Module 1

Introduction
EXECUTIVE MODULE

Prepared by:
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WHY USE HPC?

What is HPC ?

FOUR PERFORMANCE GRADES OF HPC

BASED ON:	TEST
Freeze Thaw	AASHTO T161
Sealing resistance	ASTM C672
Abrasion Resistance	ASTM C944
Chloride Penetration	ASTM T277
Strength	AASHTO T2
Elasticity	ASTM C469
Shrinkage	ASTM C157
Creep	ASTM C512

Performance Characteristics	FHWA Performance Grade			
	1	2	3	4
Freeze-Thaw (after 300 cycles)	60 to 80%	> 80%		
Scaling (after fifty cycles)	4,5	2,3	0,1	
Abrasion (mm)	2 to 1	1 to 0.5	< 0,5	
Chloride Penetration (columbs)	3000 to 2000	2000 to 800	< 800	
Compressive Strength (psc)	6,000 to 8.000	8.000 to 10,000	10,000 to 14,000	>14,000
Elasticity (psi)	4 to 6 x 10^6	6 to 7.5 x 10^6	> 7.5 x 10^6	
Shrinkage (microstrain)	800 to 600	600 to 400	< 400	
Creep (microstrain/psi)	0.52 to 0.41	0.41 to 0.31	0.31 to 0.21	< 0.21

Ref: Goodspeed et al., Fig 2

BENEFITS OF HPC

ADVANTAGES OF HPC

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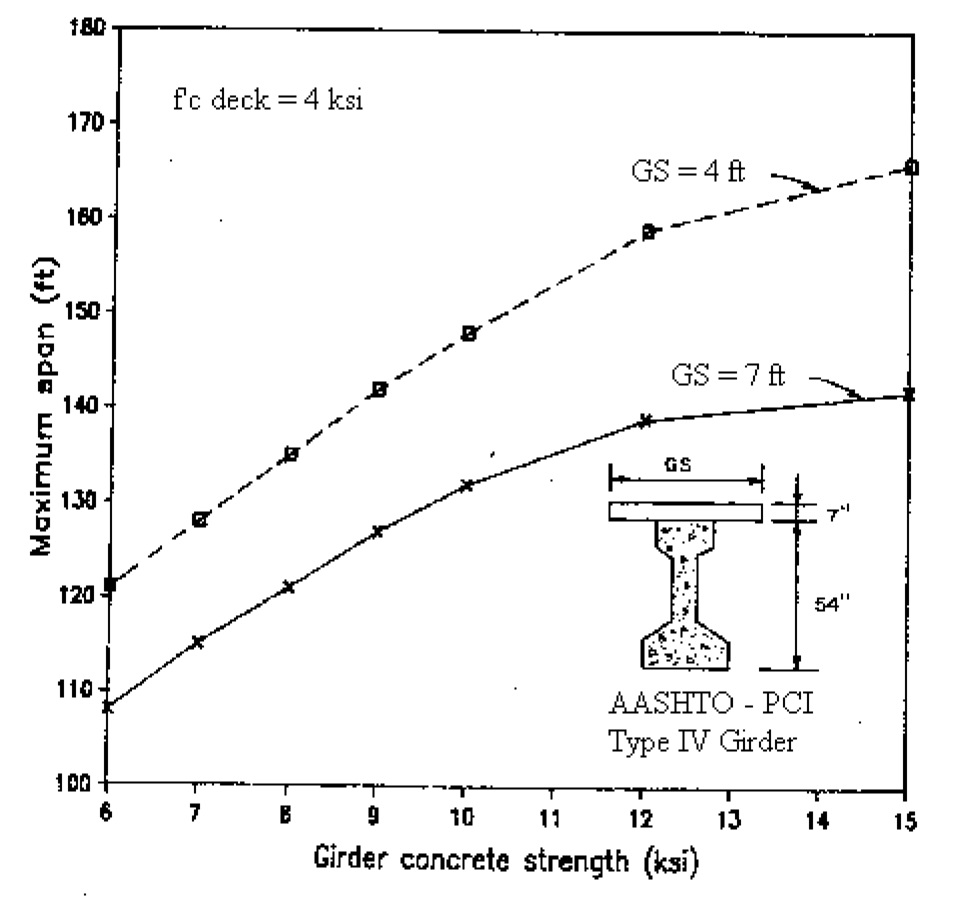
1. Longer Spans

Longer Spans

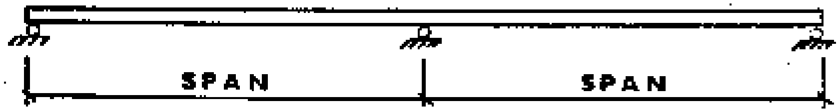
Fewer Piers

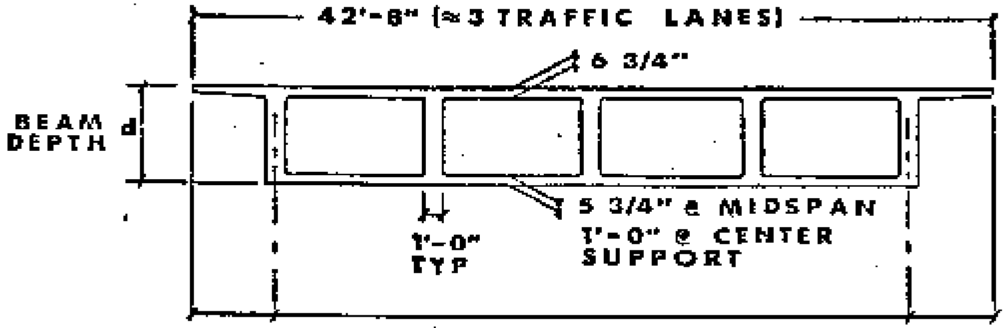
AASHTO Type IV Girder with 7” Deck



Ref: *Castrodale et al.*, Fig. 1.2

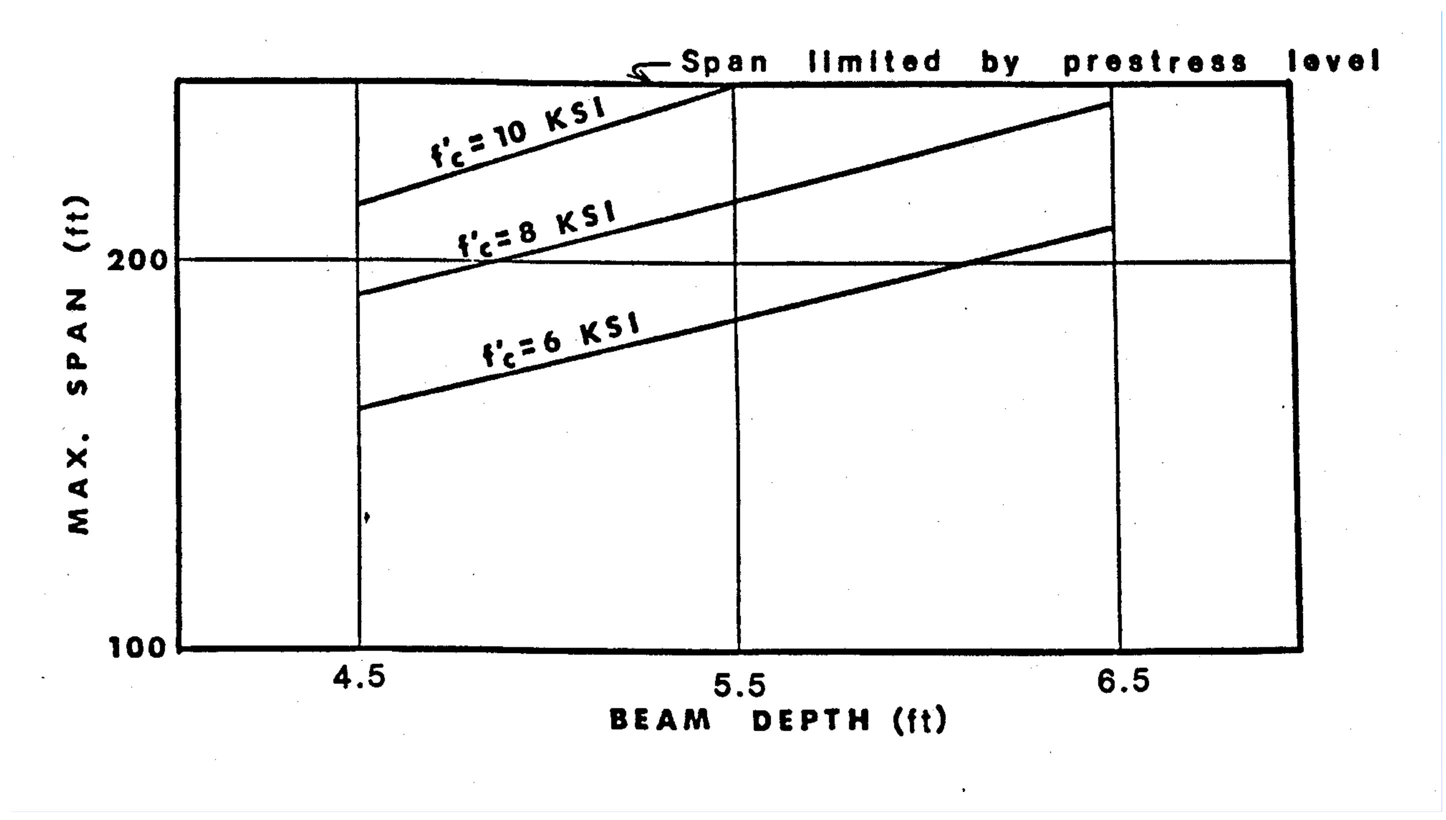
Two Span Continuous Post-Tensioned Box Girder





Reference: *Jobse*, Fig. 8

Box Beam Depth
Span length .vs. Beam Depth



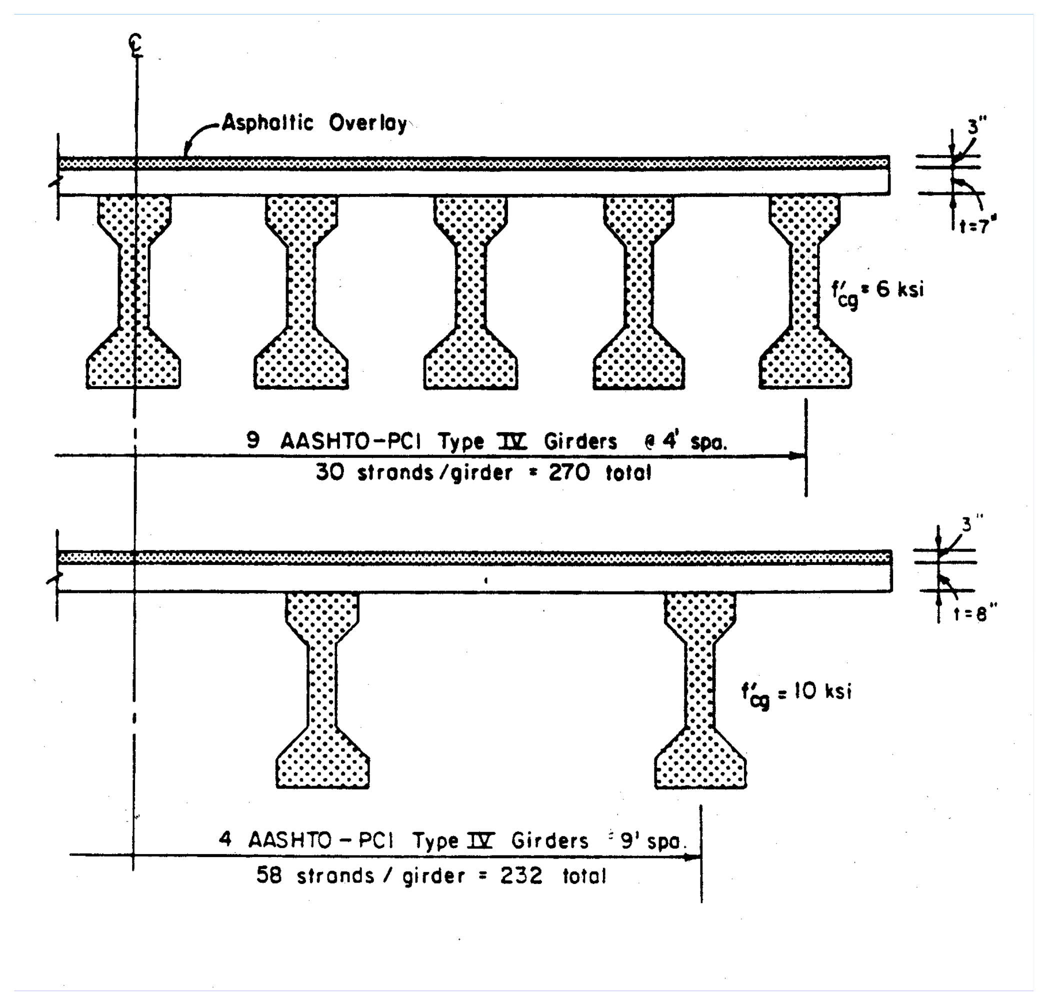
Reference: *Jobse*, Fig. 9

ADVANTAGES OF HPC

1. **Longer spans**
2. ***Increased beam spacings***

Increased Beam Spacing → Fewer Beams

AASHTO Type IV Girders



7” deck

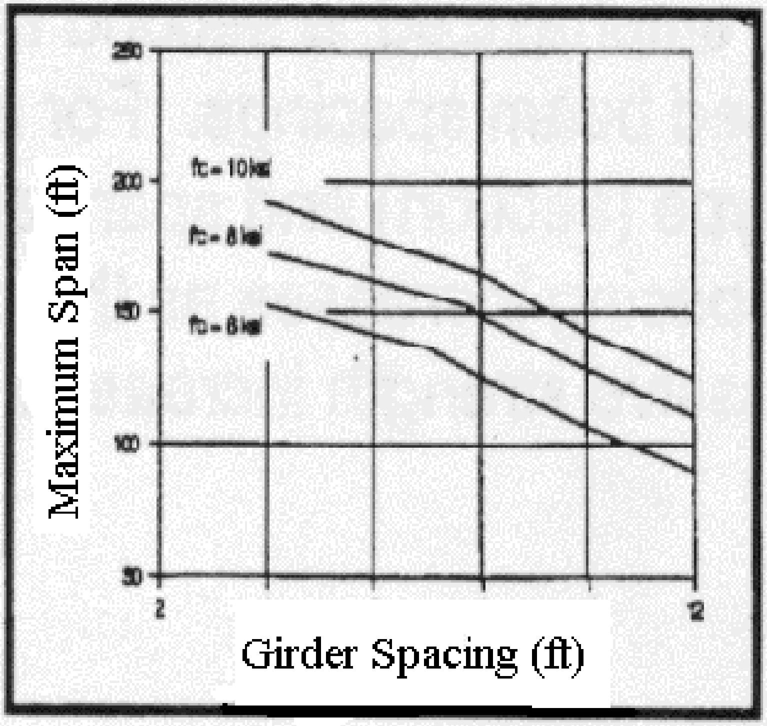
f'_c = 6 ksi

8” deck

f'_c = 10 ksi

Ref: *Castrodale et al.*, Fig. 1.1

72 inch Bulb-Tee /Section with CIP Deck



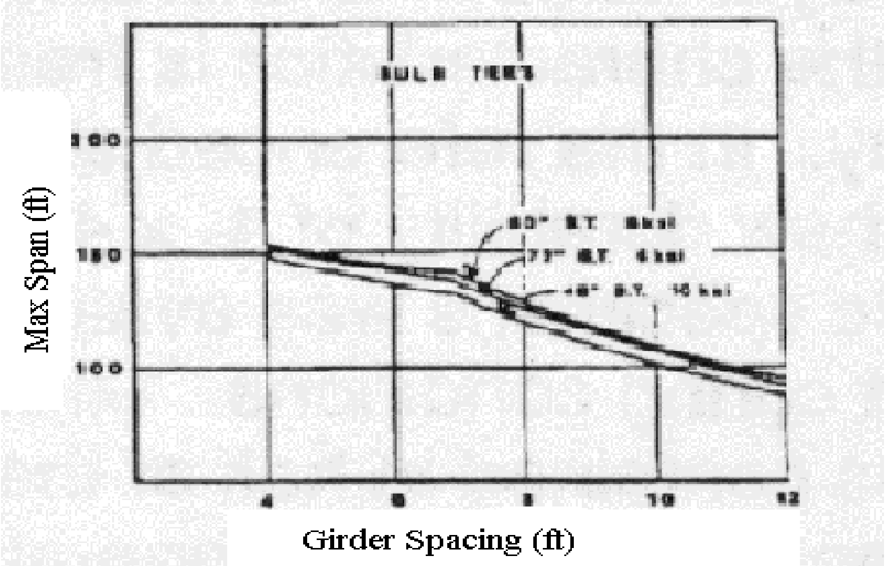
Ref: Zia et al., Fig. 2.4

ADVANTAGES OF HPC

1. **Longer Spans**
2. **Increased beam spacing**
3. ***Shallower members***

SHALLOWER MEMBERS → **INCREASED ROADWAY CLEARANCES**

Depth Variations for Bulb-Tees with CIP Deck



Ref: Jobse, Fig 6

ADVANTAGES OF HPC

1. Longer Spans
2. Increased Beam Spacings
3. Shallower Members
4. *Increased Durability*

Increased Durability → **Longer Life**

Fewer Repairs

DURABILITY

- Freeze - Thaw
- Rapid Chloride Permeability
- Abrasion Loss
- Carbonation Depth

ADVANTAGES OF HPC

1. **Longer Spans**
2. **Increased Beam Spacings**
3. **Shallower Members**
4. **Increased Durability**
5. ***Improved Mechanical Properties***

IMPROVED MECHANICAL PROPERTIES

- **Compressive Strength**
- **Modulus of Elasticity**
- **Tensile Strength**
- **Bond**

DISADVANTAGES OF HPC

1. **Quality Control Concerns**
   a. **Number of Tests**
   b. **Testing Methods**

DISADVANTAGES OF HPC

1. Quality Control Concerns

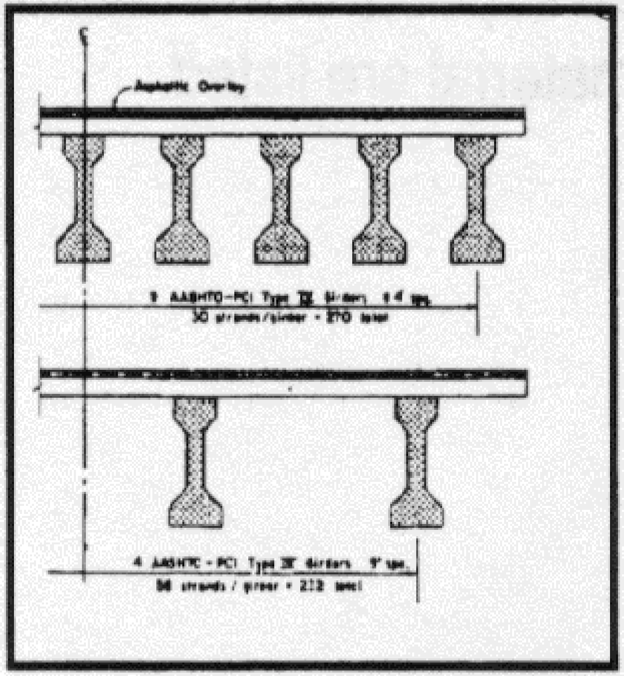
2. ***Higher Bid Prices (at least initially)***

DISADVANTAGES OF HPC

- **Quality Control Concerns**
- **Higher Bid Prices (at least initially)**
- ***Instability Cautions***

DISADVANTAGES OF HPC

- **Quality Control Concerns**
- **Higher Bid Prices (at least initially)**
- **Instability Cautions**
- ***Thicker Deck for Wider Beam Spacings***



7" deck

$f'_c = 6$ ksi

8" deck

$f'_c = 10$ ksi

Ref: *Castrodale et al.*, Fig. 1.1

DISADVANTAGES OF HPC

1. Quality Control Concerns
2. Higher Bid Prices (at least initially)
3. Instability Cautions
4. Thicker Deck for Wider Beam Spacings
5. *Risk of Trying Something New*

IMPLEMENTATION OF HPC

IMPLEMENTATION

- **Champion the Technology**
- **Partnership**
- **Demonstrate the Technology**
- **Incorporate into Everyday Use**

LEAD STATES TEAM ACTIVITIES

- **Focus Teams**
- **Life Cycle Costs**
- **Continue to Spread the Word**
- **Sunset**

COST OF HPC ?

Cost Comparison	HPC Louretta U-Beam bridge	Normal Concrete U-beam bridges
Unit bridge costs* using as-bid costs per ft^2	$24.09	$23.61

*** Unit bridge costs shown include 10 percent increases for engineering and contingencies**

Note: Total area of Louetta deck = 50,069 ft^2

ref. M.L. Ralls, Concrete International 3/98

LIFE CYCLE COSTS

Module 2
MIX DESIGN

Prepared by:

Celik Ozyildirim

PARTNERING

It is essential that HPC mixes are discussed and developed by the producer, contractor, university, DOT, and FHWA.

HPC mixes must be workable in the field.

MIX DESIGN APPROACH

- Follow concrete basics
- Use quality ingredients
- Optimize every ingredient
- Consider interactions of ingredients
- Be innovative: Try new ideas

MATERIAL SELECTION

Give proper attention to the selection of

- cement
- water
- aggregates
- chemical and mineral admixtures

PORTLAND CEMENT CHEMISTRY

Chemistry

- High C_3S and C_3A for early strengths
- High C_2S for ultimate strengths
- Low alkali content for ASR
- Low C_3A for sulfate resistance

Physical Factor

- Finer cements for early strengths

PORTLAND CEMENT

- Type I and II preferred
- Type III when needed
- Medium range fineness

WATER

- Chemicals in water may affect:
  - setting time
  - strength development
  - chemical reactions
  - corrosion of reinforcing steel

COARSE AGGREGATES

- Strength of aggregate and bond-to-paste
- Water demand (size, shape, grading)
- Elastic Modulus
- Durability: ASR, abrasion resistance, freezing and thawing

CA and STRENGTH

- Use largest aggregate size possible
- If strength is not achieved, reduce the size of aggregate or change the surface texture (different type of aggregate)

ELASTIC MODULUS (E)

- High coarse aggregate content, high E
- Type of rock

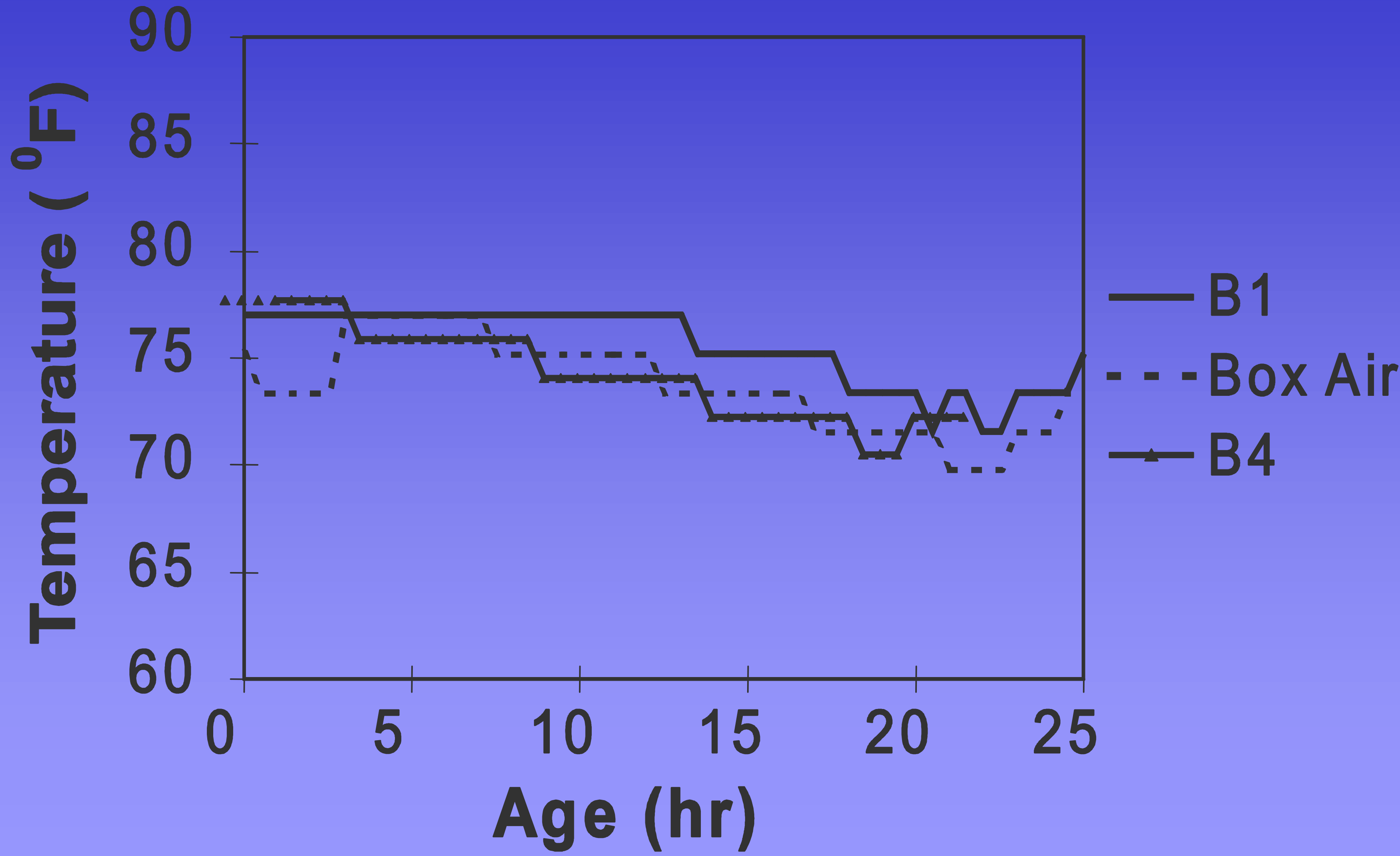
FINE AGGREGATES

- Water demand: Coarse sands have lower water demand
- Workability: Natural sand preferred

ADMIXTURES

- AEA
- Water-Reducing Admixtures
- Retarding Admixtures
- Pozzolans and slag

TRIAL BATCHING: SET 2



HYDRATION REACTION

Portland Cement + Water = CSH(Binder) + Lime

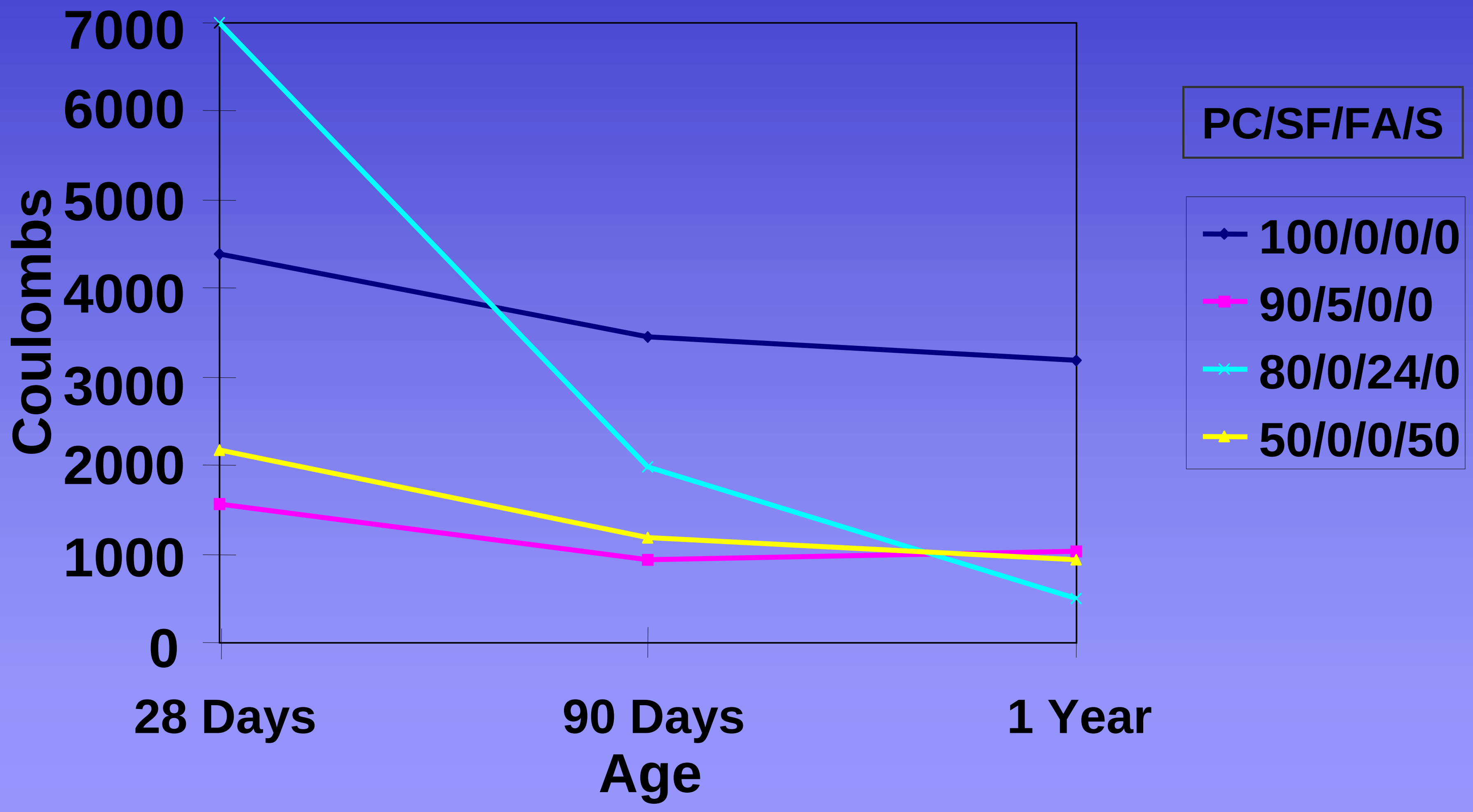
POZZOLANIC REACTION

Pozzolan or Slag + Lime + Water = CSH(Binder)

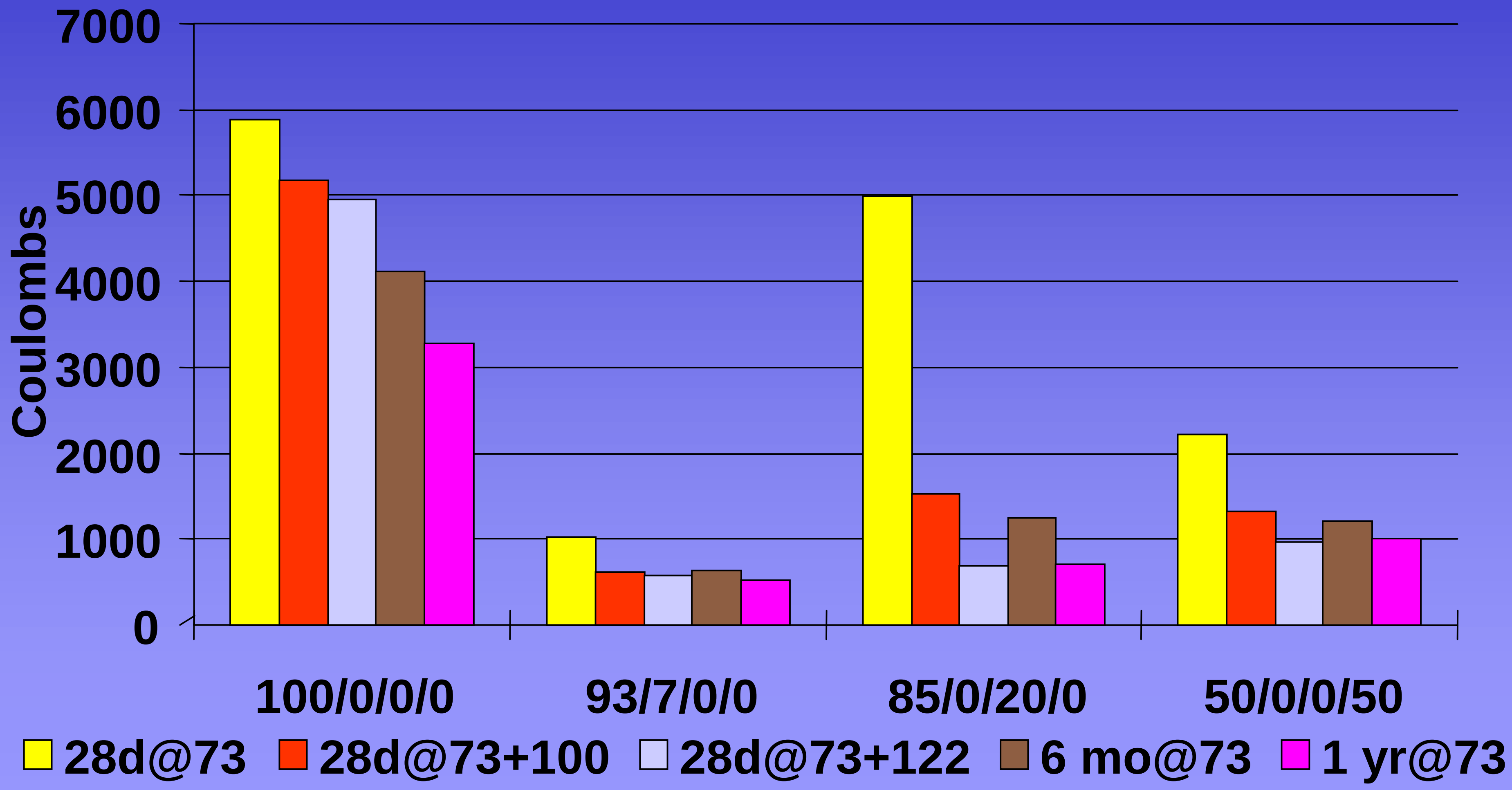
AASHTO T 277 or ASTM C 1202

Charge Passed (Coulombs)	Chloride Permeability
> 4000	High
2000 - 4000	Moderate
1000 - 2000	Low
100 - 1000	Very low
<100	Negligible

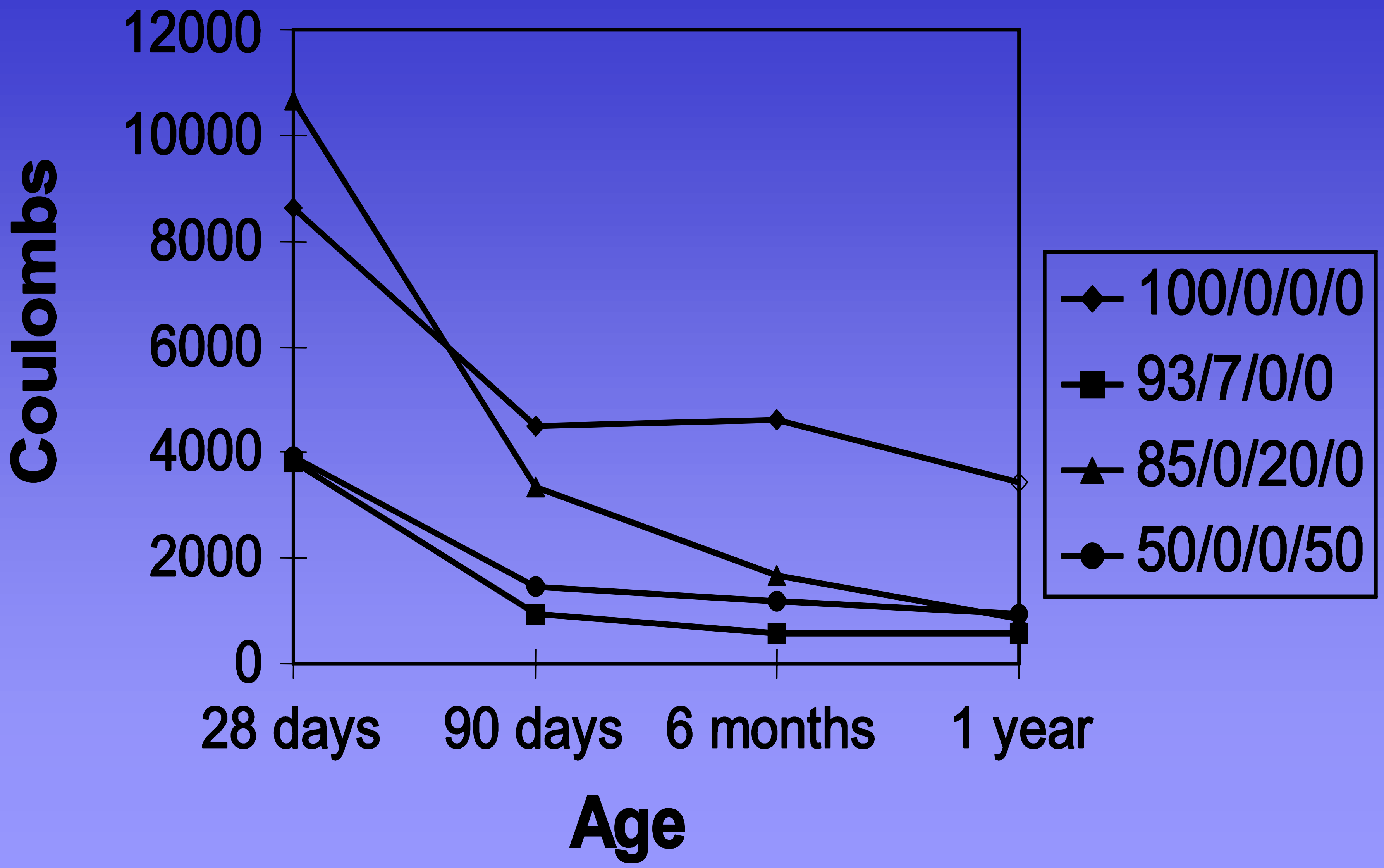
Permeability VS. AGE



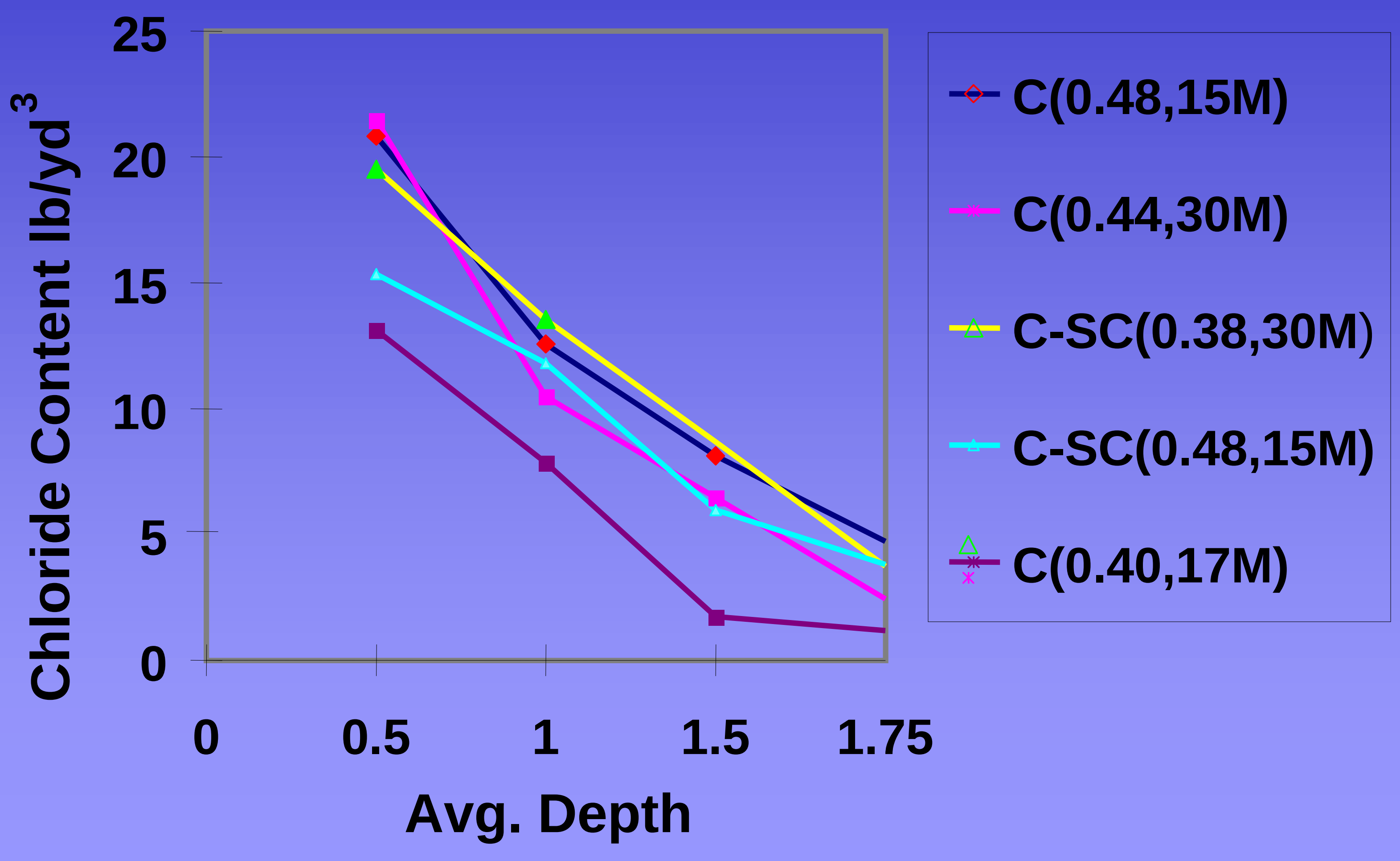
Permeability



1 MONTH AT 41°F THEN 73°F



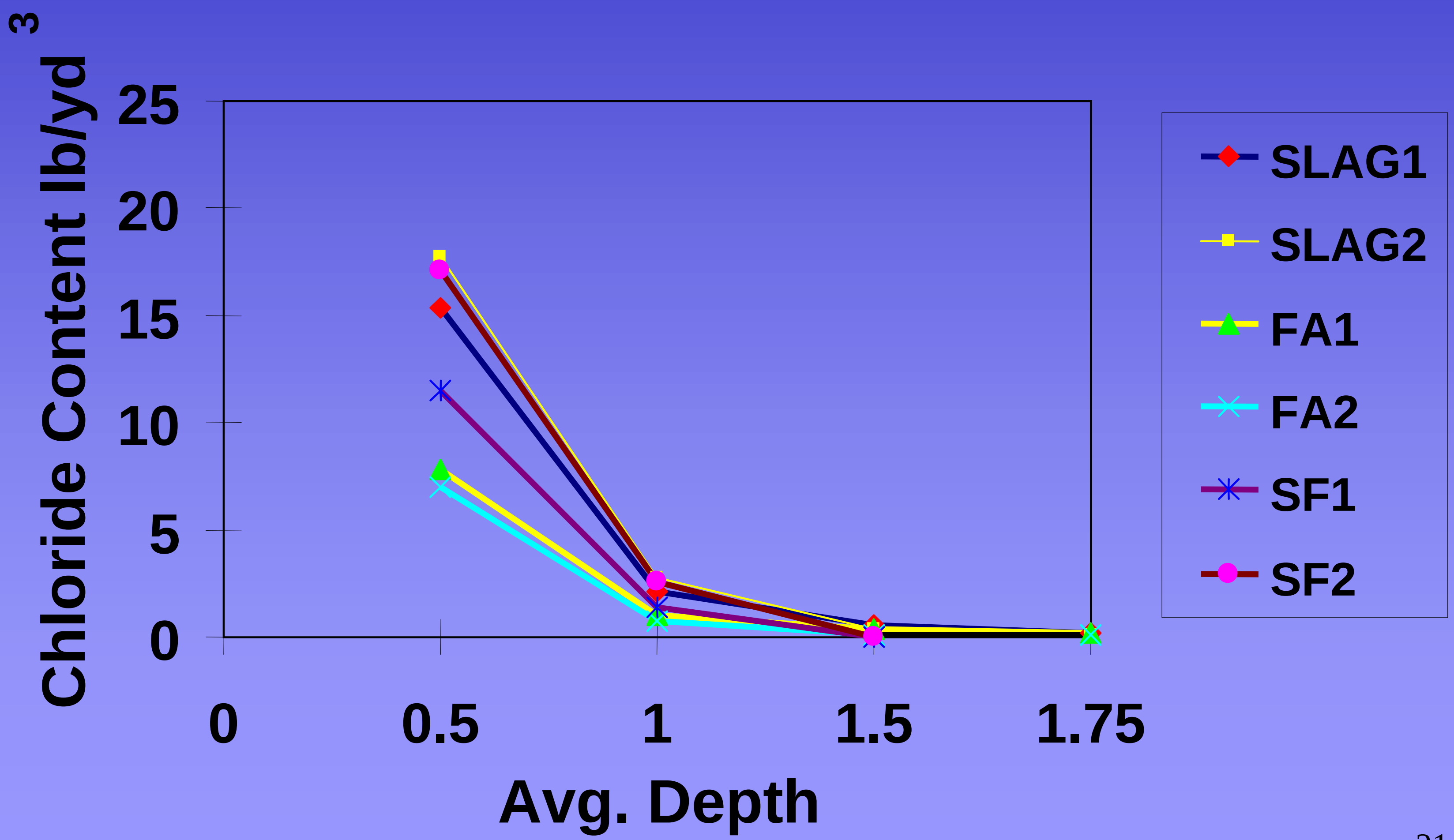
Control Concretes



CONTROL CONCRETES
(Coulombs)

Cure	W/CM	28 D	1.5 Yr
Moist	0.40	4709	3048
Moist	0.48	5198	3100
Moist	0.44	5260	---
Steam	0.38	3110	---
Steam	0.48	7578	3405

Slag, FA or SF Concretes
(15 Months of Ponding)



SLAG, FA, OR SF CONCRETES
(Coulombs)

Material	W/CM	28 D	1 Yr
Slag 1 (50%)	0.47	3502	1547
Slag 2 (50%)	0.47	2686	1187
FA 1 (25%)	0.45	5351	341
FA 2 (25%)	0.39	4456	294
SF 1 (7%)	0.40	1575	887
SF 2 (7%)	0.40	2369	1338

LOW PERMEABILITY

- AASHTO T 277 (coulombs)

1 week @ 73ºF + 3 weeks @100ºF

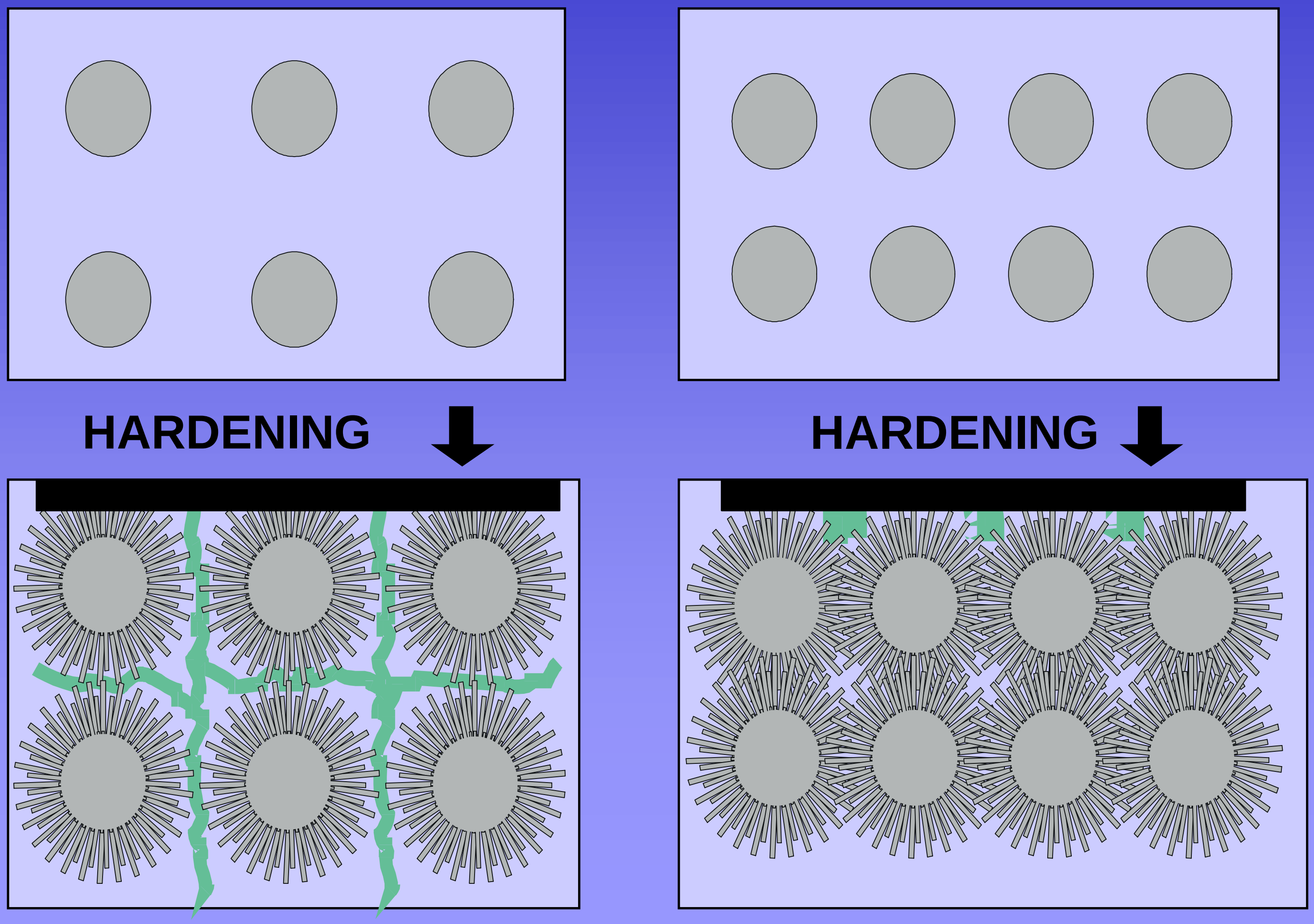
- $\leq$ 1,500 prestressed concrete
- $\leq$ 2,500 bridge decks
- $\leq$ 3,500 substructure

PROPORTIONING

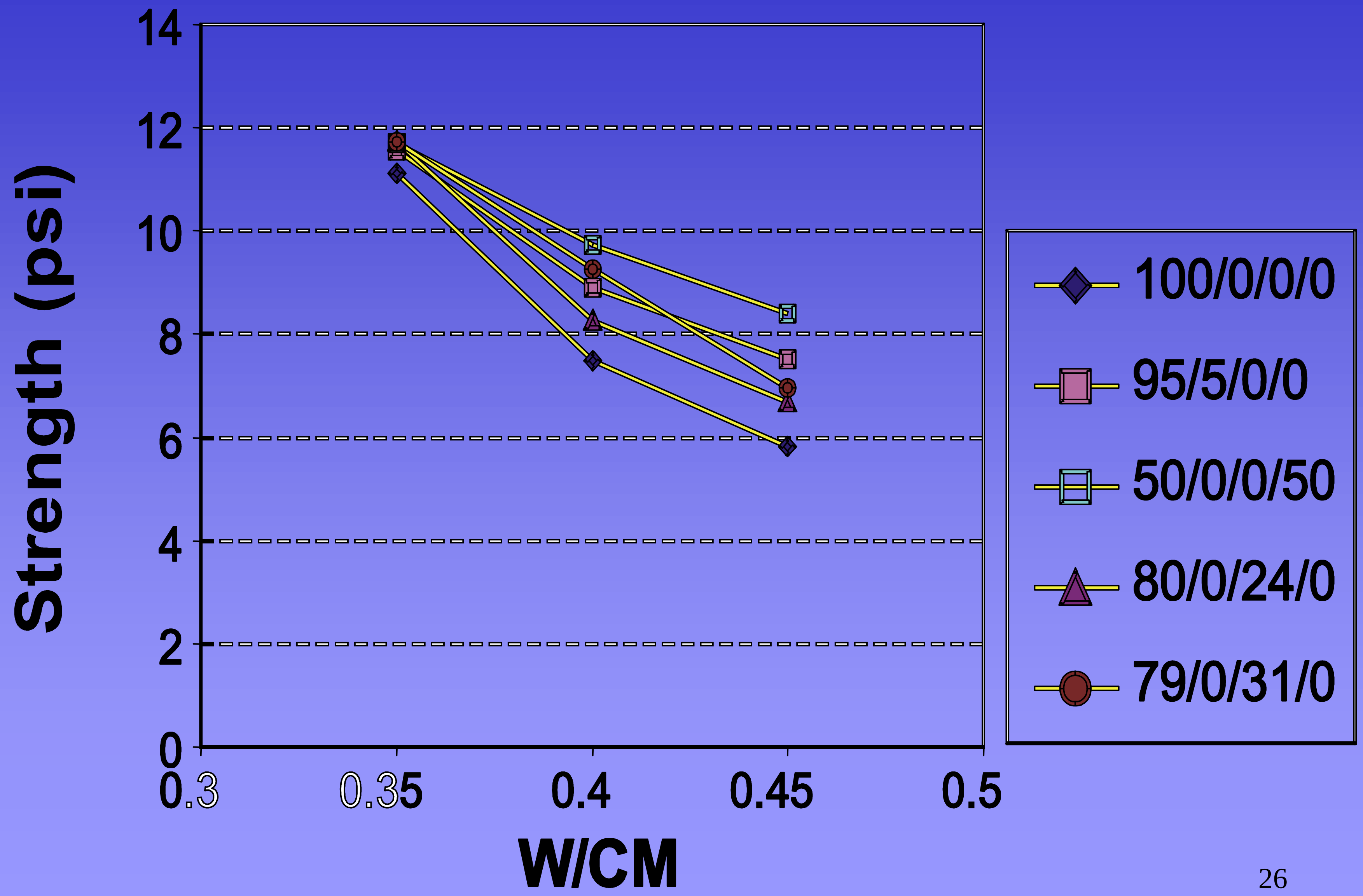
AASHTO specifies proportioning for normal weight concrete by the absolute volume method, such as described in ACI 211

WATER-CEMENT RATIO

HIGH **LOW**



ONE-YEAR COMPRESSIVE STRENGTH



PROCEDURE

- Select slump

Before HRWR, slump: 1 to 2 in.

No HRWR,   slump: 2 to 4 in.

PROCEDURE (Cont'd)

- Select maximum size aggregate

Depends on strength level:

<9000 psi, maximum size: 3/4 to 1 in.

>9000 psi, maximum size: 3/8 to 1 in.

And on geometric restraints

PROCEDURE (Cont'd)

- Select optimum coarse aggregate content

  for normal strength concrete depends on maximum size and fineness modulus of fine aggregate

  for high-strength (HPC with high cementitious content) depends on maximum size

PROCEDURE (Cont'd)

- Estimate mixing water and air content

  Mixing water depends on maximum size, particle shape, grading, and use of chemical admixtures

  Air content depends on maximum size and the severity of exposure

PROCEDURE (Cont'd)

- **Select water-cementitous material ratio (W/CM)**
  - **Develop relationships between strength and durability and W/CM**
  - **If no such data use ACI 211 Tables**

PROCEDURE (Cont'd)

- Calculate content of cementitious material

- Estimate fine aggregate content

CONCLUSION

- Select proper ingredients
- Proportion using absolute volume method
- Test to make sure that the desired properties are achieved.

