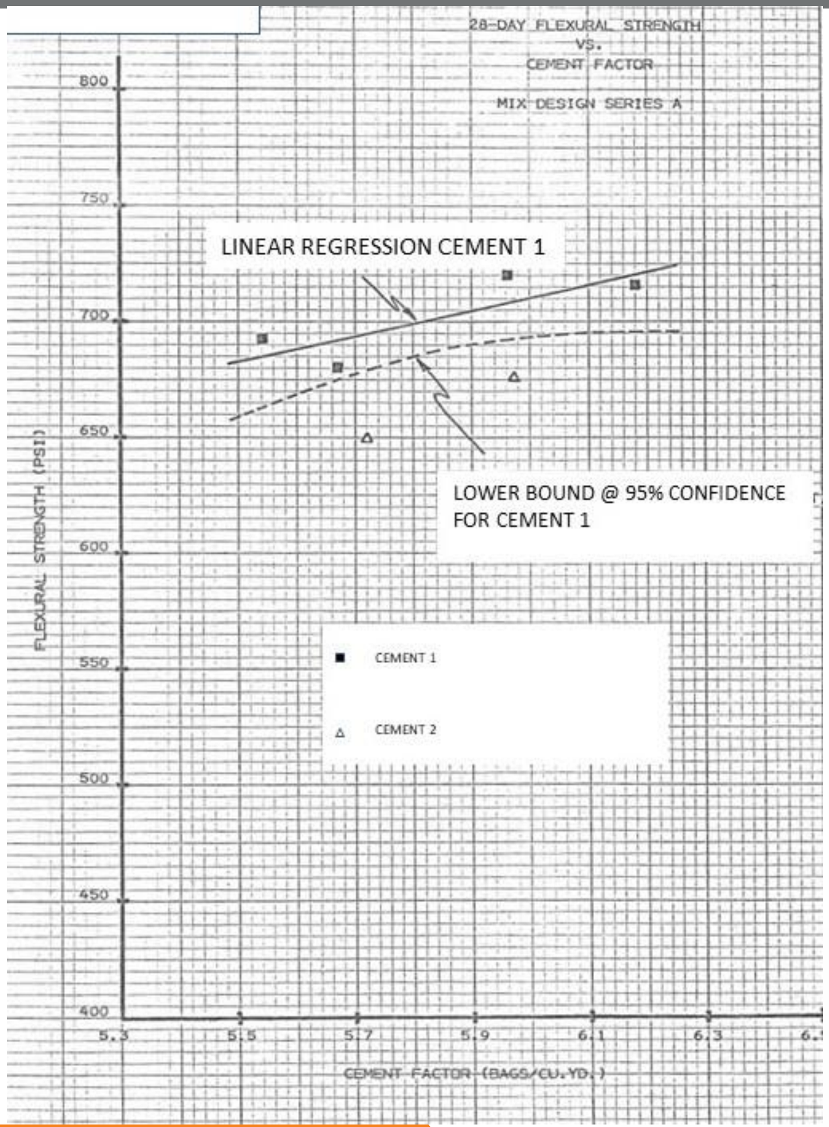


Lab Mix Design Process for Flexural Strength

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

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

FLEXURAL STRENGTH AT 28 DAYS --- SPECIAL CASE

	FLEXURAL STRENGTH --- 28 DAYS (PSI)			
	CEMENT FACTOR 1		CEMENT FACTOR 2	
	BATCH 1	BATCH 2	BATCH 1	BATCH 2
	635	630	710	670
	645	680	755	690
	685	700	760	705
	690	700		710
	690	710		715
	695	710		725
	700	720		725
	715			730
	725			735
AV	687	693	742	712
SD	29	30	28	21
RANGE	90	90	50	65
LOW-3	655	670	N/A	688
HIGH-3	713	713	N/A	730
RANGE	68	43	N/A	42