EXAMPLE MIXTURES

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VIRGINIA HPC SPECS (Rte. 40)

Property	Age (d)	Beam	Deck
Air (%)		4 to 7	5 to 8
Min. Comp. Str. (psi)	28 release	8,000 6,000	4,000
Max. Perm. (coulombs)	28	1,500	2,500

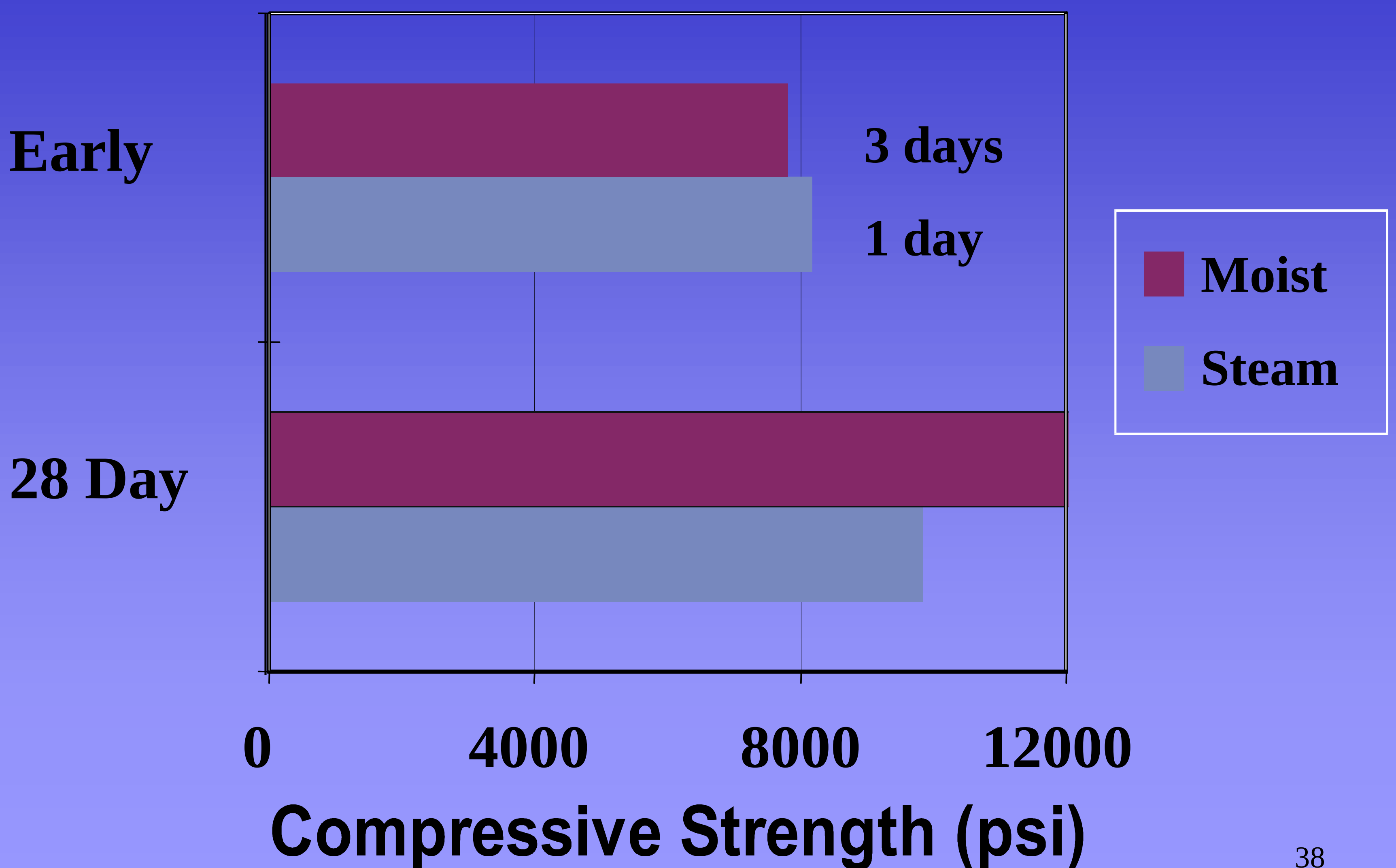
BEAM MIX PROPORTIONS (lb/yd^3)

Material	Amount
PC	752
Silica fume	55
CA	1,675
FA	1,425
w/cm	0.32
Air (%)	5.5 +/- 1.5

EARLY STRENGTHS

Batch	Cure	Age	Str. (psi)
B5	Moist	3 d	7,820
B2	Steam	18 hr	7,840
B2	TMC	18 hr	8,230

STRENGTH vs. AGE



PERMEABILITY

Batches	PC (lb/yd^3)	SF lb/yd^3)	w/cm	Perm. (coul)
B1, B2 Steam cured	752	52	0.32	272
B5, B6 Moist cured	752	52	0.32	183
B7 Comparison	752	0	0.37	4,985

DECK AND SUBSTRUCTURE PROPORTIONS (lb/yd^3)

Material	Substructure	Deck
PC	352	329
Slag	234	329
CA	1,776	1,773
FA	1,258	1,173
w/cm	0.44	0.40

ULTIMATE 28-DAY STRENGTHS

Batch	Avg. Measured (psi)	Desired Min. (psi)
Substructure	5,930	3,000
Deck	8,720	4,000

PERMEABILITY

Batch	Cure (^oF)	Coulombs
Substructure (Slag = 40%)	73	1,616
	73 + 100	1,094
Deck (Slag = 50%)	73	1,442
	73 + 100	778

ROUTE 629 BRIDGE
MIX PROPORTIONS (lb/yd^3)

Material	Amount
PC	510
Slag	340
CA	1,950
FA	988
w/cm	0.33
Air (%)	5.5$\pm$1.5

ROUTE 629 BRIDGE

Property	1 Day	28 Day
Comp. Str. (psi)	6,540	8,900
Perm. (coulombs)		430

ROUTE 10 BRIDGE MIX PROPORTIONS (lb/yd^3)

Material	Amount
Cement	510
Slag	340
CA	1,873
FA	988
Calcium nitrite	2 gal
w/cm	0.33

ROUTE 10 BRIDGE

Age (d)	Str. (psi)
1	7,040
28	9,950

TELEGRAPH ROAD BRIDGE MIX PROPORTIONS (lb/yd^3)

Material	A3	A4
Cement	294	329
Slag	294	329
CA	1,786	1,786
FA	1,207	1,157
Water	263	250
w/cm	0.45	0.38

TELEGRAPH ROAD BRIDGE

Concrete	Strength (psi)	Permeability (coulombs)
Substructure	6,438	2,147
Deck	6,690	983

VIRGINIA HPC SPECS (Richlands)

Property	Age	Beam	Deck
Air (%)		4 to 7	5 to 8
Min. Comp. Str. (psi)	28 d release	10,000 6,600	6,000
Max. perm. (coulombs)	28 d	1,500	2,500

VIRGINIA MIX PROPORTIONS
Richlands (lb/yd^3)

Material	Beam	Deck
Cement	752	560
Class F Fly Ash	----	140
Silica Fume	75	---
CA.	1,671	1,724
FA	1,350	1,004
w/cm	0.28	0.45

RICHLANDS BEAMS

Property	B1	B2
1-d strength (psi)	9,820	9,580
28-d strength (psi)	10,510	10,910
E (10^6 psi)	6.3	5.9
Splitting tensile (psi)	820	830
28-d permeability (coulombs)	122	127

RICHLANDS DECK CONCRETE

Property	B1	B2
7-d strength (psi)	4,160	4,360
28-d strength (psi)	6,150	6,380
E (10^6 psi)	5.12	5.36
Splitting tensile (psi)	570	645
28-d permeability (coulombs)	1,261	1,375

NEBRASKA HPC SPECS

Property	Age (d)	Beam	Deck
Air (%)		No AEA	5 to 7.5
Min. Comp. Str. (psi)	56 release	12,000 5,500	8,000
Max. Perm. (coulombs)	56	-------	1,800

NEBRASKA MIX PROPORTIONS (lb/yd^3)

Material	Beam	Deck
Cement	750	750
Class C Fly Ash	200	75
Silica Fume	50	---
CA	1,860	1,400
FA	990	1,400
w/cm	0.24	0.30

NEBRASKA RESULTS

Property	Age (d)	Beam	Deck
Comp. Str. (psi)	56	13,960	9,150
E (10^6 psi)	56	6.28	5.44
Flex. Str. (psi)	56	1,707	885
Splitting Tensile (psi)	56	733	611
Perm. (coulombs)	28	334	589
Wear (in)[30 min		0.024	0.033
60 min]		0.040	0.059

NEW HAMPSHIRE HPC SPECS

Property	Age (d)	Beam	Deck
Air (%)		5 to 8	6 to 9
Min. Comp. str. (psi) release	28	8,000 6,500	6,000
Max. Perm. (coulombs)	56	1,000	1,000

NEW HAMSHIRE MIX PROPORTIONS (lb/yd^3)

Property	Beam	Deck
Cement	777	607
Silica Fume	50	53
CA	1,850	1,815
FA	1,075	1,190
w/cm	0.35	0.38

NEW HAMPSHIRE RESULTS

Property	Beam	Deck
w/cm	0.36 to 0.42	0.39 to 0.40
Comp. str. (psi)	6,862 to 8,780	8,163 to 9,010
Permeability (coulombs)	1,280 to 1,855	609 and 896

OHIO HPC SPECS

Property	Age (d)	Beam
Air (%)		AEA
Min. Comp. str. (psi)	56 release	10,000 6,000
Max. Perm. (coulombs)	56	1,000

OHIO MIX PROPORTIONS (lb/yd^3)

Material	Beam
Cement	846
Silica Fume	100
CA	1,774
FA	927
w/cm	0.28

OHIO RESULTS

Property	Age (d)	Beam
Comp. Str. (psi)	18 hr	8,000
	56	11,700
E (10^6 psi)	56	4.65
Flex. Str. (psi)	28	1,300
Splitting Tensile (psi)	28	660
Perm. (coulombs)	28	380

TEXAS HPC SPECS

Property	Age (d)	Beam
Air (%)		No AEA
Min. Comp. Str. (psi)	56	13,100
	1	8,800
Max. Perm. (coulombs)	56	1,000

TEXAS MIX PROPORTIONS (lb/yd^3)

Material	Beam	Deck
Cement	671	473
Class C Fly Ash	316	221
CA	1,918	1,811
FA	1,029	1,811
w/cm	0.25	0.35

TEXAS RESULTS

Property	Age (d)	Beam	Deck
Comp. Str. (psi)	16-21 hr	8,690	
	28	13,900	9,220
	56	15,200	
E (10^6 psi)	28	6.00	4.73
	56	7.00	
Splitting Tensile (psi)	56	940	725
Perm. (coulombs)	28	560	900

WASHINGTON HPC SPECS

Property	Age	Beam
Air (%)		No AEA
Min. Comp.	56	10,000
d		7,400
Str. (psi)		
release		
Max. Perm.	56 d	1000
(coulombs)		

WASHINGTON MIX PROPORTIONS (lb/yd^3)

Material	Beam
Cement	728
Class C Fly Ash	222
Silica Fume	50
CA	1,870
FA	890
w/cm	0.26

WASHINGTON RESULTS

Property	Age	Beam
Comp. Str. (psi)	56 d	11,140 to 12,910 Avg. 12,117
Release (psi)	22 hr	7,160 to 8,400 Avg. 7,755

CONCLUSIONS

- Low permeability is emphasized for durability.
- Air entrainment is needed in concretes exposed to freezing and thawing.
- Low-permeability and high strength concretes can be obtained with locally available materials using pozzolans or slag with low w/cm.
- Control retardation and temperature for high early and high ultimate strengths.

QUALITY CONTROL

Celik Ozyildirim

Virginia Transportation Research Council, VDOT

TESTING

- Mixes must be tested to ensure properties are achieved.

- Lab mixes
- Field mixes

MAKING AND CURING

- **Follow standard procedures in batching, mixing, placing, and curing:**
  - **For strength, lab specimens kept moist at 73F, field specimens 60F to 80F up to 48 hours then 73F**

FRESH CONCRETE

- **Slump**
- **Air content**
- **Temperature**
- **Unit weight**
- **Time of setting**

HARDENED CONCRETE

- Compressive strength
- Modulus of elasticity
- Flexural strength
- Splitting tensile strength
- Permeability
- Freezing and Thawing
- Drying shrinkage

ADDITIONAL TESTS

- Maturity
- Surface air flow
- AC impedance
- Impact echo
- Thermal coefficient of expansion
- Creep
- Abrasion resistance

TEST AGE

- **Acceptance at 28 days?**
- **Is 56 days acceptable?**

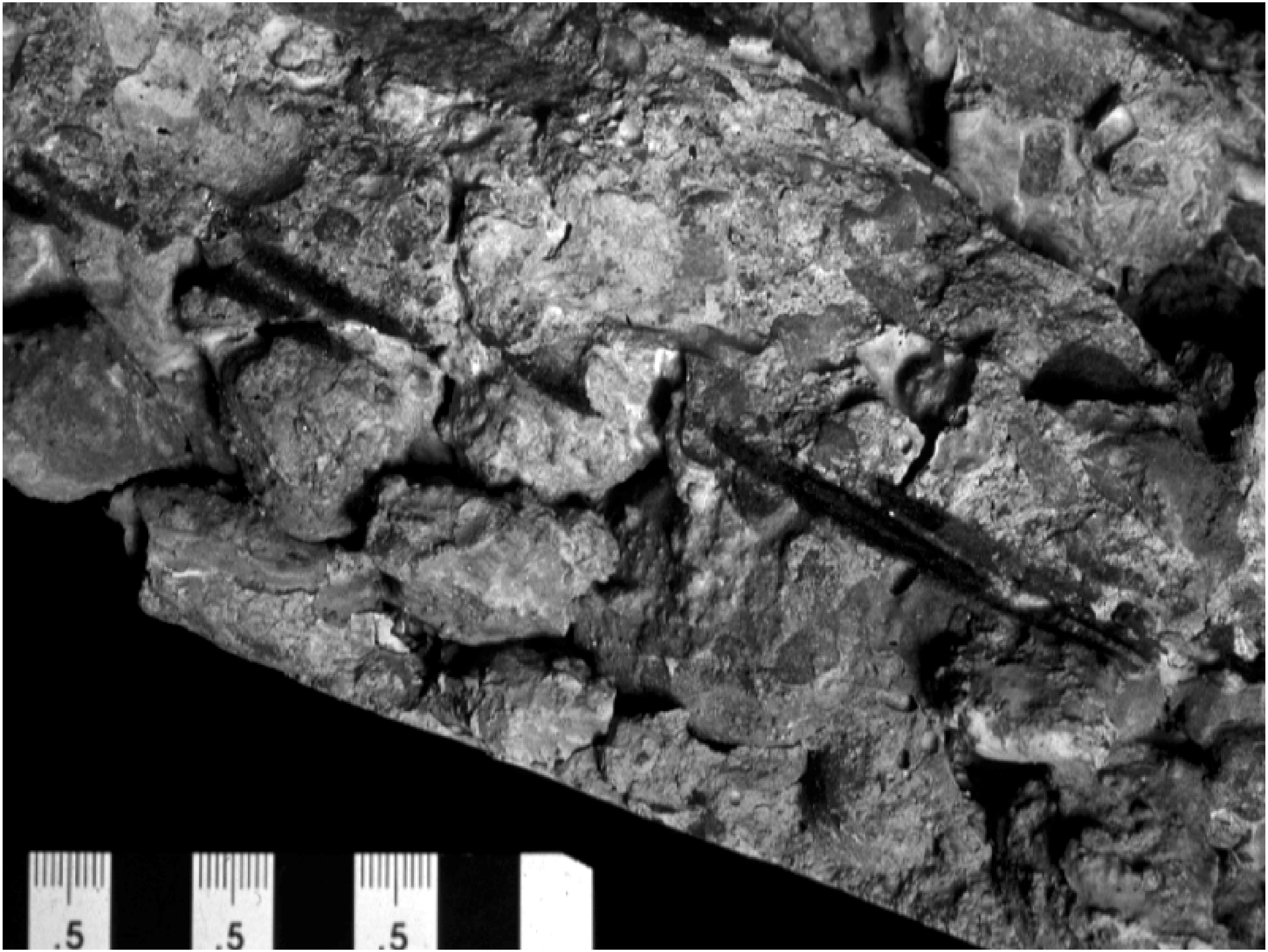
SPECIMEN SIZE, CAPPING, AND LOADING

- **6X12 versus 4x8**
- **Unbonded capping, grinding**
- **Load to failure**

FIELD TRIALS

- Produce large size concrete mixes at the plant.

- Produce large size elements even though they may not be the exact size.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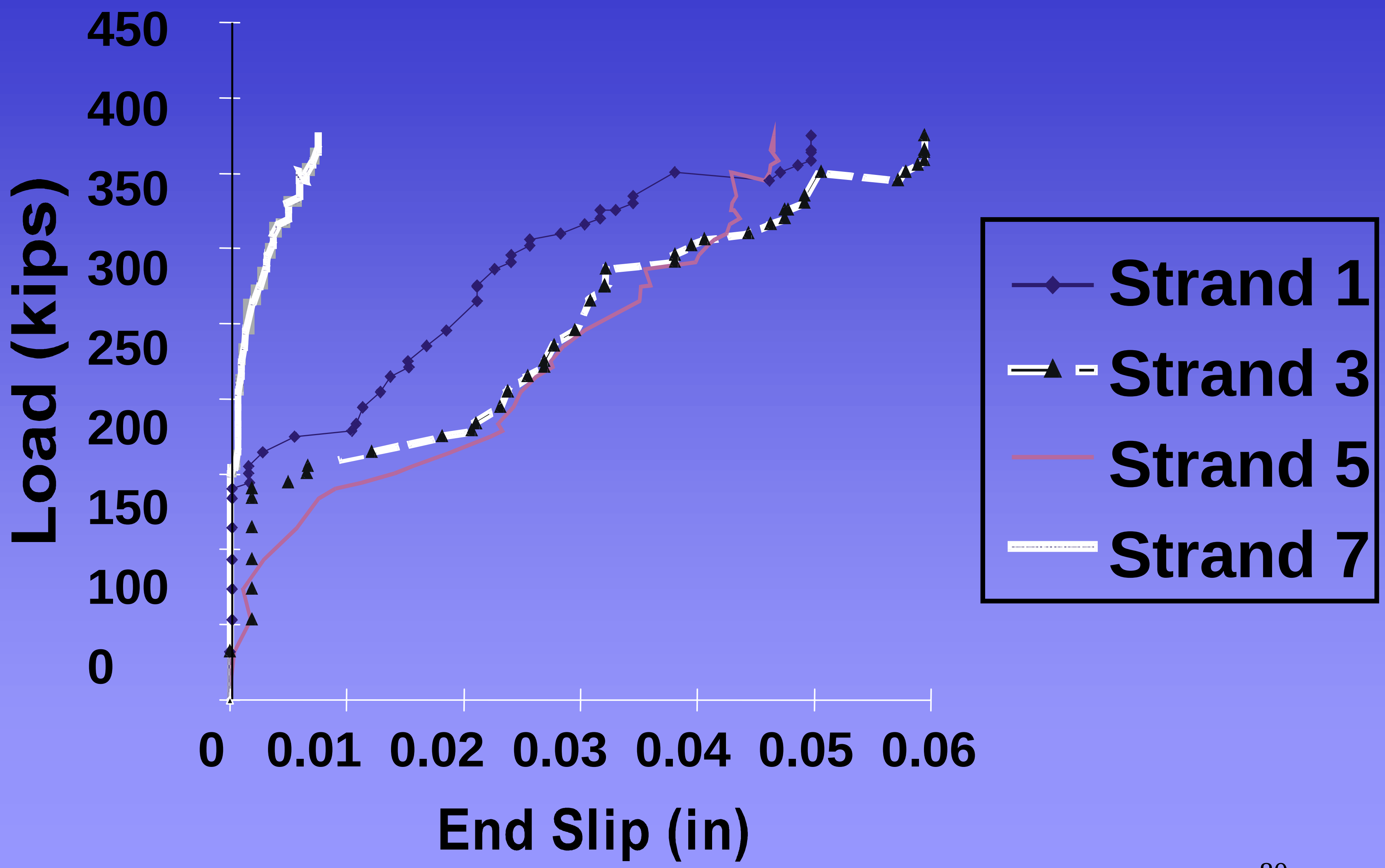
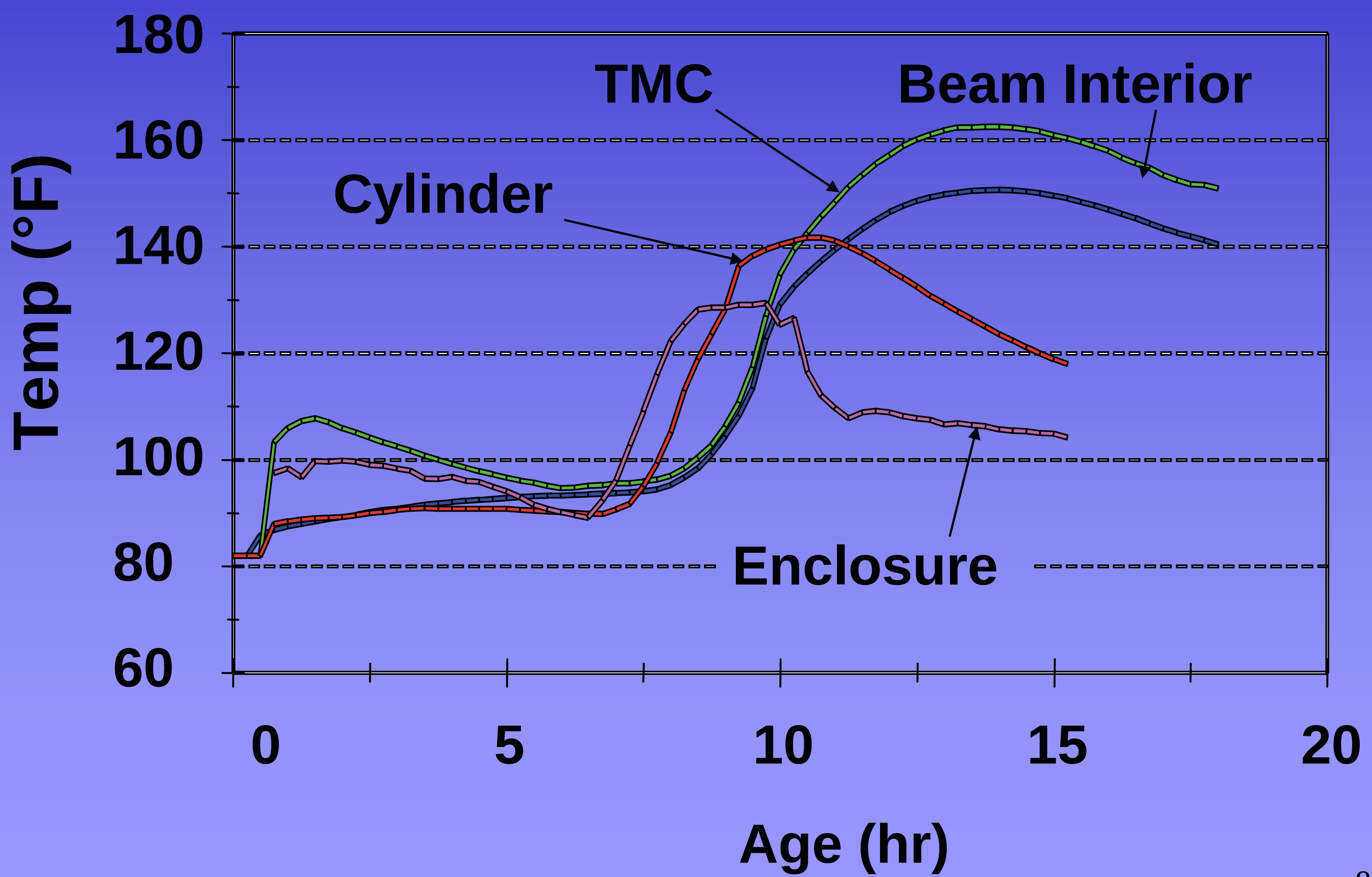
END SLIP READINGS: FIRST TEST



STEAM-CURED BEAM



STEAM CURED-BEAM

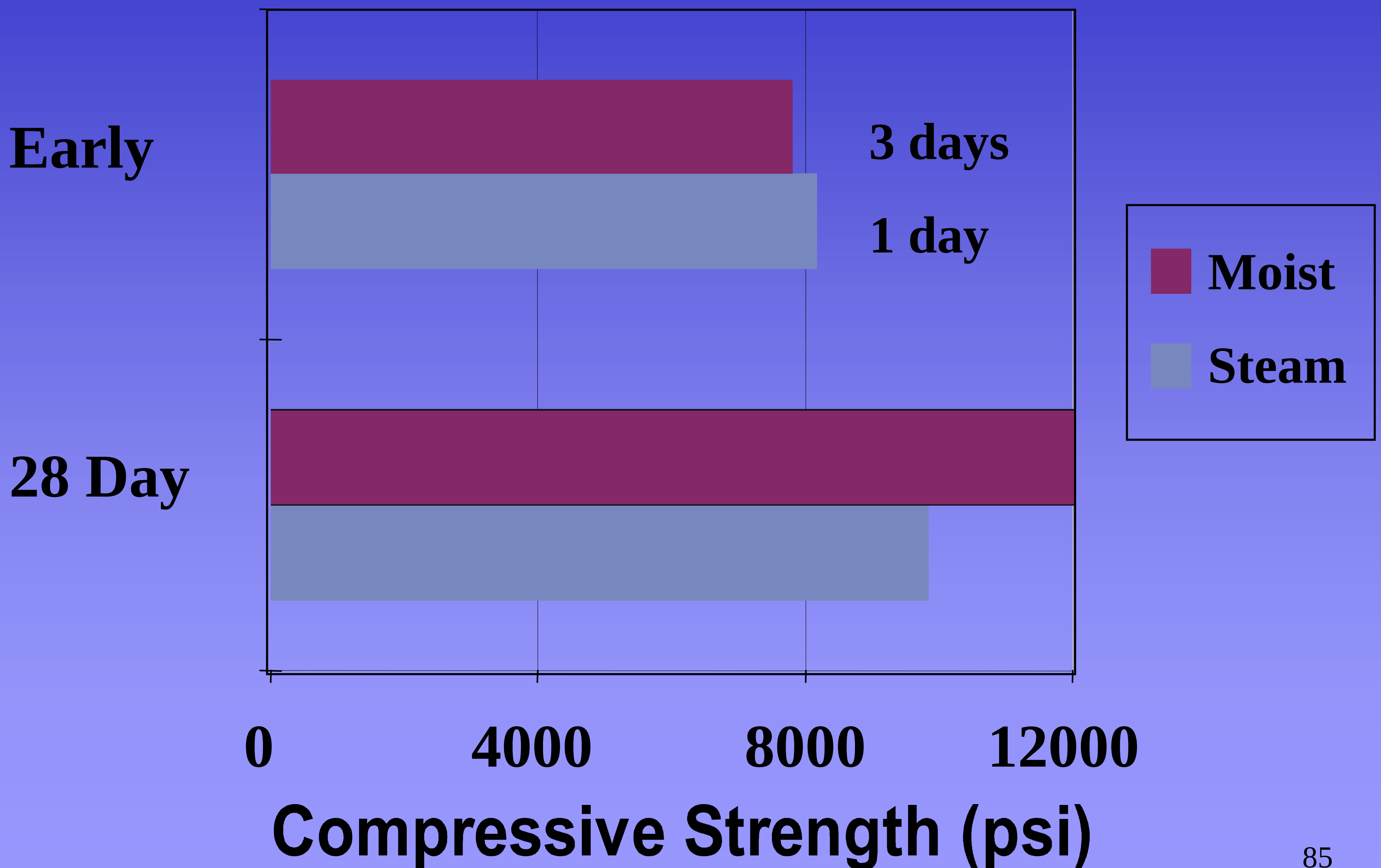
PC=611 lb/yd^3, SF=45, W/CM=0.33, Air=7.5%

AGE	CURE	STR (psi)
19 hr	TMC	8,070
19 hr	Stm	5,850
28 d	Stm+Air	9,190

EARLY STRENGTHS (psi)

	B1	B2	B3	B4
Portland cement (lb/yd^3)	752	752	611	611
Silica fume (lb/yd^3)	53	53	45	45
TMC 1-day strength	8430	8230	8040	8070
Steam cured 1-day strength	8170	7840	6010	5850

STRENGTH vs. AGE



CONCLUSIONS

- Test small scale lab trial batches

- Test large scale field mixes and test elements

IMPLEMENTING HIGH-PERFORMANCE CONCRETE

Celik Ozyildirim

Virginia Transportation Research Council,
VDOT

CHALLENGES

- Increased traffic volume
- Increased traffic loads
- More deicers
- Longer service lives

TYPES OF DISTRESS

- Corrosion of steel
- Alkali-aggregate reactivity
- Freeze-thaw damage
- Sulfate attack

ACHIEVEMENT OF HPC

- Structural design
- Materials
- Construction practices

DESIGN

- Provide adequate cover
- Minimize exposure to the environment
  – avoid leaking joints, provide drainage
- Control cracking
  – minimize skews and flexible spans

MATERIALS

- Low w/cm
- Pozzolans (fly ash, silica fume) or slag

DIRECT PERMEABILITY TESTS

- Water permeability
- Ponding

- Difficult, time-consuming

INDIRECT PERMEABILITY TEST

Rapid chloride permeability test (RCPT) (AASHTO T 277, ASTM C 1202):

- Measures electrical conductance of concrete
- Convenient

QUESTIONS ON RCPT

- Does RCPT indicate permeability?
- Does RCPT correlate with direct permeability tests?

MODIFICATIONS TO RCPT

- Measure concentration of chlorides in the solution.
- Determine chloride penetration by colorimetric method.

COLORIMETRIC METHOD

- Spray with silver nitrate.
- Color change indicates depth of chloride penetration.

CONSTRUCTION PRACTICES

- Batching
- Mixing
- Transportation
- Placement
- Consolidation
- Finishing
- Curing

SPECIFICATIONS

- Method type
- Quality assurance
- Performance-related

PRESENT SPECIFICATIONS

- Air content, slump, temperature
- Minimum cement content
- Maximum *w/cm*
- Minimum compressive strength

NEW SPECIFICATIONS

- Quality assurance
- Performance-related

INSPECTION AND TESTING

Pennies now
or
dollars later!

Performance Parameters

Field Conditions	Definition Parameters
• **Climatic** – **Temperature** – **Moisture**	• **Freezing/ thawing**
• **Ambient** – **salts** – **chemicals**	• **Scaling** • **Permeability**
• **Loading** – **traffic / applied** – **wind**	• **Abrasion / f'c/E** • **Shrinkage/creep**

Durability Definition Parameters

Performance	Grade 1	Grade 2	Grade 3	N/A
F / T	60≤X<80%	80≤X		
Scaling	X = 4,5	X = 2,3	X = 0,1	
Abrasion	2>X ≥1	1>X ≥0.5		
Perm.	3000≥X X >2000	2000≥X X>800	800≥ X	

Strength Definition Parameters

Performance	Grade 1	Grade 2	Grade 3	Grade 4
Strength	$41 \le x < 55$ MPa	$55 \le x < 69$ MPa	$69 \le x < 97$ MPa	$x \ge 97$ MPa
Elasticity	$28 \le x < 40$ GPa	$40 \le x < 50$ GPa	$x \ge 50$ GPa	
Shrinkage	$800 > x \ge 600$	$600 > x \ge 400$	$400 \ge x$	
Creep	$75 \ge x > 60$ MPa	$60 \ge x > 45$ MPa	$45 \ge x > 30$ Mpa	30 MPa $\ge x$

Freeze/Thaw Durability

AASHTO T 161

ASTM C 666 Procedure A

Grade	Performance
1	60% < X < 80%
2	80% < X

X = relative dynamic modulus of elasticity after 300 cycles

Freeze/Thaw Durability

Grade	Exposure
N/A	X < 3
1	3 < X < 50
2	50 < X

X = Freeze Thaw cycles per year

HPC IMPLEMENTATION

- **Project needs**
- **Mixture Specifications**
- **Quality control**

Module 3
Construction

Prepared by:
Mary-Lou Ralls, P.E.

CONSTRUCTION
TOPICS

Communications

Construction Documents

Concreting Practices

QC/QA for cast-in-place HPC

COMMUNICATIONS

PRE-BID MEETING

Presentation of Innovations

(who, what, when, where, why)

- Owner
- Researchers
- FHWA

Specification changes

Discussion / Q & A

PARTICIPANTS

- Contractor
- Subcontractors
- Researchers
- FHWA
- Owner

PARTNERING

- Specification
- Workshops
  - Initial Team Building
  - Follow-up (as needed)
  - Close-Out
- Voluntary basis
- Shared expenses

INITIAL TEAM-BUILDING WORKSHOP

- Third-party facilitator
  - Selected by contractor
- Content
  - Team-building
  - Issues
- Action Plans

PRE-CONSTRUCTION MEETING

- Contractor's construction schedule
- Review of variations from standard practice
- Research activities
  - Details
  - Coordination
- Discussion / Q & A

COMMUNICATIONS

Pre-Bid Meeting

(1-2 week before letting)

Partnering Workshop

(1-2 months after letting)

Pre-Construction Meeting

(1 month after Partnering Workshop)

COMMUNICATIONS AS NEEDED

Conference calls

Meetings

Action Plans

(who, what, when)

CONSTRUCTION DOCUMENTS

Standard Specifications & Special Specifications

Contract Plans

General Notes and Specification Data

Special Provisions

CONSTRUCTION DOCUMENTS

Coordination of Work with Contractor

Identification of HPC members

HPC Mix Development

Laboratory & Field Testing

Structure Monitoring

EXAMPLES OF CHANGES TO CONSTRUCTION SPECIFICATIONS

- Waiver on maximum slump
- Researcher designation of admixture types
- Permeability specimens
- Project acceptance at 56 days for high-strength HPC
- Additional strength specimens

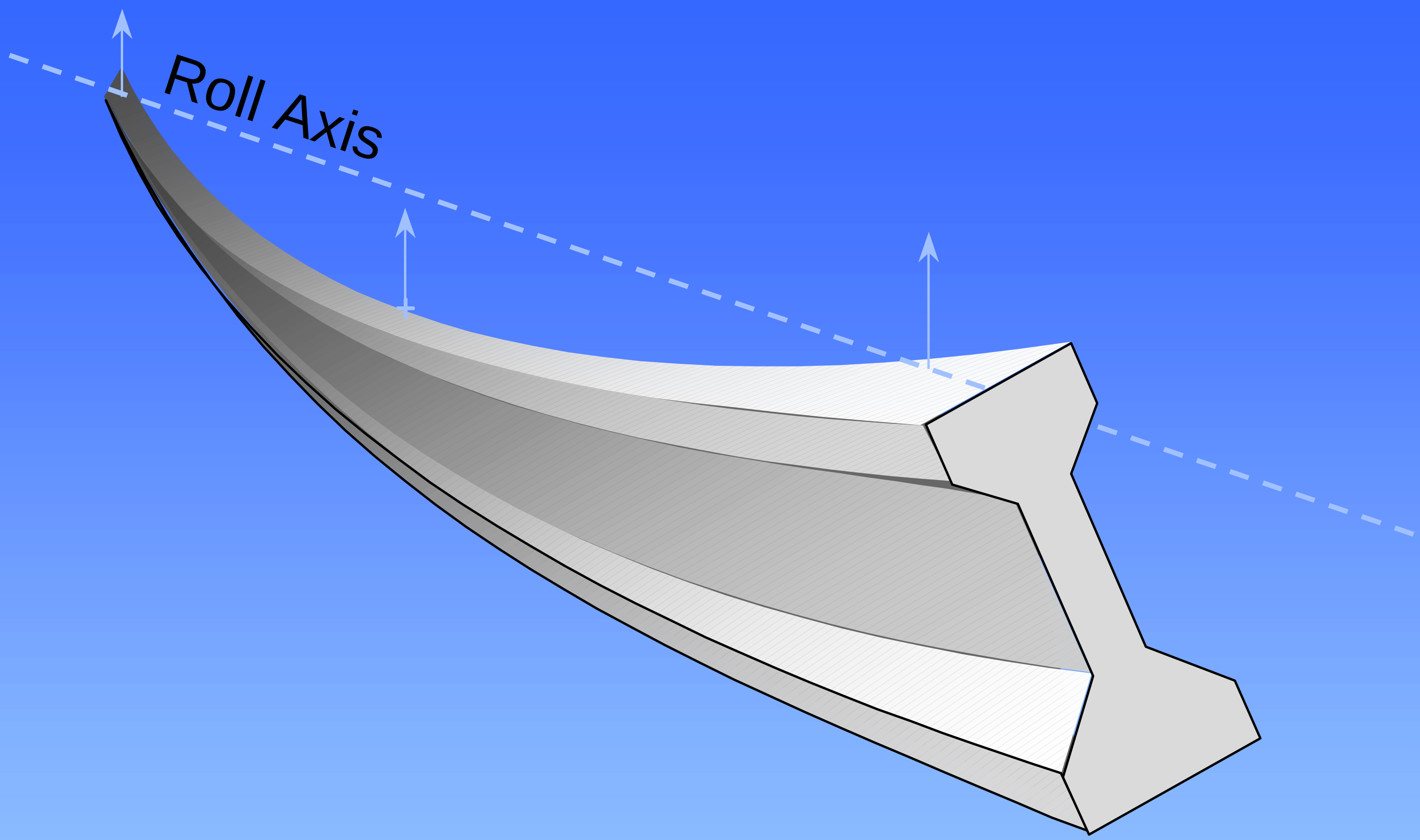
CONSTRUCTIBILITY

Placement

Workability

Finishability

Curing



Perspective of a Beam Free to Roll and Deflect Laterally


CAT


OVERSIZE LOAD


LINK-BELT

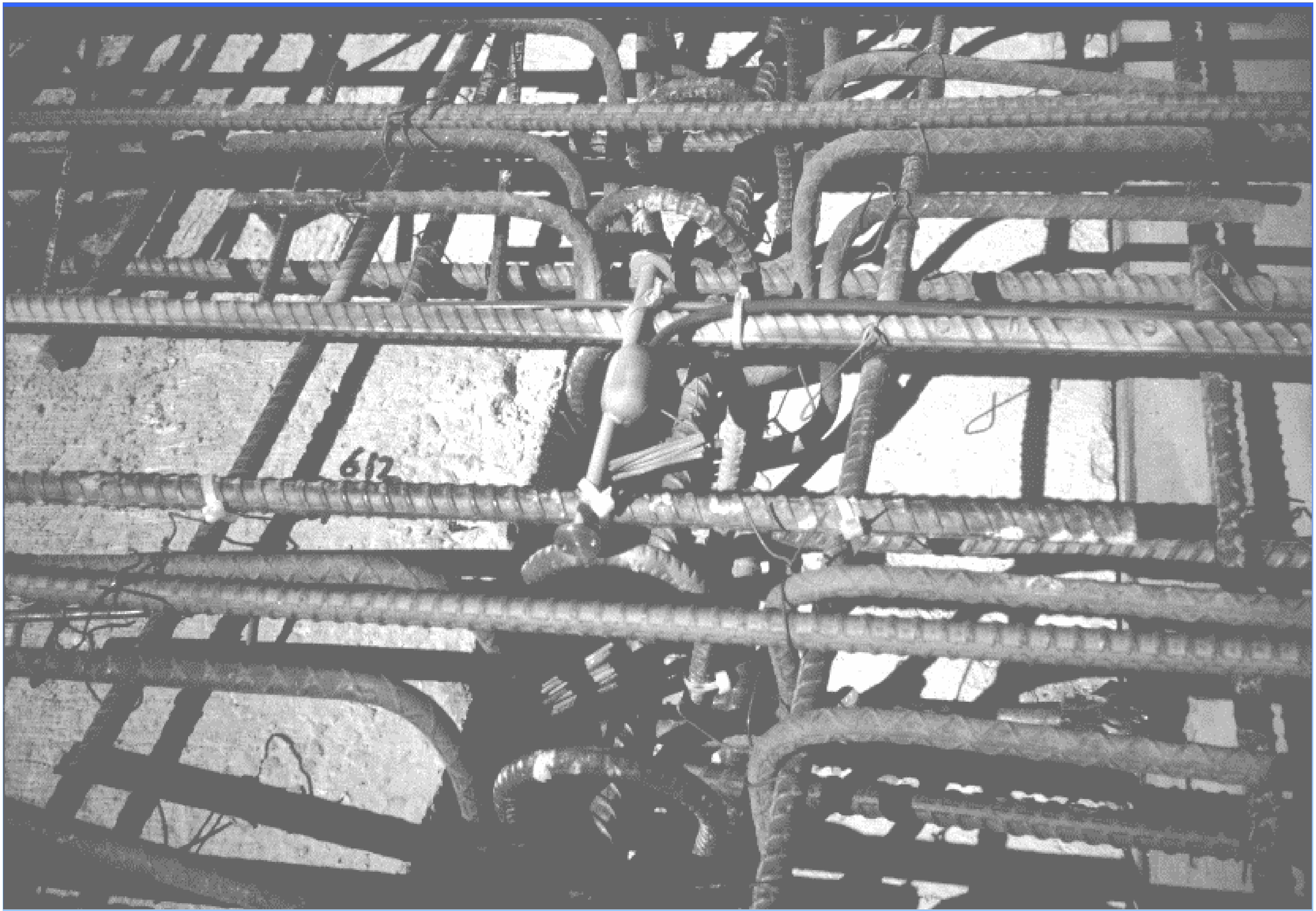

63

conventional 0.5-inch diameter strands
& normal-strength concrete

7 beams
Span No. 1
San Angelo Westbound Mainlanes

0.6-inch diameter strands
& high-strength HPC concrete

4 HPC beams
Span No. 1
San Angelo Eastbound Mainlanes


612


BIDWELL

Louetta Road Overpass
Houston

North Concho River, US 87, & South Orient RR Overpass
San Angelo

Module 4

Cost Estimating and
Life-Cycle Cost Analysis

Prepared by:
M. Myint Lwin

Purpose

- **Cost data and Methods**
- **Initial Cost**
- **Life-Cycle Cost**

Types of Cost Estimates

- **Project Cost Estimate**
  - Square Foot Cost
  - Square Foot Superstructure Cost
  - Square Foot Substructure Cost
  - Preliminary Quantity and Unit Price

Examples

- **Square Foot Cost**
  - **P.S. Girder Bridges - 80 to 140 feet spans:**
    - **Water Crossing with Pile Footings: $55 - $100 /SF**
    - **Water Crossing w/ Spread Footings: $50 - $90 /SF**
    - **Dry Crossing with Pile Footings: $50 - $90 /SF**
    - **Dry Crossing with Spread Footings: $45 - $80 /SF**

Example

- **Unit Prices**
  - **Steel reinforcing bars** **$0.35 - $0.50/lb.**
  - **Epoxy coated rebars** **$0.45 - $0.70/lb.**
  - **Concrete for bridge deck** **$350 - $500/cy**
  - **Concrete for substructure** **$250 - $350/cy**
  - **P.S. Girders (60' to 100')** **$100 - $115 /LF**
  - **P.S. Girders (100' to 150')** **$110 - $135 /LF**

Types of Cost Estimates

- **Contract Cost Estimate**
  - **Materials**
  - **Equipment**
  - **Labor**
  - **Overhead**
  - **Profit**

Example

Concrete Cost:

- **Normal Mix (5.5 sack)**

5.0 sack	**$55.00**
0.50 sack	**$ 2.30**
Total	**$57.30 x 770 cy = $44,121**

- **HPC Mix (5.0 sack, fly ash, mid-range plasticizer)**

5.0 sack	**$55.00**
80 lbs. Fly ash	**$ 2.00**
Mid-range plasticizer	**$ 3.76**
Total	**$60.76 x 770 cy = $46,785**

Example

Pump Cost:

- **Normal Mix**

30 cy/hour @ 4" slump

770 cy/30 cy per hour	**= 25.7 hrs**
25.7 hours x $95.00/hour	**= $2,442**
770 cy x $2.00/cy pump cost	**= $1,540**
8 pours x $50/pour mobilization	**= $400**
Total	**= $ 4,382**

Example (continued)

- **HPC Mix**

  34.5 cy/hour at 5" to 7" slump

  770 cy/34.5 cy per hour = 22.3 hrs

  22.3 hours x $95.00/hour = $2,119

  770 cy x $2.00/cy pump cost = $1,540

  8 pours x $50/pour mobilization = $400

  Total = $ 4,059

Example (continued)

Placing Labor Cost

- **Normal Mix**

  Concrete placed at a 4" slump requires 3 persons

  3 persons x $40/hour = $120/hr

  $120/hour x 25.7 hours = $3,084

- **HPC Mix**

  Concrete placed at 5”-7" slump requires 2 persons

  2 persons x $40/hour = $80/hr

  $80/hour x 22.3 hours = $1,784

Example (continued)

Sacking Cost

- **Normal Mix**

  20,738 sq. ft. x $1.00/sq. ft. = $20,738

- **HPC Mix**

  20,738 sq. ft. x $0.50/sq. ft. = $10,369

Example (continued)

Summary

Mix	Normal Mix	HPC
• **Concrete Cost**	**$44,121**	**$46,785**
• **Pump Cost**	**$ 4,382**	**$ 4,059**
• **Placing Labor**	**$ 3,084**	**$ 1,784**
• **Sacking**	**$20,738**	**$10,369**
Total	$72,325	$62,997

Savings = $9,328 = $ 12.11/cy

Life-Cycle Cost

- **Initial Cost - Planning, Design, Construction**
- **Maintenance**
- **Repair**
- **Rehabilitation**
- **Disposal**

Long Term Monitoring

- FHWA HPC Demonstration Projects
  - Long-term performance
  - Design assumptions
  - Temperature
  - Deflection
  - Cost effectiveness

Mechanical Properties

Performance Characteristic	Standard Test Method	FHWA HPC Performance Grade			
		1	2	3	4
Strength (x = compressive strength)	AASHTO T 2 ASTM C 39	6<x<8 ksi	8<x<10 ksi	10<x<14 ksi	x>14 ksi
Elasticity (x = modulus of elasticity)	ASTM C 469	4<x<6x10^{6} psi	6<x<7.5x10^{6}	x>7.5x10^{6}	
Shrinkage (x = microstrain)	ASTM C 157	800>x>600	600>x>400	400>x	
Creep (x = microstrain/pressure unit)	ASTM C 512	0.52>x>0.41 /psi	0.41>x>0.31 /psi	0.31>x>0.21 /psi	

Durability Characteristics

Performance Characteristic	Standard Test Method	FHWA HPC Performance Grade			
		1	2	3	4
Freeze-Thaw Durability (x = relative dynamic modulus of elasticity after 300 cycles)	AASHTO T 161 ASTM C 666	60%<x<80%	80%<x		
Scaling Resistance (x = visual rating of surface after 50 cycles)	ASTM C 672	x=4.5	x=2.3	x=0.1	
Abrasion Resistance (x = average depth of wear in mm)	ASTM C 944	2.0>x>1.0	1.0>x>0.5	0.5>x	
Chloride Penetration (x = coulombs)	AASHTO T 277 ASTM C 1202	3000>x>2000	2000>x>800	800>x	

Constructability Issues
Potential for Cost Savings

- **Trial Concrete Mix Design**
- **Air Entrainment**
- **Curing of Concrete**
- **Quality Control and Quality Assurance**

Cost Effective Designs

- Engineering Properties of HPC
- Different Approach to Design
- New Standard Sections
- Input from Fabricators and Contractors

Cost Effectiveness

- **<u>Research Studies</u>**
- **Actual Bid Prices**
- **Life-Cycle Cost**

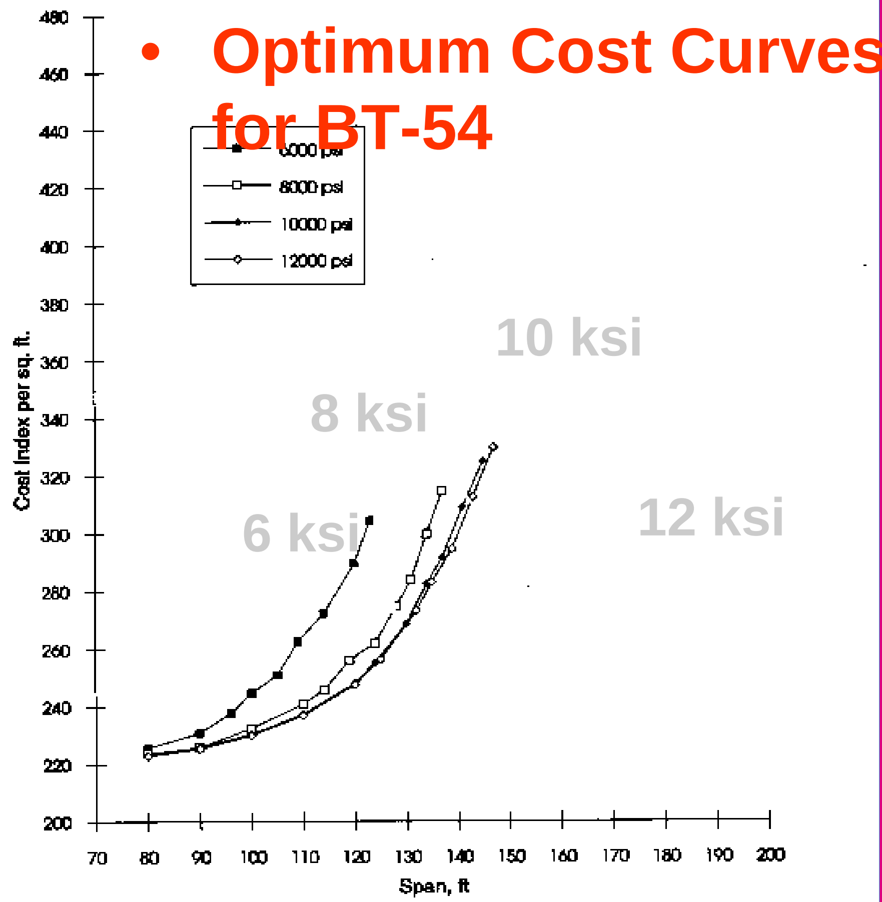


Figure 10. Optimum Cost Curves for a BT-54.

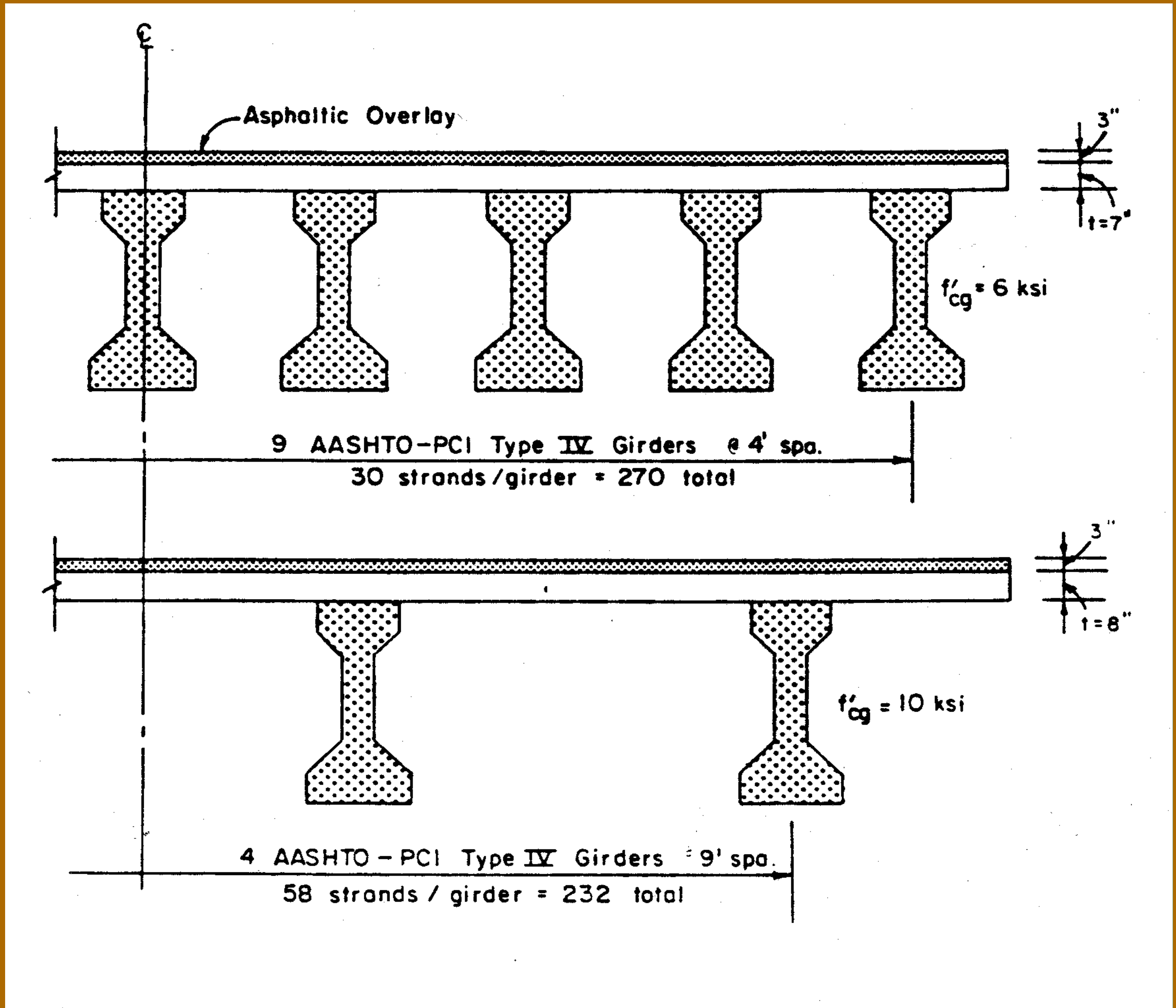
Ref: ***Russell, Volz and Bruce,*** **Fig. 10**

Effective Use of HPC

- Reduce weight by using fewer lines of beams
- Use shallow beams to solve vertical clearance Problems
- Increase span lengths to reduce number of piers
- Increase short- and long-term durability

Initial Cost Savings

- Use few beams or lines of girders
- Use longer beams or girders
- Use shallower members
- Combination of above



7"deck

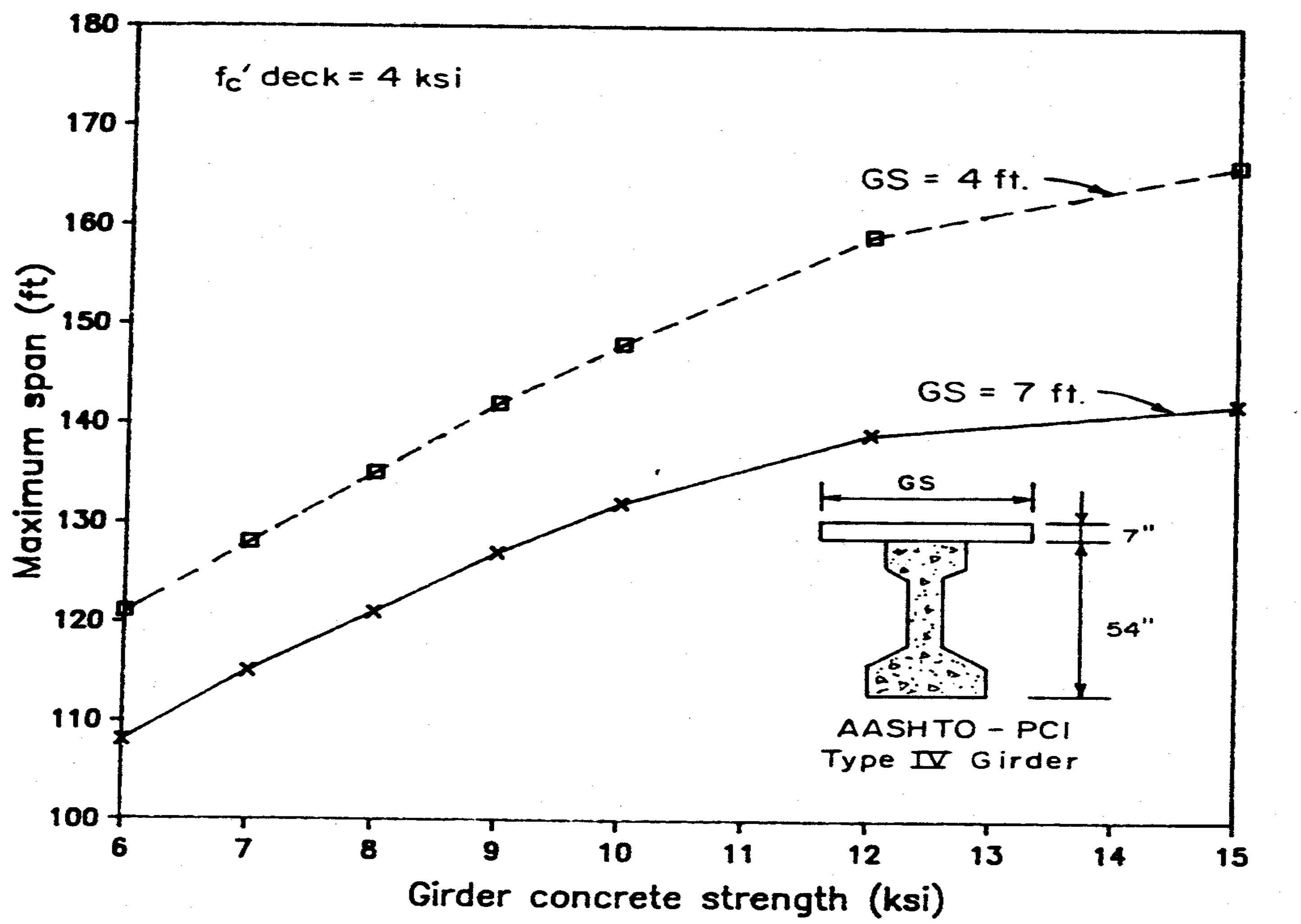
$f'_c = 6$ ksi

8" deck

$f'_c = 10$ ksi

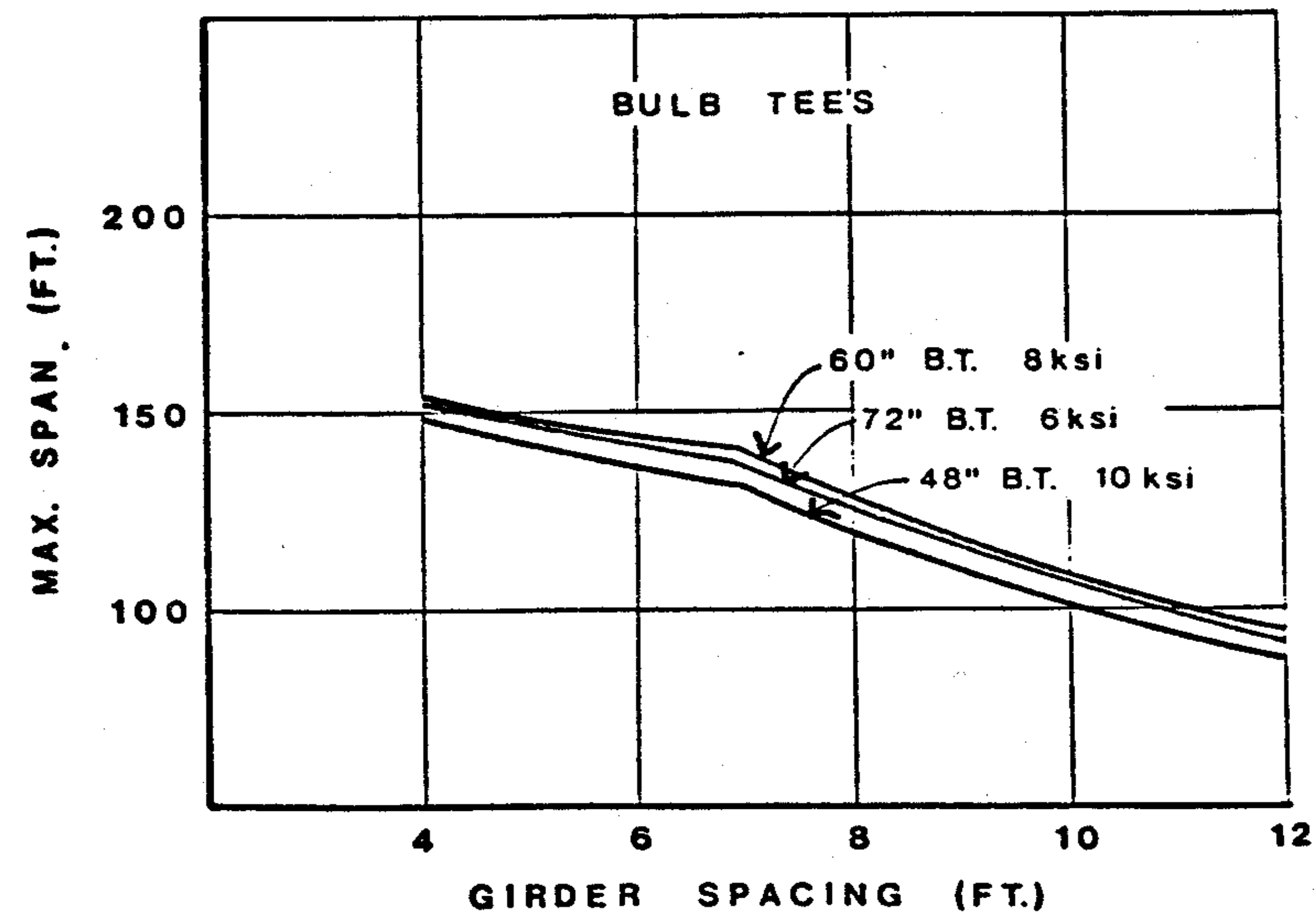
Ref: *Castrodale et al.*, Fig. 1.1

AASHTO Type IV Girder with 7" Deck



Ref: *Castrodale et al.*, Fig. 1.2

Depth Variations for Bulb-Tees with CIP Deck



(Reference: *Jobse*, Fig. 6)

Long-Term Cost Savings

- Freeze-thaw resistance
- Low permeability
- High abrasion resistance
- Scaling Resistance

Life-Cycle Cost Analysis

- **Definition**
  - **A process**
  - **Economic worth**
  - **Initial costs**
  - **Discounted future cost**
    - **maintenance, reconstruction, rehabilitation, restoring and resurfacing**
  - **Life of Project**

Life-Cycle Costs

- Initial Construction
- Operation
- Maintenance
- Repair
- Rehabilitation
- Disposal

Formula 1

- **Future cost (FC) is given by**

$$FC = C(1+i)^t \qquad (1)$$

Where C = present cost

i = inflation or deflation rate

t = number of years

Formula 2

- $PV = FC / (1 + d)^t$ (2)

Where d = discounted rate

t = number of years Present

value (PV) is given by

Bridge LCC

- **Developed by National Institute of Standard and Technology (NIST)**
- **For Bridge Designers**
- **For Comparing Cost Effectiveness of Alternatives**
- **Compare Life-Cycle Costs of 2 to 4 Alternatives**

Bridge LCC (Contd)

- **Computer System Requirements:**
  - **Windows™ 95/98 and NT**
  - **486-66 MHz,**
  - **8 Megabytes of RAM**
  - **15 megabytes of hard disk space**

Bridge LCC (Contd)

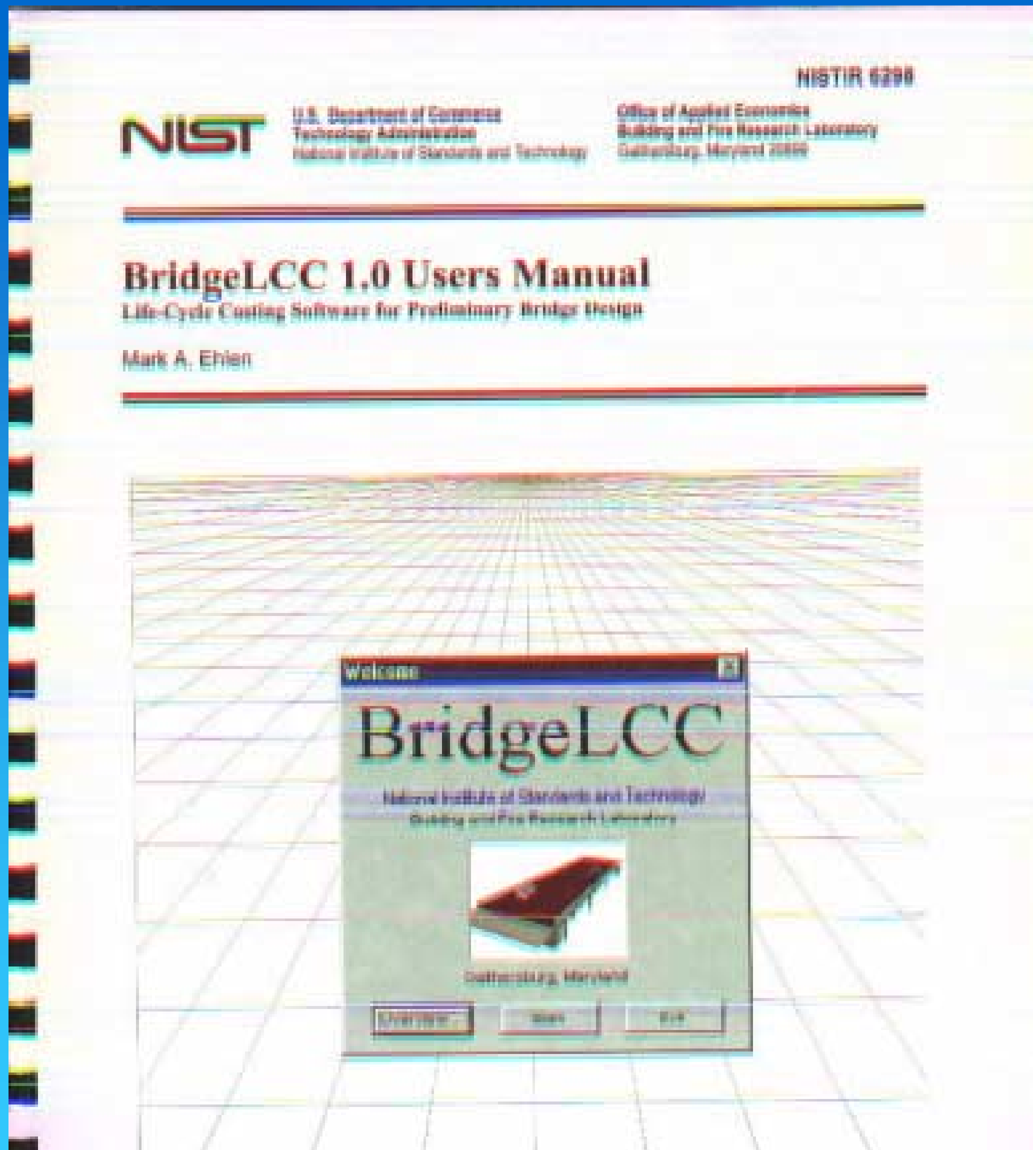
- Video card - 800 x 600 resolution or better
- On CD or download
- http://www.bfrl.nist.gov/BridgeLCC/welcome. html

Bridge LCC (Contd)

- **Applications:**
  - **Accept/Reject Decision**
  - **Material/Design Decision**
  - **Efficiency Level or Size Decision**

Bridge LCC (Contd)

- **Users Manual**
  - **Performing LCCA**
  - **Examples**
  - **First time users**
  - **http://www.bfrl.nist.gov/oae.html**


BridgeLCC 1.0 Users Manual
Life-Cycle Costing Software for Preliminary Bridge Design
Mark A. Ehlen
Welcome
BridgeLCC

Life-Cycle Cost Analysis for Bridges (BLCCA)

- NCHRP 12-43
- Started May 1996
- Methodology
- Guidance Manual
- Software with Users Manual
- Available early 2000

HPC Cost Data

State	Bridge			Deck		Beam		Substructure		Square Foot Cost	
	Length (Feet)	Main Span(Ft.)	Width (Ft.)	Strength psi.	Cost $/Unit	Strength psi.	Cost $/Unit	Strength psi.	Cost $/Unit	Superstr $/SF	Total $/SF
Alabama	>600	81-120	33-40								
Delaware	81-120	81-120	49-56		10/sf		35/sf		630/cy	64	197
Florida										26	49
Georgia											
Kentucky	301-400	81-120	49-56		363/cy						
Nebraska	181-240	80	>77		511/cy		720/cy				67
NewHamp.	80	80	57-68		545/cy		255/lf			59	
New York	80-600	80-180	26-77		21/sf						
N. Carolina											
S. Carolina											
Tennessee											39
Texas					9/sf		115/lf		413/cy	15-32	24-47
Virginia											50
Washington	241-300	121-180	33-40			10,000	153/lf			26	62
Wisconsin											

Concluding Remarks

- Think cost savings! Think HPC!
  - Design Flexibility
  - Long Service Life
  - Low Life-Cycle Cost

Module 5
Structural Design using HPC

By:

Maher Tadros

Topics

- **Introduction**
- **Girder Type Selection**
- **Materials**
- **Flexural Design**
- **Prestress Losses**
- **Ultimate Strength**
- **Shear Design**
- **Transfer & Development Length**
- **Deflection**
- **Continuity**

Introduction

BENEFITS OF HIGH PERFORMANCE CONCRETE

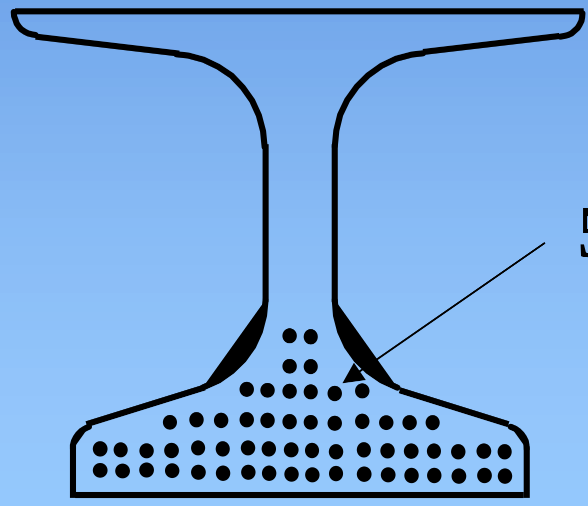
- Better Performance - Other than higher strength
- Better Performance - Related to higher strength

HIGH PERFORMANCE CONCRETE DECKS

- **Low permeability**
- **Low shrinkage**
- **High modulus of elasticity**
- **Better abrasion resistance**
- **Improved life cycle performance**

Example 1

Spacing = 12 ft
Slab thickness = 7 1/2”
Superimposed dead load on composite section = 40 psf
HS - 25 truck loading



58 - 0.6” low-relaxation strands

Interior Girder = NU1100

Example 1

When using high performance concrete:

f'_c at service = 12,000 psi

f'_{ci} at release = 9,500 psi

The bridge can span 95 ft, and

Bottom fiber stress at service

$= -620$ psi $< 6\sqrt{f'_c} = -657$ psi

Bottom fiber stress at release

$= 5689$psi $< 0.6\, f'_{ci} = 5700$psi

Example 2

When using normal strength concrete:

f'_c at service = 5,000 psi

f'_{ci} at release = 4,240 psi

The bridge can only span 68 ft, and

Bottom fiber stress at service

$= -398$ psi $< 6\sqrt{f'_c} = -424$ psi

Bottom fiber stress at release

$= 2543$psi $< 0.6\, f'_{ci} = 2544$psi

Girder Type Selection

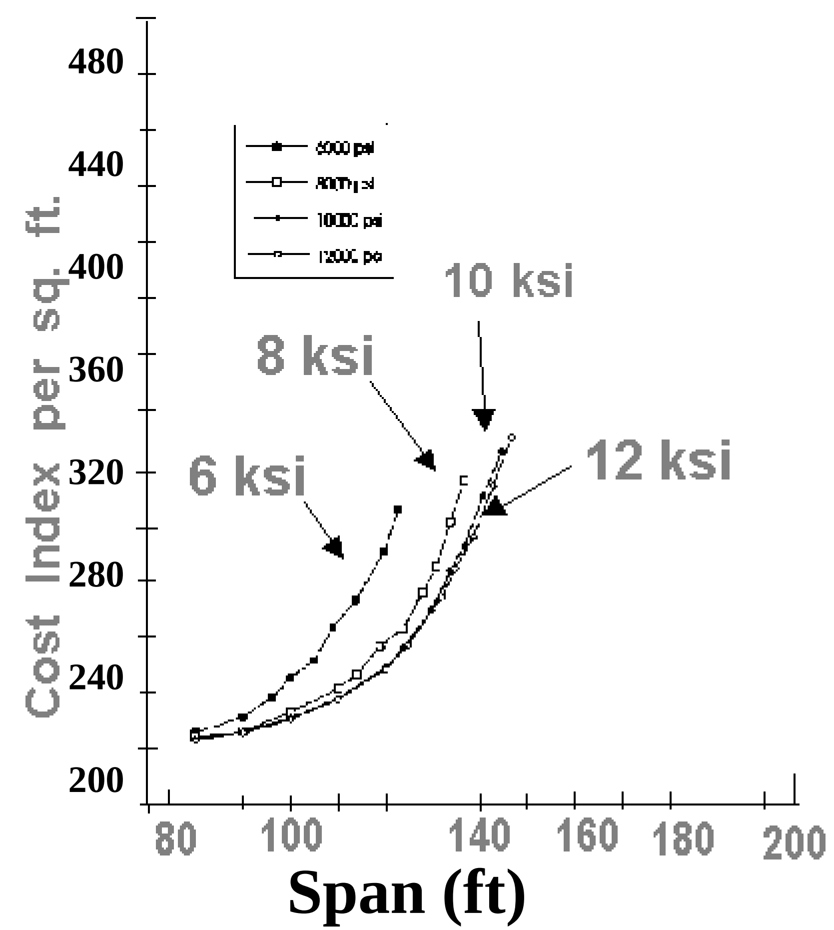
Features of an Efficient HPC Girder

- **Wide, Bulky Bottom Flange**
- **Wide, Shallow Top Flange**
- **Narrow Web**

Samples of HPC Girder

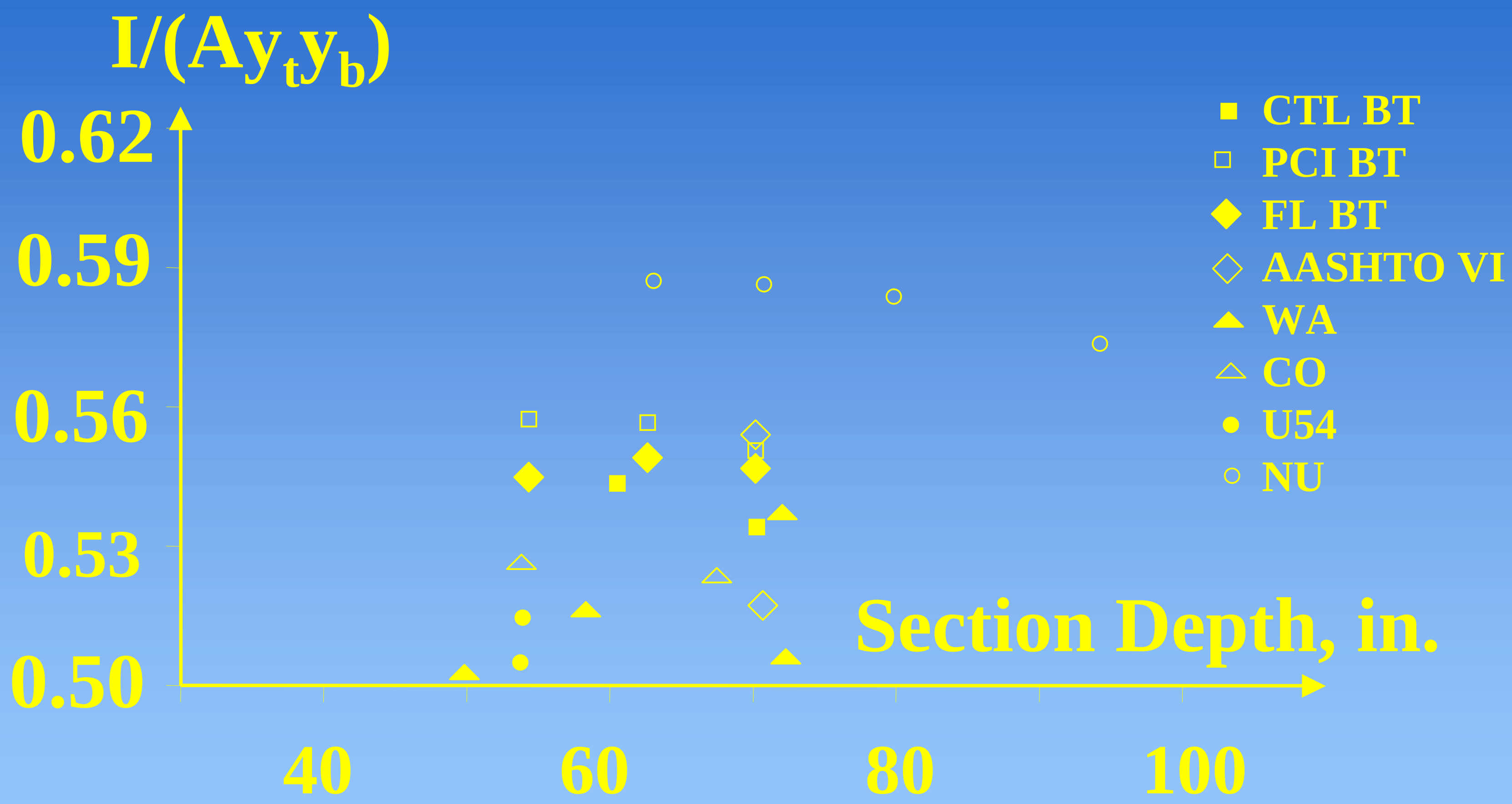
- **Florida Bulb Tee**
- **NU Girder**
- **Washington Bulb Tee**
- **Texas U Beam**
- **Colorado Box Section**

Optimum Cost Curves for BT-54



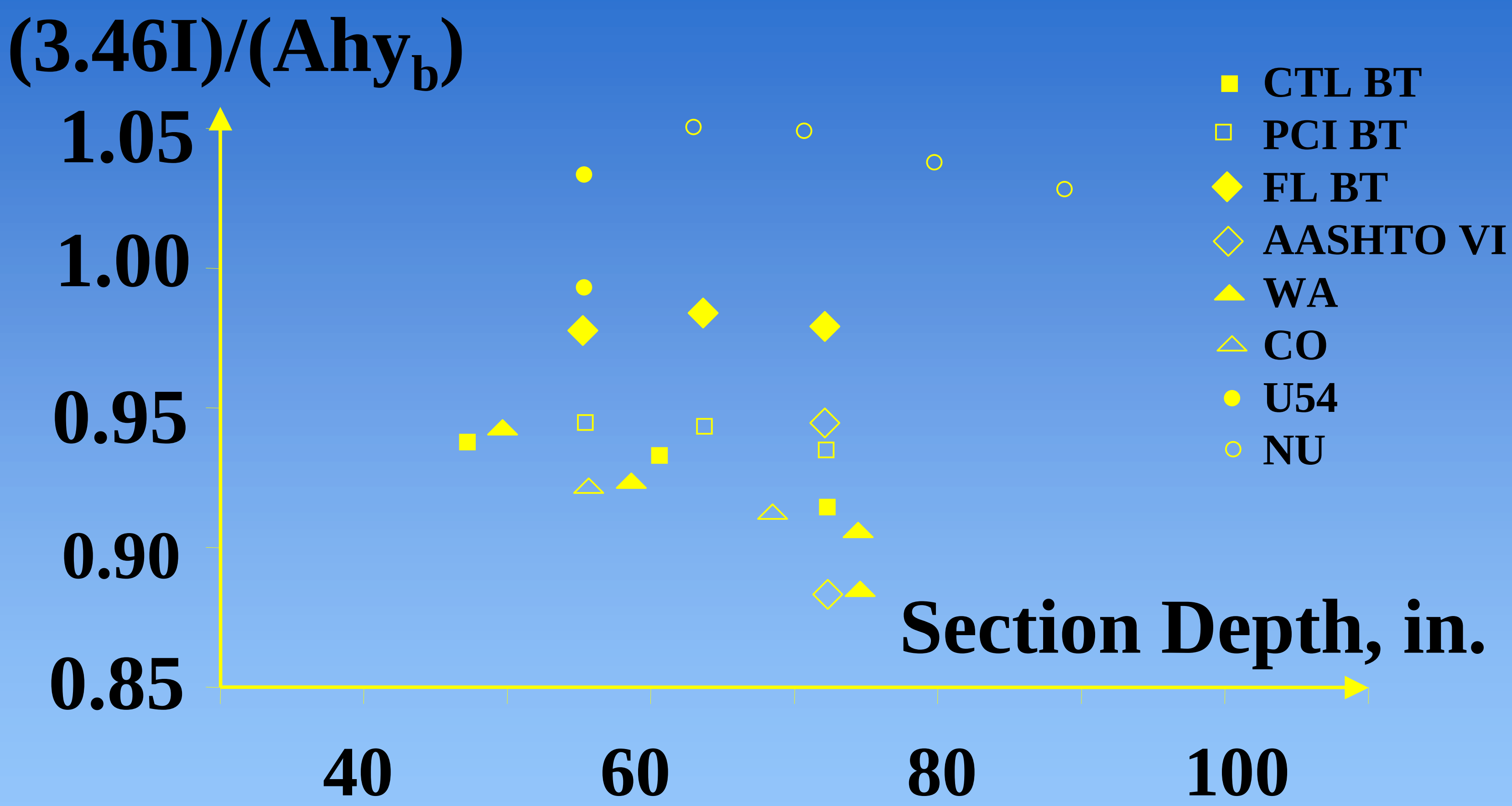
Ref: ***Russell, Volz and Bruce,*** **Fig. 10**

Variation of Guyon Efficiency Factor with Depth of Section

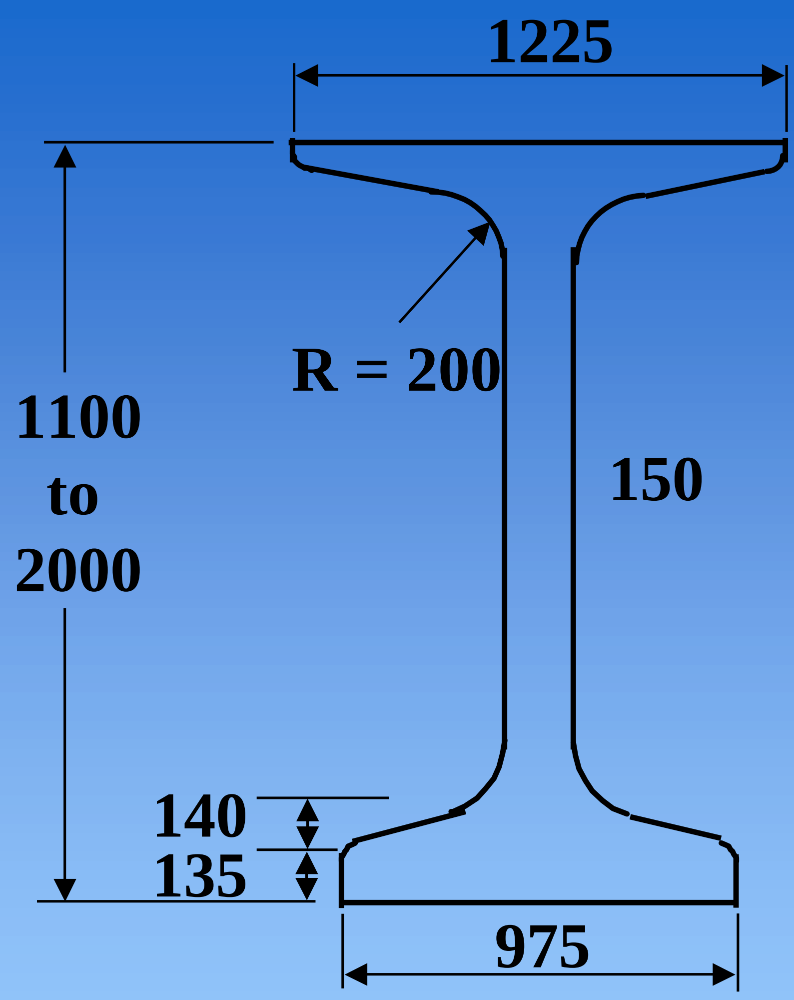


Ref: ***Russell, Volz and Bruce*****, Fig. 2**

Variation of Aswad Efficiency Ratio with Depth of Section

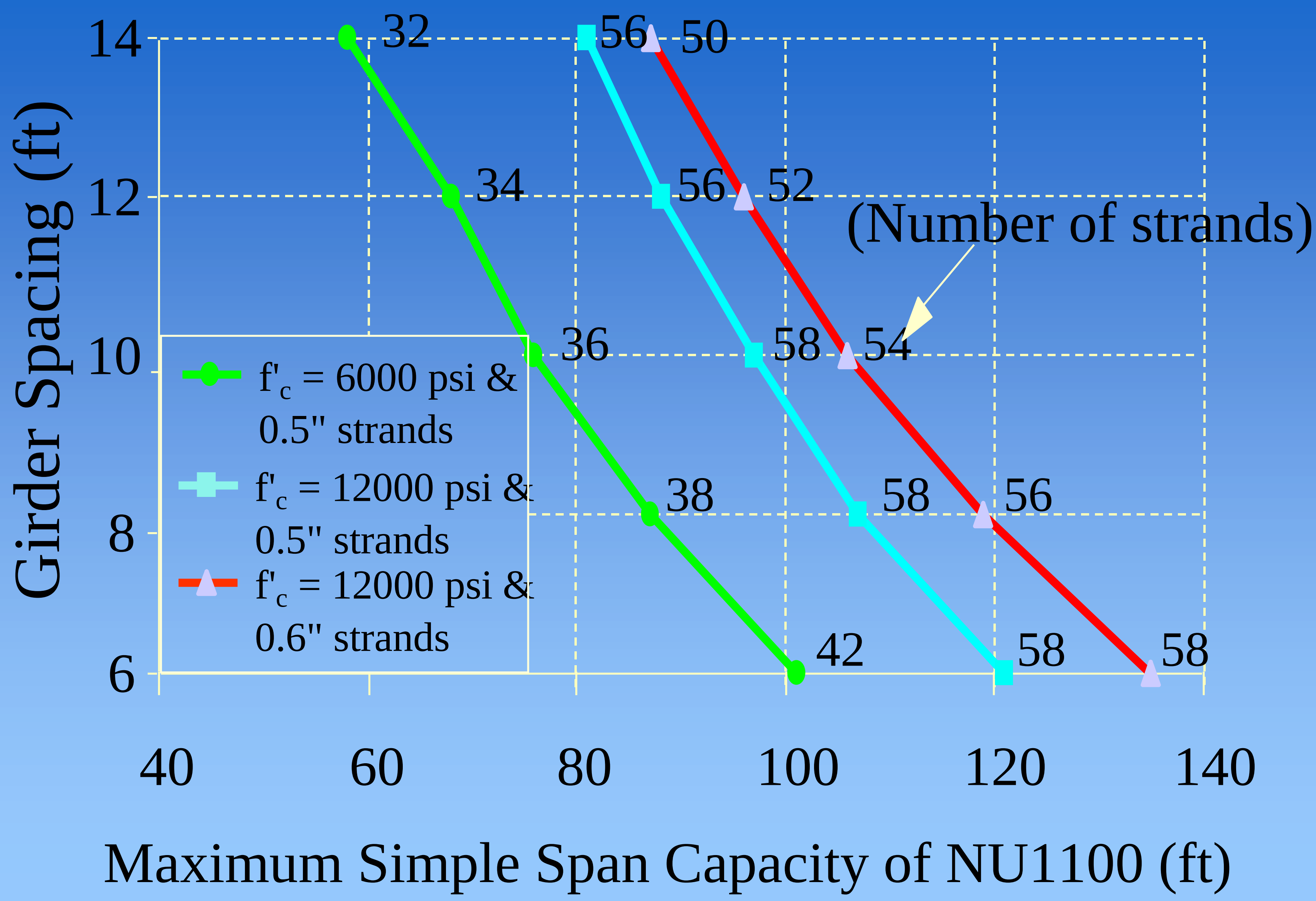


Ref: *Russell, Volz and Bruce*, Fig. 3



Metric dimensions are in mm.

NU GIRDER



Girder Spacing (ft)
14
12
10
8
6
40
60
80
100
120
140
Maximum Simple Span Capacity of NU1100 (ft)
(Number of strands)
f'c = 6000 psi & 0.5" strands
f'c = 12000 psi & 0.5" strands
f'c = 12000 psi & 0.6" strands
32
34
36
38
42
56
56
58
58
58
50
52
54
56
58

Materials

SAMPLE MIX DESIGN FOR TEXAS HPC BEAMS

COMPONENT	QUANTITY	TYPE
Coarse Aggregate	1918 pcy	Crushed dolomitic limestone, ½” max, ASTM GR 7
Fine Aggregate	1029 pcy	Sand
Water	247 pcy	Potable
Cement	671 pcy	Type III
Fly Ash	316 pcy	ASTM Class C
Retarder	27 oz/cy	ASTM Type B
Superplasticizer	178-227 oz/cy	ASTM Type F

SAMPLE MIX DESIGN FOR NEBRASKA HPC BEAMS-12SF

COMPONENT	QUANTITY	TYPE
Coarse Aggregate	1860 pcy	Crushed limestone, ½” max, ASTM C33, #7
Fine Aggregate	990 pcy	Sand ASTM C33
Water	240 pcy	Potable
Cement	750 pcy	Type I
Fly Ash	200 pcy	ASTM Class C
Retarder	40 oz/cy	ASTM Type A
Superplasticizer	300 oz/cy	ASTM Type F
Silica Fume	50 pcy	ASTM C1240

SAMPLE MIX DESIGN FOR NEBRASKA HPC BEAMS - 12FA

COMPONENT	QUANTITY	TYPE
Coarse Aggregate	1913 pcy	Crushed limestone, ½” max, ASTM C33, #7
Fine Aggregate	933 pcy	Sand ASTM C33
Water	254 pcy	Potable
Cement	680 pcy	Type III
Fly Ash	320 pcy	ASTM Class C
Retarder	40 oz/cy	ASTM Type A
Superplasticizer	340 oz/cy	ASTM Type F

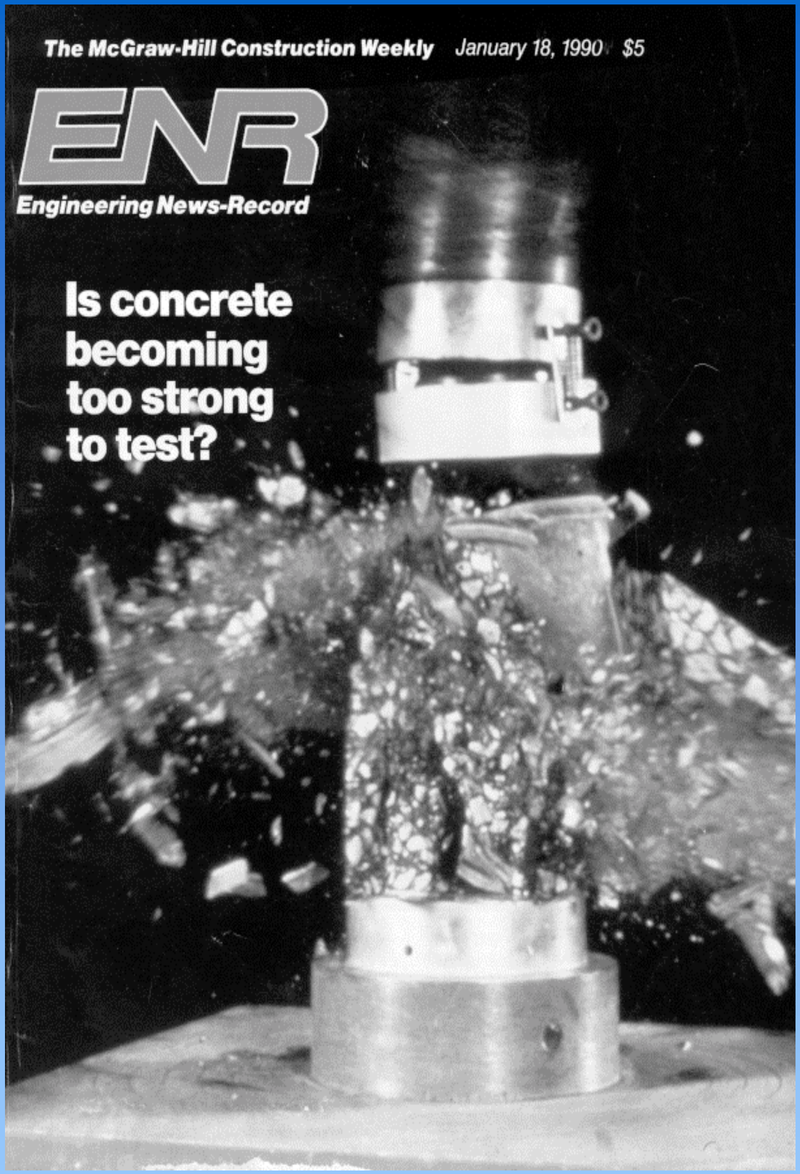
SAMPLE MIX DESIGN FOR NEBRASKA HPC BEAMS - 8FA

COMPONENT	QUANTITY	TYPE
Coarse Aggregate	1400 pcy	Crushed limestone, ½" max, ASTM C33, #7
Fine Aggregate	1400 pcy	Sand ASTM C33
Water	255 pcy	Potable
Cement	750 pcy	Type IP
Fly Ash	75 pcy	ASTM Class C
Retarder	32 oz/cy	ASTM Type A
Superplasticizer	144 oz/cy	ASTM Type F

Material Properties

- **Compressive Strength**
- **Modulus of Elasticity**
- **Unit Weight**
- **Modulus of Rupture**
- **Creep & Shrinkage**

Compressive Strength



Ref: *ENR*, 1/18/90

“As concrete strength increases, the effects of improper testing and sampling procedures grow as well”

Ref: ***Russell, Gebler and Whiting***

Modulus of Elasticity

MODULUS OF ELASTICITY

E_c

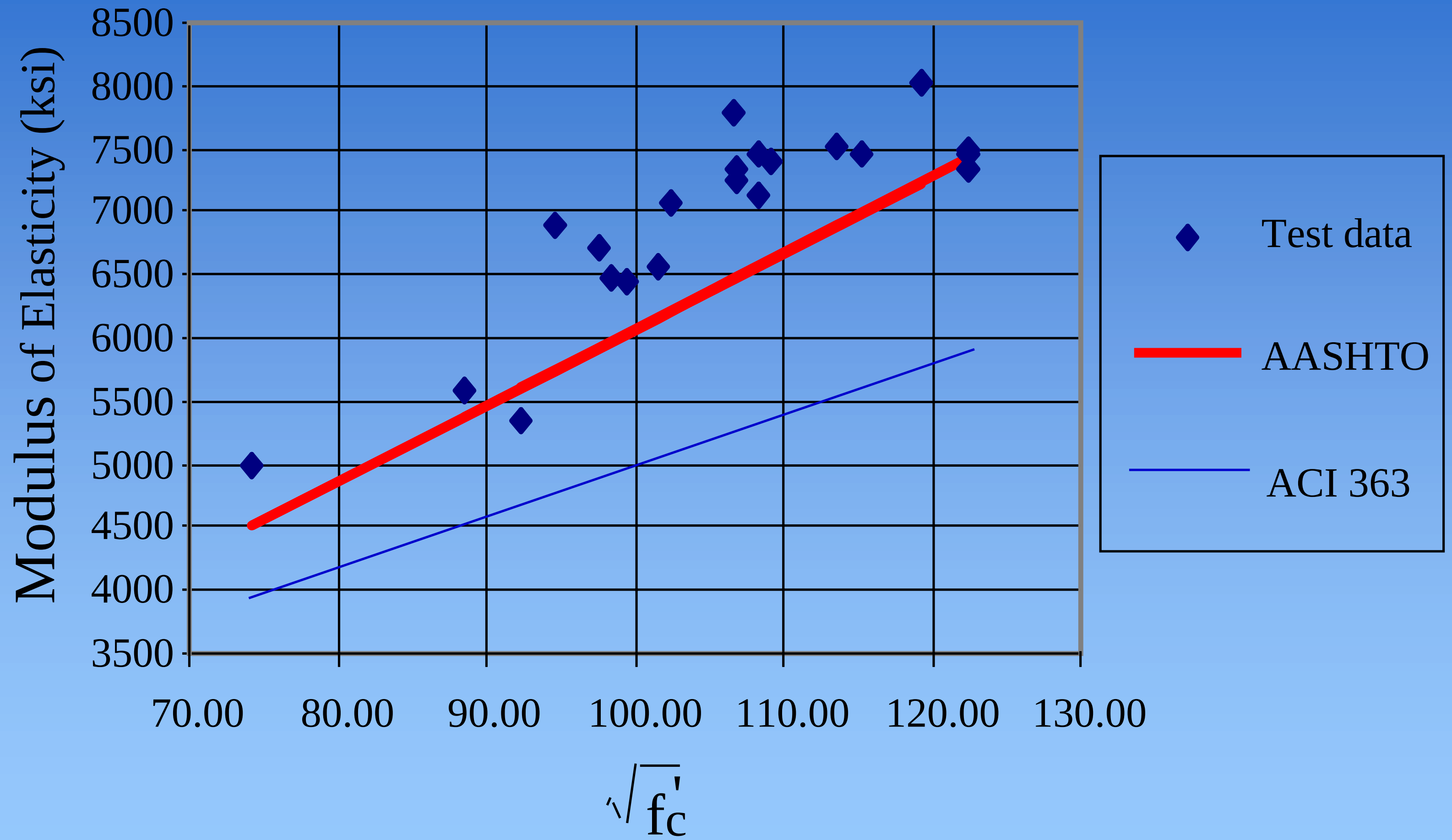
Need for:

- **Transformed Section**
- **Camber and Deflection**
- **Prestress Losses**

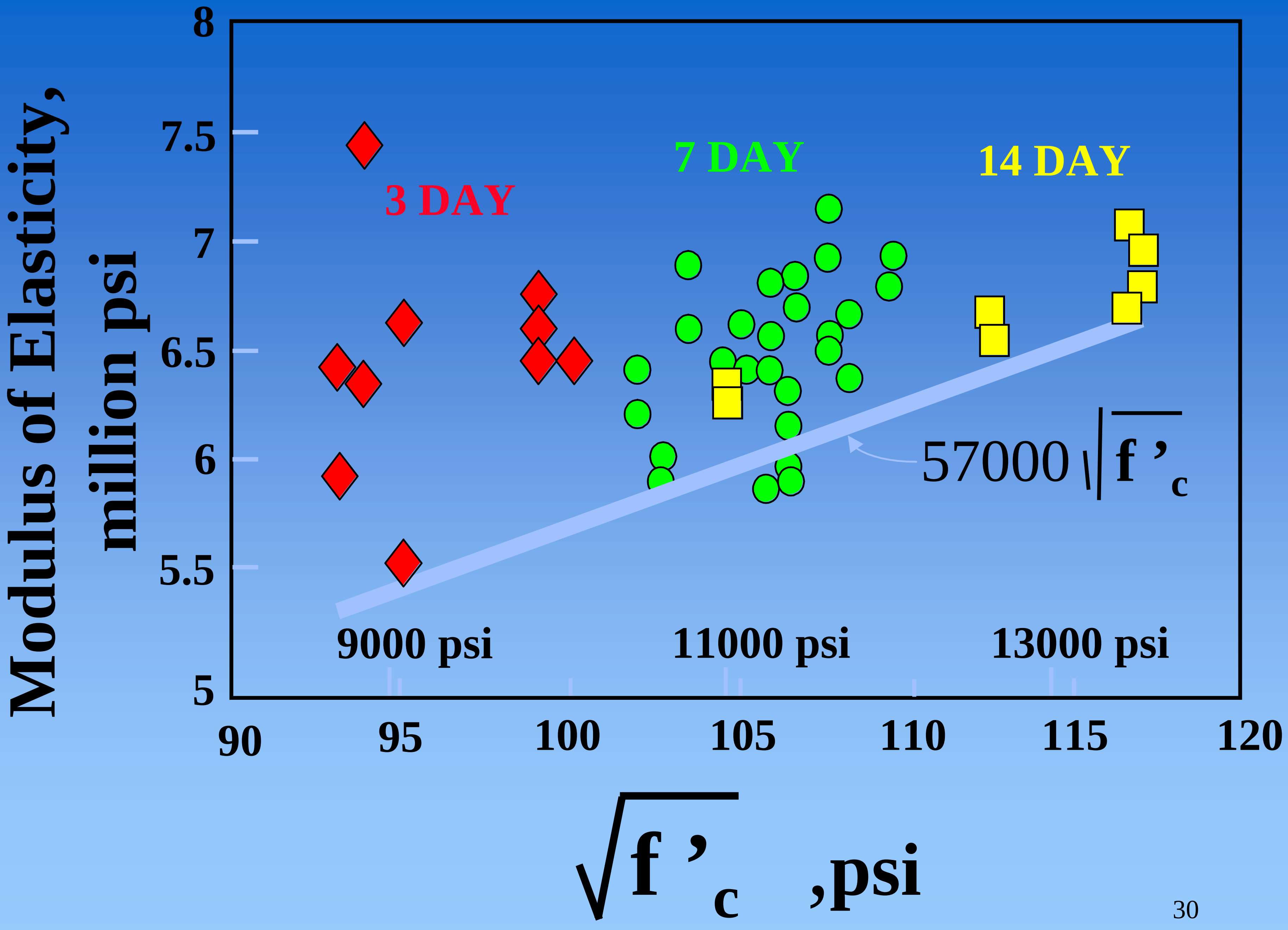
How to Calculate E_c

- **AASHTO: $E_c = 33\,(w)^{1.5}\sqrt{f'_c}$**
- **ACI 318: $E_c = 33\,(w)^{1.5}\sqrt{f'_c}$**
- **ACI 318: $E_c = 57{,}000\sqrt{f'_c}$**
- **ACI 363: $E_c = (40{,}000\sqrt{f'_c} + 1.0 \times 10^6)$**
- **Experimental results for local materials**

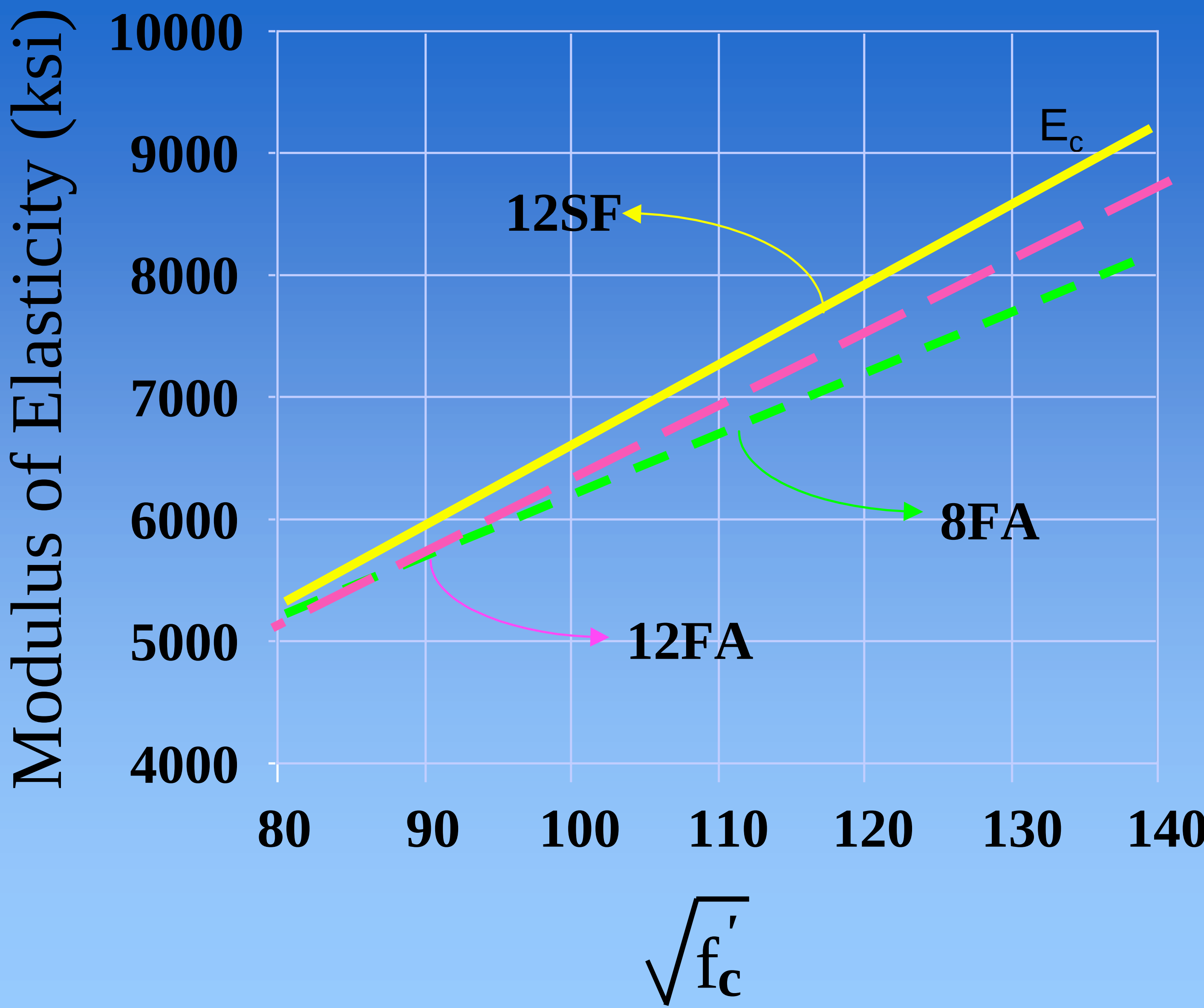
Mix 12SF



8500
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
Modulus of Elasticity (ksi)
70.00
80.00
90.00
100.00
110.00
120.00
130.00
√fc'
Test data
AASHTO
ACI 363



Modulus of Elasticity, million psi
8
7.5
7
6.5
6
5.5
5
3 DAY
7 DAY
14 DAY
57000 √f 'c
9000 psi
11000 psi
13000 psi
90
95
100
105
110
115
120
√f 'c ,psi



$$E_c = a\sqrt{f'_c} + b$$

12SF
a = 61900
b = 462600

12FA
a = 63000
b = 0

8FA
a = 45850
b = 1789000

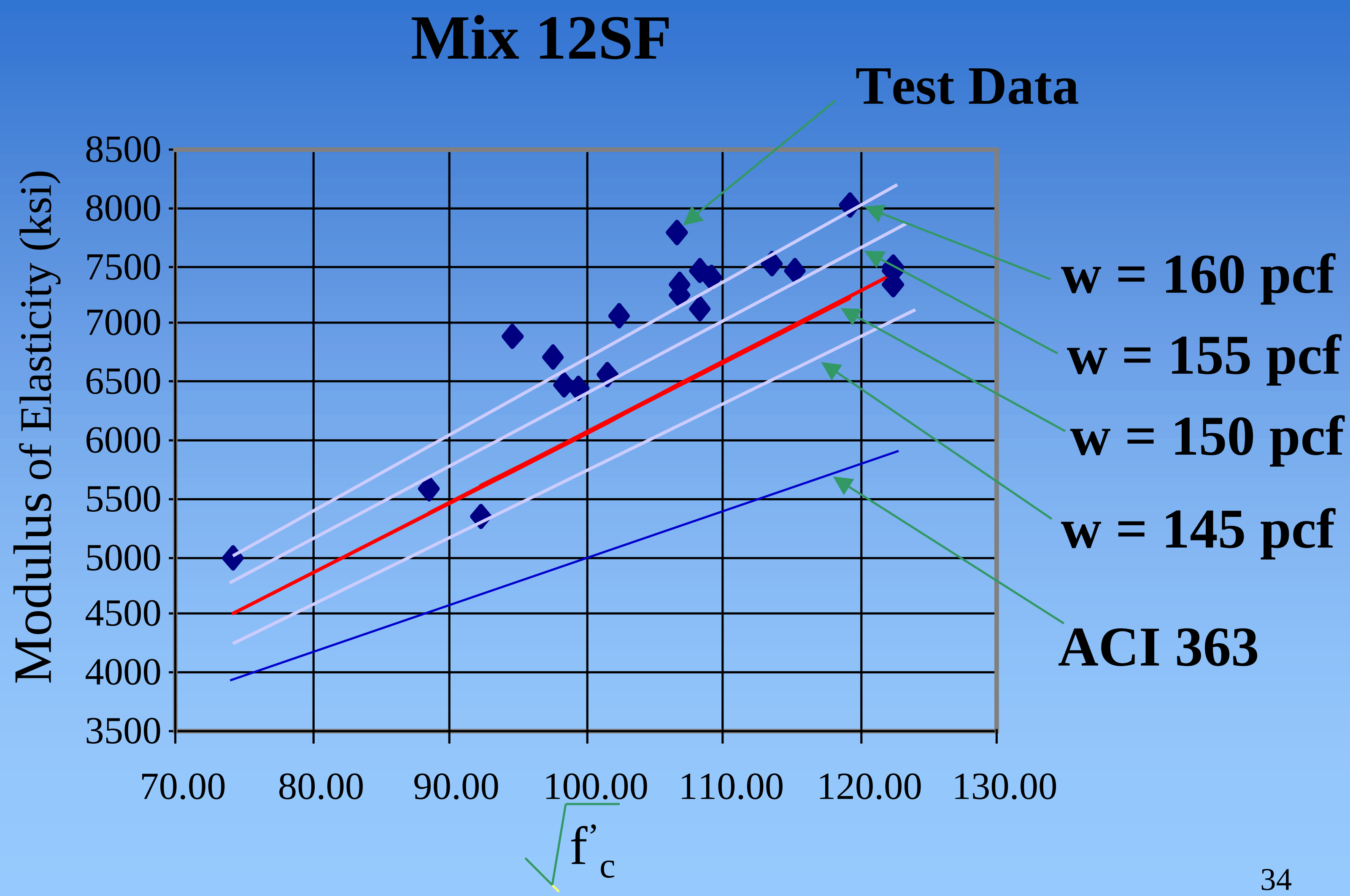
Amount and type of coarse aggregates affect value of E_c. E_c of HPC should be determined through experiments with local materials.