Fast Forward to 2018…………
Lab Mix Design Process

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

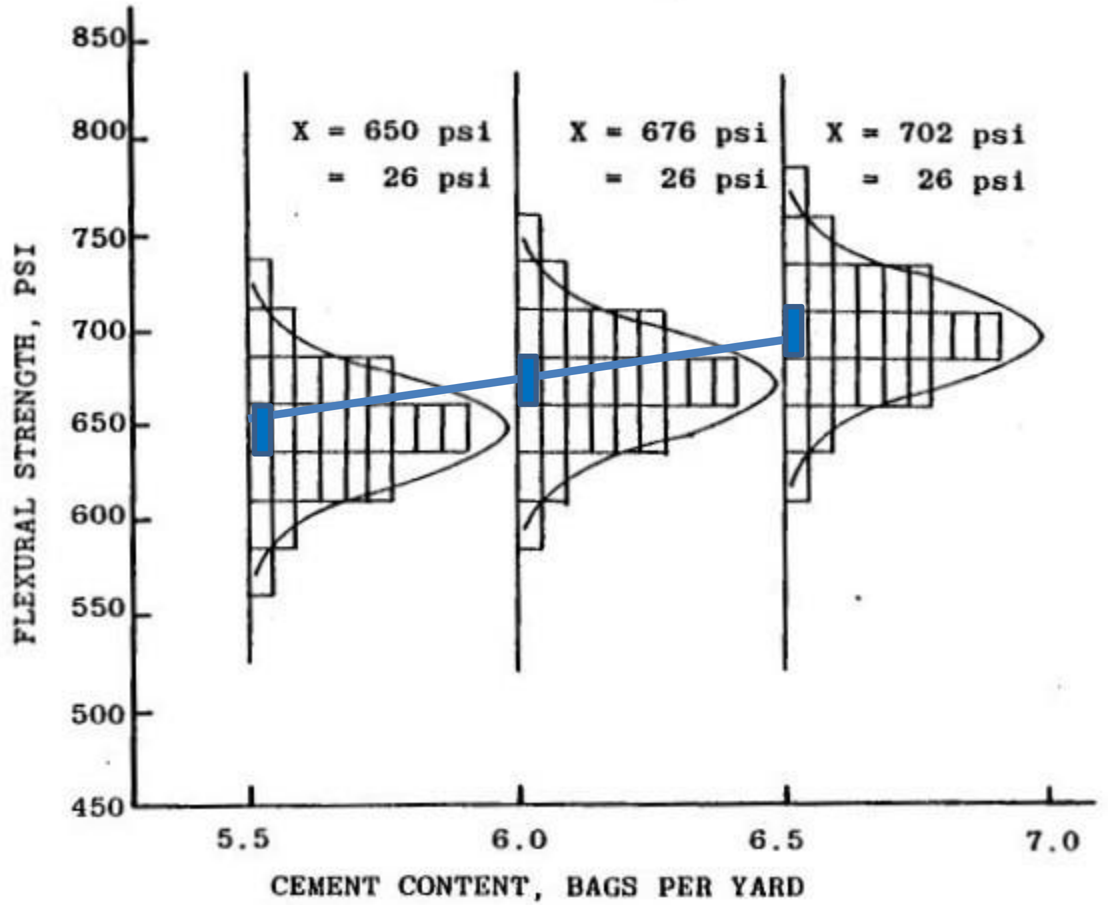
Average Strength Tends to Increase with Increased Cement

However,

If One Batch per Cement Content

Strength Sometimes Can Drop at Higher Cement Content

How Can This Be?



Fast Forward to 2018…………
Lab Mix Design Process

Prepare Strength vs Cement Content Curve

in Lab at 3-4 cement contents

Variability

If You Prepare Multiple Batches of Mix at each Cement Co

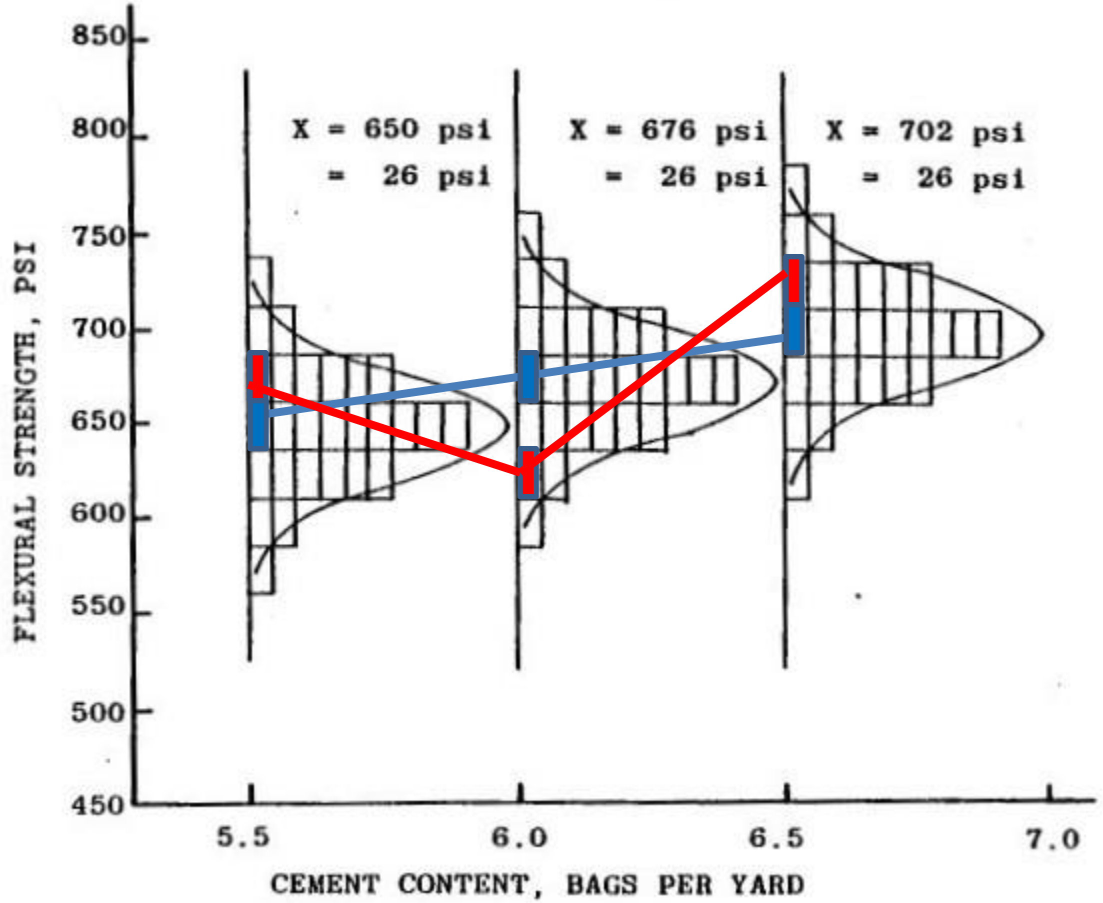
You Will Get a Range of Average Strengths of the Batc