UNIT WEIGHT

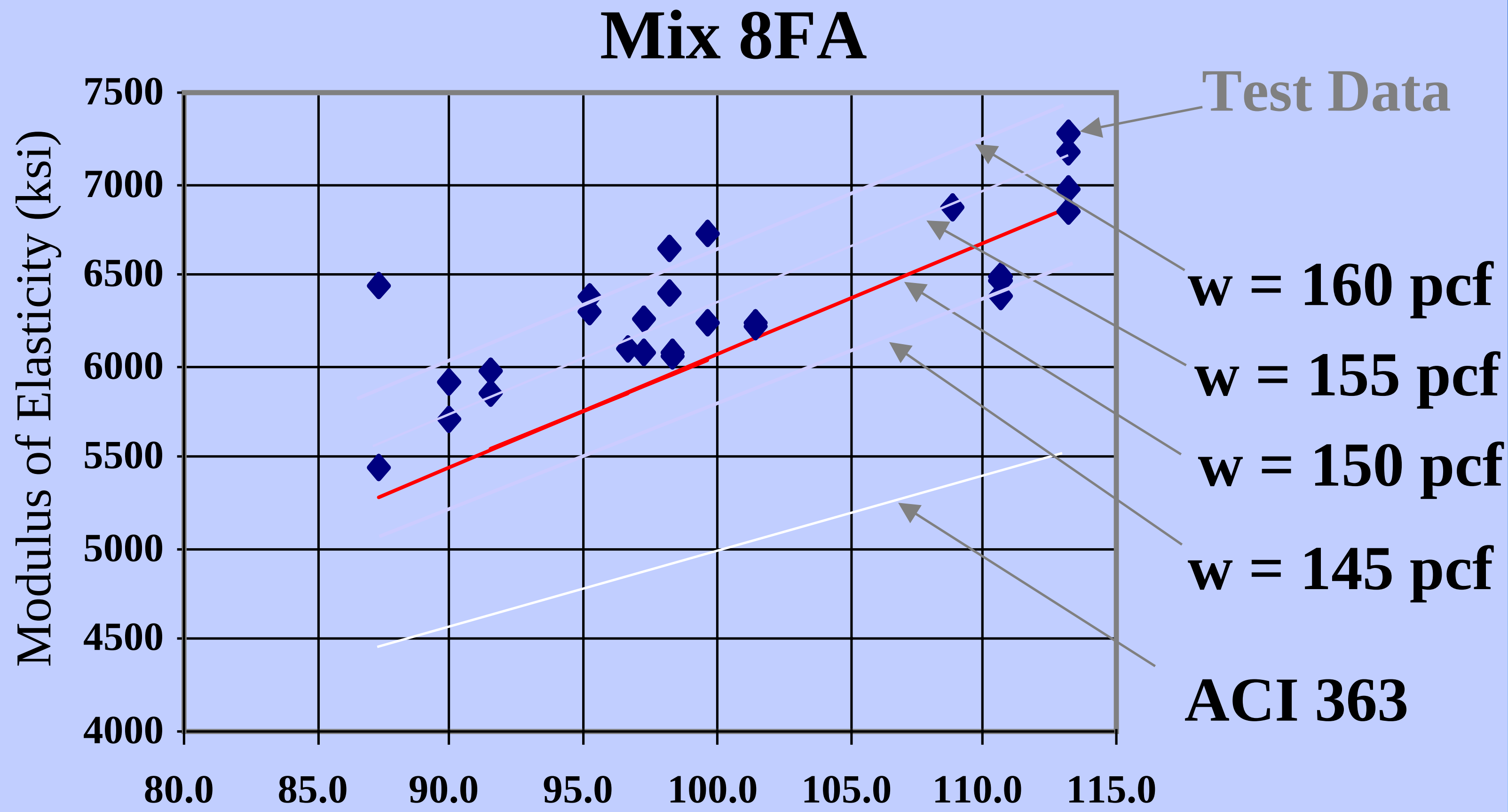
- **For Normal Strength Concrete:**
  - **w = 145pcf (plain concrete)**
  - **w = 150pcf (reinforced concrete)**

- **For High Strength Concrete:**
  - **w = 145 - 160pcf (plain concrete)**
  - **w = 150 - 165pcf (reinforced concrete)**

$$E_c = 33\, w^{1.5} \sqrt{f_c'}$$

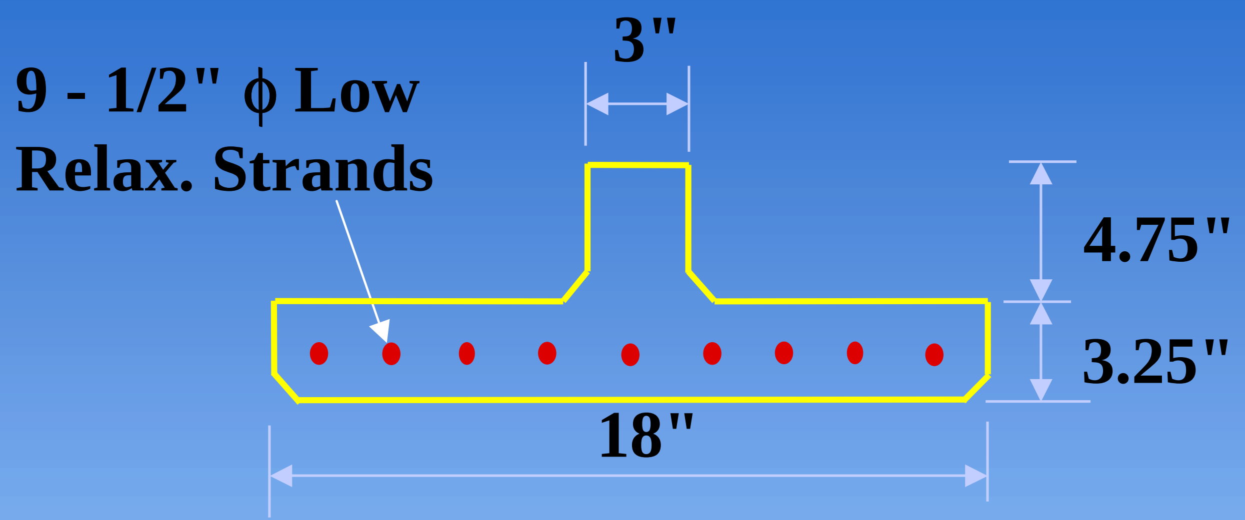


$$E_c = 33\, w^{1.5} \sqrt{f_c'}$$



$\sqrt{f'_c}$

Example



Span = 32 ft

When w = 150 pcf & $E_c = 33\,(145)^{1.5}\sqrt{f_c'}$, Δ = 1.60 in. ↑

When w = 165 pcf & $E_c = 33\,(160)^{1.5}\sqrt{f_c'}$, Δ = 1.28 in. ↑

Modulus of Rupture
or
Flexural Tensile Strength

The flexural tensile strength or modulus of rupture is defined as:

$$f_r = K\lambda\sqrt{f_c^{'}}$$

Where:

f_r = modulus of rupture, psi

K = a constant, usually taken as 7.5

λ = 1.0 for normal weight concrete

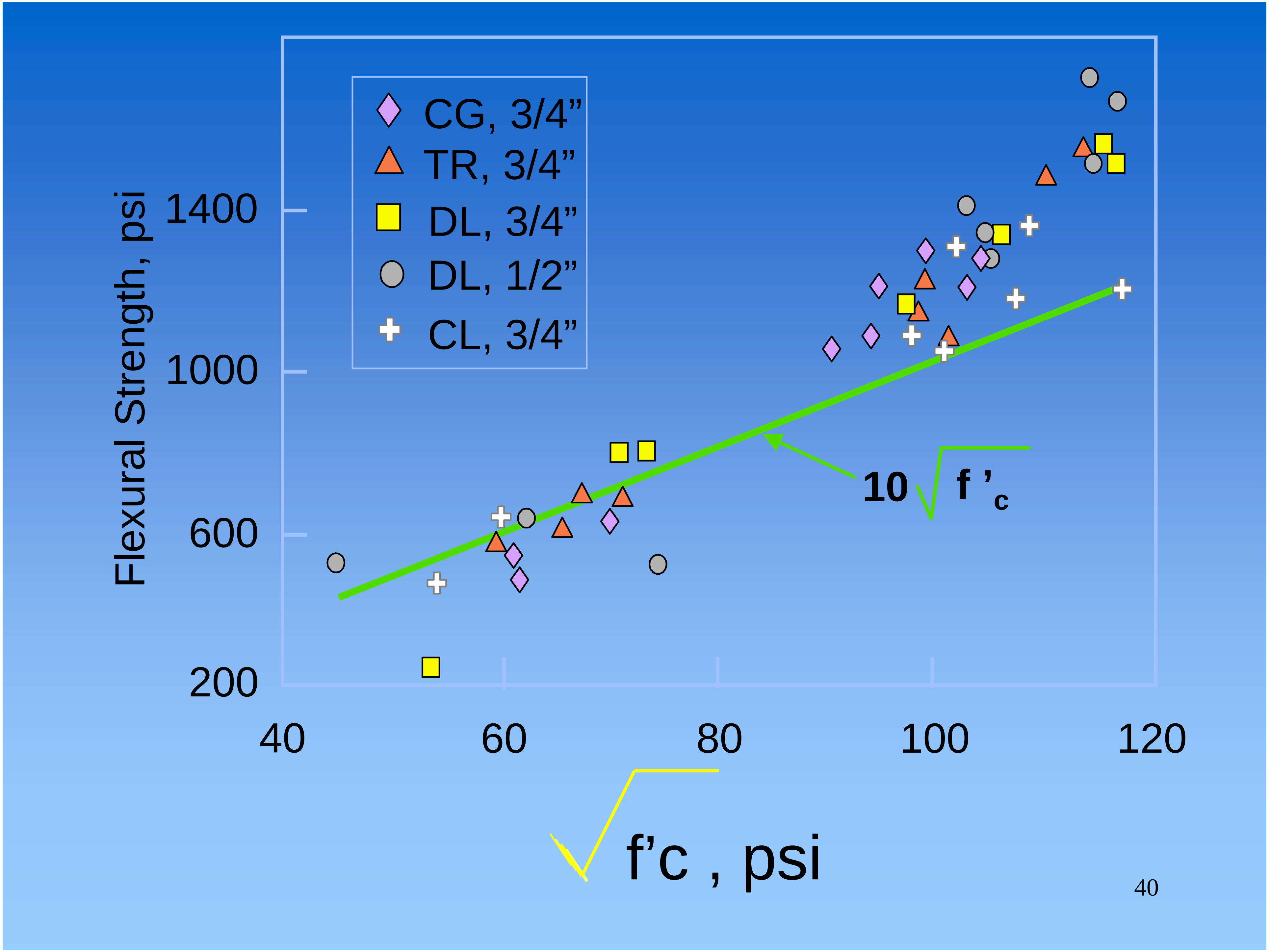
0.85 for sand-lightweight concrete

0.75 for all-lightweight concrete

For HPC a value of K greater than 7.5 is proposed

BEAM DESIGN COMPARISON PARAMETERS

	HIGH PERFORMANCE CONCRETE	NORMAL STRENGTH CONCRETE
f ’ci (psi)	9,800 psi (max)	6,000 psi (max)
f ’c (psi)	13,000 psi (max)	8,000 psi (max)
Allowable tension at release	$10\sqrt{f_c'}$	$7.5\sqrt{f_c'}$
Allowable tension at service	$8\sqrt{f_c'}$	$6\sqrt{f_c'}$



CG, 3/4"
TR, 3/4"
DL, 3/4"
DL, 1/2"
CL, 3/4"
Flexural Strength, psi
1400
1000
600
200
40
60
80
100
120
10 √f'c
√f'c , psi

Creep & Shrinkage

Creep and Shrinkage

Needed for:

- **Camber and deflection**
- **Prestress losses**
- **Stress redistribution in composite members**
- **Continuity reinforcement over piers**

ACI 209 - Creep

For Conventional Concrete:

$C_t = 2.35\ (CF)_H\ (CF)_{LA}\ (CF)_{LD}$

$(CF)_H = 1.27 - 0.0067(H)$

$(CF)_{LA} = 1.13 t_{LA}^{-0.095}$ (for steam Cured concrete)

$$(CF)_{LD} = \left(\frac{t^{0.6}}{10 + t^{0.6}} \right)$$

For H=70%, LA=1-2 days, LD=infinity, C_u =2.00

Cornell Study

Cornell University and also AASHTO LRFD creep coefficient at time t:

$$\phi(t, t_i) = 3.5 k_c k_f (1.58 - \frac{H}{120}) t_i^{-0.118} \frac{(t - t_i)^{0.6}}{10 + (t - t_i)^{0.6}}$$

k_f = factor on influence of concrete strength

$$k_f = 1/[0.67 + (f_c^{'}/9000)] \text{ psi}$$

for f'_c = 3,000 to 12,000 psi, k_f = 1.0 to 0.5

Nebraska Creep Test

Test on local materials at University of Nebraska provided following results:

Test performed on
4” x 4” x 24” specimens
Three mixes
Two curing conditions

Average relative humidity : 40%
Average Temperature: 65^{o}F

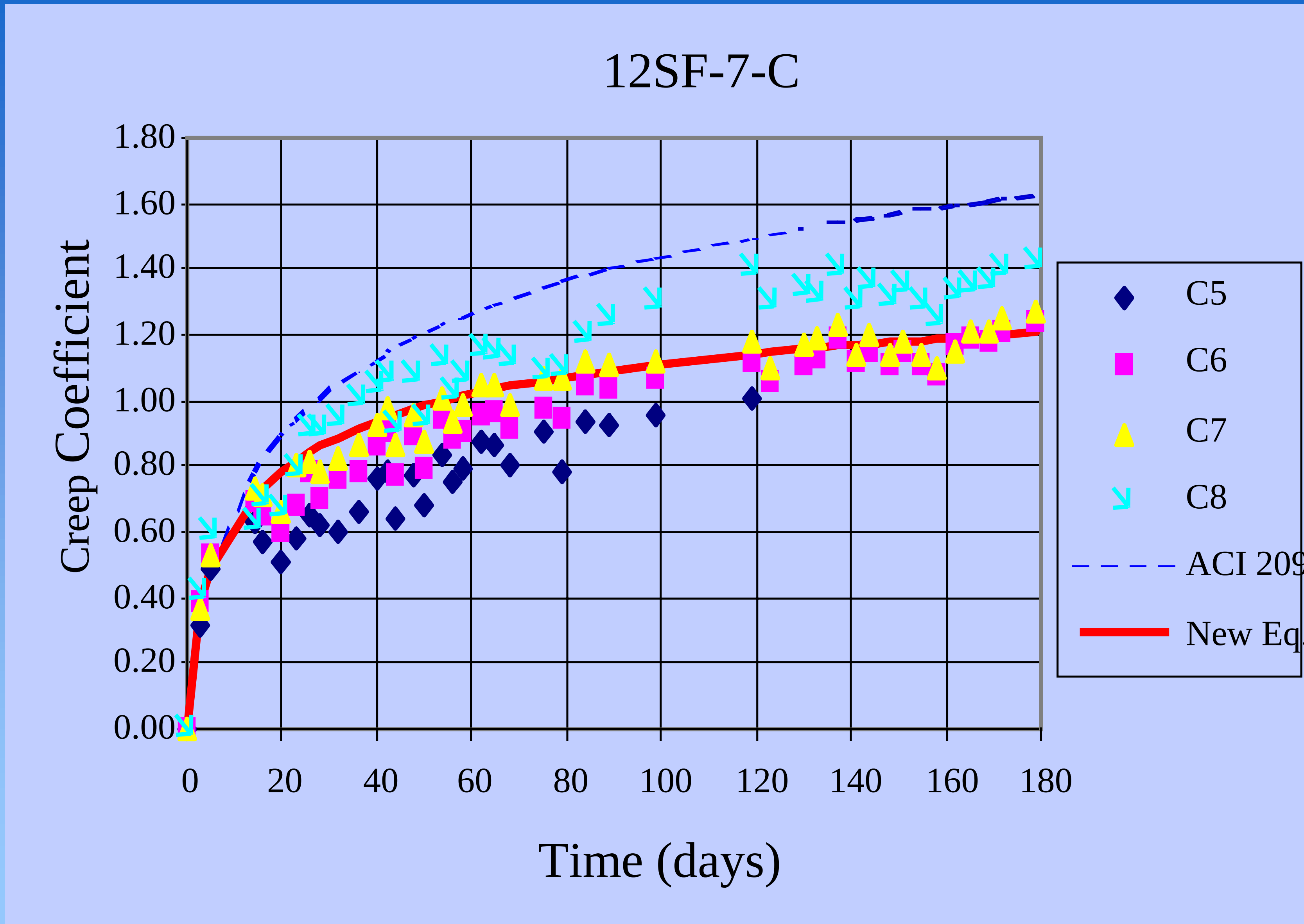
Creep Prediction

$$C_t = 2.35\,\gamma_c \frac{t^{0.6}}{K_c + t^{0.6}}$$

$$K_c = 12 - 0.50\,f'_c$$

γ_c is a product of correction factors for R.H., size, ... etc. It is proposed that γ_c include a new correction factor $\gamma_{st,c}$ for strength.

$$\gamma_{st,c} = 1.18 - 0.045\,f'_c$$


12SF-7-C
Creep Coefficient
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0
20
40
60
80
100
120
140
160
180
Time (days)
C5
C6
C7
C8
ACI 209
New Eq.

ACI 209 - Shrinkage

The shrinkage strain of conventional concrete:

$$\varepsilon_{sh,t} = 780 \times 10^{-6}(1.40 - 0.010H)\frac{t}{35 + t}$$

for H = 60% and t = infinity

$$\varepsilon_{sh,u} = 624 \text{ x } 10^{-6}$$

AASHTO LRFD

AASHTO LRFD shrinkage coefficient

Moist cured concrete

$$\varepsilon_{sh} = -k_s k_h \left(\frac{t}{35.0 + t} \right) 0.51 \times 10^{-3}$$

Steam cured concrete

$$\varepsilon_{sh} = -k_s k_h \left(\frac{t}{55.0 + t} \right) 0.56 \times 10^{-3}$$

t = drying time (day)

k_s = size factor

k_h = humidity factor

Nebraska Shrinkage Test

AT UNIVERSITY OF NEBRASKA ON LOCAL MATERIALS

Test performed on 4” x 4” x 24” specimens

Three mixes
Two curing conditions

Average relative humidity : 40%
Average Temperature: 65ºF

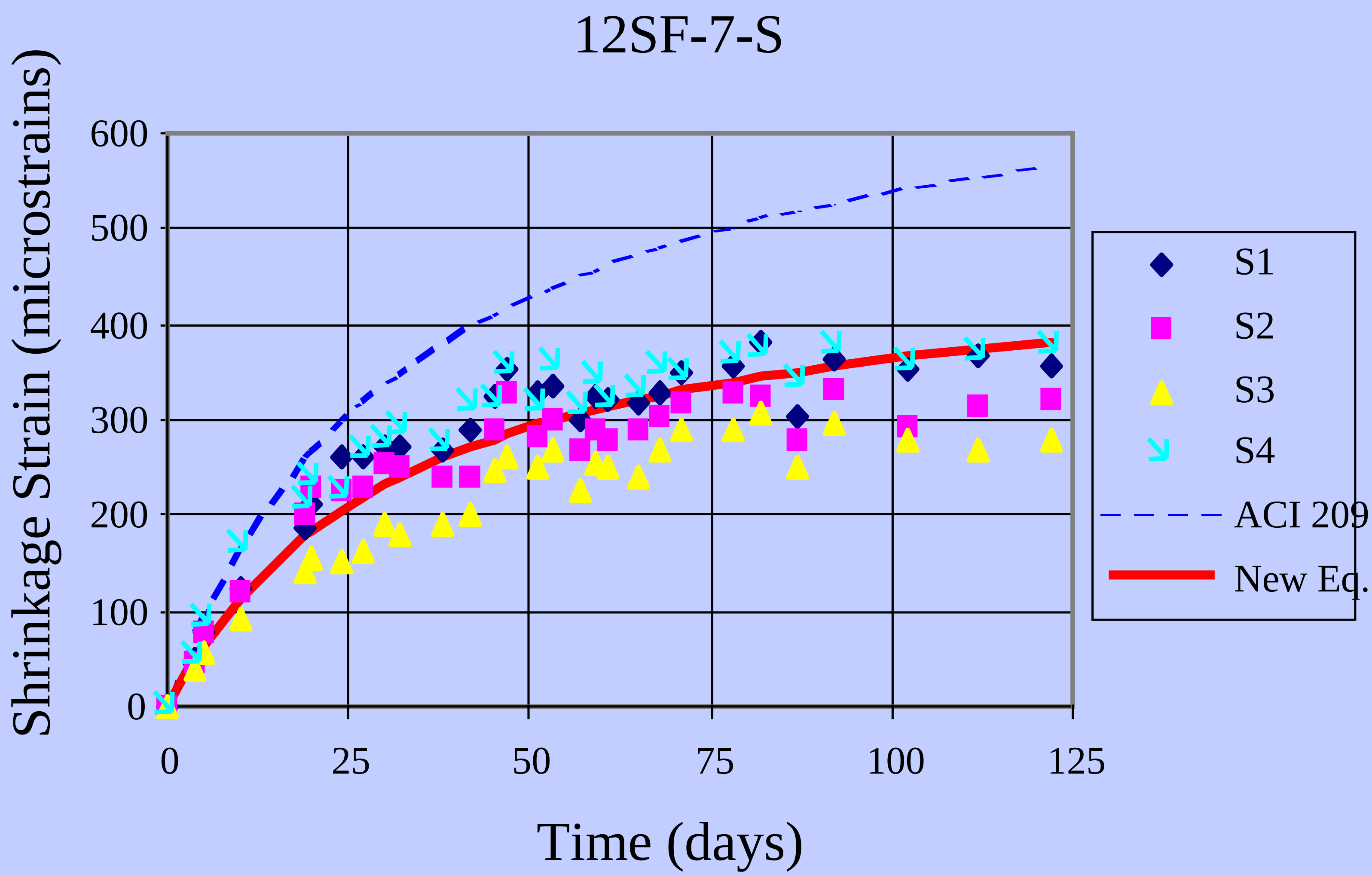
Shrinkage Prediction

$$\varepsilon_{sh} = 780 \times 10^{-6} \gamma_{sh} \frac{t}{K_s + t}$$

$$K_s = 45 - 2.5 f'_c$$

γ_{sh} **is a product of correction factors for R.H., size, ... etc. It is proposed that γ_{sh} include a new correction factor $\gamma_{st,s}$ for strength .**

$$\gamma_{st,s} = 1.2 - 0.05 f'_c$$



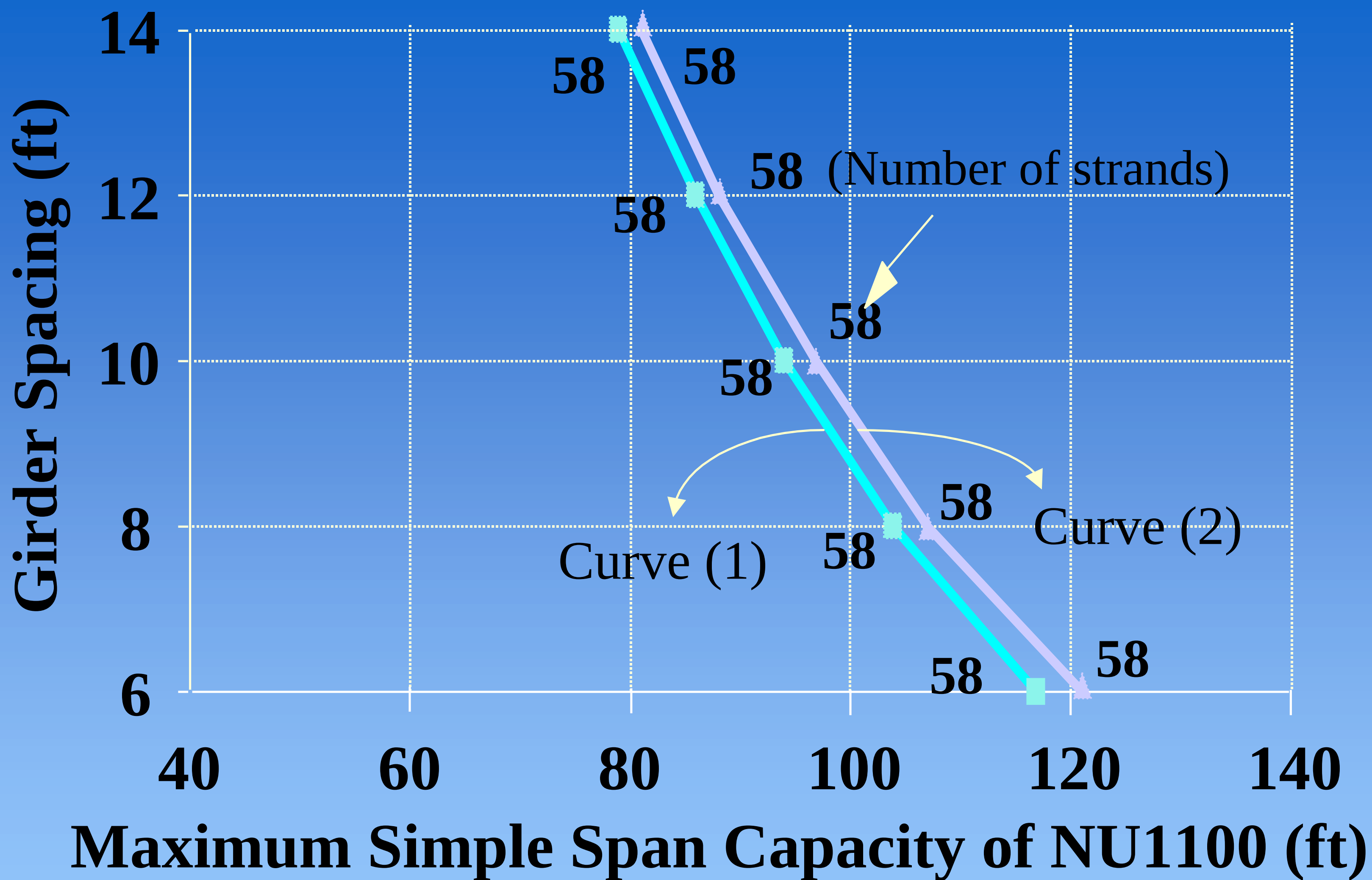
12SF-7-S
Shrinkage Strain (microstrains)
600
500
400
300
200
100
0
0
25
50
75
100
125
Time (days)
S1
S2
S3
S4
ACI 209
New Eq.

Flexural Design

Factors Impacting Flexural Design

- **Tension at service**

The tensile stress at service primarily controls the design of girders.



Allowable tension at service:

Curve (1) - $6\sqrt{f_c'}$ & Curve (2) - $8\sqrt{f_c'}$

- **Compression at release**

The compressive stress at release will control the number of strands that can be placed in a member.

OBSERVATIONS:

(1) Allowable compression at release has the most impact on span capacity.

(2) Allowable tension at service has minor impact.

(3) Allowable tension at release has practically no impact.

Prestress Losses

TIME-DEPENDENT PRESTRESS LOSSES

- **Loss due to elastic shortening**
- **Loss due to concrete shrinkage**
- **Loss due to creep of concrete**
- **Loss due to relaxation of prestressing steel**

METHODS IN PREDICTING PRESTRESS LOSSES

- **AASHTO-Standard Method**
- **AASHTO-LRFD Lump Sum Estimation**
- **AASHTO-LRFD Refined Estimation**
- **Recommended Method**

AASHTO Standard

- **AASHTO - 9.16.2**

Prestress loss due to creep:

$CR_c = 12\ f_{cir} - 7\ f_{cds}$

f_{cir} = stresses in concrete at center of gravity of tendons due to all superimposed permanent dead loads that are applied to the member after it has been prestressed.

f_{cds} = concrete stress at the center of gravity of the prestressing steel due to all dead loads except that dead load present at the time the prestressing force is applied.

$$CR_c = 12\, f_{cir} - 7\, f_{cds}$$

$C_{t1}\,(E_s/E_{ci})\,(E_s/E_c)$ ← $12\, f_{cir}$ $7\, f_{cds}$ → C_{t2}

$$C_t = C_u\,(CF)_H(CF)_{LA}(CF)_{LD}$$

$$C_{t1} = 2.0,\ (E_s/E_{ci}) = 6$$

$$C_{t2} = 1.3,\ (E_s/E_c) = 5.4$$

Prestress loss due to shrinkage (AASHTO):

Pretensioned Members

$$SH = 17{,}000 - 150H \qquad \text{(Eq. 9-4)}$$

H = mean annual ambient relative humidity in percent

$$SH = 15{,}000(1.13-0.01H)$$

$$= 530 \times 10^{-6}(E_s)(1.13-0.01H)$$

AASHTO-LRFD LUMP SUM ESTIMATION

For I-shaped girders, prestressed with low-relaxation strands (ultimate strength of 270 ksi)

$$\Delta f_{PT} = 33.0\ [\ 1\text{-}0.15\ (\ f'_c - 6.0\ )\ /\ 6.0]\ \ (\text{ksi})$$

$$(\ f'_c - 6.0\ )\ \text{need not be taken} < 0.0$$

RECOMMENDED MODIFICATION TO AASHTO-LRFD METHOD SHOWN IN

$$SH = (17 - 0.15\ H)\ \gamma_{st,\ s} \quad \text{(ksi)}$$

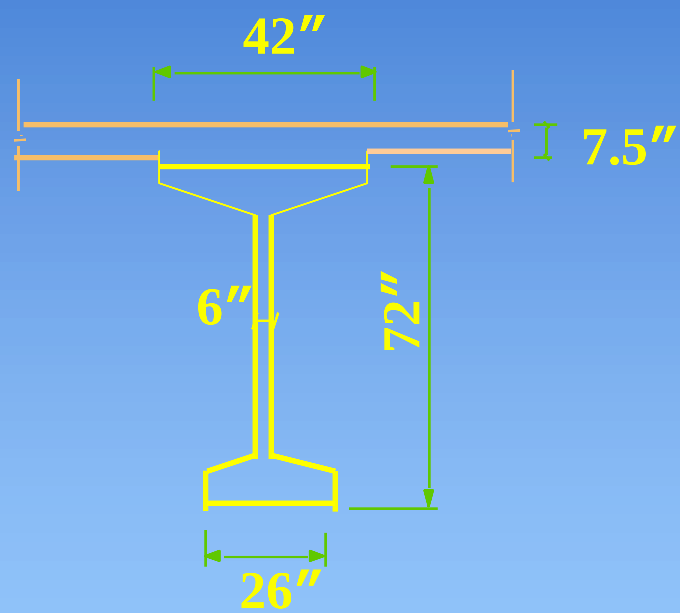
$$\gamma_{st,\ s} = 1.20 - 0.05\ f'_c$$

$$CR_c = (12\ f_{cir} - 7\ f_{cds})\ \gamma_{st,\ c} \quad \text{(ksi)}$$

$$\gamma_{st,\ c} = 1.18 - 0.045\ f'_c$$

$$CR_s = 5 - 0.1\ ES - 0.05\ (\ SH + CR_c) \quad \text{(ksi)}$$

Girder Elevation and Strand Pattern



72” Bulb Tee Girder Section

DESIGN DATA

Bridge: Span = 119 ft
Spacing = 12 ft

Steel: 44 - ϕ = 1/2″
low relaxation strands

Conventional concrete
$f'_{c,\ girder} = 7{,}000$ psi
$f'_{c,\ deck} = 4{,}000$ psi

High performance concrete
$f'_{c,\ girder} = 13{,}000$ psi
$f'_{c,\ deck} = 4{,}000$ psi

COMPARISON ON TIME-DEPENDENT PRESTRESS LOSSES OF DIFFERENT METHODS

	AASHTO Standard	AASHTO LRFD Lump Sum	AASHTO LRFD Refined	Recommended with strength modification	Computer analysis
Loss due to shrinkage (ksi)	6.50	-	6.50	3.58	-
Loss due to creep (ksi)	23.64	-	23.64	14.00	-
Loss due to steel relaxation (ksi)	1.67	-	2.23+ 2.00	3.18	-
Total (ksi)	31.81	29.7	34.37	20.76	17.5

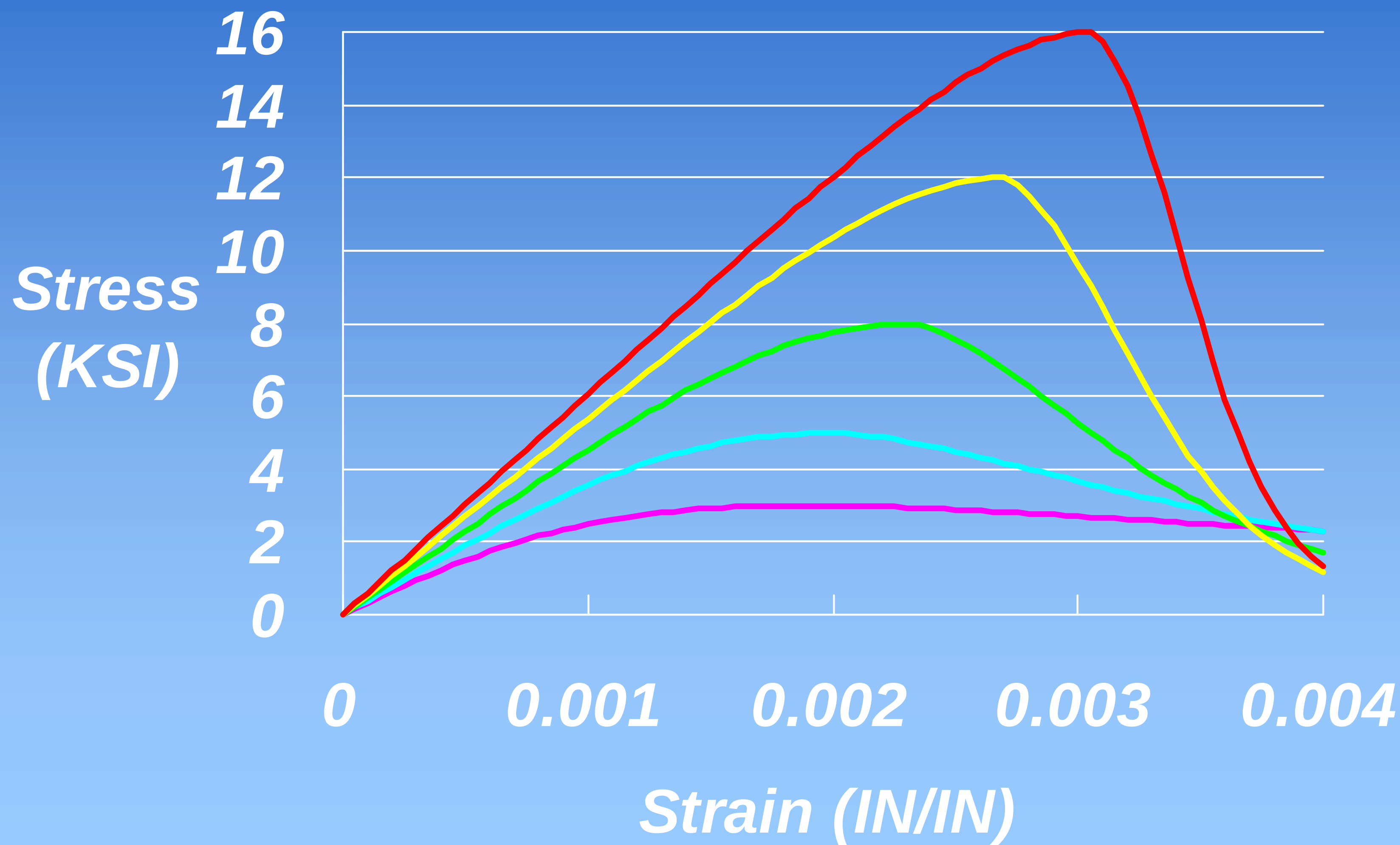
Use proposed method to calculate prestress losses.

Ultimate Strength

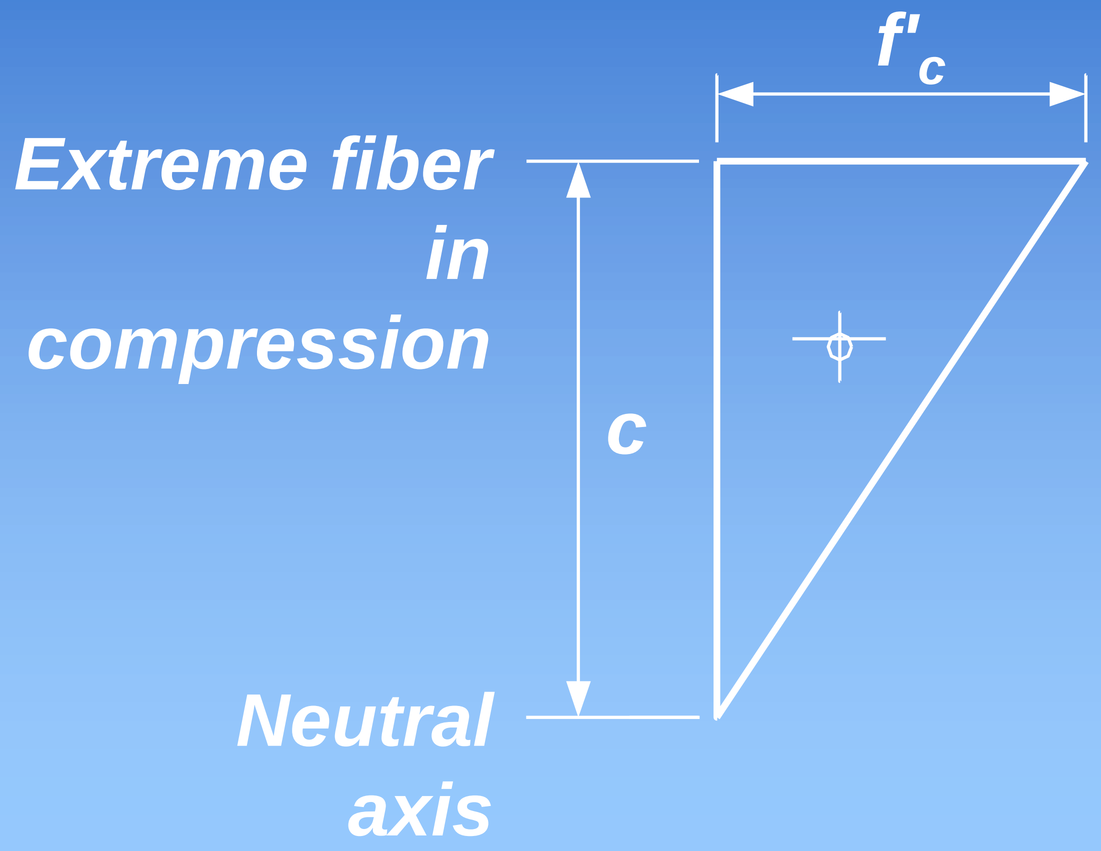
Design Issues for HSC

- **Concrete stress-strain curve in compression**
- **Equivalent rectangular stress block**
- **Reinforcement limits**
- **Strength of composite sections**
- **Efficient use of HSC**

Concrete Stress-Strain Curves in Compression



Idealized Stress-Strain Curve for Very High Strength Concrete



Idealized Stress-Strain Curve for Very High Strength Concrete

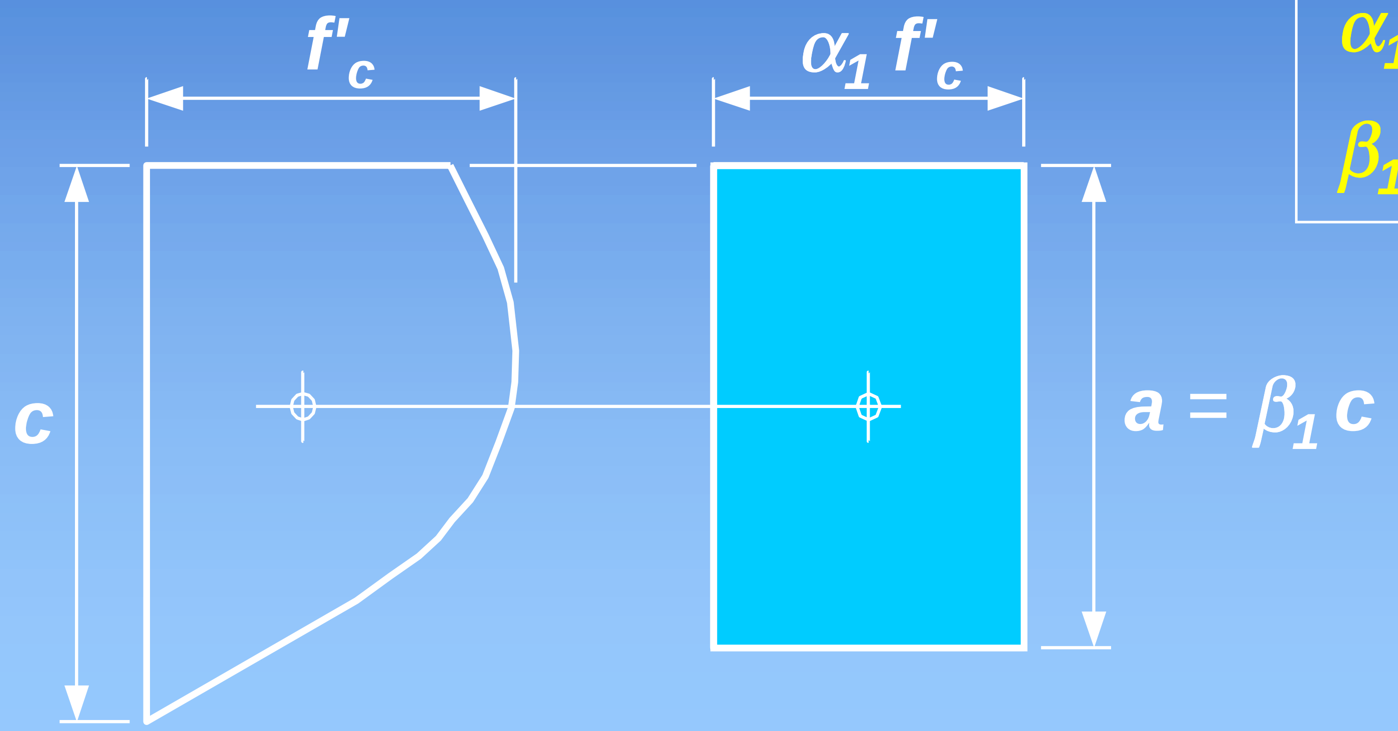
An equivalent rectangular stress block for very high strength concrete is needed

- To simplify design

- To maintain consistency with design using normal strength concrete

Equivalent Rectangular Stress Block

Normal Strength Concrete:

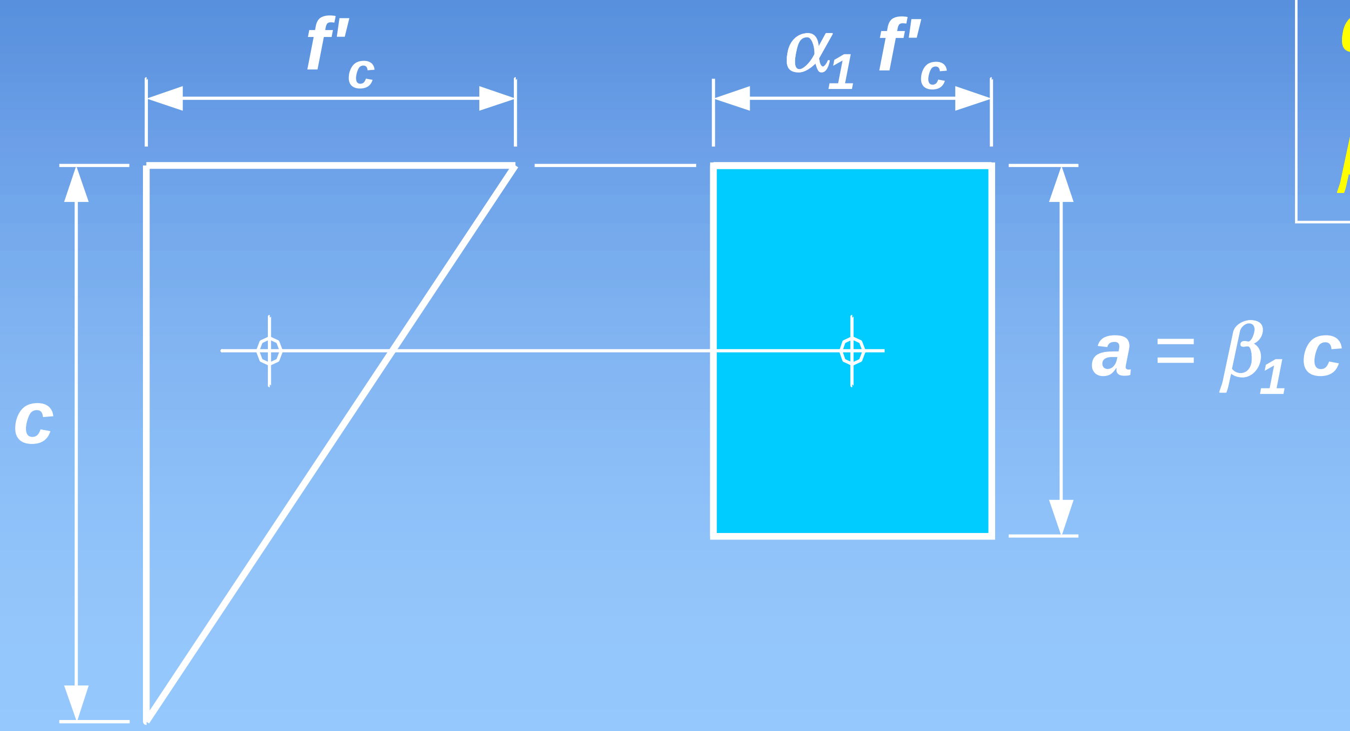


$\alpha_1 = 0.85$

$\beta_1 = 0.85$

Equivalent Rectangular Stress Block

Very High Strength Concrete:



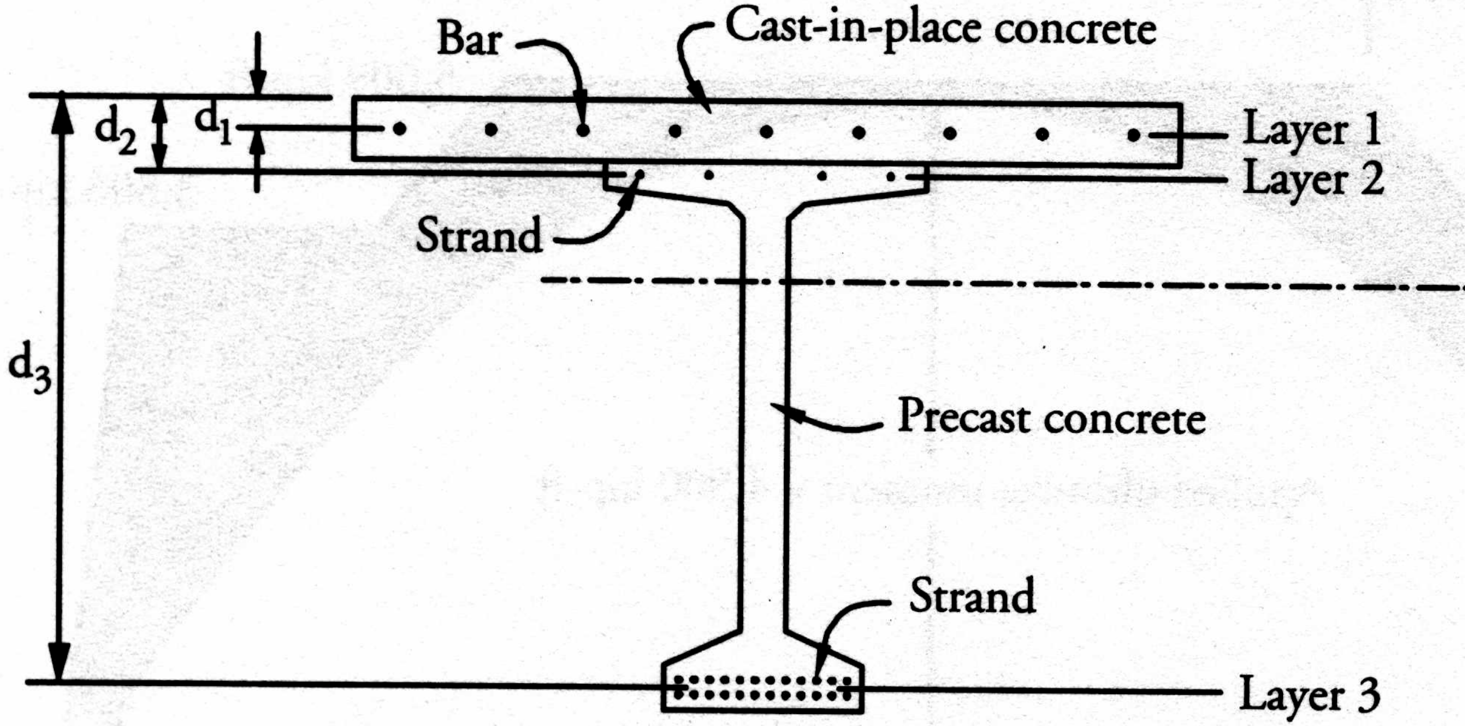
$\alpha_1 = 0.75$

$\beta_1 = 0.65$

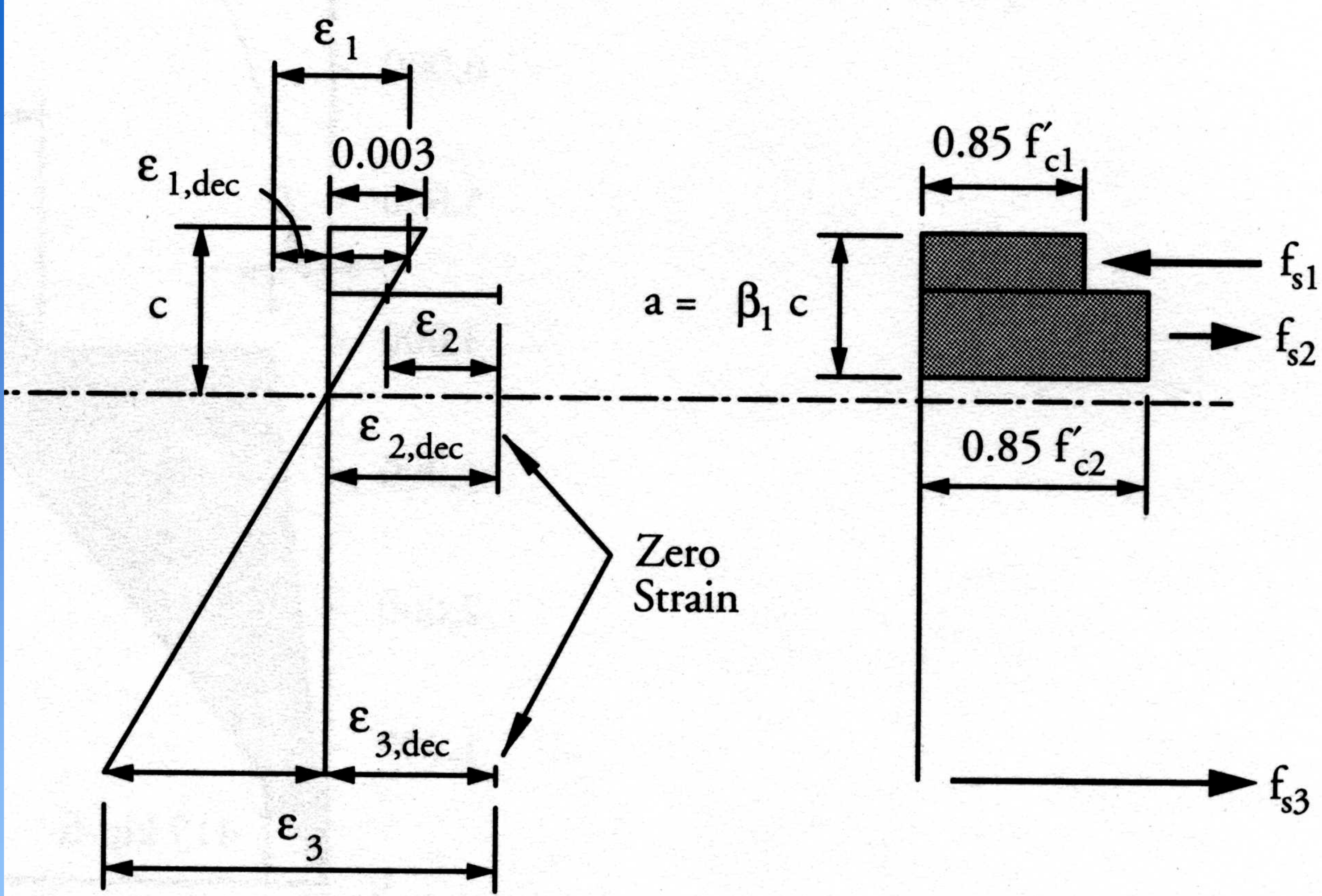
Strength of Composite Sections

Difficulties:

- **Different concrete strengths**
- **Location of neutral axis**
- **Ductility**
- **Strand stress**
- **Strain in top of girder**
- **Proper modeling of conditions**



(a) Cross Section



(b) Strains

(c) Forces

Shear Strength

AASHTO -Standard

Article 9.20

$$V_u \leq \phi\left(V_c + V_s\right)$$

V_u = factored shear

V_c = nominal shear strength provided by concrete

V_s = nominal strength provided by web reinforcement

AASHTO-Standard

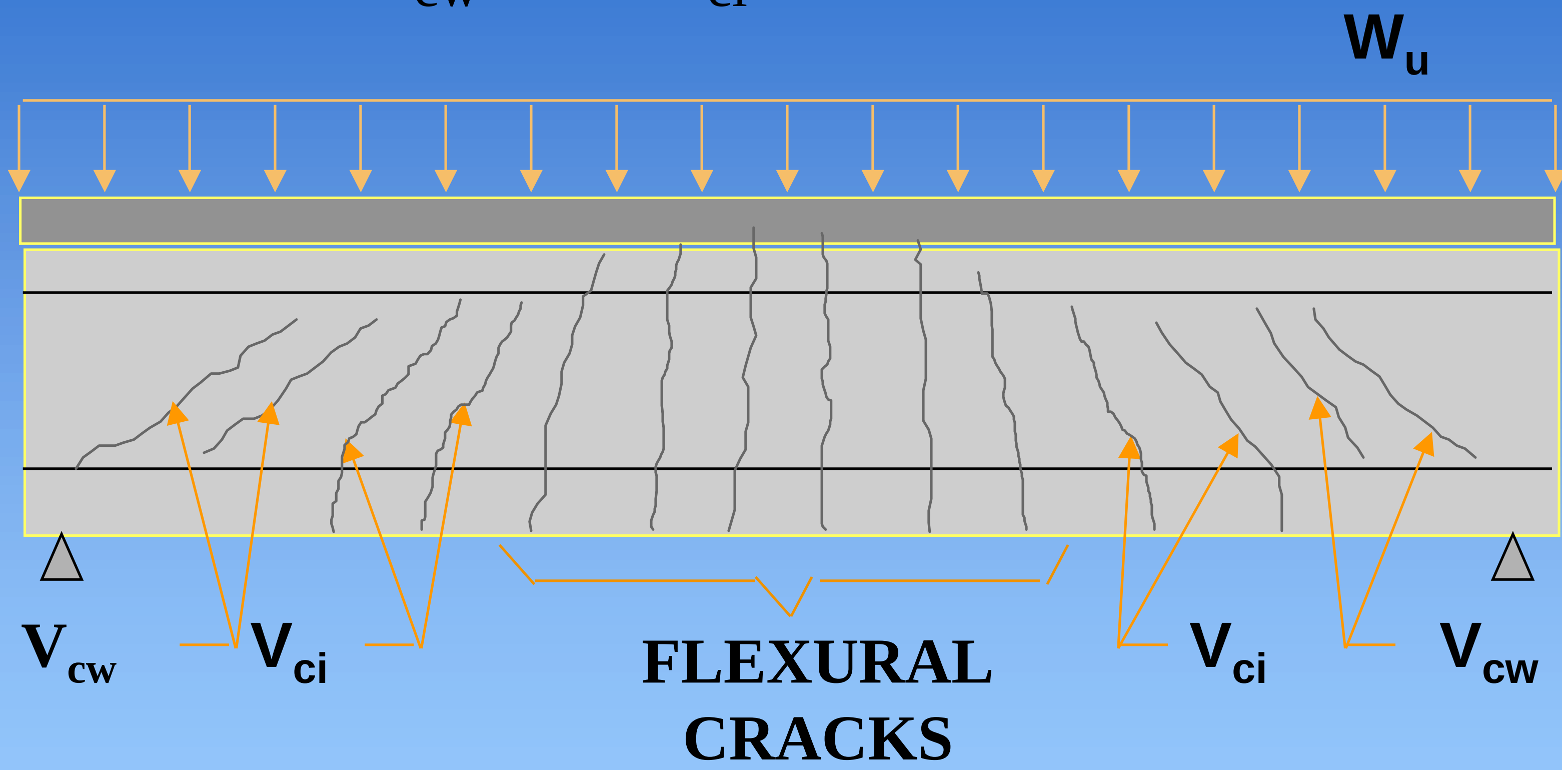
V_c is lesser of V_{ci} or V_{cw}

$$V_{ci} = 0.6\sqrt{f_c^{'}}\,b'd + V_d + \frac{V_i M_{cr}}{M_{max}}$$

$$V_{cw} = (3.5\sqrt{f_c^{'}} + 0.3f_{pc})b'd + V_p$$

SHEAR STRENGTH CODE PROVISIONS

V_{cw} and V_{ci} Shear Cracks



SIDE ELEVATION OF BEAM

AASHTO -Standard

$$V_s = \frac{A_v f_{sy} d}{s}$$

V_s shall not be taken greater than $8\sqrt{f_c^{'}}b^{'}d$

AASHTO LRFD

Nominal Shear Resistance - Article 5.8.3.3

$$V_n = V_c + V_s + V_p$$

$$V_c = 0.0316\beta\sqrt{f'_c}\, b_v\, d_v \qquad (f'_c \text{ in KSI})$$

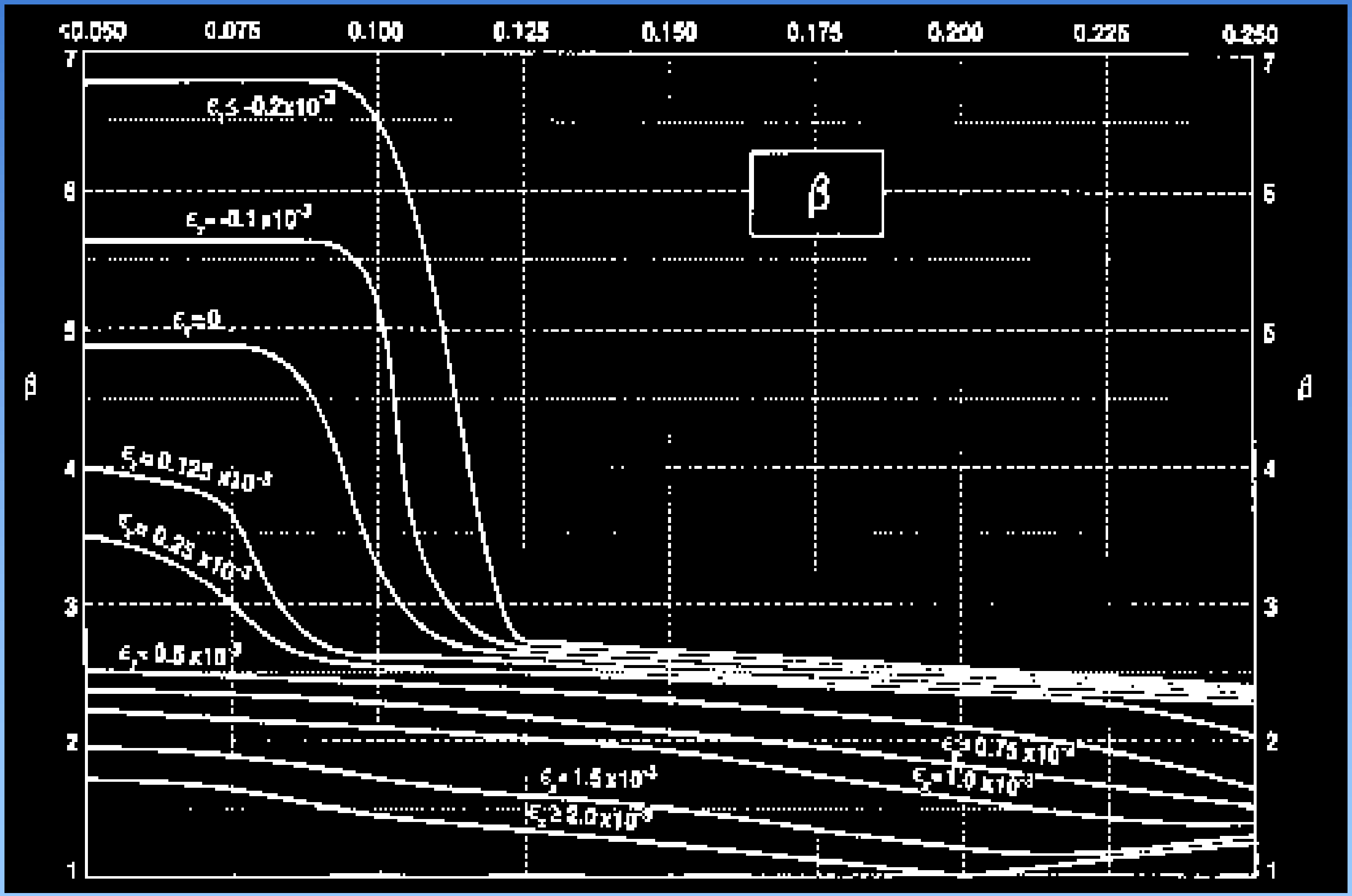
$$V_s = \frac{A_v f_y d_v (\cot\theta + \cot\alpha)\sin\alpha}{s}$$

V_p = vertical component of PS force

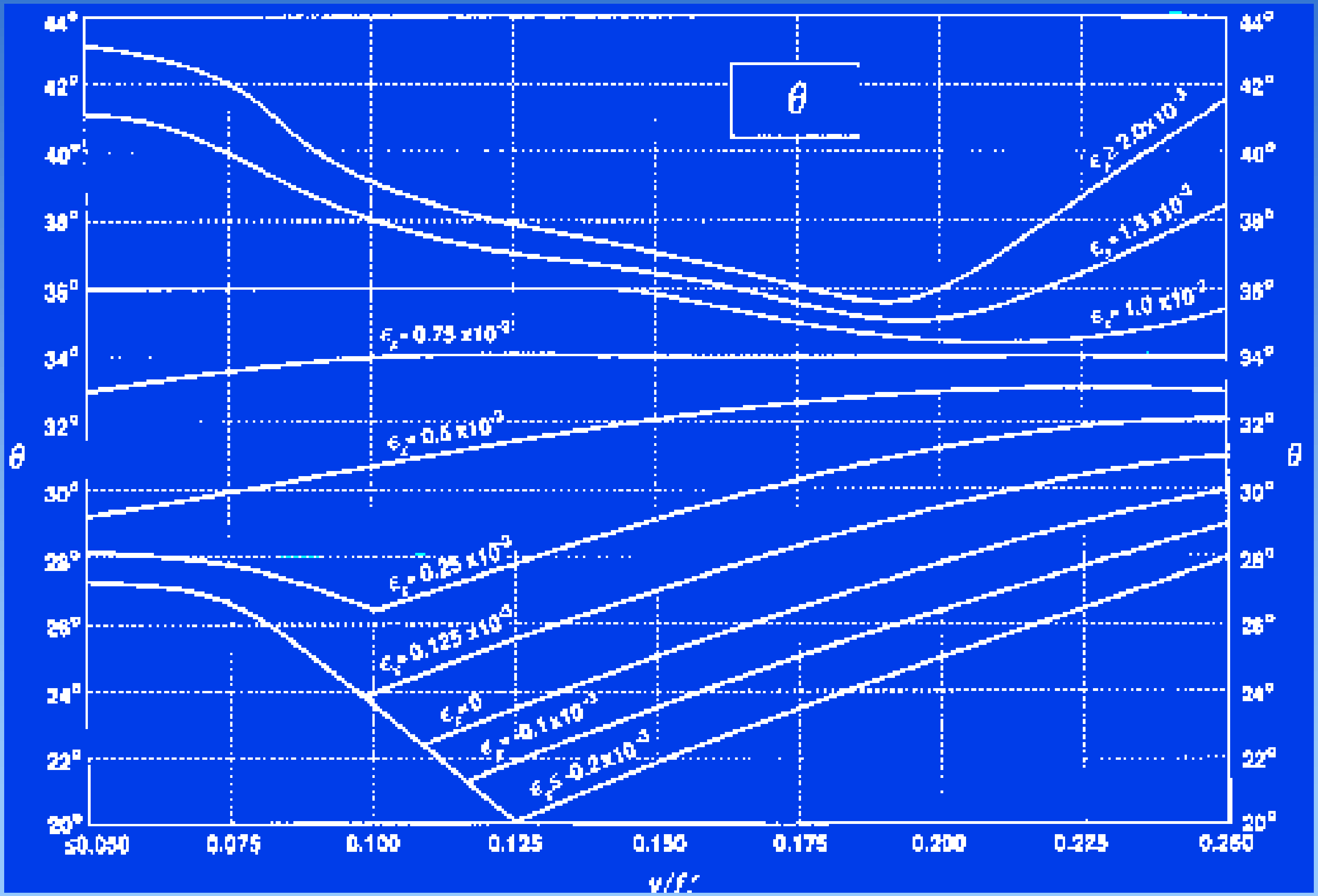
β & θ with Transv. Reinforcement - Table 5.8.3.4.2-1

$\frac{v}{f'_c}$	$\epsilon_x \times 1{,}000$										
	-0.2	-0.15	-0.1	0	0.125	0.25	0.5	0.75	1	1.5	2
<= 0.05	27.0 6.78	27.0 6.17	27.0 5.63	27.0 4.88	27.0 3.99	28.5 3.49	29.0 2.51	33.0 2.37	36.0 2.23	41.0 1.95	43.0 1.72
0.075	27.0 6.78	27.0 6.17	27.0 5.63	27.0 4.88	27.0 3.65	27.5 3.01	30.0 2.47	33.5 2.33	36.0 2.16	40.0 1.90	42.0 1.65
0.1	23.5 6.50	23.5 5.87	23.5 5.31	23.5 3.26	24.0 2.61	26.5 2.54	30.5 2.41	34.0 2.28	36.0 2.09	38.0 1.72	39.0 1.45
0.125	20.0 2.71	21.0 2.71	22.0 2.71	23.5 2.60	26.0 2.57	28.0 2.50	31.5 2.37	34.0 2.18	36.0 2.01	37.0 1.60	38.0 1.35
0.15	22.0 2.66	22.5 2.61	23.5 2.61	25.0 2.55	27.0 2.50	29.0 2.45	32.0 2.28	34.0 2.06	36.0 1.93	36.5 1.50	37.0 1.24
0.175	23.5 2.59	24.0 2.58	25.0 2.54	26.5 2.50	28.0 2.41	30.0 2.39	32.5 2.20	34.0 1.95	35.0 1.74	35.5 1.35	36.0 1.11
0.2	25.0 2.55	25.5 2.49	26.5 2.48	27.5 2.45	29.0 2.37	31.0 2.33	33.0 2.10	34.0 1.82	34.5 1.58	35.0 1.21	36.0 1.00
0.225	26.5 2.45	27.0 2.38	27.5 2.43	29.0 2.37	30.5 2.33	32.0 2.27	33.0 1.92	34.0 1.67	34.5 1.43	36.5 1.18	39.0 1.14
0.25	28.0 2.36	28.5 2.38	29.0 2.32	30.0 2.30	31.0 2.28	32.0 2.01	33.0 1.64	34.0 1.52	35.5 1.40	38.5 1.30	41.5 1.25

β for Sections with Transv. Reinf. -Fig. 5.8.3.4.2-1



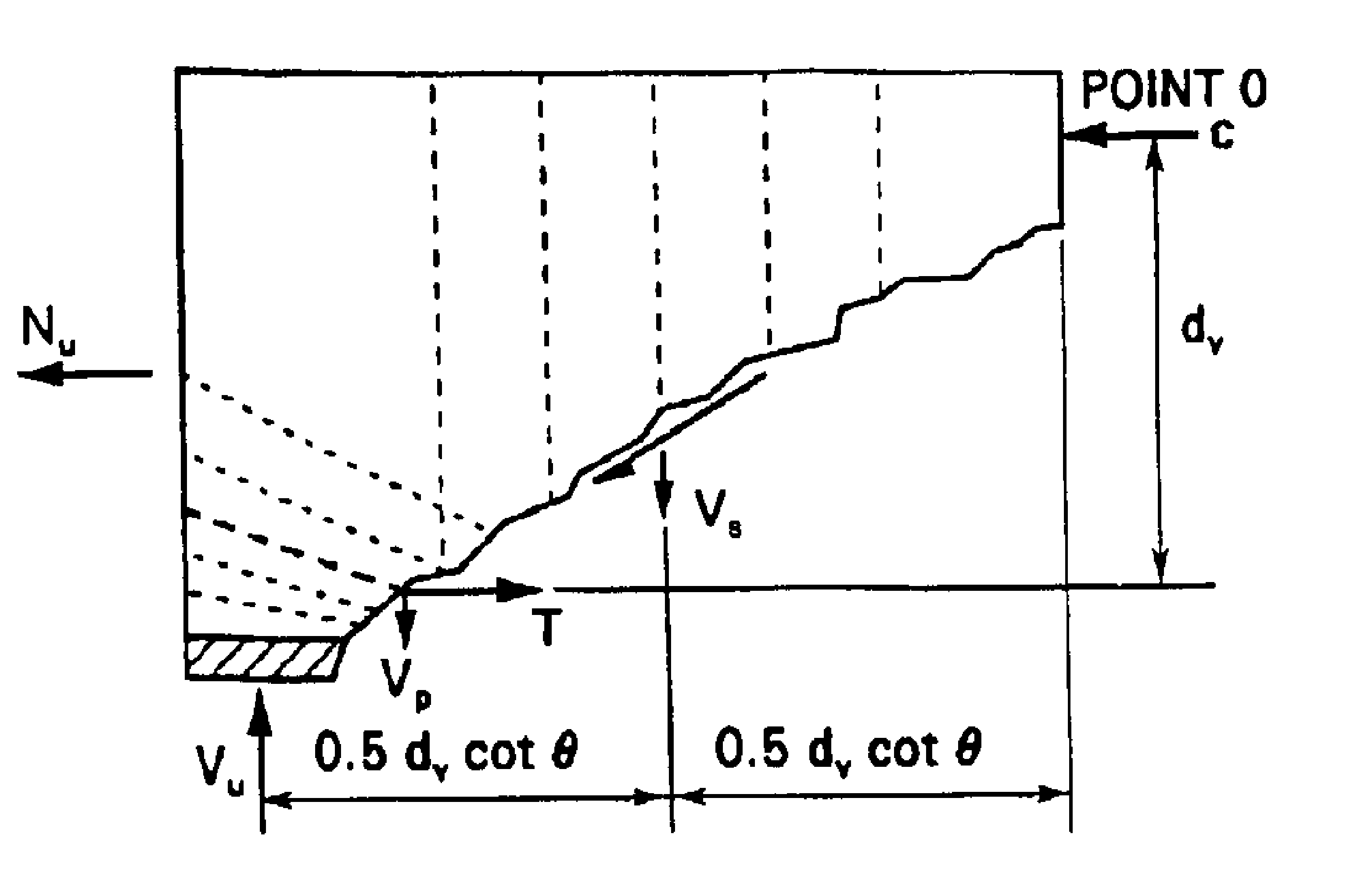
θ for Sections with Transv. Reinf. -Fig. 5.8.3.4.2-1



Longitudinal Reinforcement - Article 5.8.3.5

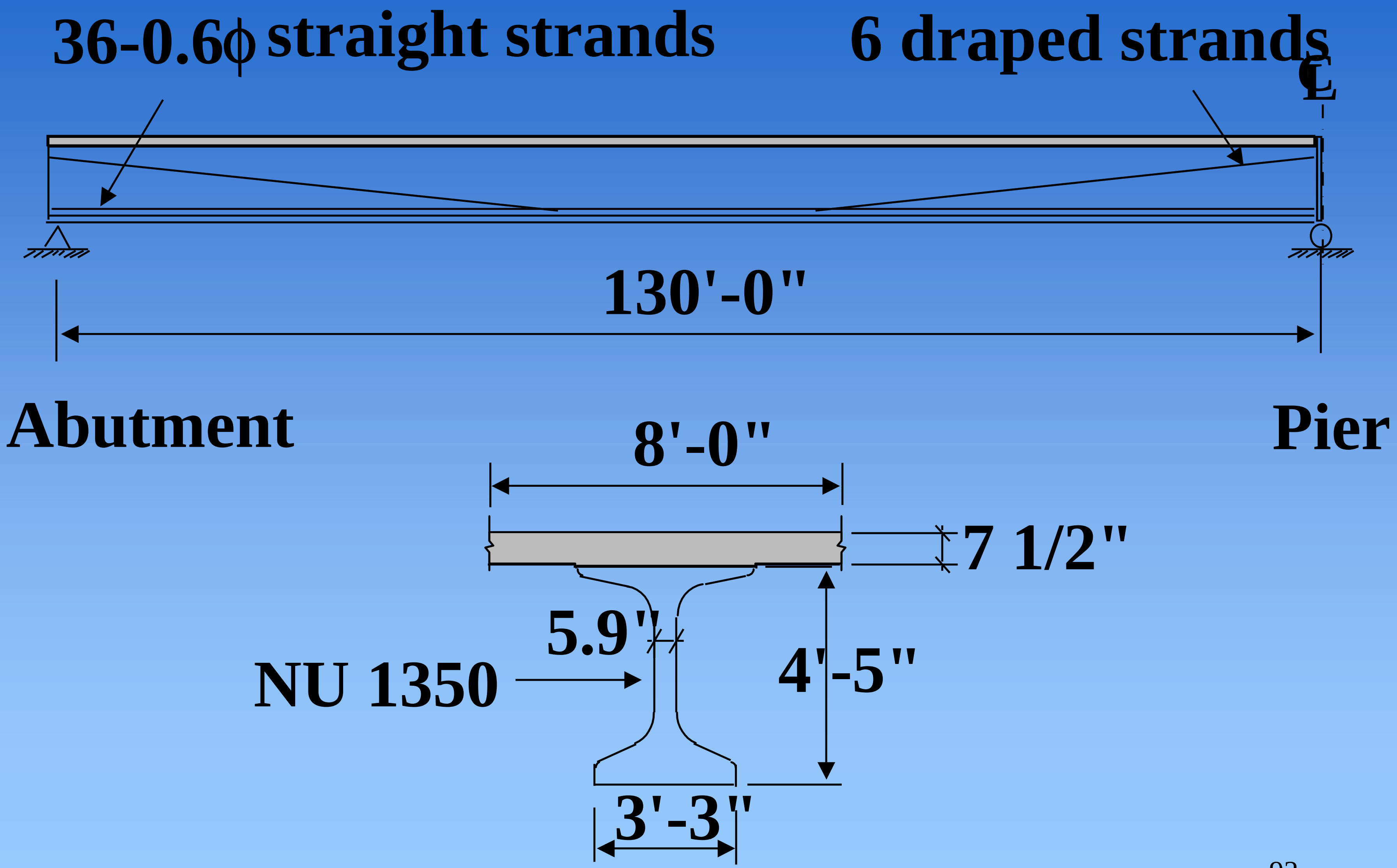
$$T \geq \left[\frac{M_u}{d_v \phi} + 0.5 \frac{N_u}{\phi} + \left(\frac{V_u}{\phi} - 0.5V_s - V_p \right) \cot\theta \right]$$

Longitudinal Reinforcement - Fig. C5.8.3.5-1



- **Do we have to have complicated V_c formulas?**

I-Beam Example



I-Beam Example

HS - 25 truck loading

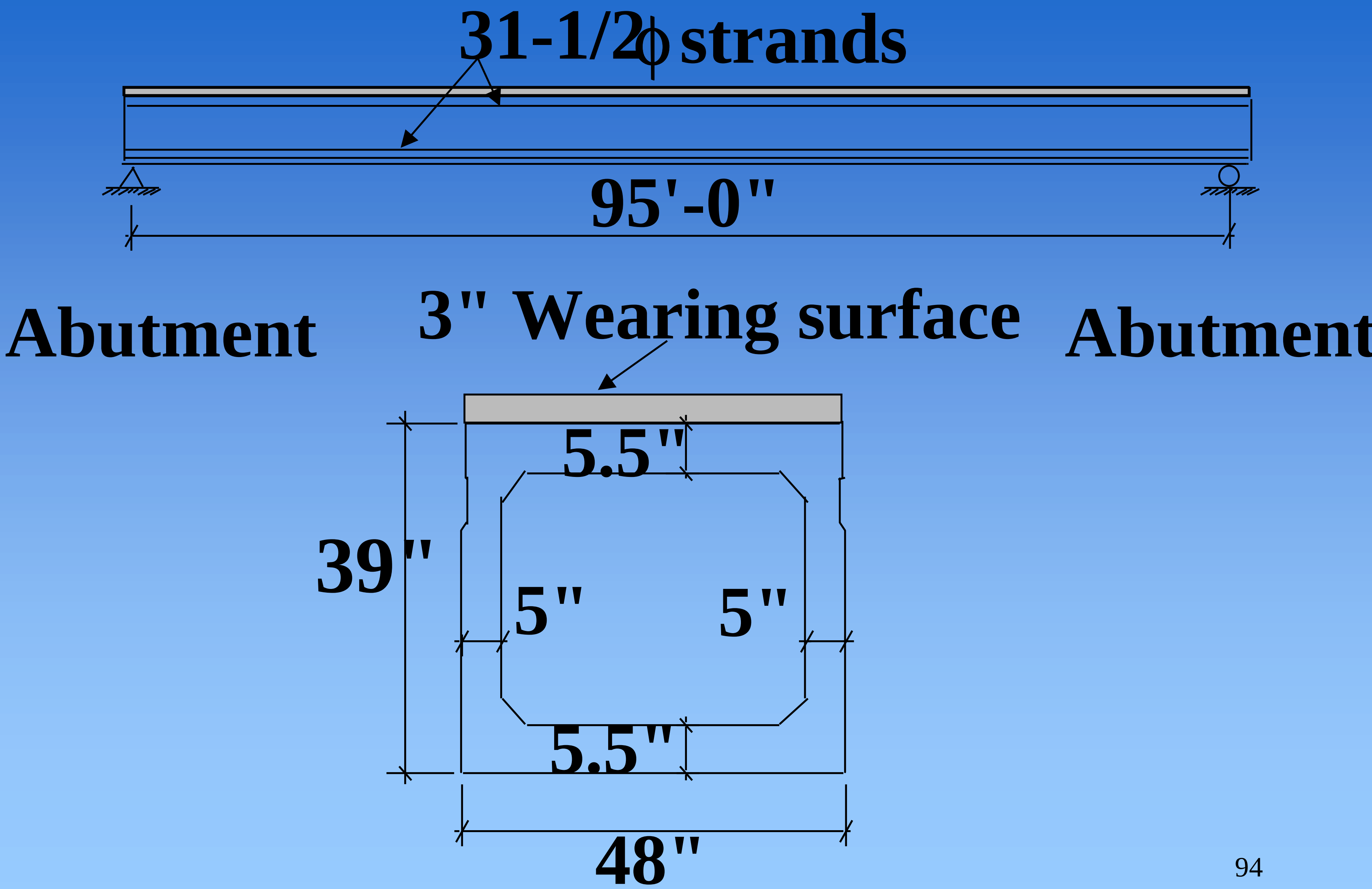
I-Beam strength:

at release = 7,000 psi

at service = 10,000 psi

Deck strength = 5,000 psi

Adjacent Box Example



Adjacent Box Example

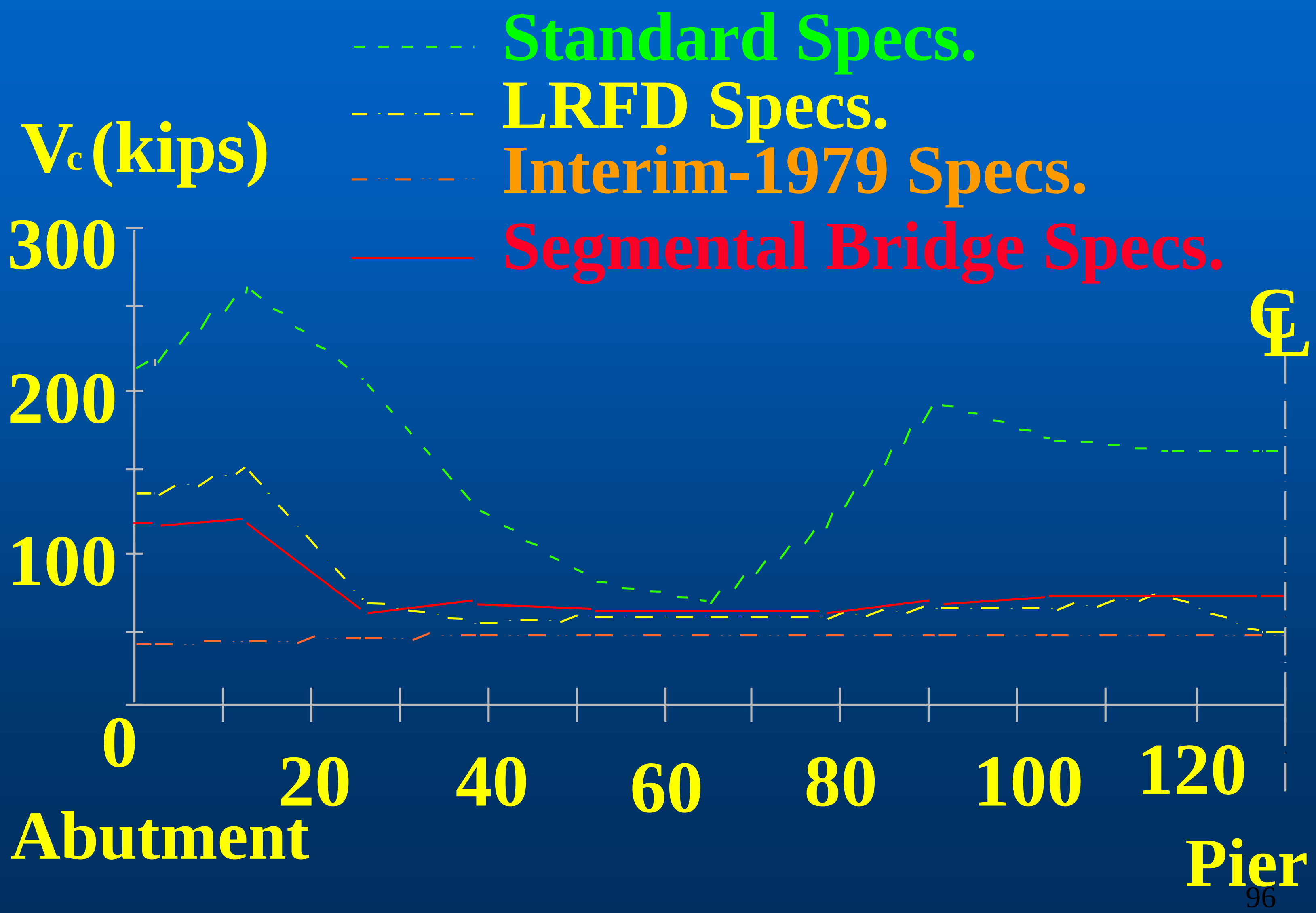
HS - 25 truck loading

Beam strength:

at release = 4,000 psi

at service = 5,000 psi

Calculated V_c



Cost Analysis Assumptions

Precast concrete beams = $600/cu. yd.

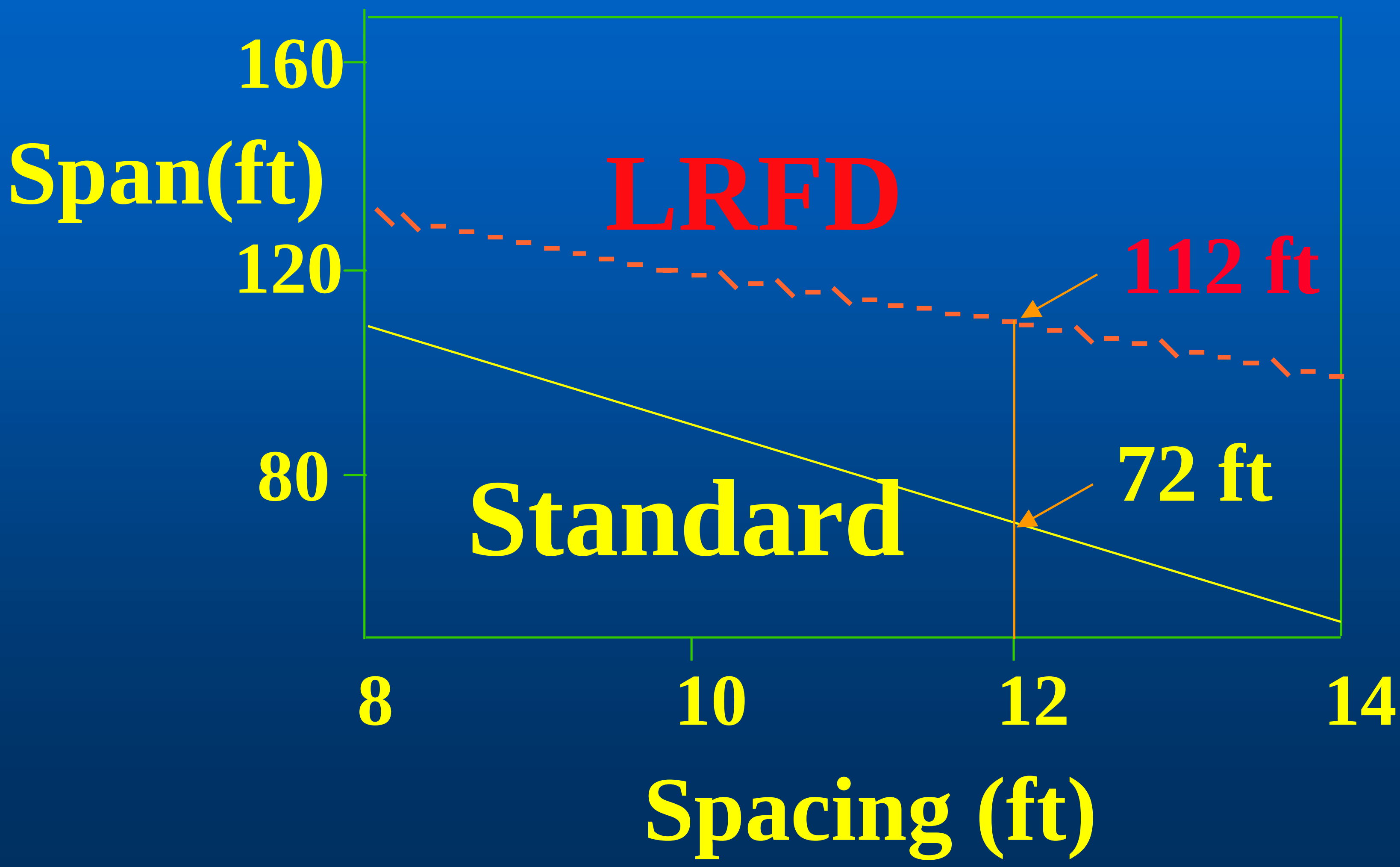
Stirrups = $0.50/lb

Relative Total Cost

Maximum Shear Limit
Article 5.8.3.3

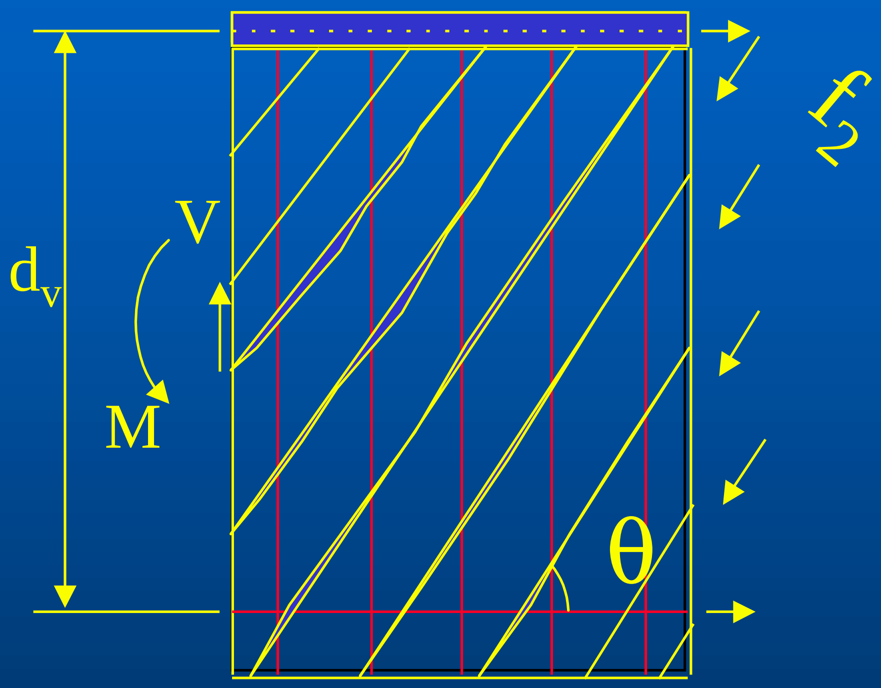
LRFD: $V_n \leq 0.25 f'_c b_v d_v + V_p$

Continuous Span Capacity of NU 1100
(Three span post-tensioned)



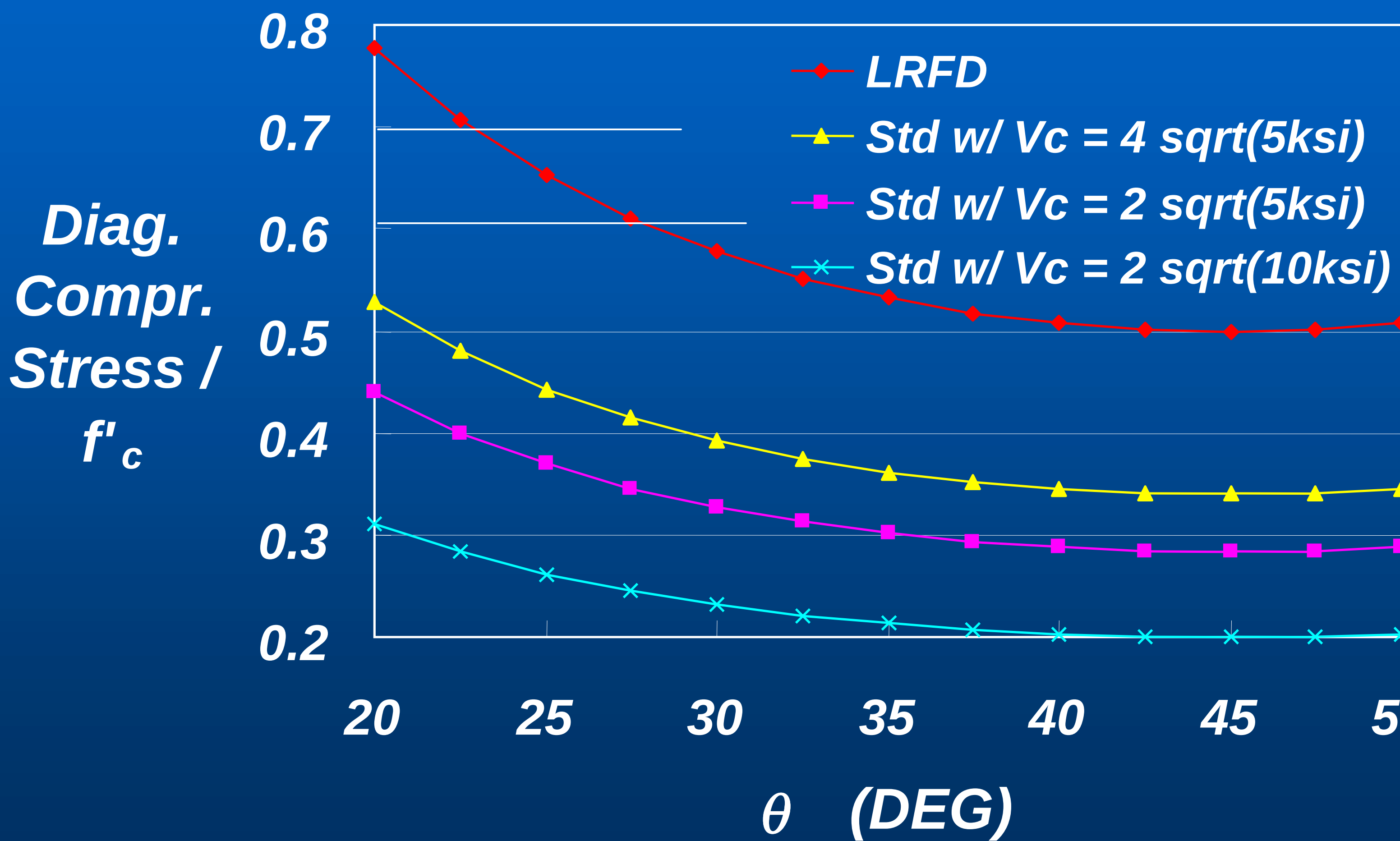
Compression Field Theory
(CAN3-A23.3-M84 & AASHTO LRFD)

Equilibrium of Forces:



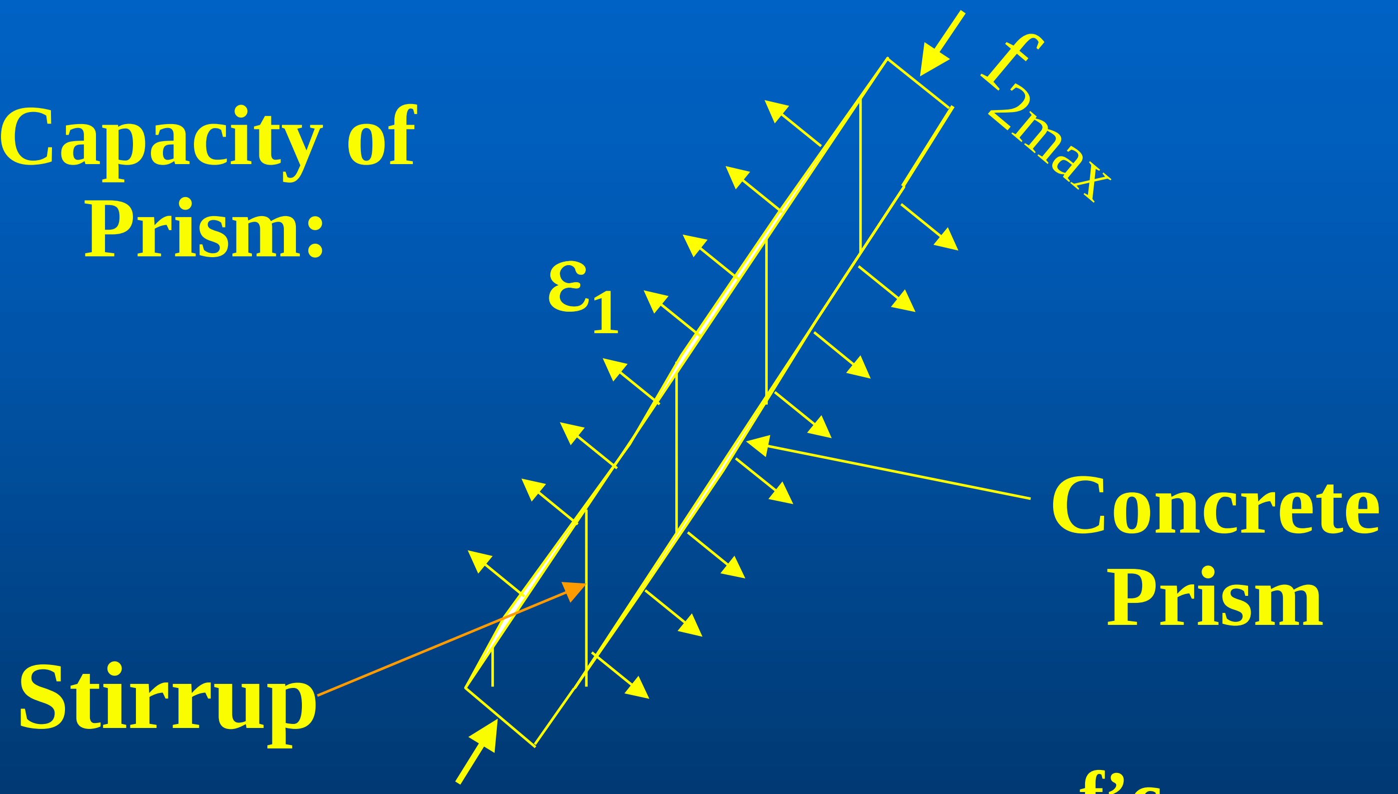
$$f_2 = \frac{V}{b_v d_v \sin\theta \cos\theta}$$

Stress in Compression Diagonal at Limiting Shear, V_n



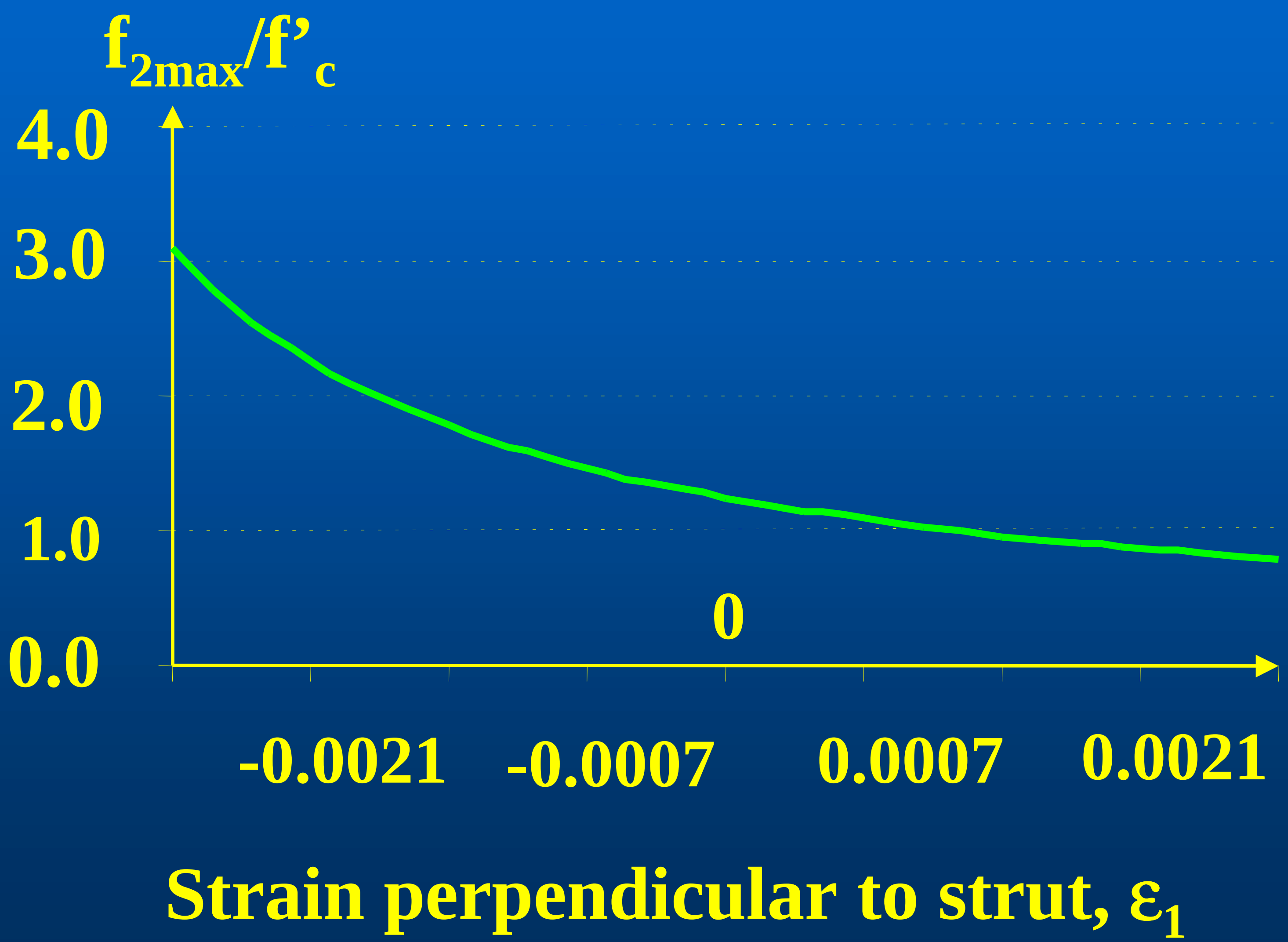
Compression Field Theory (CAN3-A23.3-M84 & AASHTO LRFD)

Capacity of Prism:

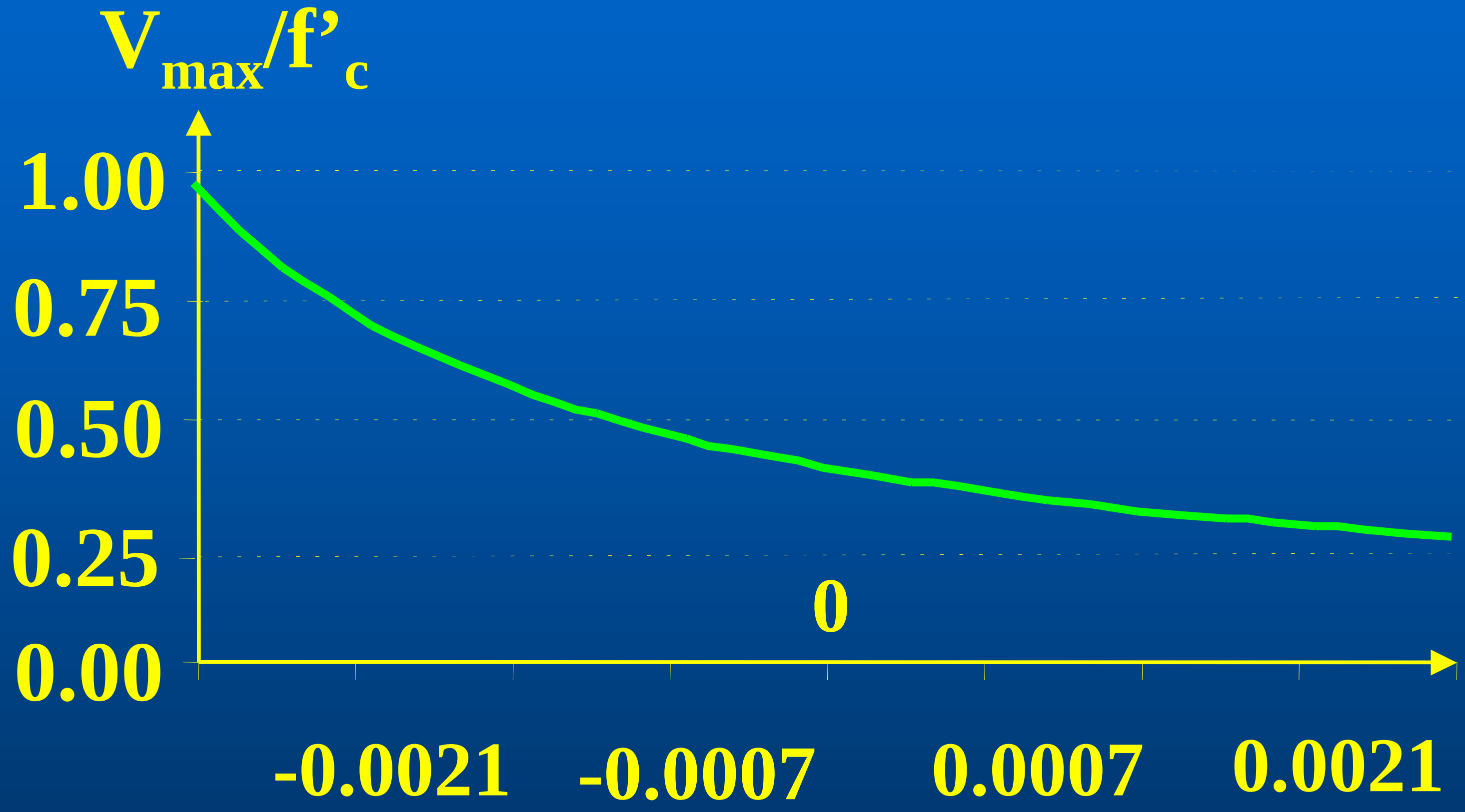


$$f_{2max} = \frac{f'c}{0.8+170\varepsilon_1}$$

f_{2max} vs ε_1



V_{max} vs ε_1

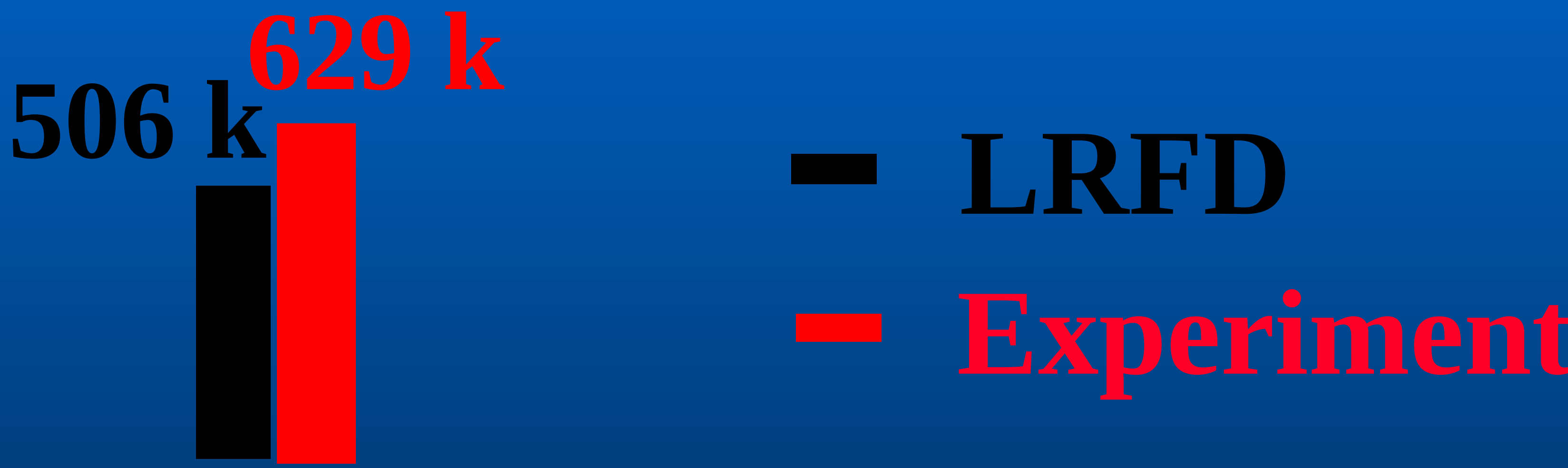


Strain perpendicular to strut, ε_1

(Assume $\theta = 20^0$)

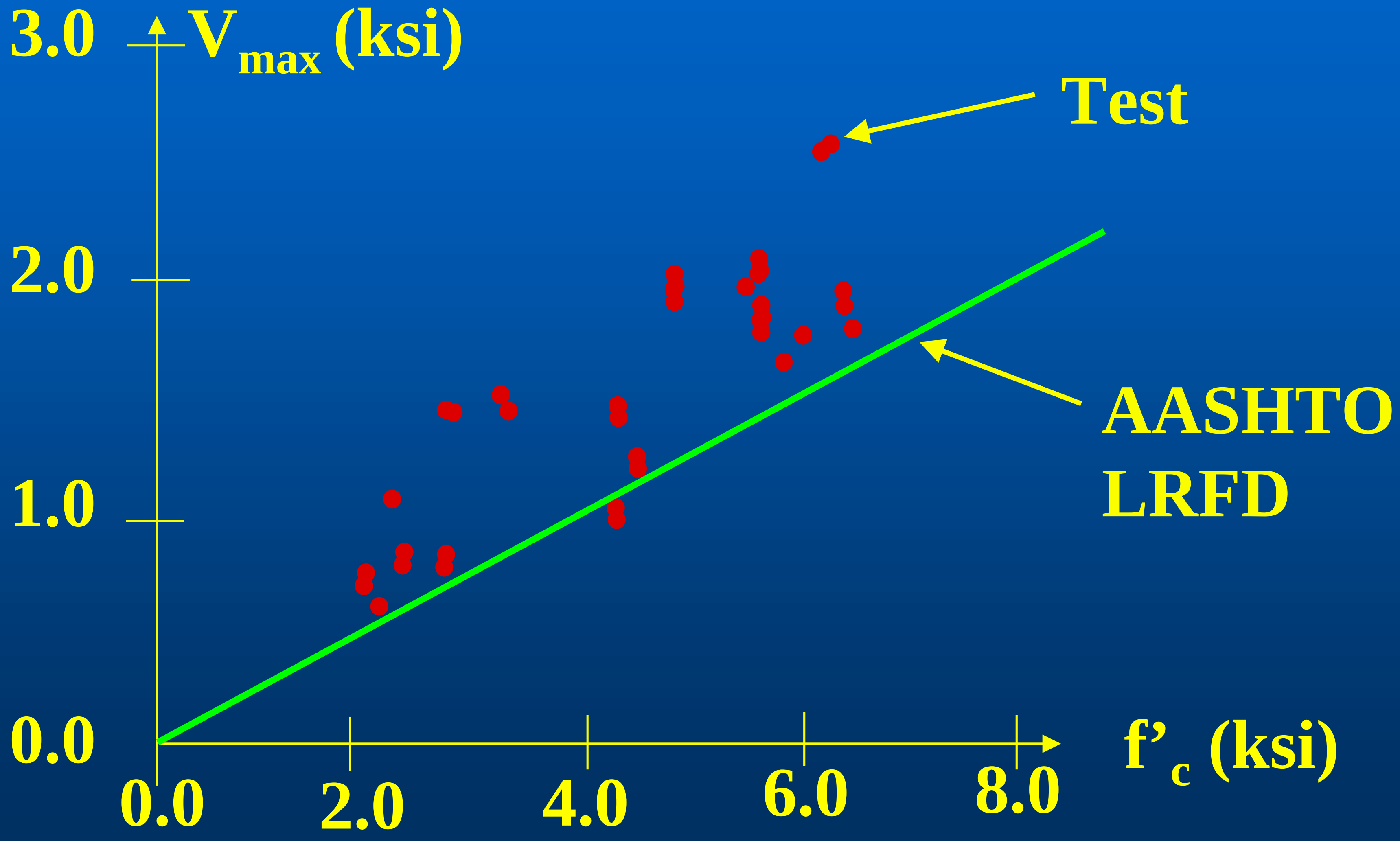
Nebraska’s Experiment

(Example)



Ramirez's Research

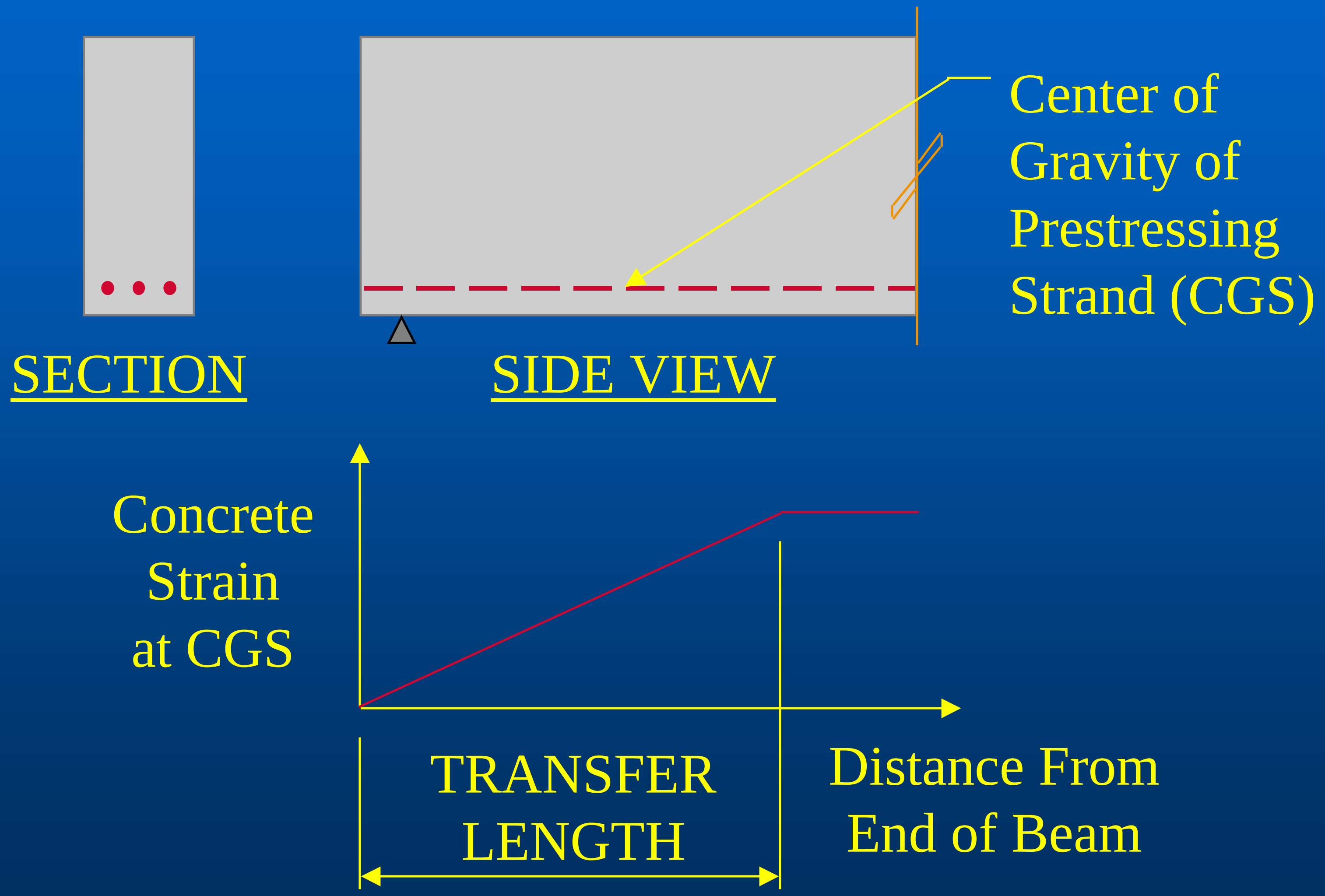
(ASBI Newsletter Article)



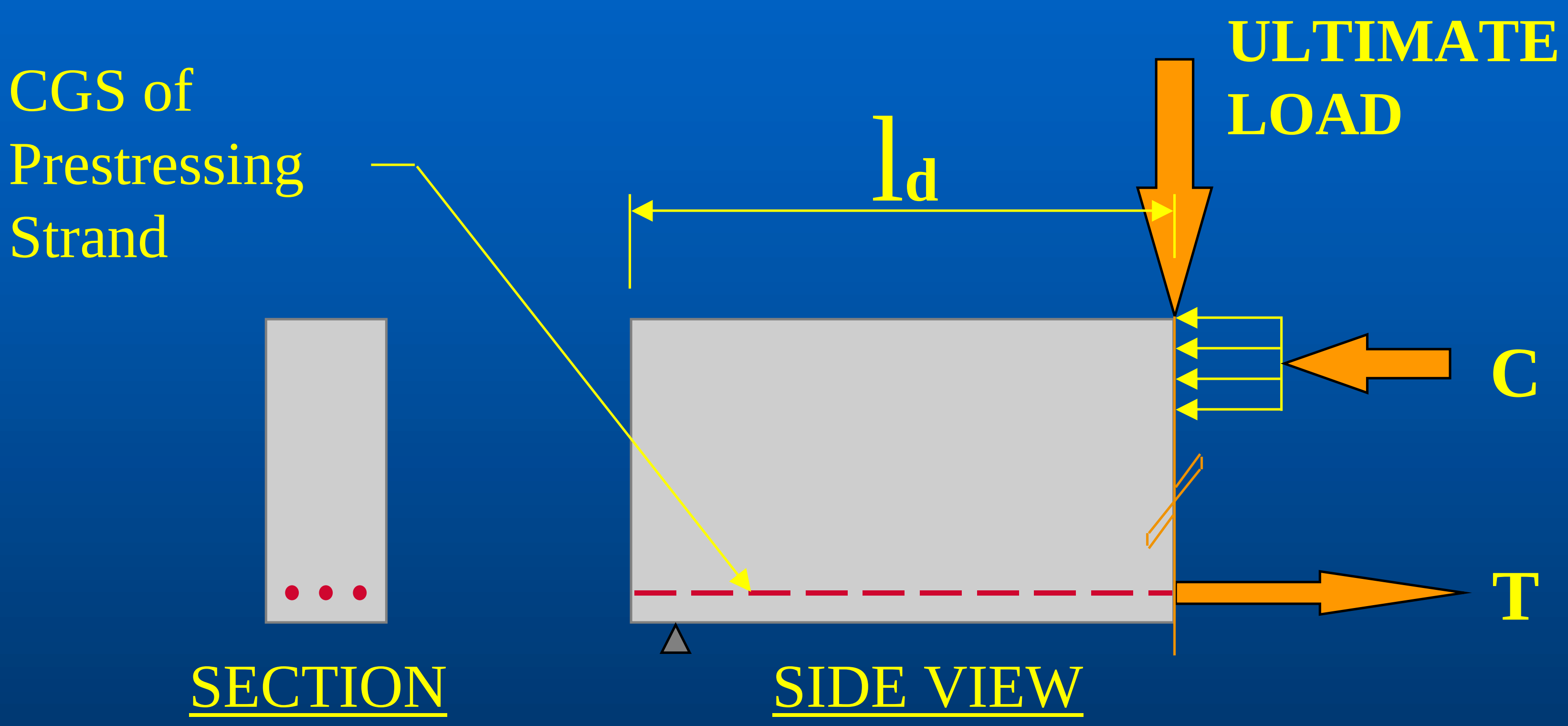
Based on theory and experiments, the 0.25f’c maximum allowed by LRFD Specifications is conservative

Transfer and Development Length

TRANSFER LENGTH (l_t)
(DEFINITION)



DEVELOPMENT LENGTH (l_d)
(DEFINITION)



AASHTO Development Length Equation

$$\left(f^*_{su} - \frac{2}{3} f_{se}\right)(D)$$

WHERE:

f^*_{su} = Average stress in prestressing at ultimate load (psi)

f_{se} = Effective steel prestress after losses (psi)

D = Diameter of strand (in)

AASHTO Equation

"It should be noted that according to ACI 318R-63 Commentary, 'the value of 1/3 $f_{se}D$ for transfer length is an average value based on data reported by Kaar et al.' Therefore, this relationship was not meant to be a conservative estimate, rather an estimate of an average transfer length."