Average Strength Tends to Increase with Increased Ceme

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,

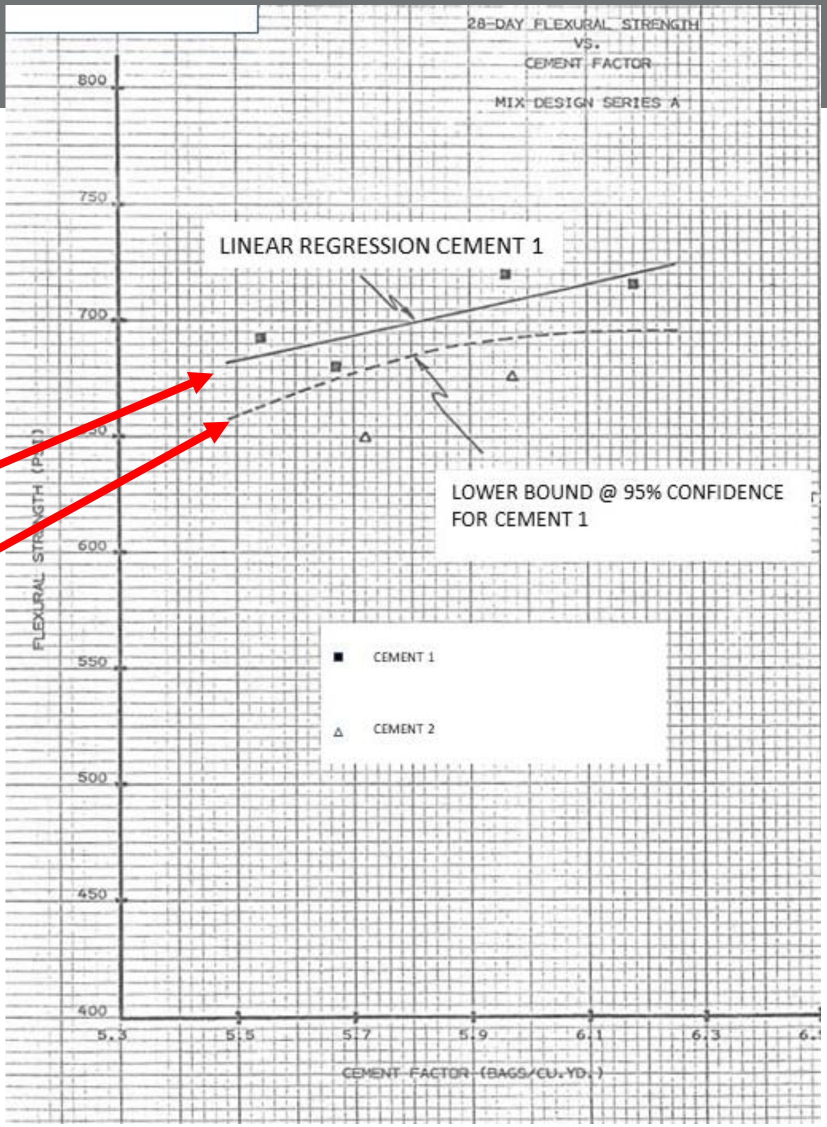
Prepare Multiple Batches for Each Cement Content and

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?