(Ref= Tabatabai and Dickson)

AASHTO Equation

"The Flexural bond length relationship ((f^*_{su} - f_{se})D) is the equation of a line drawn through data points on a graph of (f^*_{su}-f_{se}) versus (($L-L_t$)/D). In the view of the ACI Committee 423, the proposed line represented a reasonable mean for the data points without being unreasonable for long bonded lengths."

(Ref.= Tabatabai and Dickson)

Development Lengths Summary Table, FHWA Data

UNCOATED STRANDS IN GIRDER ALONE*

Type of Girders	AASHTO L_D (in.)	Measured L_D (in.)
0.5 @ 2.0”; 5 ksi	75.9	106
0.5 @ 2.0”; 10 ksi	76.5	86
0.5 @ 1.75”; 5 ksi	76.5	116
0.6 @ 2.0”; 5 ksi	92.5	143
0.6 @2.0”; 10 ksi	94.4	102

* (STRAIN IN STRANDS NEAR YIELD, 0.010)

Proposed FHWA Transfer Length Expression

$$L_t = \left(\left[\frac{(4)(f_{pt})(D)}{f_c^{'}} \right] - 5 \right)$$

WHERE:

L_t = Transfer length (in.)

f_{pt} = Stress in prestressing steel immediately prior to transfer (psi)

D = Diameter of strand (in.)

f'_c = Compressive strength of concrete at 28 days (psi)

With value of f'c greater than 10,000 PSI being taken as 10,000 PSI

Proposed FHWA Development Length Equation

$$L_D = \left\{\left(\left[\frac{(4)(f_{pt})(D)}{f_c^{'}}\right] - 5\right) + \left(\left[\frac{(6.4)(f_{su}^{*} - f_{se})(D)}{f_c^{'}}\right] + 15\right)\right\}$$

WHERE:

L_D = Development length (in.)

f_{pt} = Stress in prestressing steel immediately prior to transfer (psi)

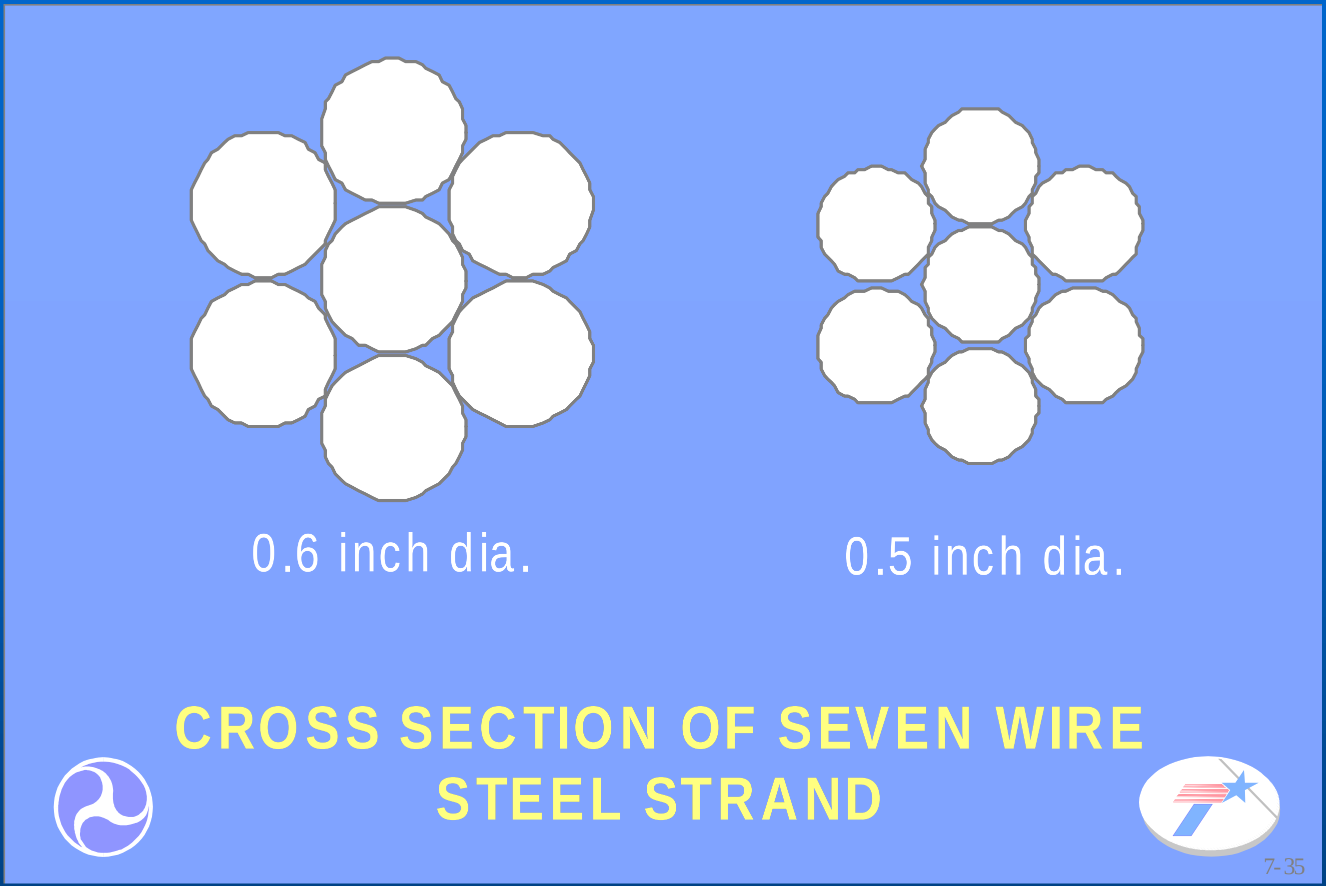
D = Diameter of strand (in.)

f'_c = Compressive strength of concrete at 28 days (psi)

f^*_{su} = Average stress in prestressing steel at ultimate load (psi)

f_{se} = Effective steel prestress after losses (psi)

With values of f'_c greater than 10,000 PSI being taken as 10,000 PSI



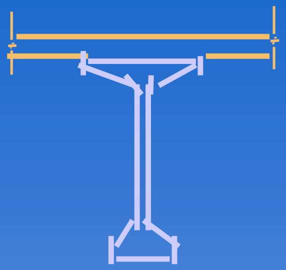
To effectively use higher concrete strength - a larger diameter strand is required

Second FHWA Memorandum (May, 1996)

- Allowed use of 0.6” Dia strand
- Allowed the following center-to-center strand spacing:
  - 0.6” Dia strand @ 2” spacing
  - 0.5” Dia strand @ 1.75” spacing
- Retained multipliers specified for use with AASHTO development length equation

Deflection

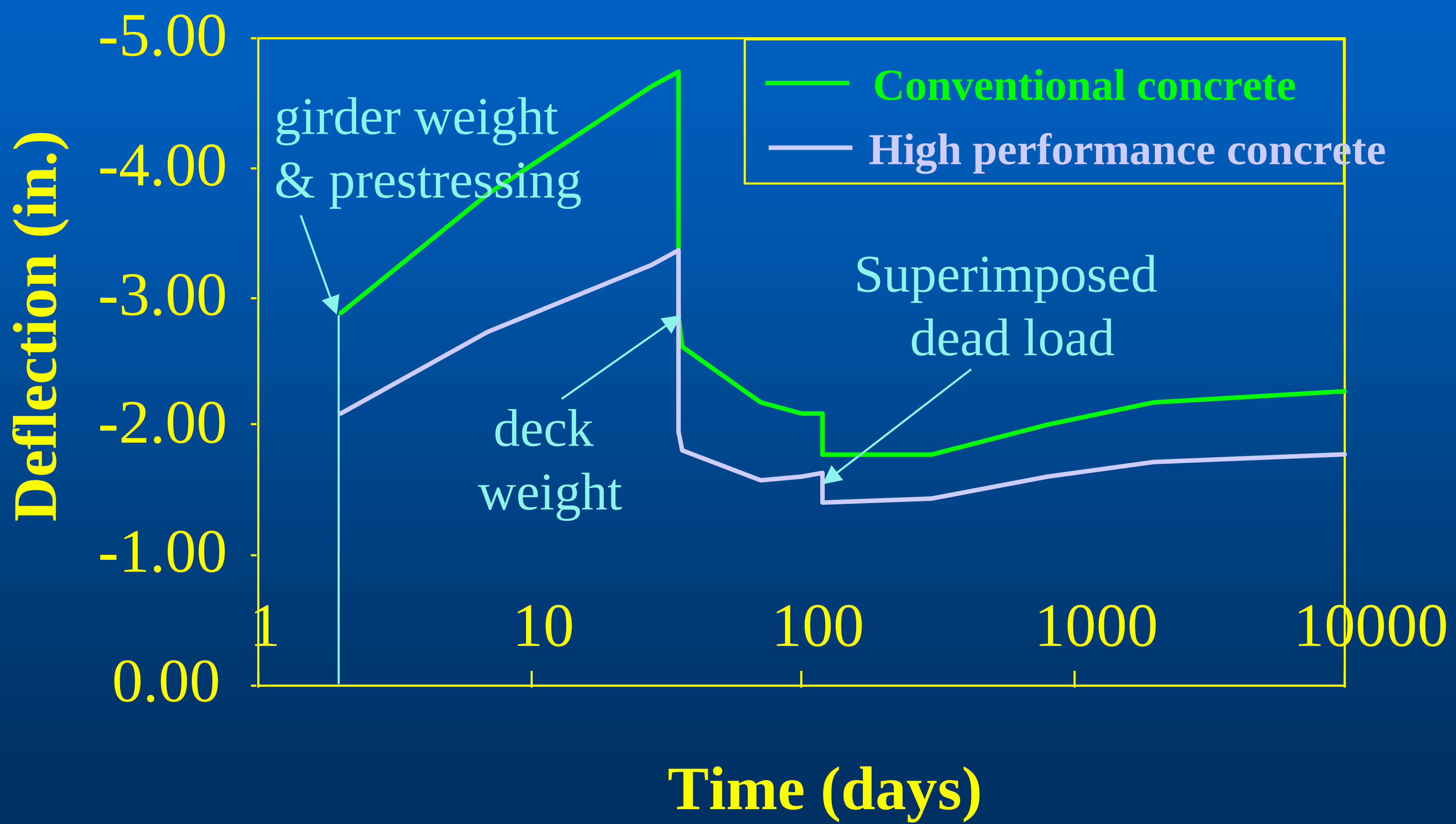
The construction stages are as follows:



(1) release prestressing force at 1 day;
(2) apply girder self weight at 1 days;
(3) pour cast-in-place deck at 35 days; and
(4) apply superimposed dead load at 120 days.

The computer program *CREEP3* was used to determine the time-dependent deformation in each stage of construction.

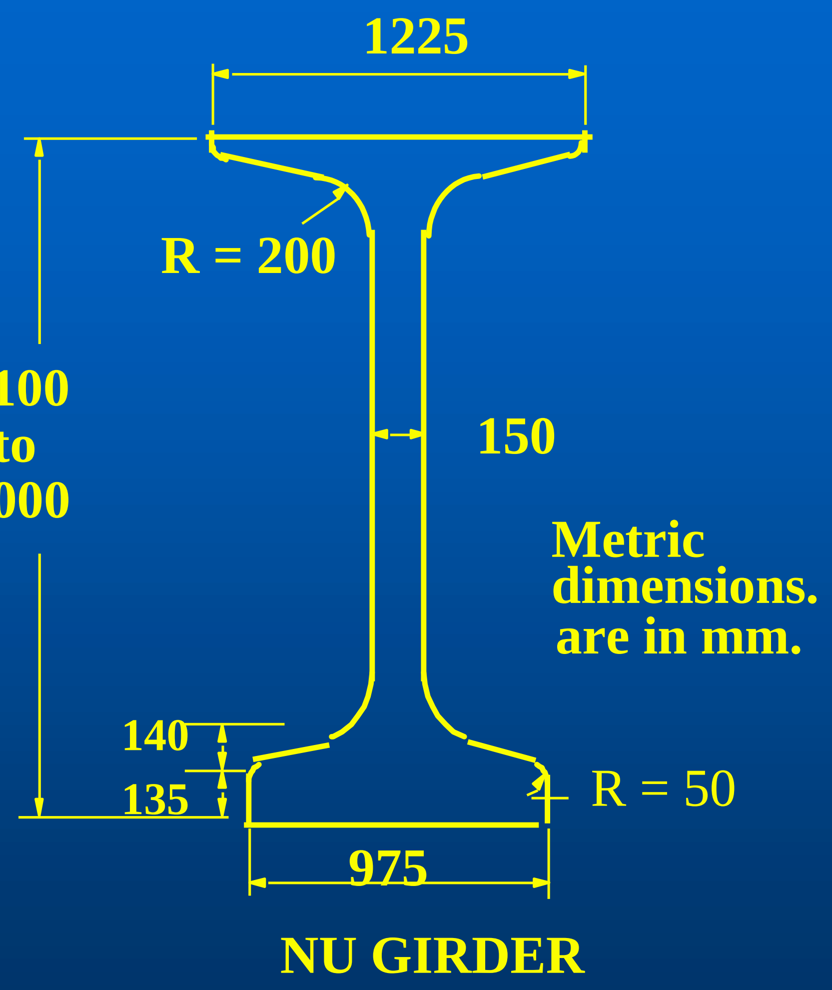
DEFLECTION (HPC)



Girders:
NU1100 - NU2000

Girder spacing:
6 ft - 12 ft

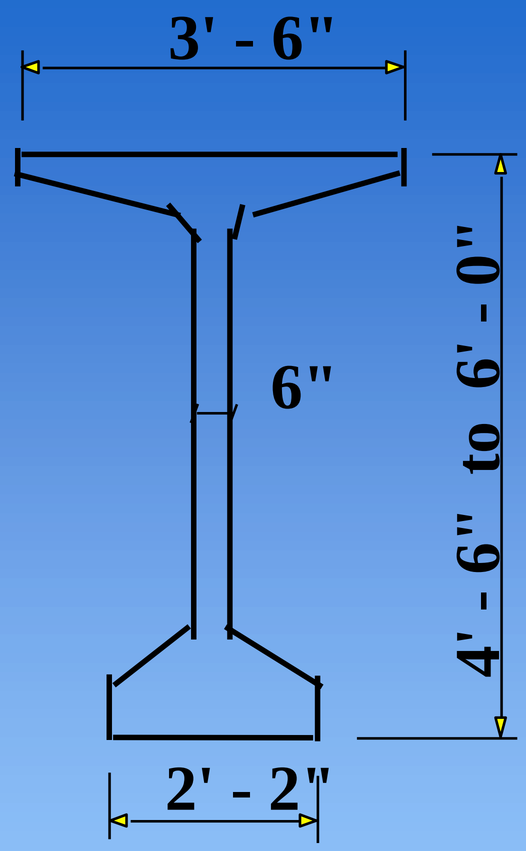
$f'_{c,\ girder}$ = 8,000 psi
$f'_{c,\ deck}$ = 5,000 psi



Girders:
BT54 - BT72

Girder spacing:
6 ft - 12 ft

$f'_{c,\,girder} = 6{,}000$ psi
$f'_{c,\,deck} = 4{,}000$ psi



BULB TEE GIRDER SECTION

RECOMMENDED DEFLECTION MULTIPLIERS AT ERECTION TIME

Load condition	Formula
Initial prestress	$0.94 (1 + C_a)$
Member weight	$1 + C_a$
Superimposed dead load	1.00

C_a - creep coefficient for loading duration from release to erection

RECOMMENDED DEFLECTION MULTIPLIERS AT FINAL TIME

	With composite topping
Initial prestress	$1 + 0.80\ C_u$
Girder weight	$1 + 0.77\ C_u$
Composite topping	$1 + 0.61\ C_u$
Superimposed dead load	$1 + 0.54\ C_u$

C_u - Ultimate creep coefficient

PCI deflection multipliers at final time are not accurate. The proposed multipliers which are the function of creep coefficient can be used for conventional and HPC members.

Continuity

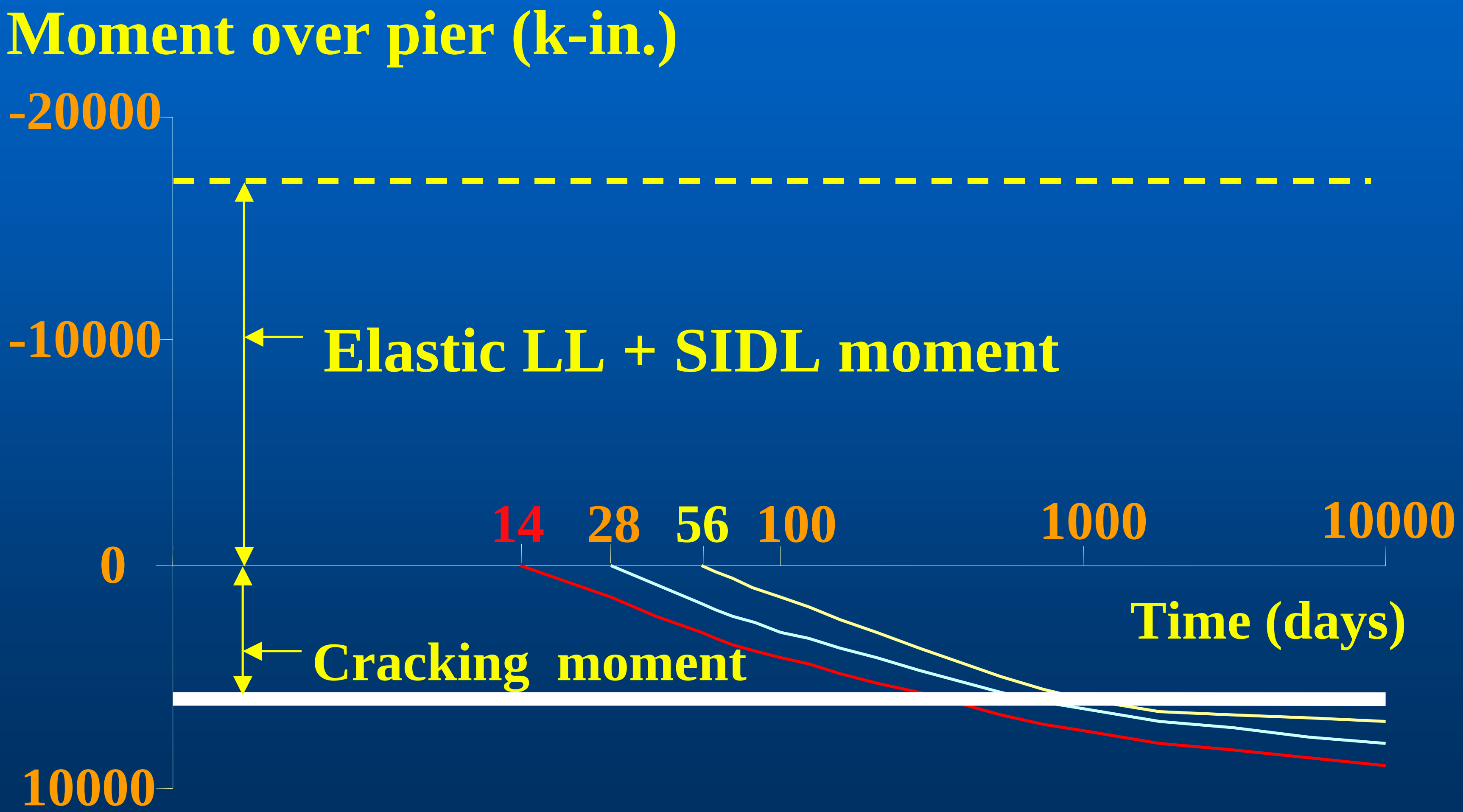
THREE CASES OF CONSTRUCTION SEQUENCE

Case 1 - Cast diaphragm only (no deck)

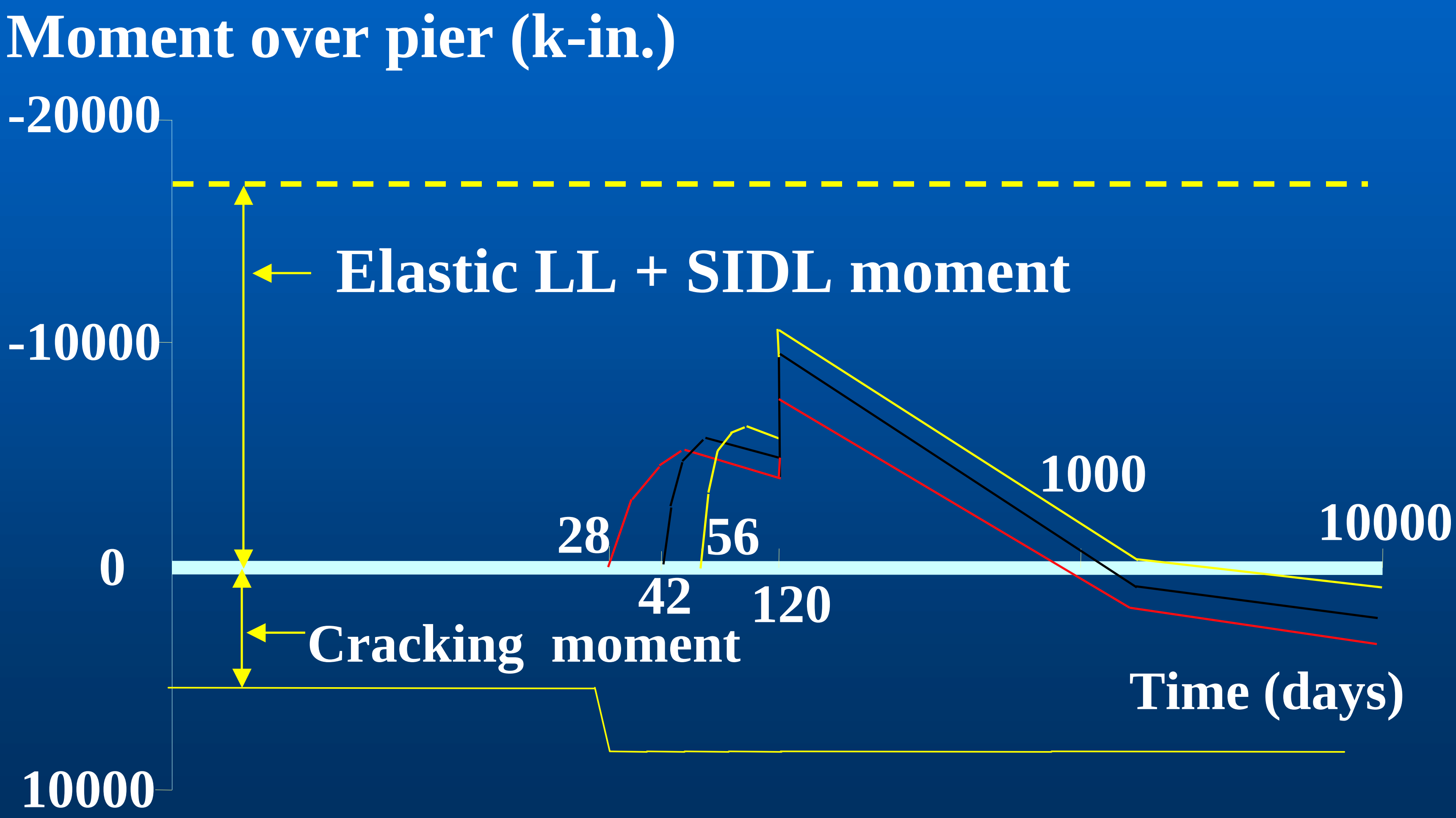
Case 2 - Continuous after deck placement
- **Deck and diaphragm cast simultaneously**
- **Diaphragm cast first but girder is flexible to rotate**

Case 3 - Continuous for deck weight

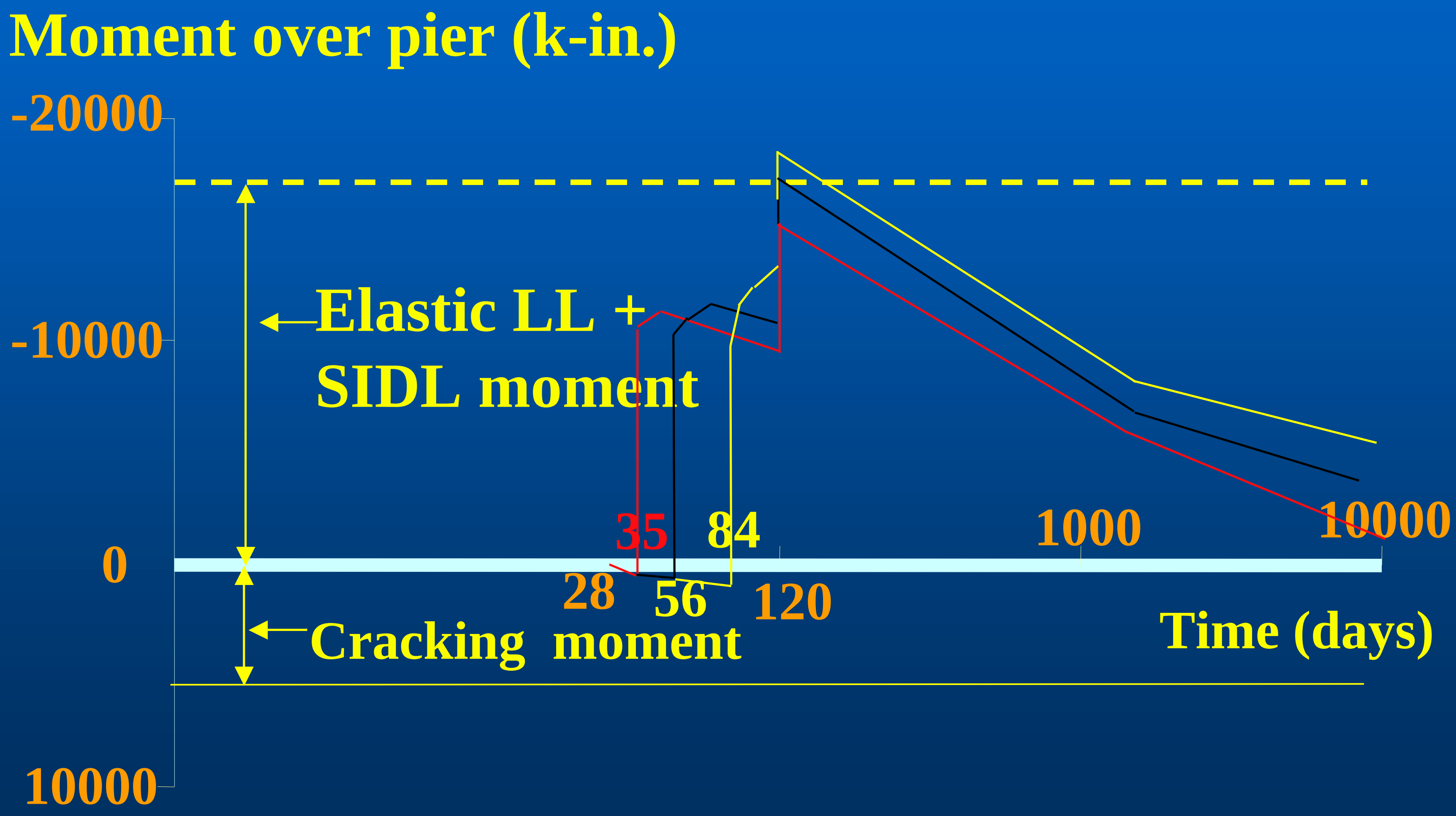
Time-Dependent Restraint Moment Diaphragm Only (No Deck)



Time-Dependent Restraint Moment Diaphragm & Deck Cast Simultaneously



Time-Dependent Restraint Moment Diaphragm Cast Before Deck



RECOMMENDATIONS ON CONTINUITY

(1) If diaphragm must be cast ahead of the deck and if the girders must be rigidly connected to the diaphragm, then it is important to

(a) Have adequate positive moment and negative moment capacity of the girder line over the pier.

(b) Cast the deck as early as possible.

RECOMMENDATIONS ON CONTINUITY (cont.)

(2) The most favorable time-dependent behavior is when the diaphragm does not restrain the girder end rotation. To achieve this:

(a) Cast the diaphragm and deck simultaneously

(b) Cast the diaphragm first but minimize the girder embedment and provide a "debonding" detail between the girder and the diaphragm.

RECOMMENDATIONS ON CONTINUITY (cont.)

(3) The most structurally efficient detail is to make the girders continuous for deck weight. This solution

(a) increases the span capacity of a given size by about 10 to 20% and,

(b) minimizes the need for possible positive moment reinforcement at the piers.

According to the time-dependent analysis of continuous bridges, the most favorable construction sequence is to cast diaphragm and deck simultaneously.

MODULE 6

Research and Long-Term Monitoring

Prepared by:

Henry G. Russell

Part A

INSTRUMENTATION for LONG-TERM MONITORING

SCOPE

Basic Program

Optional Program

Types of Instrumentation

Data Acquisition

Data Interpretation

BASIC PROGRAM

Temperatures

Long-Term
Strains

Deflections

TEMPERATURES

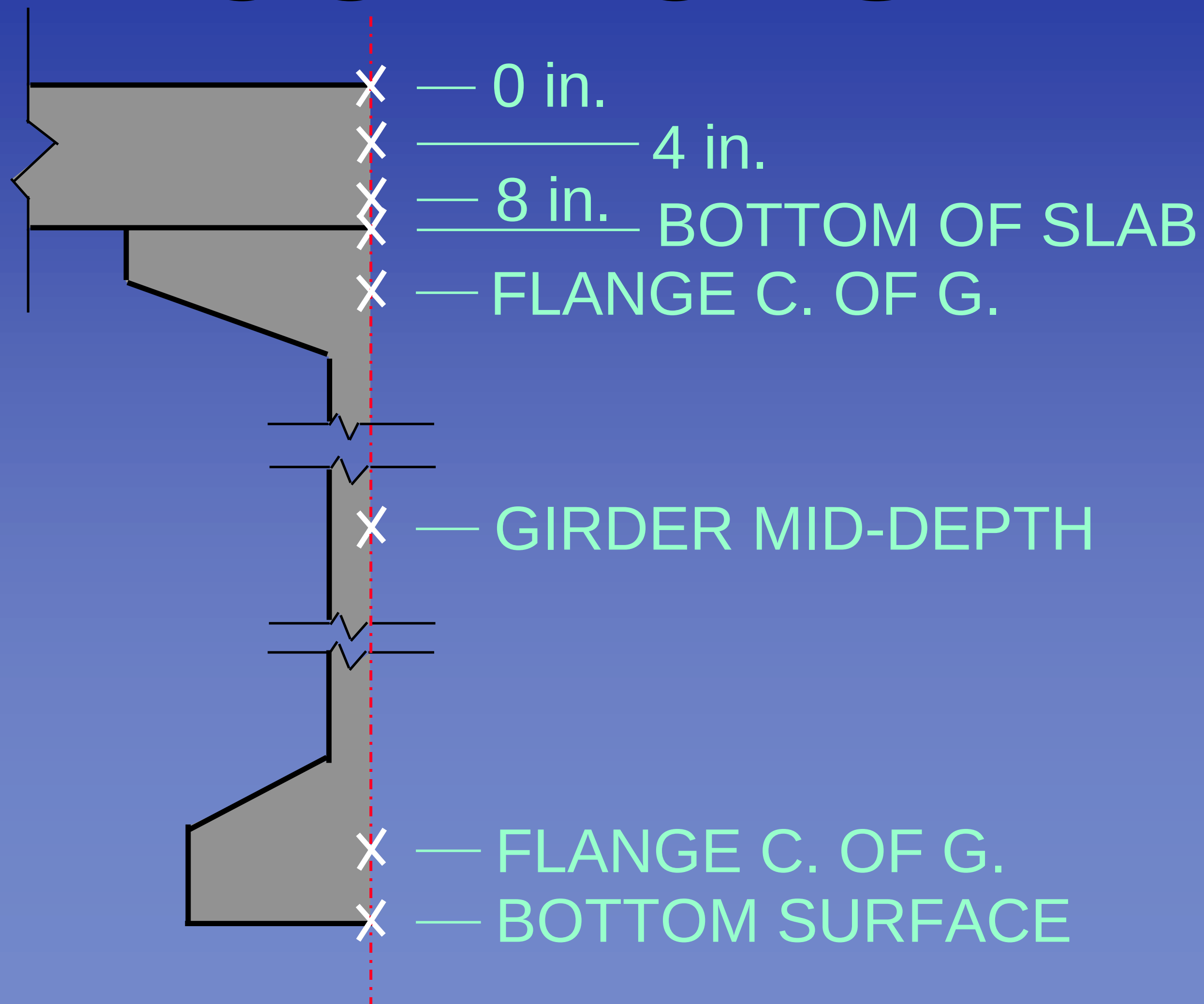
Heat of Hydration

Temperature Gradients

Freeze - Thaw Cycles

Temperature Correction

THERMOCOUPLE LOCATIONS



LONG-TERM STRAINS

Prestress Losses

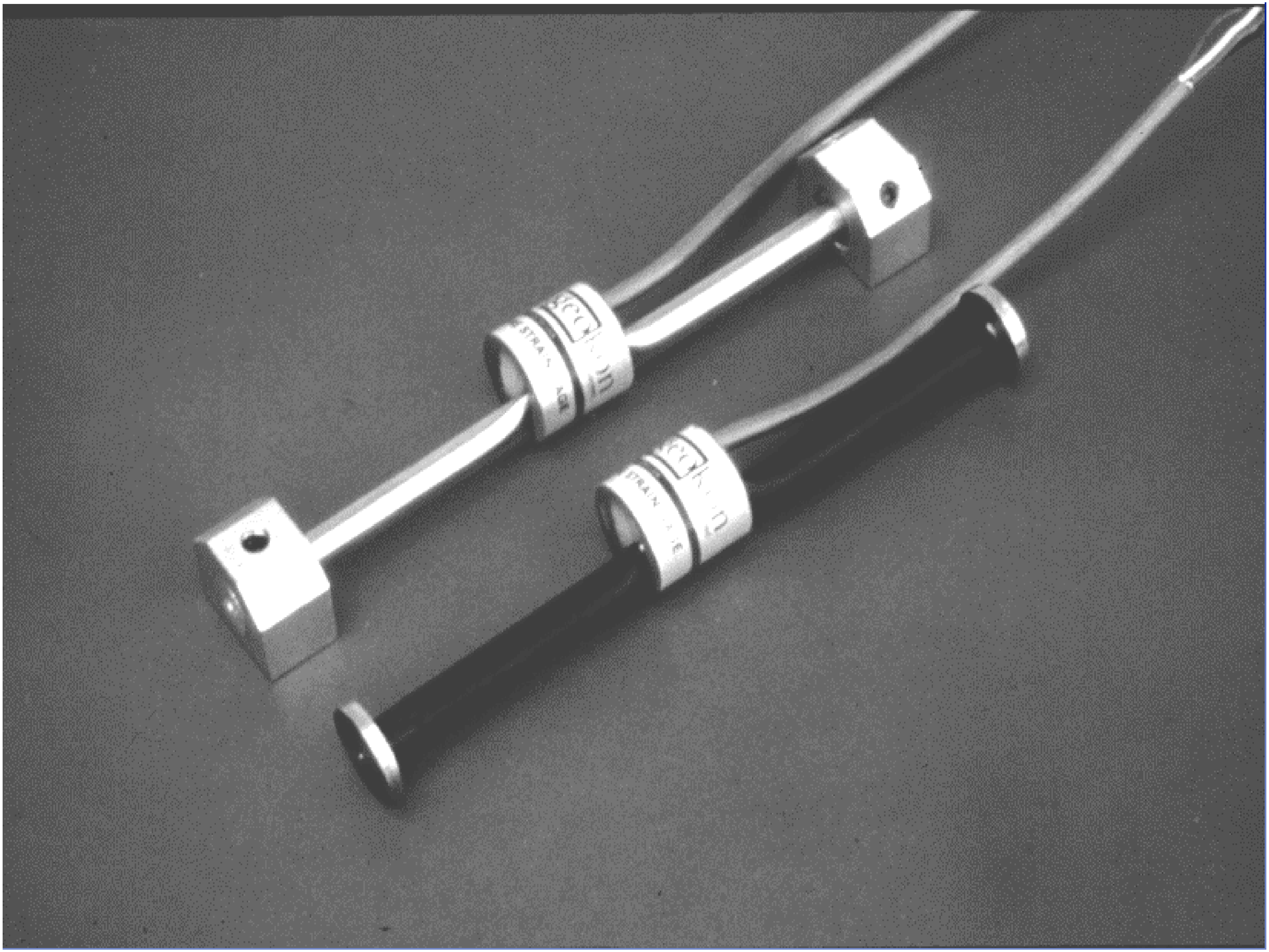
Temperature Effects

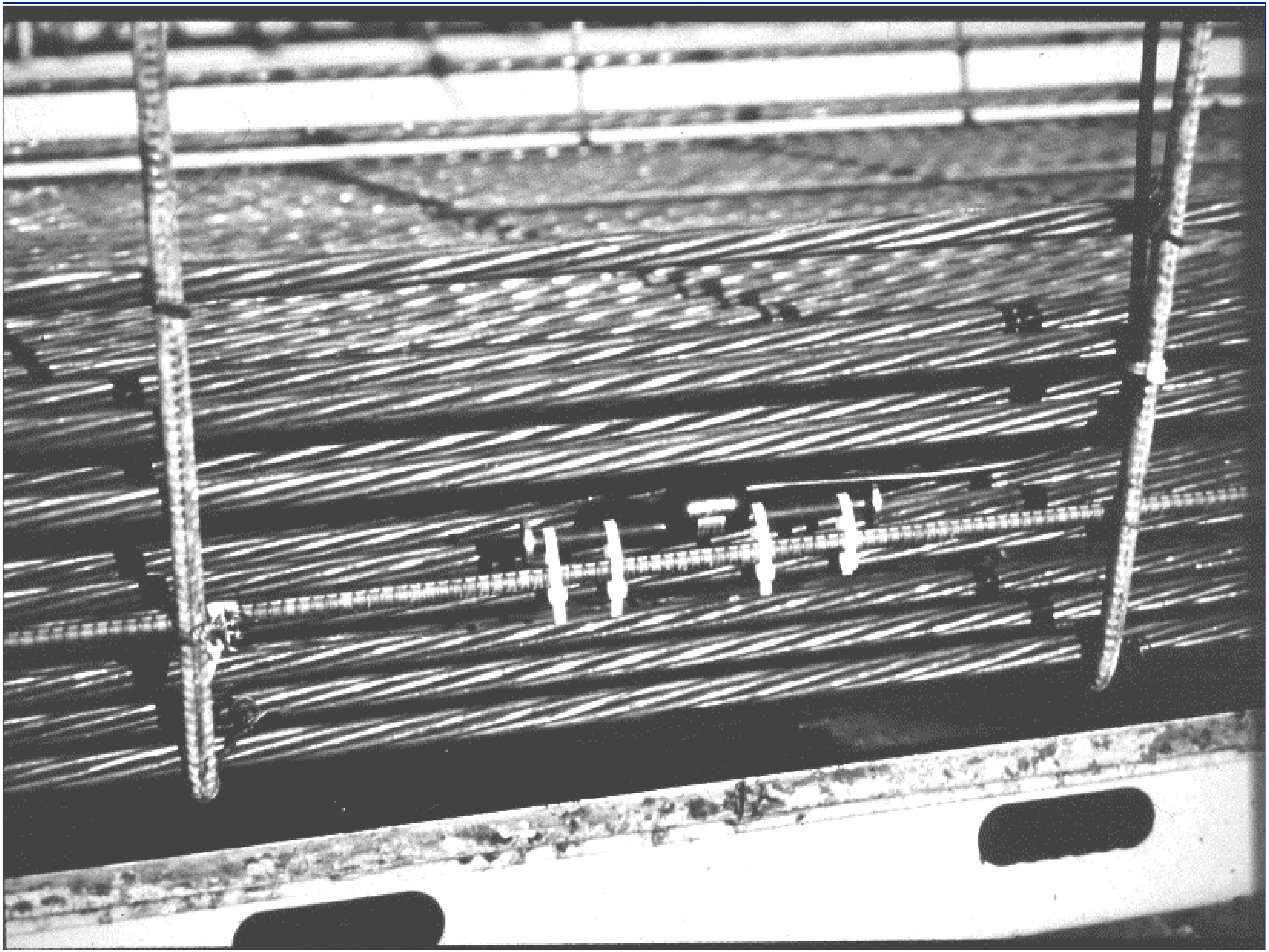
LONG-TERM STRAINS

Vibrating Wire Gages

Carlson Strain Meters

(Mechanical Strain Gages)





Vibrating Wire Strain Gages

Frequency principle

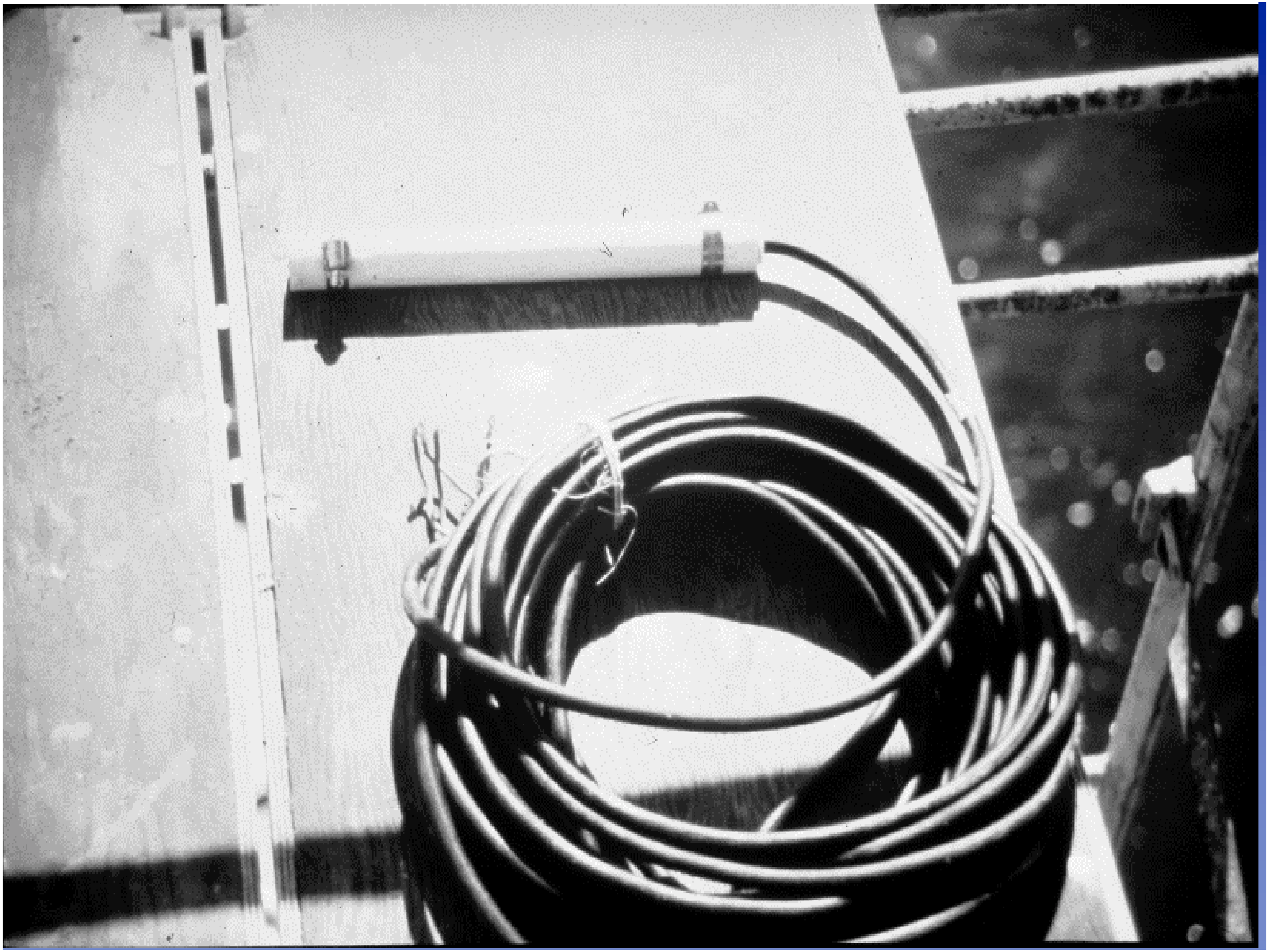
Tied to rebar cage

Reliable and durable

Strong protective shell

Expected life of many years

Expensive



CARLSON STRAIN METER

- Resistance principle
- Tied to rebar cage
- Reliable and durable
  - Strong protective shell
  - Expected life of many years
- Expensive

DEFLECTIONS

Detensioning

Dead Load

Long-Term

DEFLECTIONS

Precise Surveying

Tensioned Wire

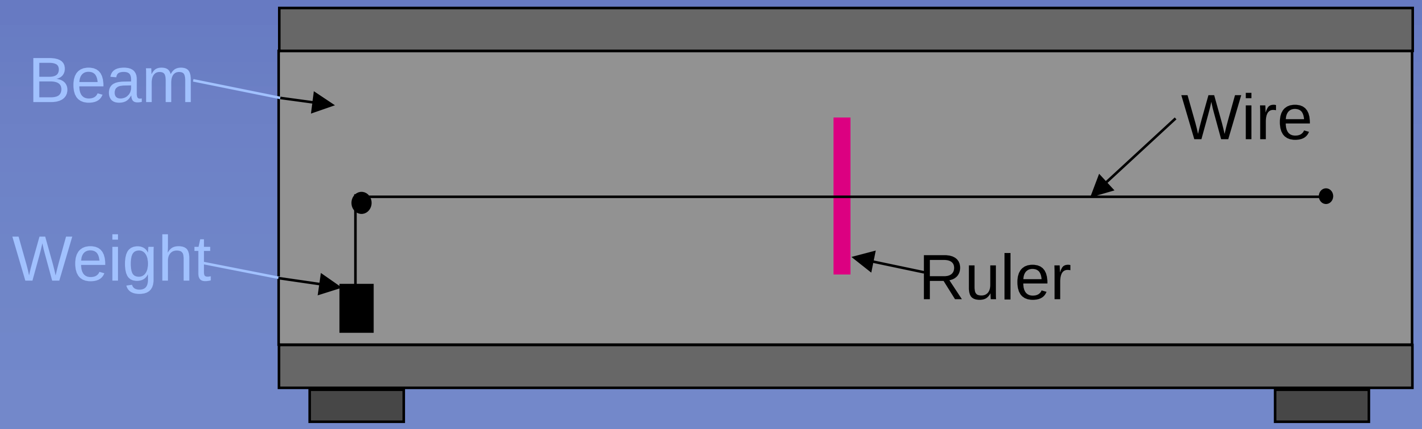
CAMBER / DEFLECTIONS

Tensioned Wire System

Wire attached to beam at bearing locations

Steel ruler fixed to beam at midspan

Beam moves relative to tensioned piano wire



OPTIONAL PROGRAM

Extension of Basic Program

Additional Types of Instrumentation

Live Load Tests

ADDITIONAL TYPES

Slopes

Prestressing Forces

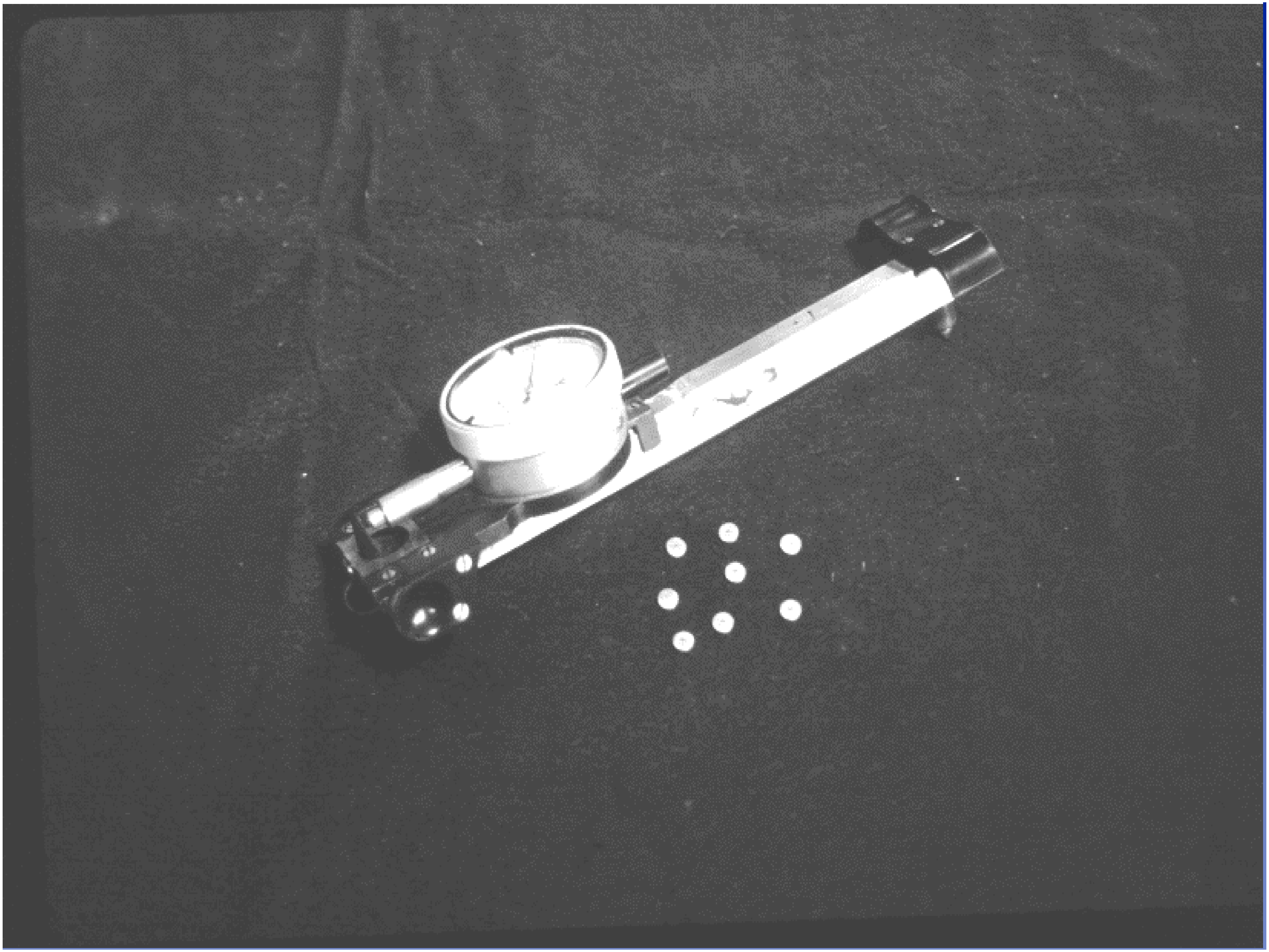
Transfer Lengths

Strand Slip

Experimental Instrumentation


SPERRY
4
SPERRY

WD17
WD18
WD19




2

LIVE LOAD TESTS

Impact Factors

Lateral Load distribution

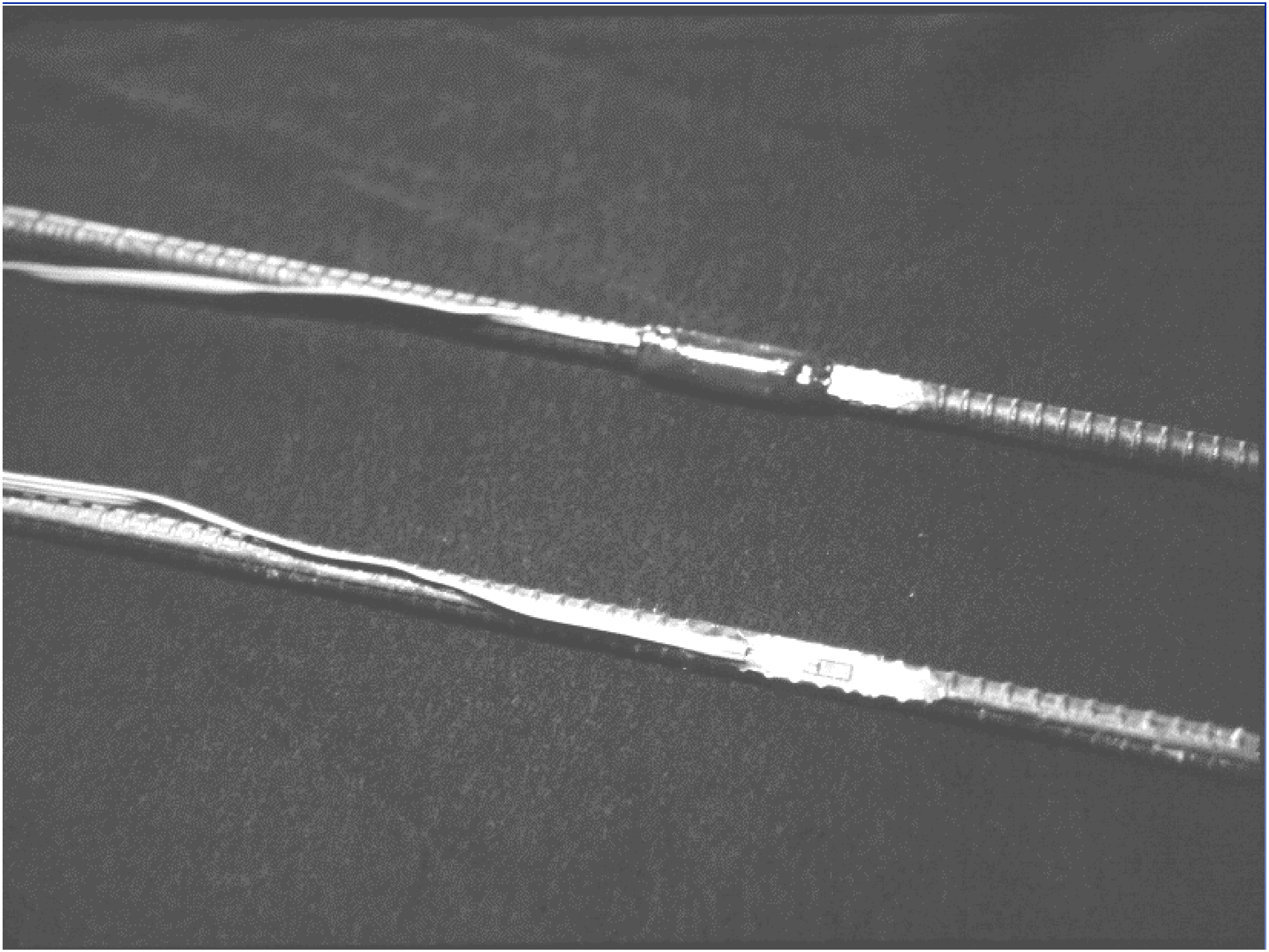
Shear Lag

LIVE LOAD TESTS

Deflections

Reinforcement Strains

Concrete Strains



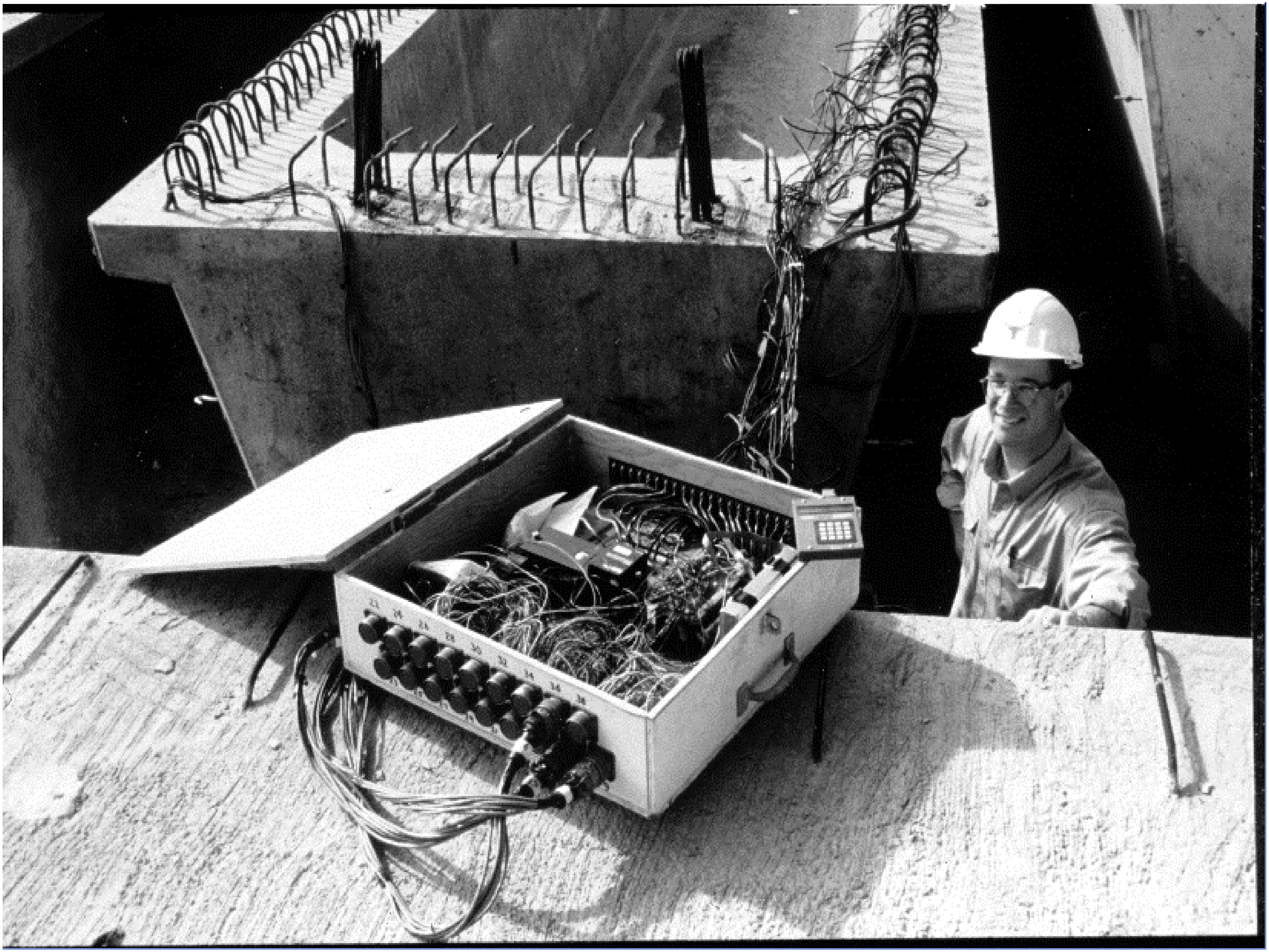
Bonded Strain Gage (ERSG)

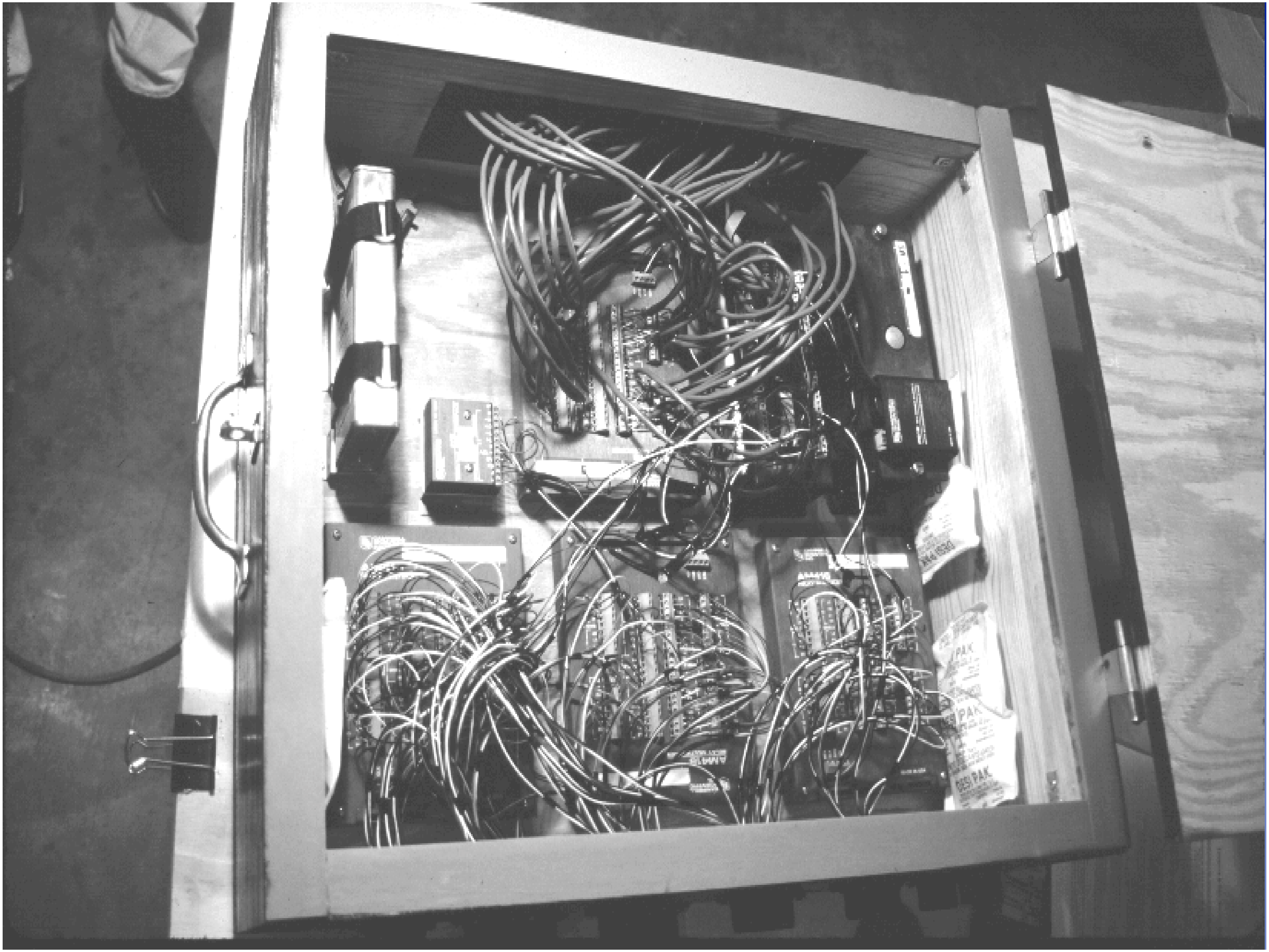
- Resistance principle
- Bonded to piece of rebar
- Tied to rebar cage at specific locations
- Reliability and durability
  - Difficult to protect
  - Limited life
- Inexpensive

DATA ACQUISITION

Manual boxes

Automated Systems




DESI PAK

DATA INTERPRETATION

Coefficient of Thermal Expansion

Modulus of Elasticity

Creep and Shrinkage

THANK YOU

MODULE 8

Research and Long-Term Monitoring

Prepared by

Henry G. Russell

Part B

Research Results

Structural Material Properties

Durability

Structural Design

Serviceability

Strength

Load Tests

Lessons Learned

Structural Material Properties

Curing Temperature

Compressive Strength

Modulus of Elasticity

Tensile Strength

Shrinkage

Creep

Structural Material Properties

Curing Temperature

Compressive Strength

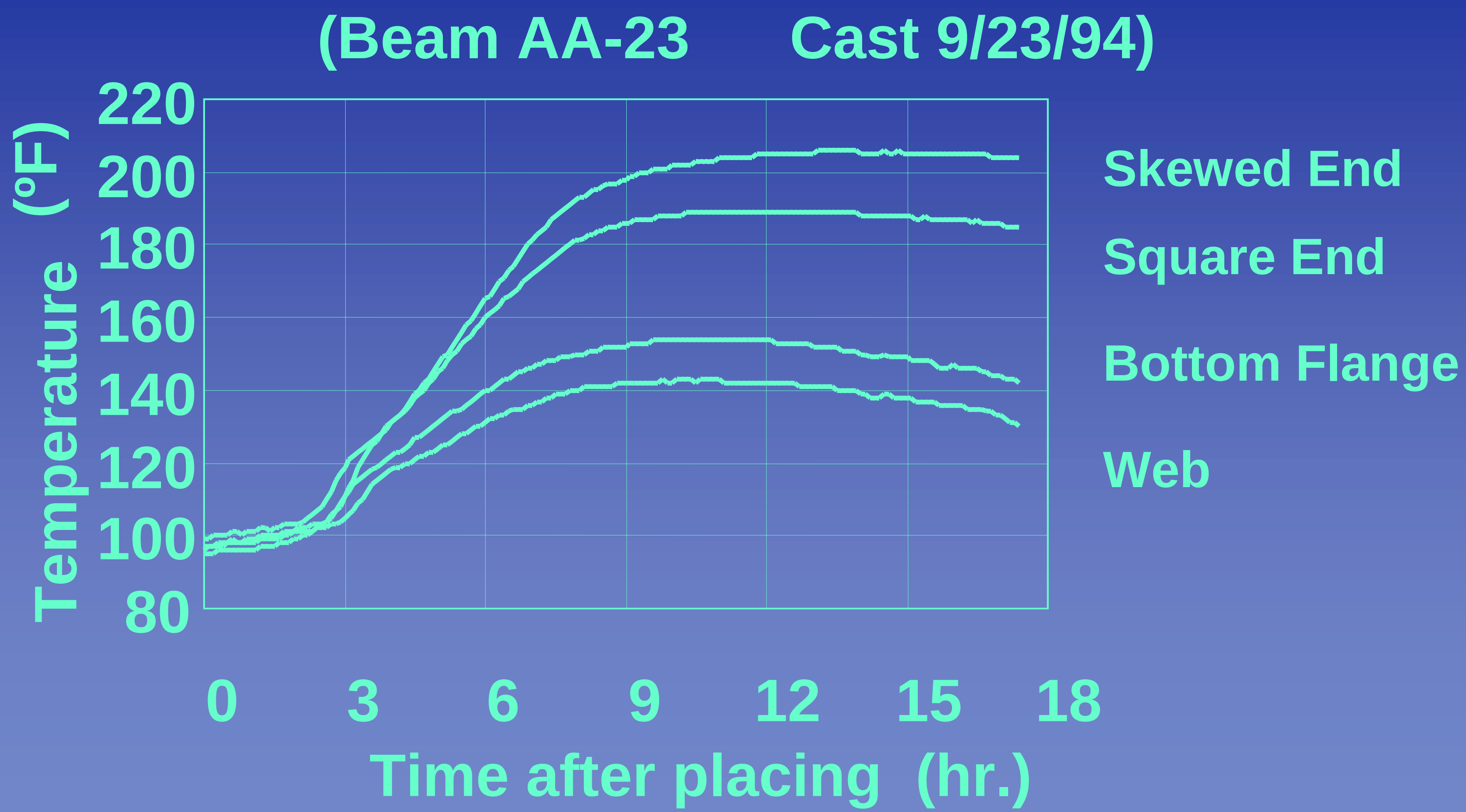
Modulus of Elasticity

Tensile Strength

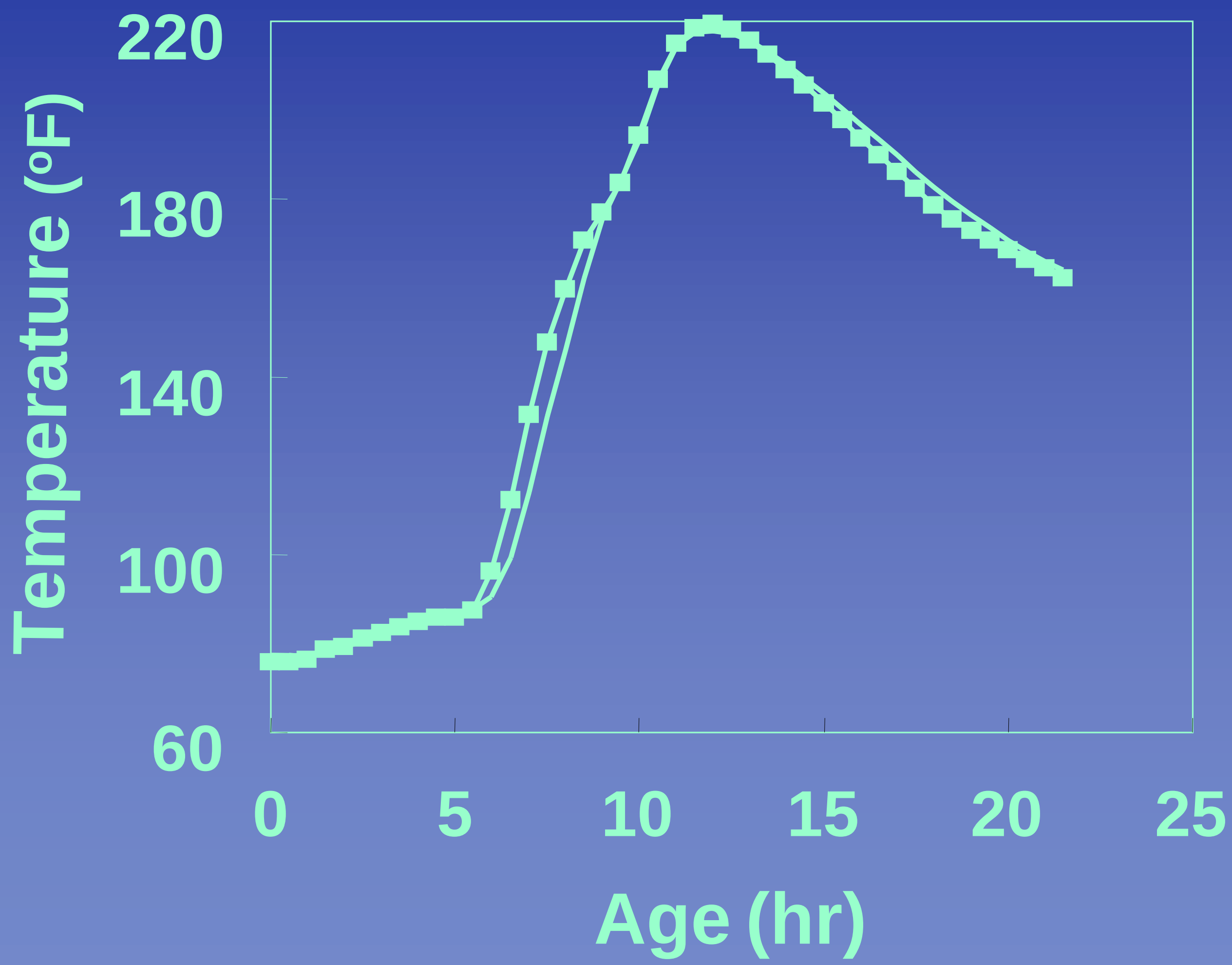
Shrinkage

Creep

Typical Hydration Curves



HIGH TEMPERATURES IN BEAM CURING



Structural Material Properties

Curing Temperature

Compressive Strength

Modulus of Elasticity

Tensile Strength

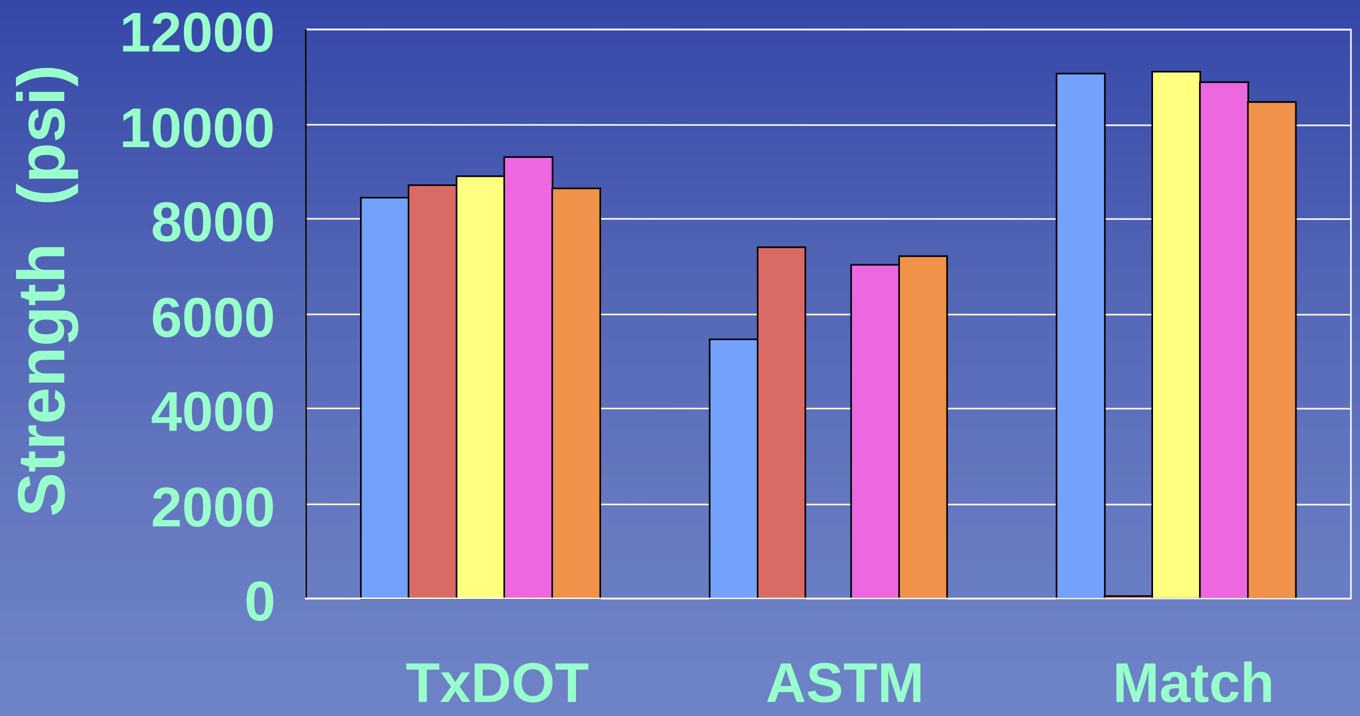
Shrinkage

Creep

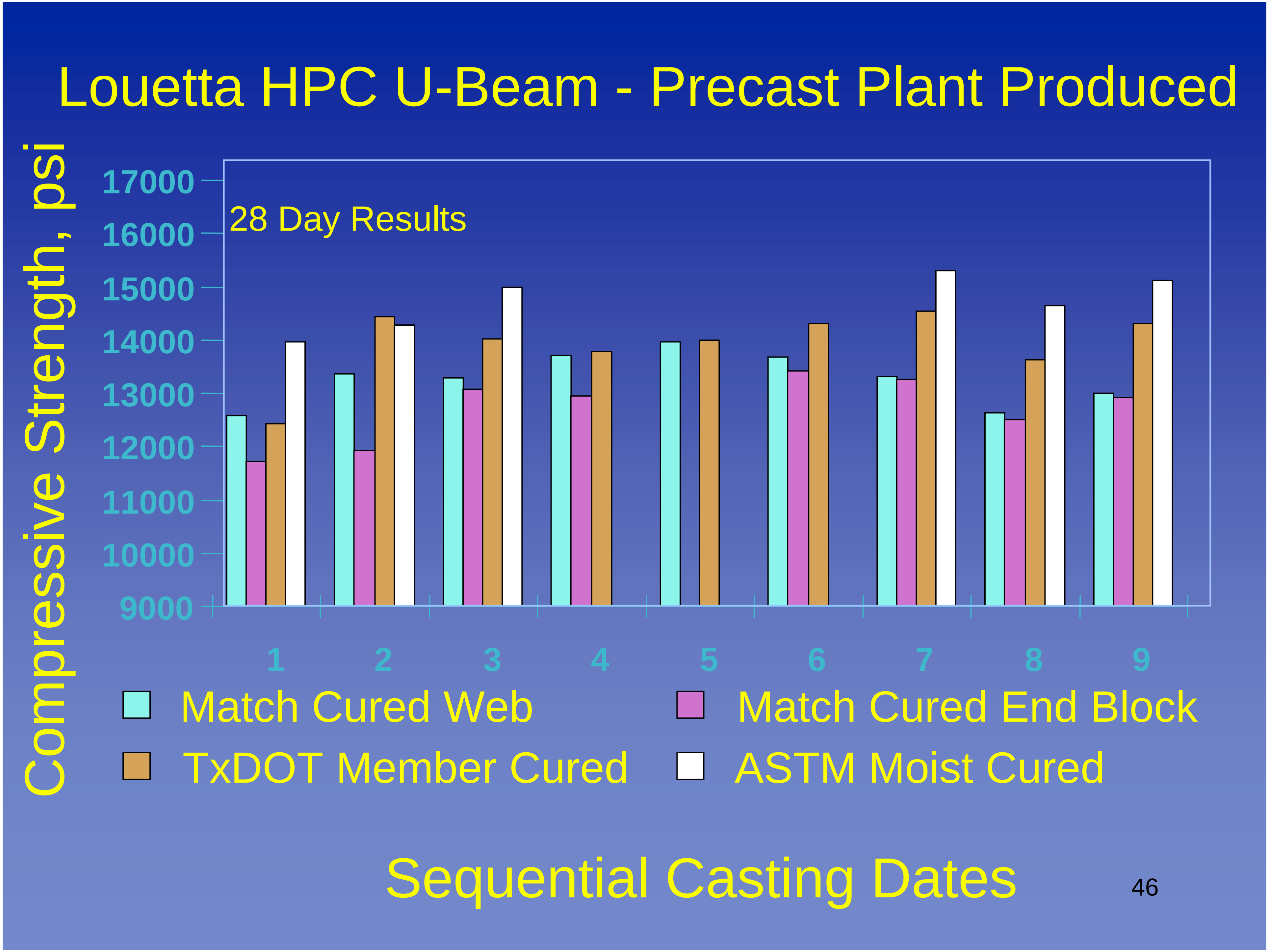
Cylinder Curing Schemes

	Before Release	After Release
ASTM	73^0F room	Moist (tank)
TxDOT	Alongside member	Moist (tank)
Member	Alongside member	Stored with member
Match	Follows internal member temp.	Stored with member

Compressive Strength - Release (~ 24 hr)

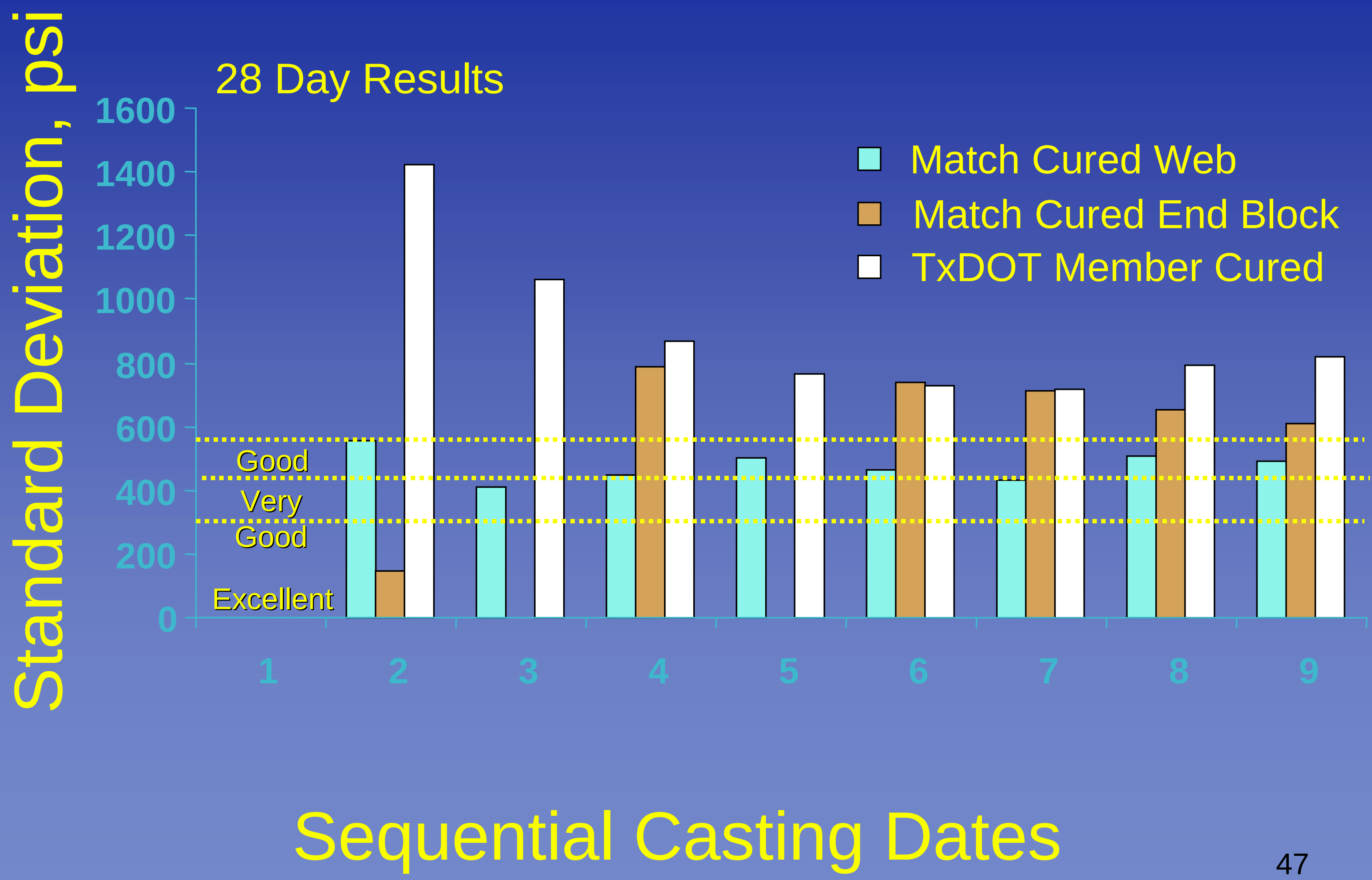


Compressive Strength - 28 days



Louetta HPC U-Beam - Precast Plant Produced
Compressive Strength, psi
17000
16000
15000
14000
13000
12000
11000
10000
9000
28 Day Results
1
2
3
4
5
6
7
8
9
Match Cured Web
Match Cured End Block
TxDOT Member Cured
ASTM Moist Cured
Sequential Casting Dates

Louetta HPC U-Beam - Precast Plant Produced



Structural Material Properties

Curing Temperature

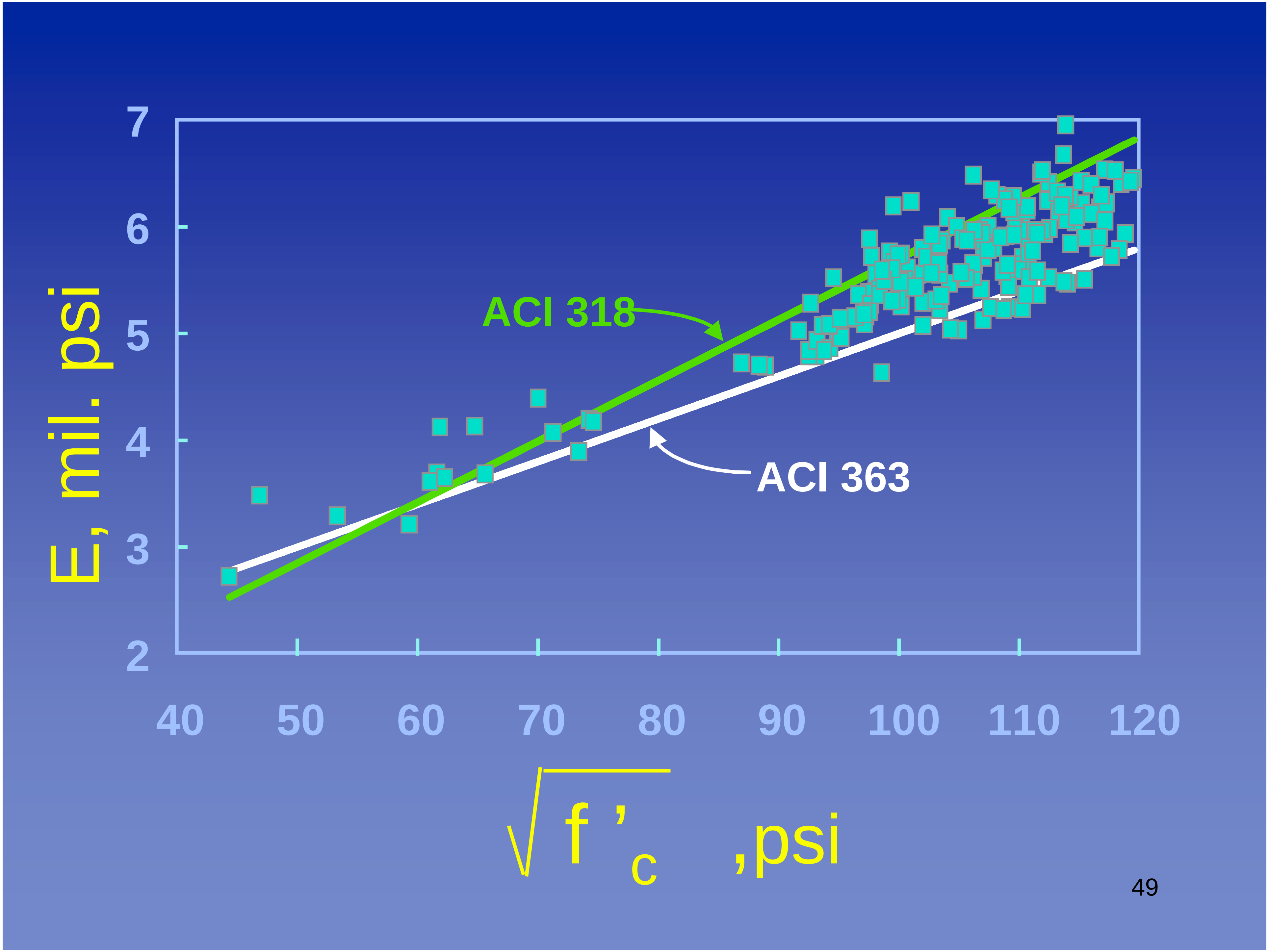
Match-Curing Techniques

Modulus of Elasticity

Tensile Strength

Shrinkage

Creep


E, mil. psi
7
6
5
4
3
2
ACI 318
ACI 363
40
50
60
70
80
90
100
110
120
$\sqrt{f'_c}$,psi

COARSE AGGREGATE			TEST AGE days	STRENGTH psi	MOE ksi
TYPE	MAX. SIZE in.	CONTENT %			
TRAP ROCK	0.5	40	3	8840	6390
CRUSHED LIMESTONE	0.5	40	7	11050	6350
	0.5	41	7	11320	6670
	0.5	44	3	9880	6540
	0.5	44	14	12730	6700

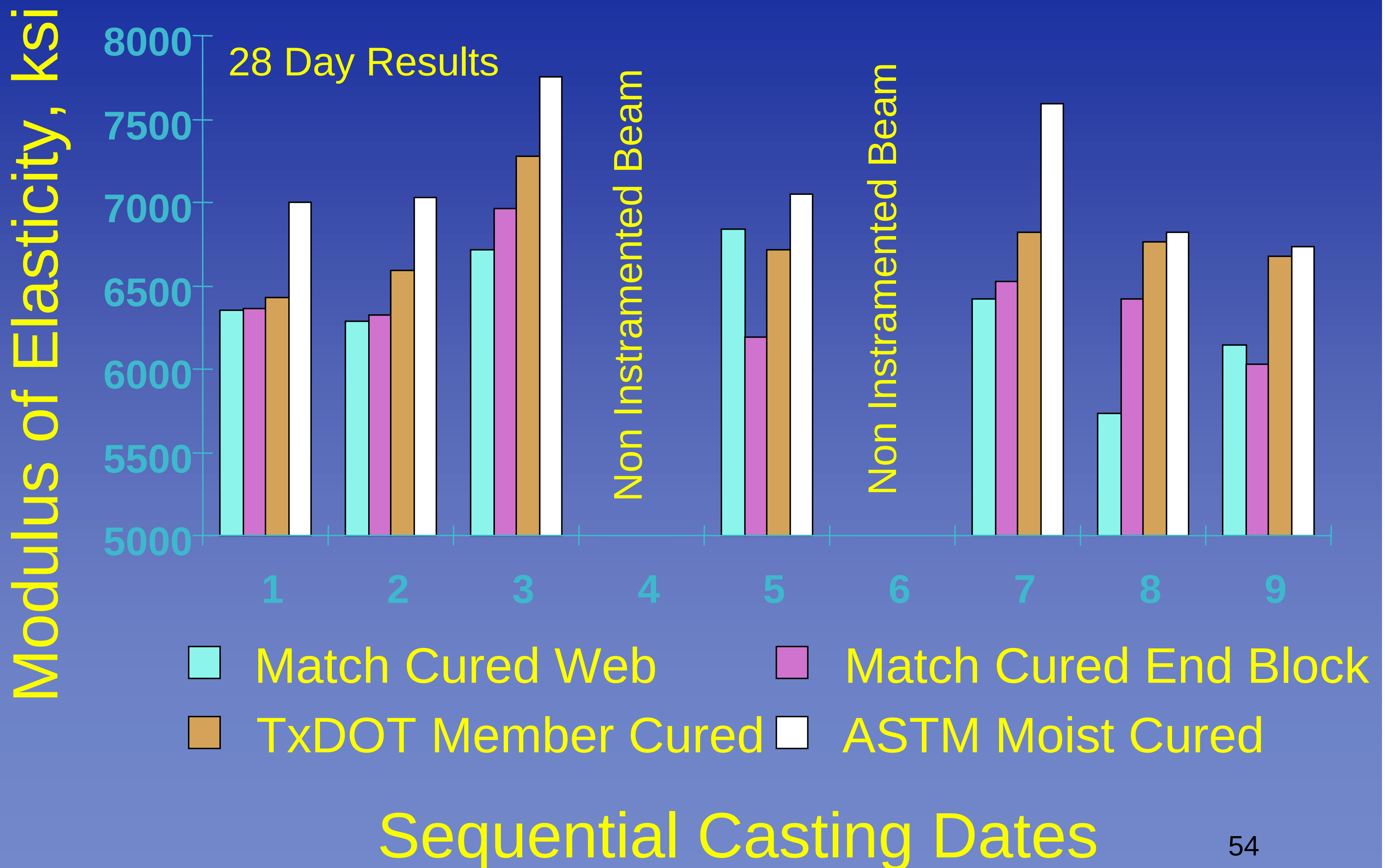
COARSE AGGREGATE			TEST AGE days	STRENGTH psi	MOE ksi
TYPE	MAX. SIZE in.	CONTENT %			
TRAP ROCK	**0.5**	**40**	**3**	**8840**	**6390**
CRUSHED LIMESTONE	**0.5**	**40**	**7**	**11050**	**6350**
	0.5	41	7	11320	6670
	0.5	44	3	9880	6540
	0.5	44	14	12730	6700

COARSE AGGREGATE			TEST AGE days	STRENGTH psi	MOE ksi
TYPE	MAX. SIZE in.	CONTENT %			
TRAP ROCK	**0.5**	**40**	**3**	**8840**	**6390**
CRUSHED LIMESTONE	**0.5**	**40**	**7**	**11050**	**6350**
	0.5	41	7	11320	6670
	0.5	44	3	9880	6540
	0.5	44	14	12730	6700

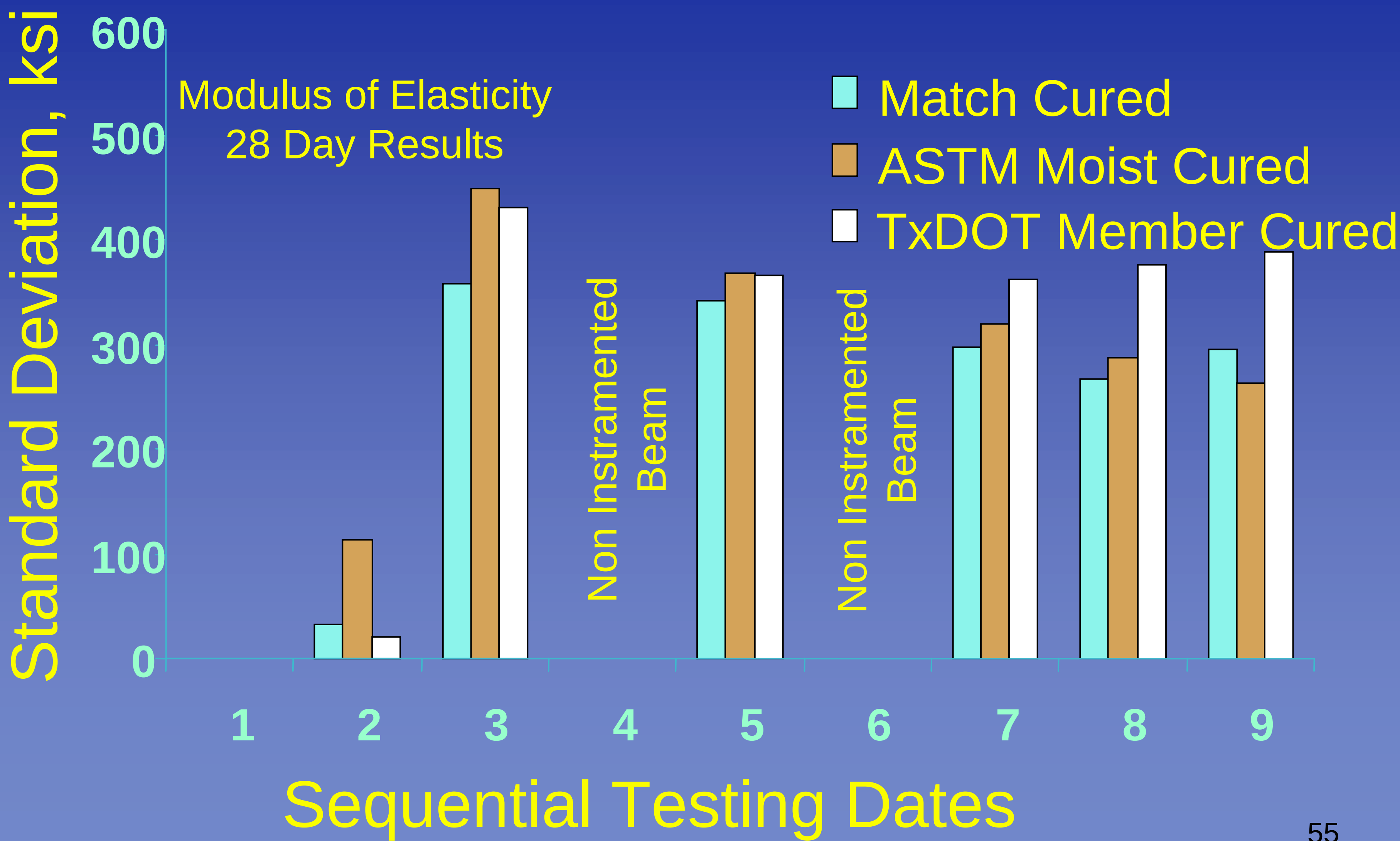
Modulus of Elasticity, ksi

Pour	Release	28 days	Release specimens
1	6420	5730	match cured
2	-	6930	
3	6380	7500	28-day specimens
5	5800	-	member cured
7	5480	6460	
Avg.	6020	6660	

Louetta HPC U-Beam - Precast Plant Produced



Louetta HPC U-Beam - Precast Plant Produced



Structural Material Properties

Curing Temperature

Compressive Strength

Modulus of Elasticity

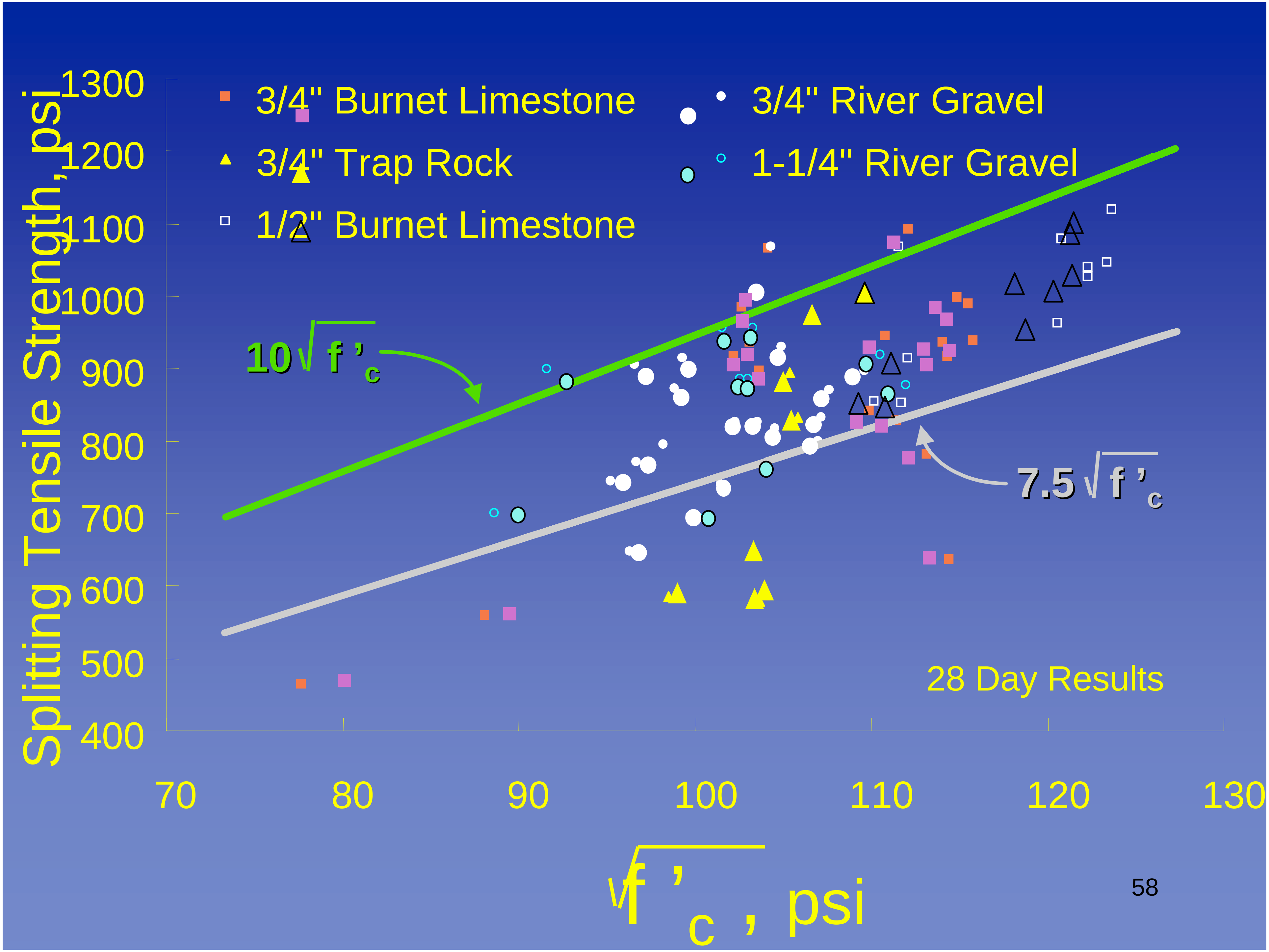
Tensile Strength

Shrinkage

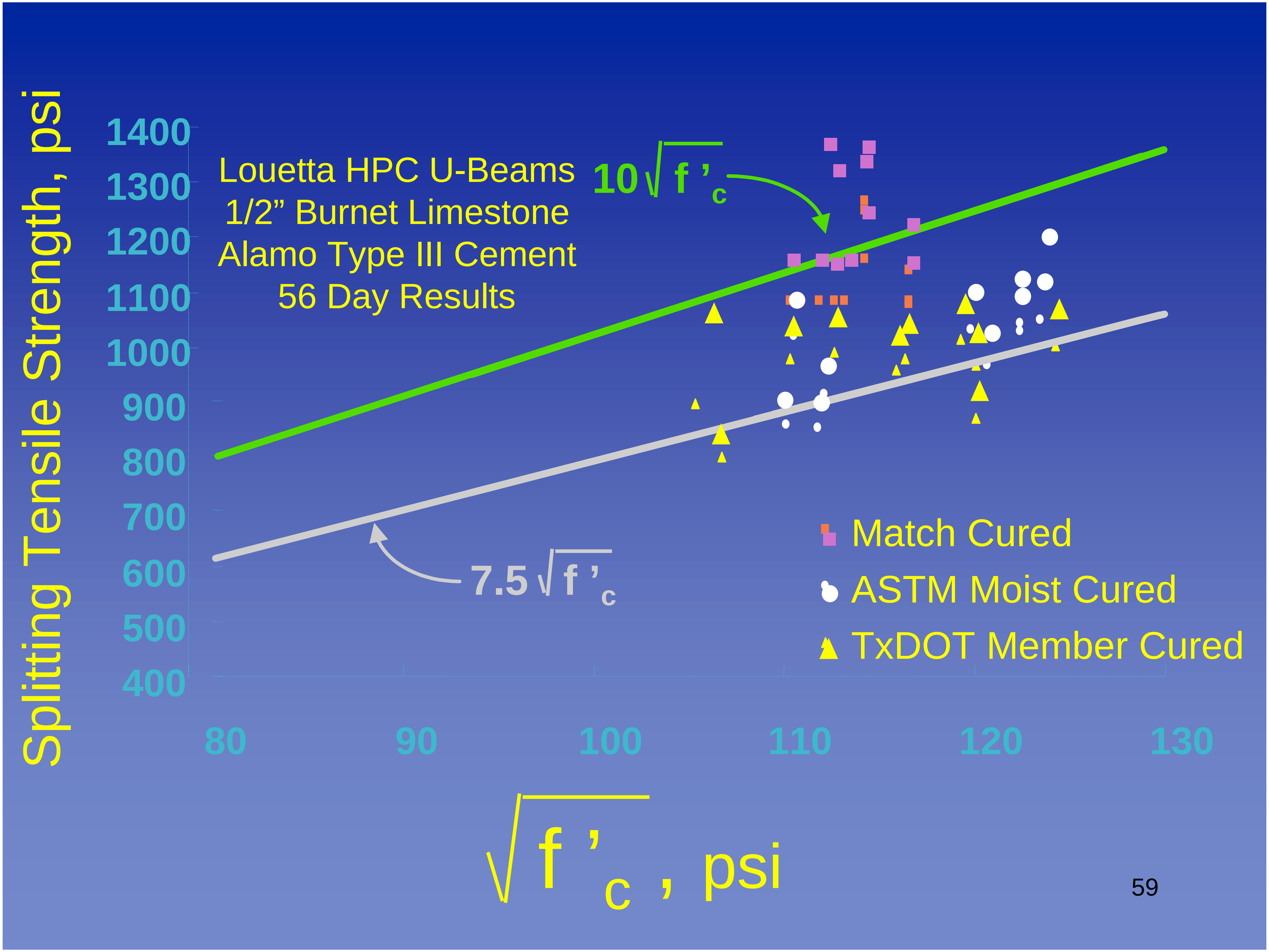
Creep

Modulus of Rupture

Strength	Moist	Air
psi	Cured, psi	Cured, psi
12,550	1,370	890
13,920	1,440	810
14,560	1,470	770
17,310	1,390	940
19,120	1,990	980



3/4" Burnet Limestone
3/4" River Gravel
3/4" Trap Rock
1-1/4" River Gravel
1/2" Burnet Limestone
10 √f 'c
7.5 √f 'c
28 Day Results
Splitting Tensile Strength, psi
1300
1200
1100
1000
900
800
700
600
500
400
70
80
90
100
110
120
130
√f 'c , psi



Splitting Tensile Strength, psi
1400
1300
1200
1100
1000
900
800
700
600
500
400
Louetta HPC U-Beams
1/2” Burnet Limestone
Alamo Type III Cement
56 Day Results
10 √f ’c
7.5 √f ’c
Match Cured
ASTM Moist Cured
TxDOT Member Cured
80
90
100
110
120
130
√f ’c , psi

Structural Material Properties

Curing Temperature

Compressive Strength

Modulus of Elasticity

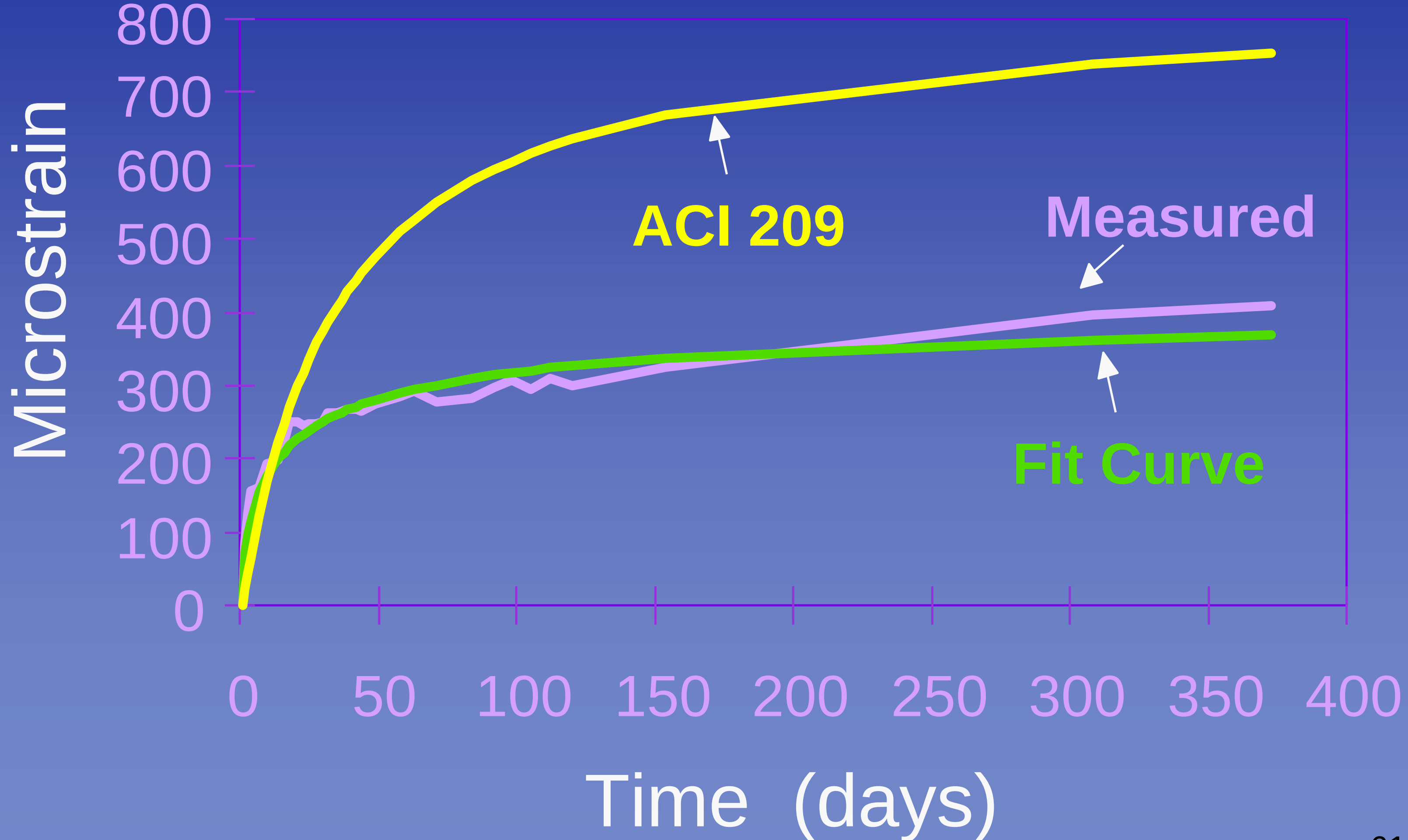
Tensile Strength

Shrinkage

Creep

Shrinkage Strain

(high curing temp.)



Structural Material Properties

Curing Temperature

Compressive Strength

Modulus of Elasticity

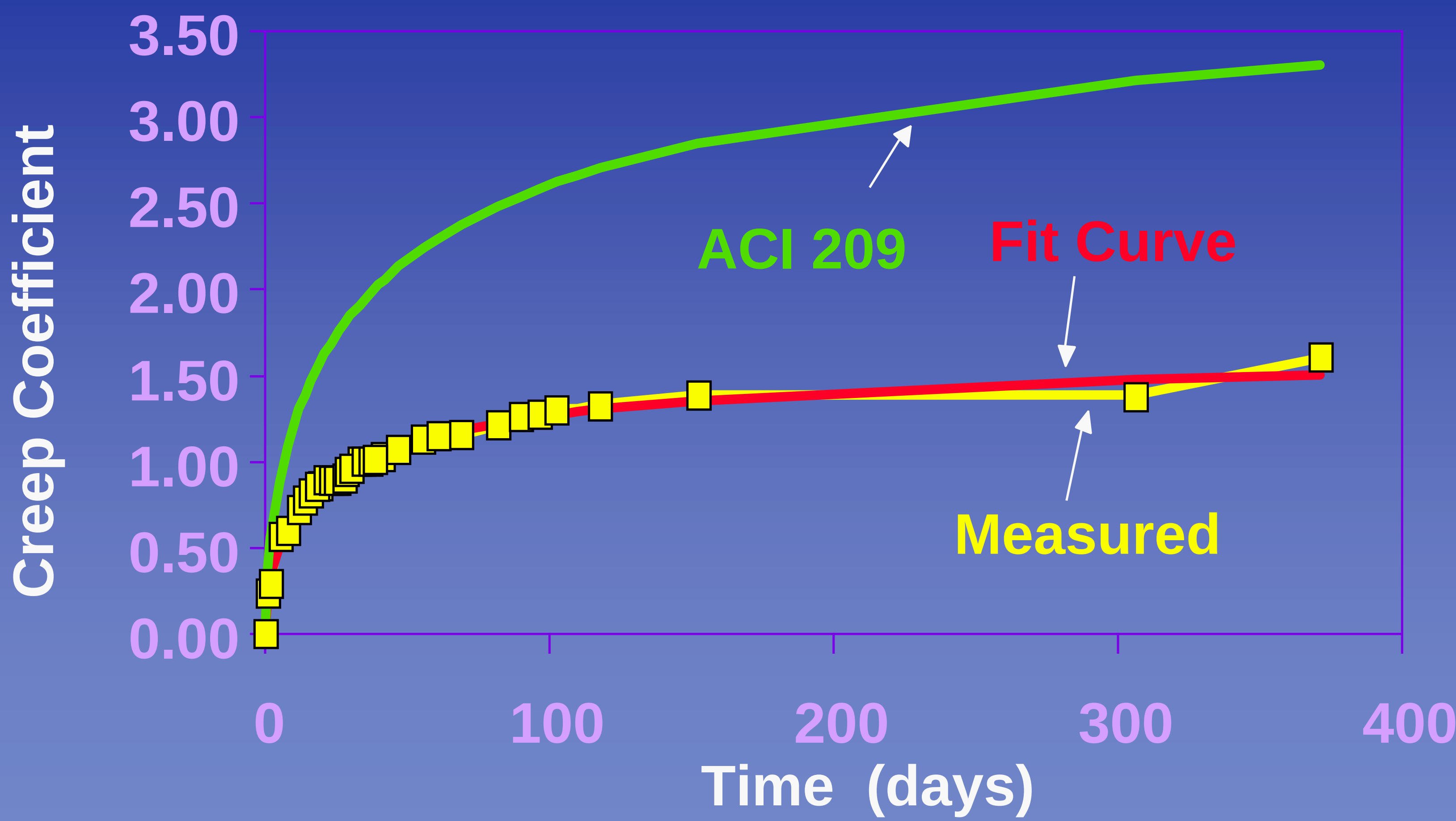
Tensile Strength

Shrinkage

Creep

Creep Coefficient

(3000 psi @ 1 day; high curing temp.)



Creep & Shrinkage Summary

Less ultimate creep & shrinkage

35% lower creep for loading at 28 days (vs. loading at 2 days)

Creep: $C_{ct} = (1.79) \dfrac{t^{0.6}}{6 + t^{0.6}}$

Shrinkage: $\varepsilon_{sh} = (.000420) \dfrac{t^{0.6}}{5 + t^{0.6}}$

Durability

Rapid Chloride Permeability

Freeze-Thaw Resistance

Deicer Scaling

Abrasion Resistance

Durability

Rapid Chloride Permeability

Freeze-Thaw Resistance

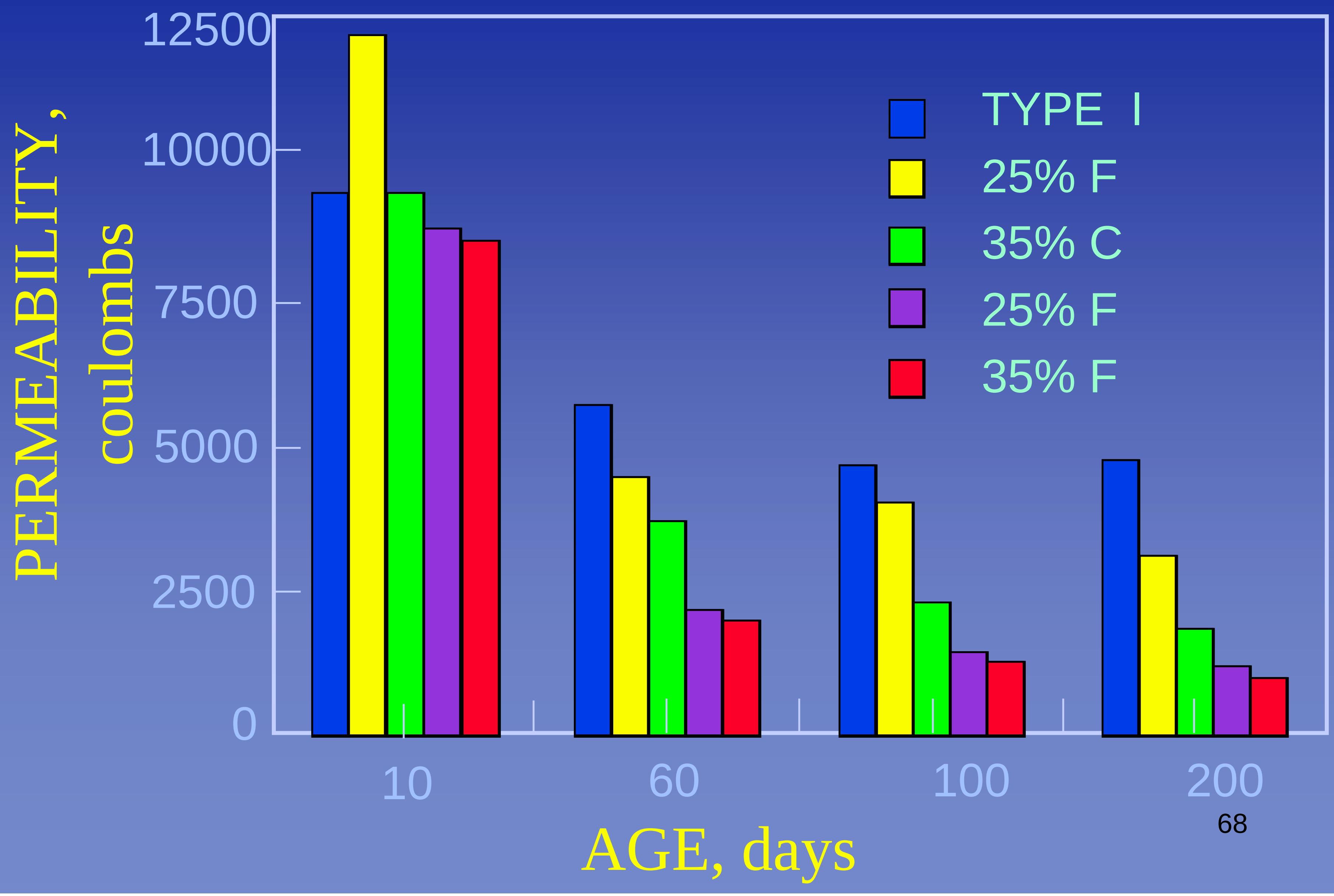
Deicer Scaling

Abrasion Resistance

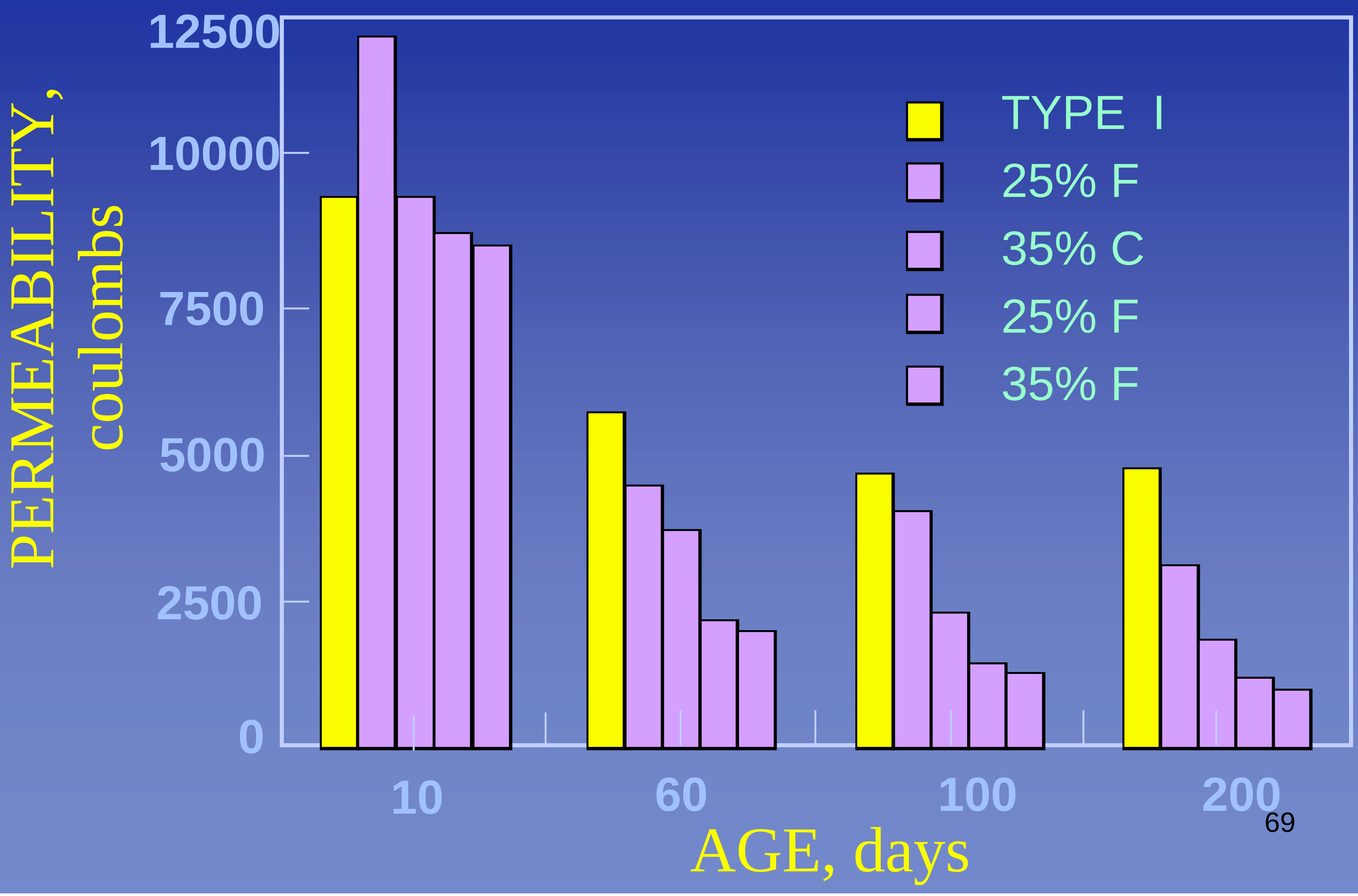
Rapid Chloride Permeability

- AASHTO T277
- ASTM C 1202
- Age = 56 days
- Virginia uses 28 days
  - Accelerated curing

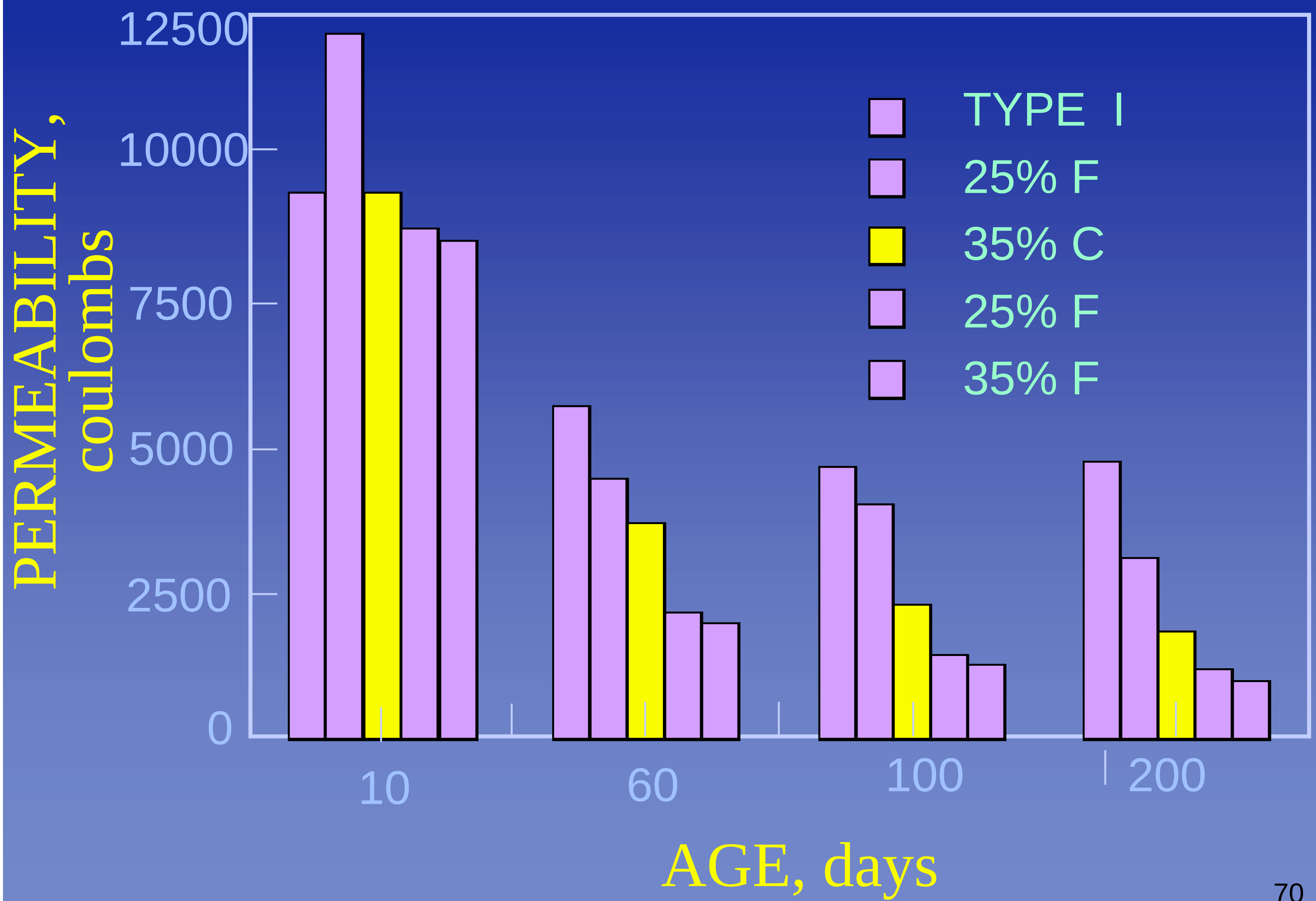
CHLORIDE ION PERMEABILITY OF CONCRETE



CHLORIDE ION PERMEABILITY OF CONCRETE

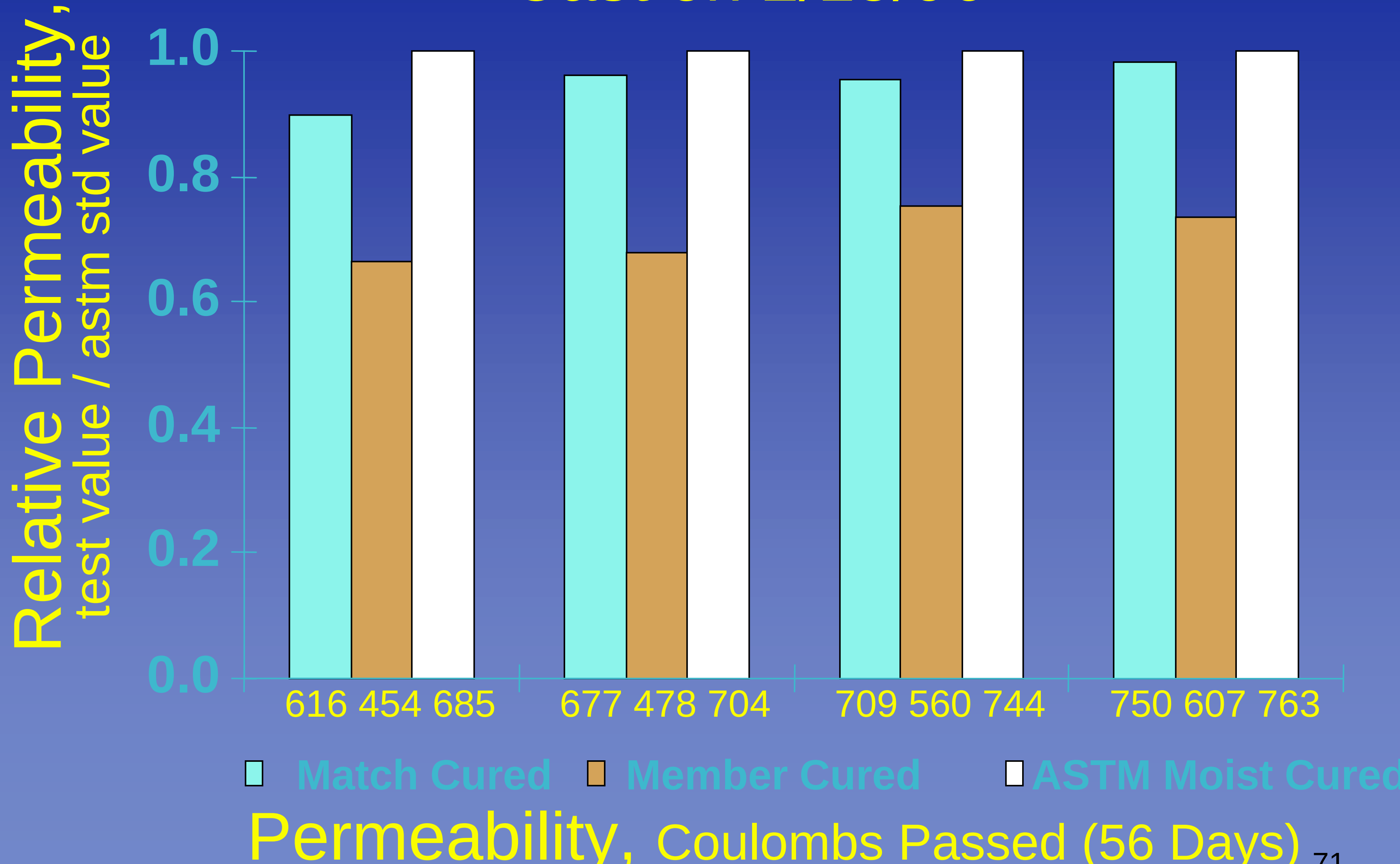


CHLORIDE ION PERMEABILITY OF CONCRETE



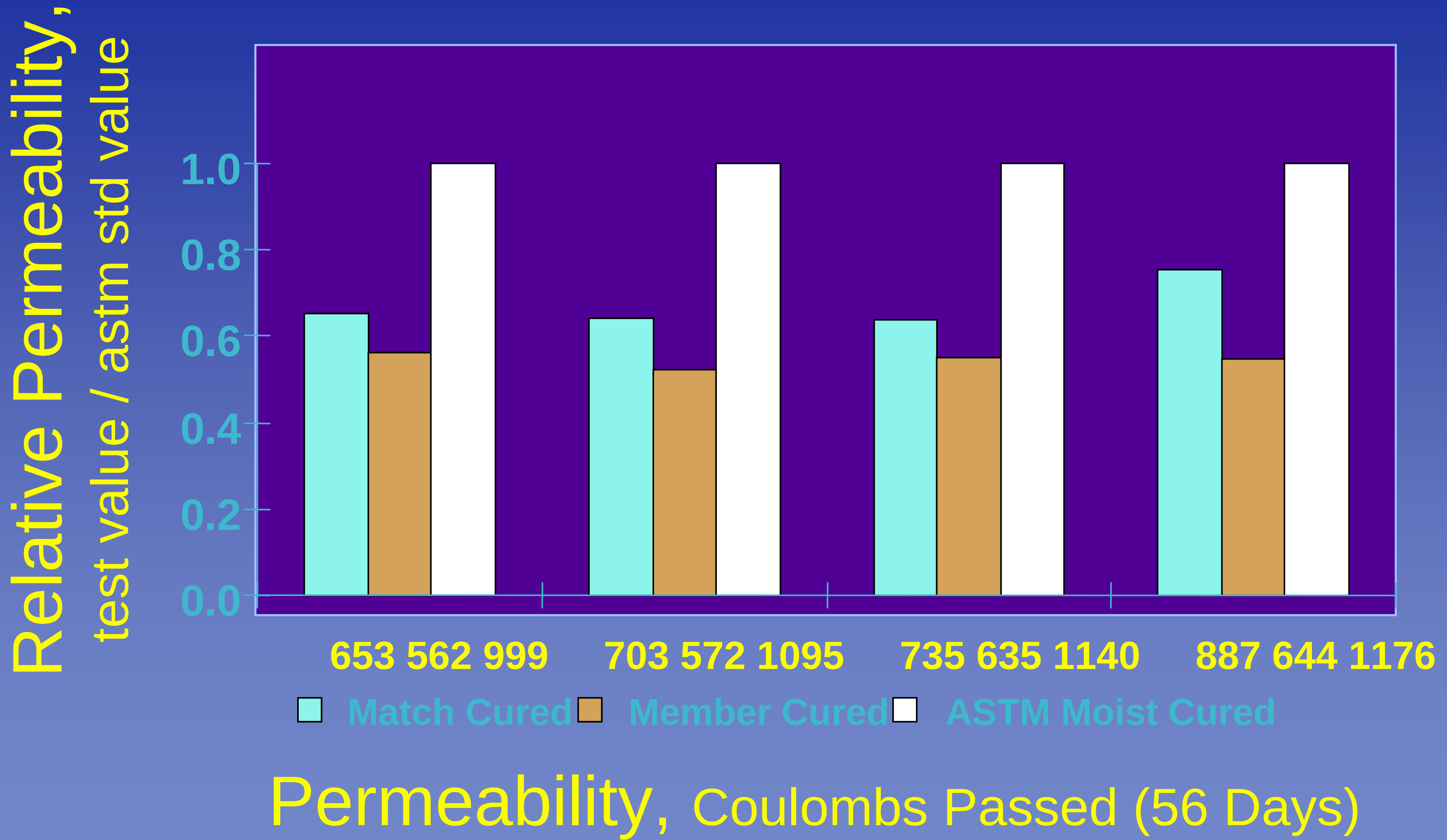
U-Beam Member Permeability Results

Cast on 2/15/96

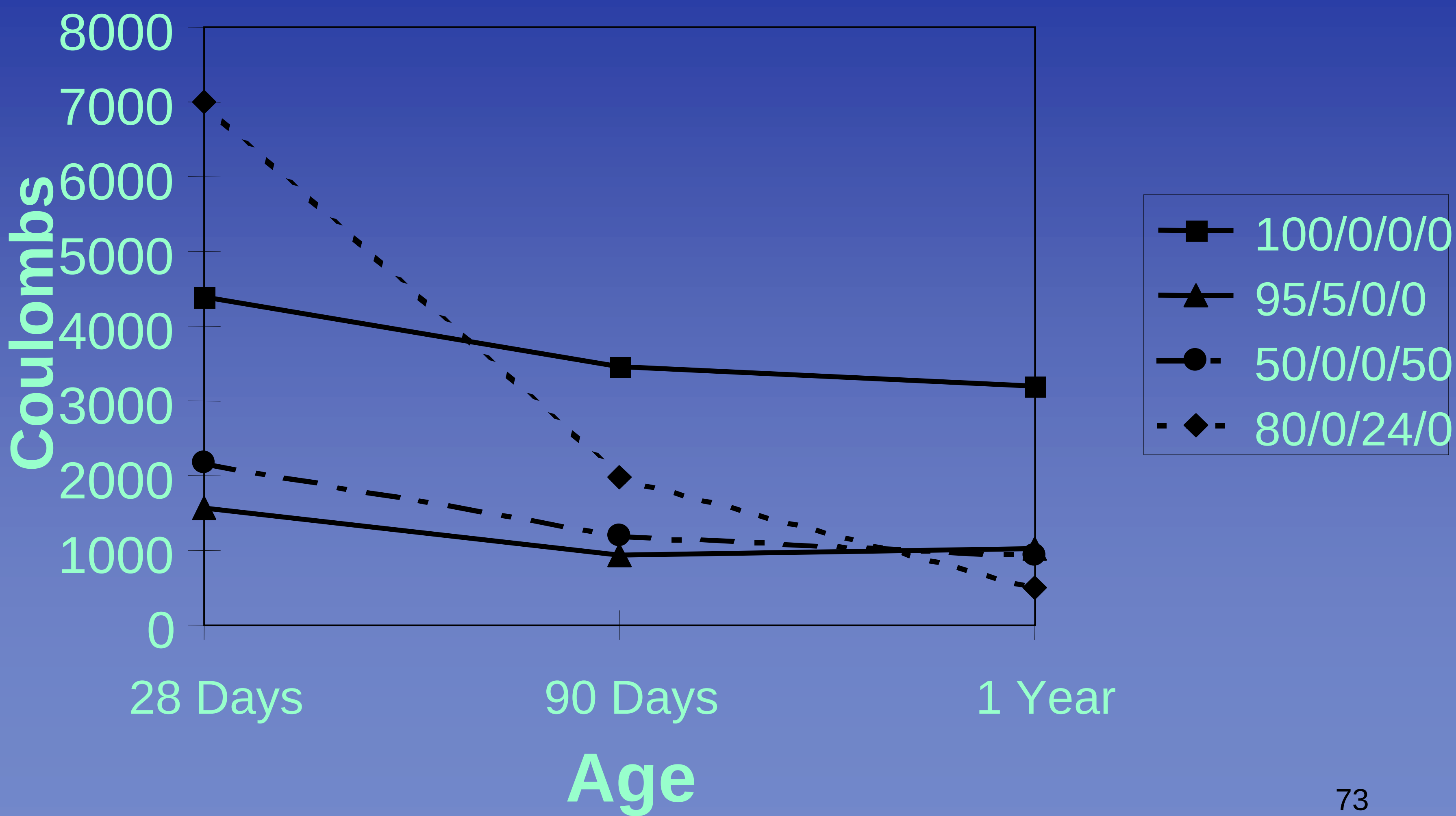


U-Beam Member Permeability Results

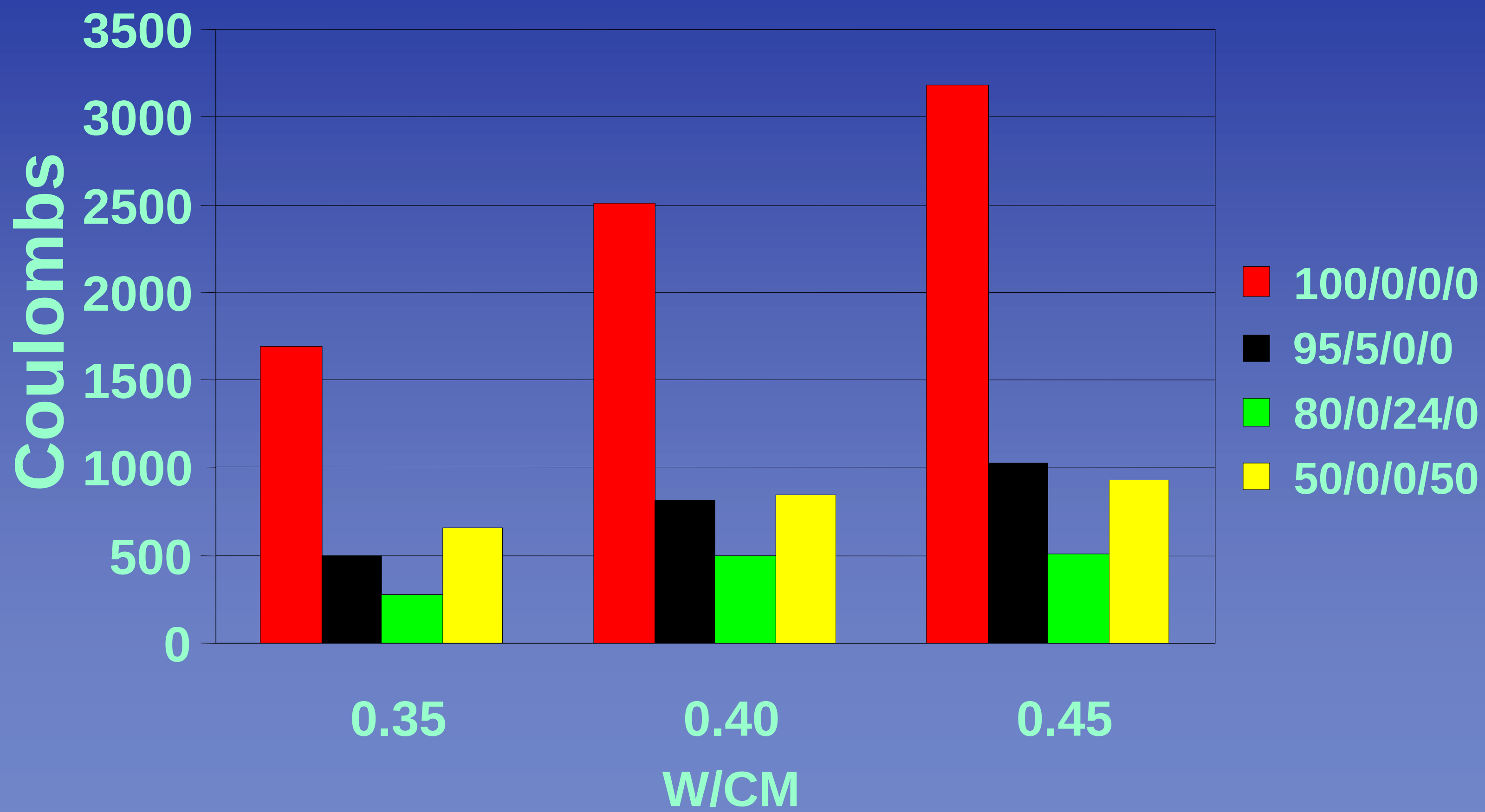
Cast on 2/26/96



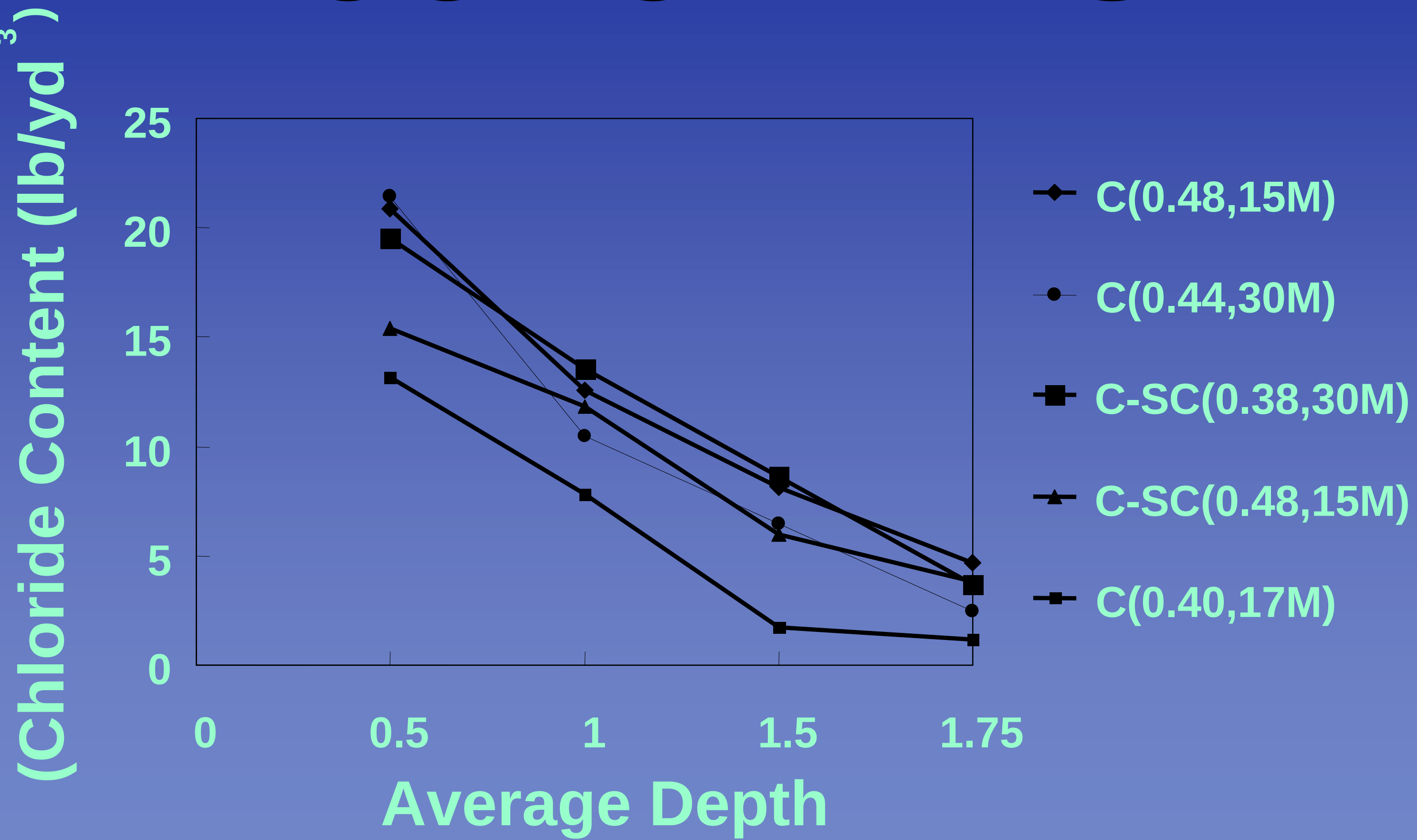
PERMEABILITY VS. AGE



1-YR PERMEABILITY VS. W/CM



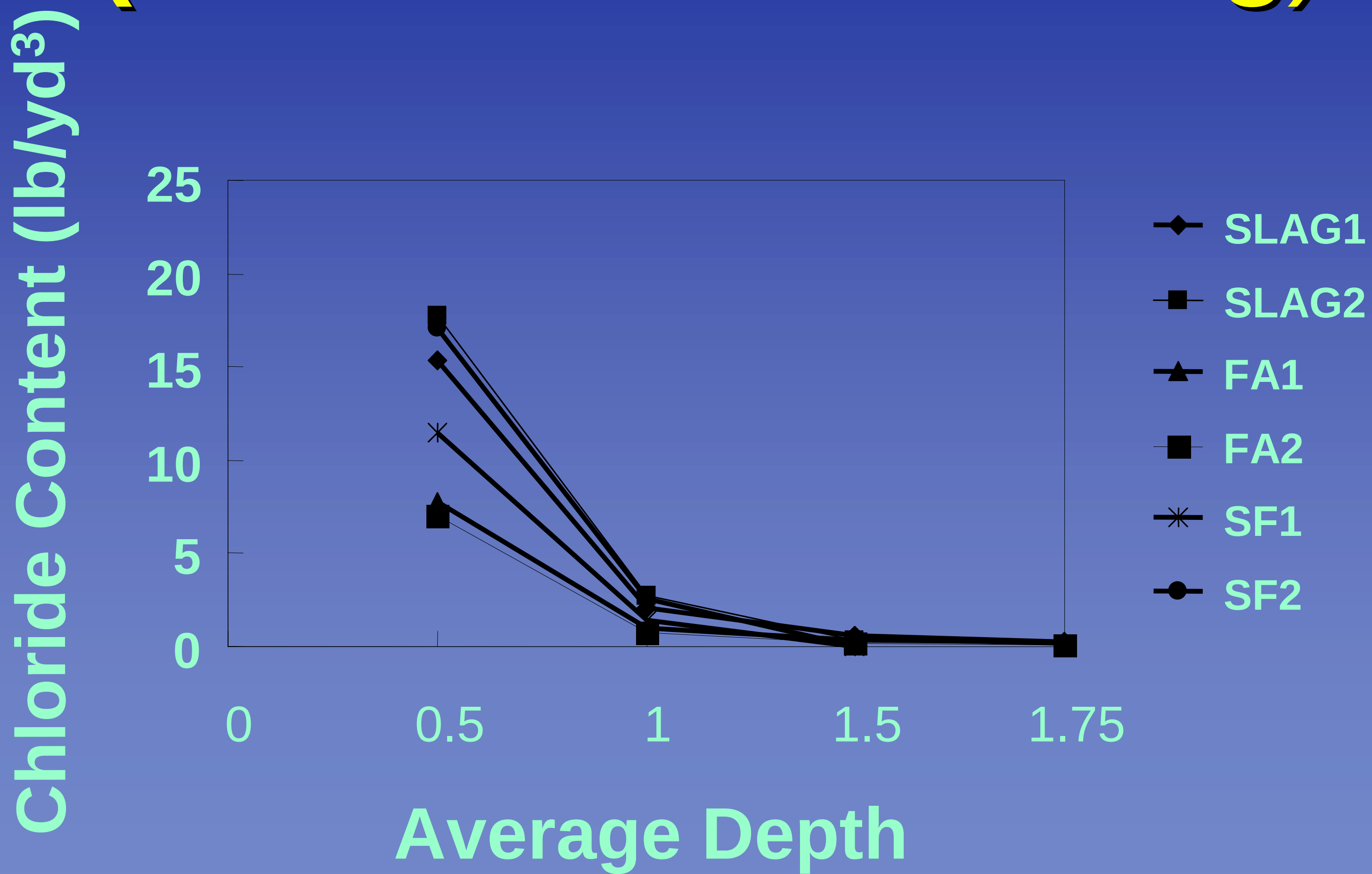
CONTROL CONCRETES



CONTROL CONCRETES (Coulombs)

Curing	w/cm	28 d	1.5 yr
Moist	0.40	4709	3048
Moist	0.48	5198	3100
Moist	0.44	5260	-
Steam	0.38	3110	-
Steam	0.48	7578	3405

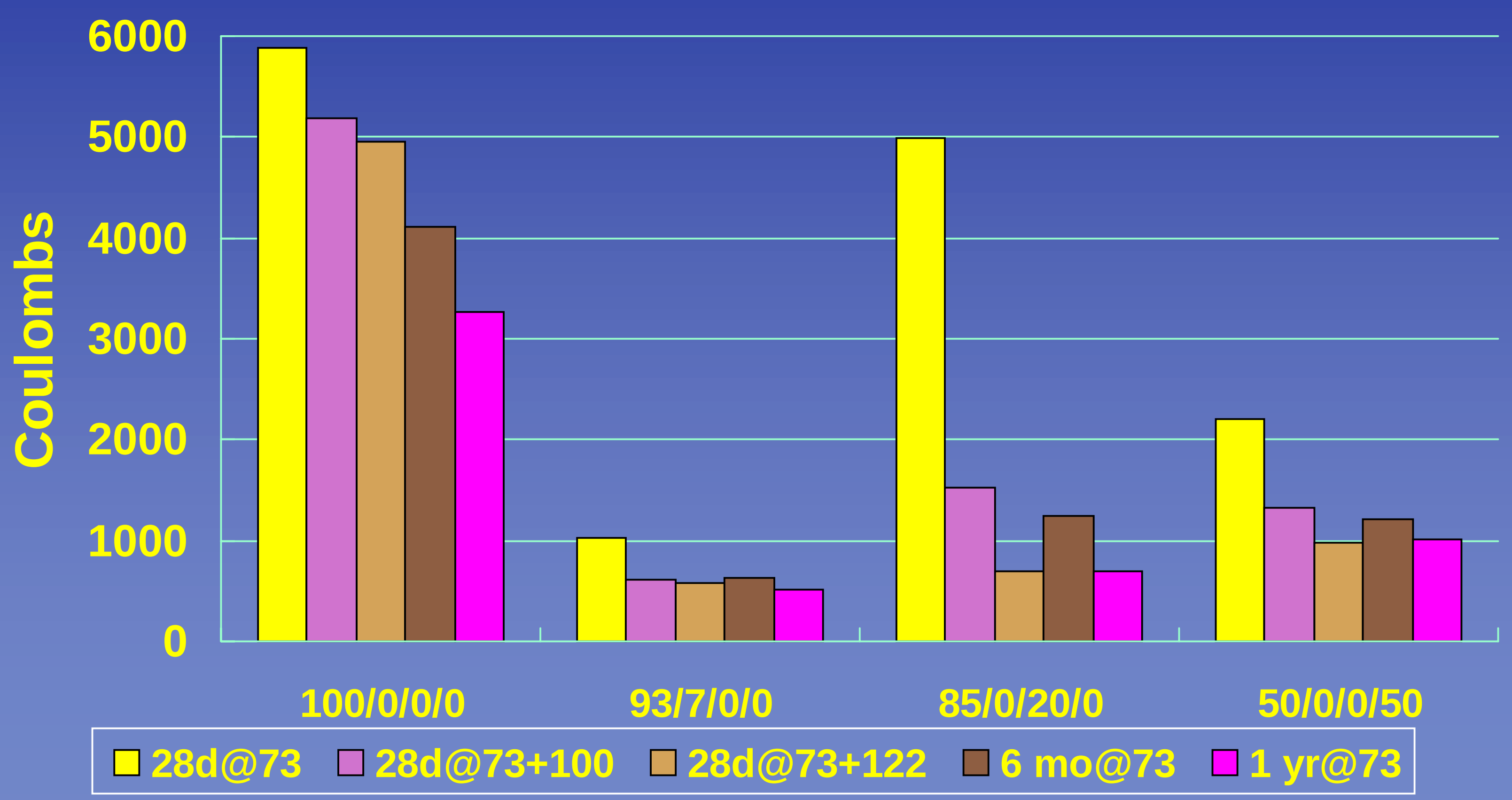
SLAG, FA, or SF CONCRETES (15 Months of Ponding)



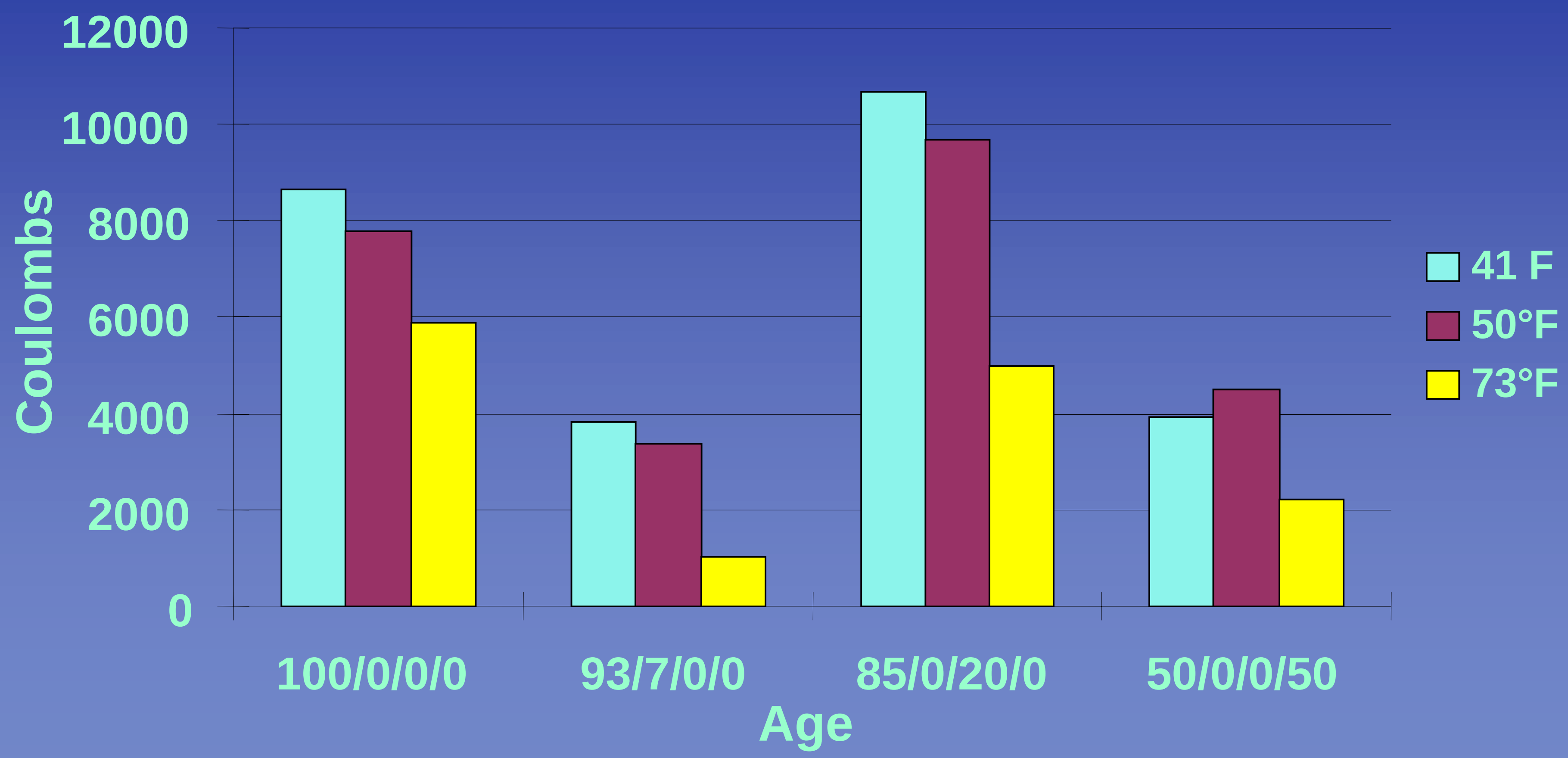
SLAG, FA, OR SF CONCRETES (Coulombs)

Material	w/cm	28 d	1yr
Slag 1 (50%)	0.47	502	1547
Slag 2 (50%)	0.47	2686	1187
FA 1 (25%)	0.45	5351	341
FA 2 (25%)	0.39	4456	294
SF 1 (7%)	0.40	1575	887
SF 2 (7%)	0.40	2369	1338

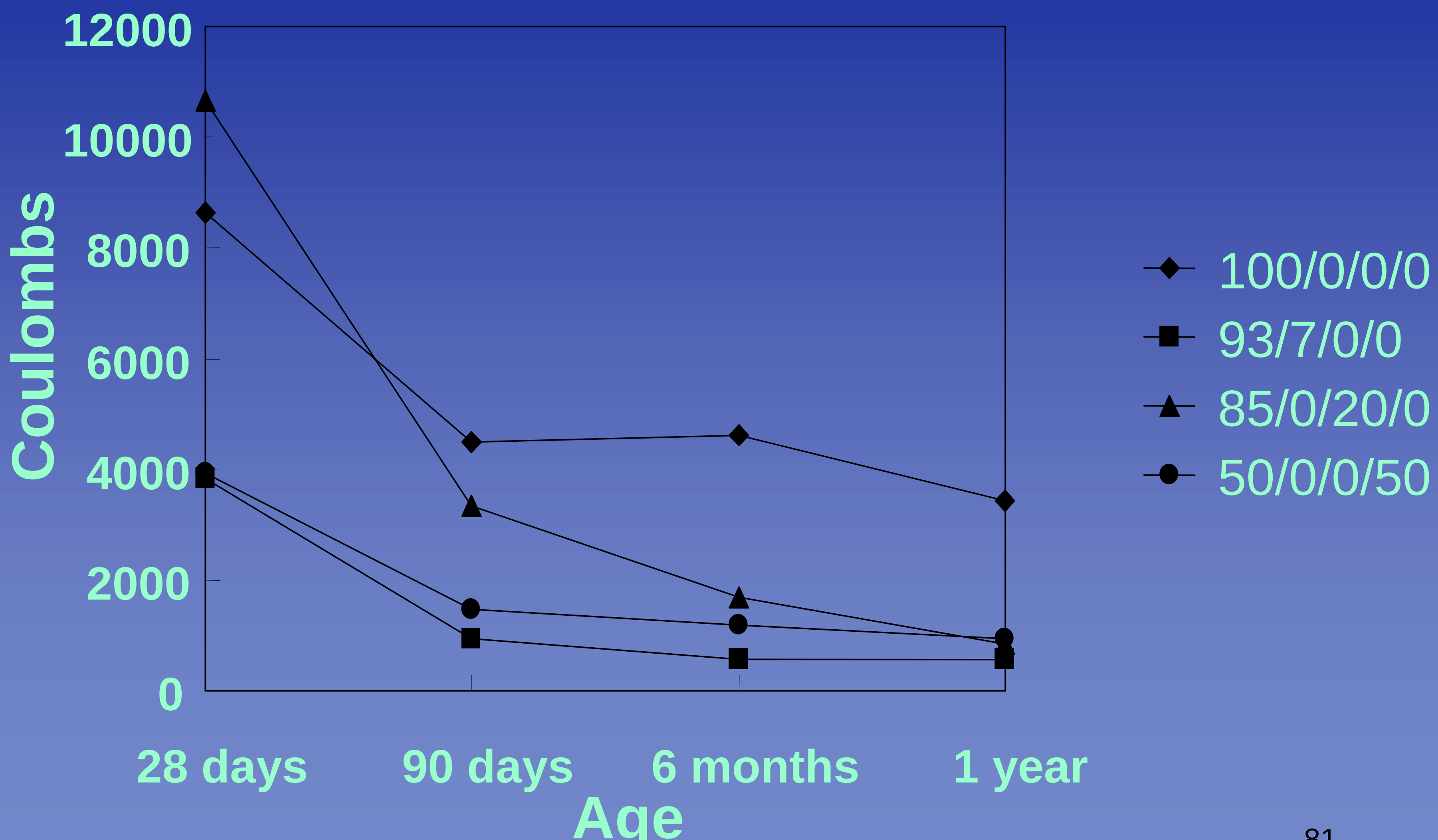
PERMEABILITY



Cold Temperature Effects



1 MONTH AT 41°F THEN 73°F



COULOMB VALUES
Coefficient of Variation

	LABORATORY		FIELD	
Range	No. of COV	No. of COV	Spec.(%)	Spec. (%)
0 - 1000	**88**	**4.8**	**34**	**6.6**
1001 - 2000	**59**	**5.9**	**130**	**6.6**
2001 - 4000	**56**	**5.8**	**194**	**6.7**
> 4000	**35**	**5.4**	**91**	**8.2**

LOW PERMEABILITY

AASHTO T 277 (coulombs)

1 week @ 73ºF + 3 weeks @100ºF

$\leq$ 1,500 prestressed concrete

$\leq$ 2,500 bridge decks

$\leq$ 3,500 substructure

Durability

Rapid Chloride Permeability

Freeze-Thaw Resistance

Deicer Scaling

Abrasion Resistance

Durability

Rapid Chloride Permeability

Freeze-Thaw Resistance

Deicer Scaling

Abrasion Resistance

Durability

Rapid Chloride Permeability

Freeze-Thaw Resistance

Deicer Scaling

Abrasion Resistance

Structural Design - Serviceability

Optimized Sections

Tensile Stress Limits

Transfer Length

Development Length

Camber

Prestress Losses

Live Load Deflection

Structural Design - Serviceability

Optimized Sections

Tensile Stress Limits

Transfer Length

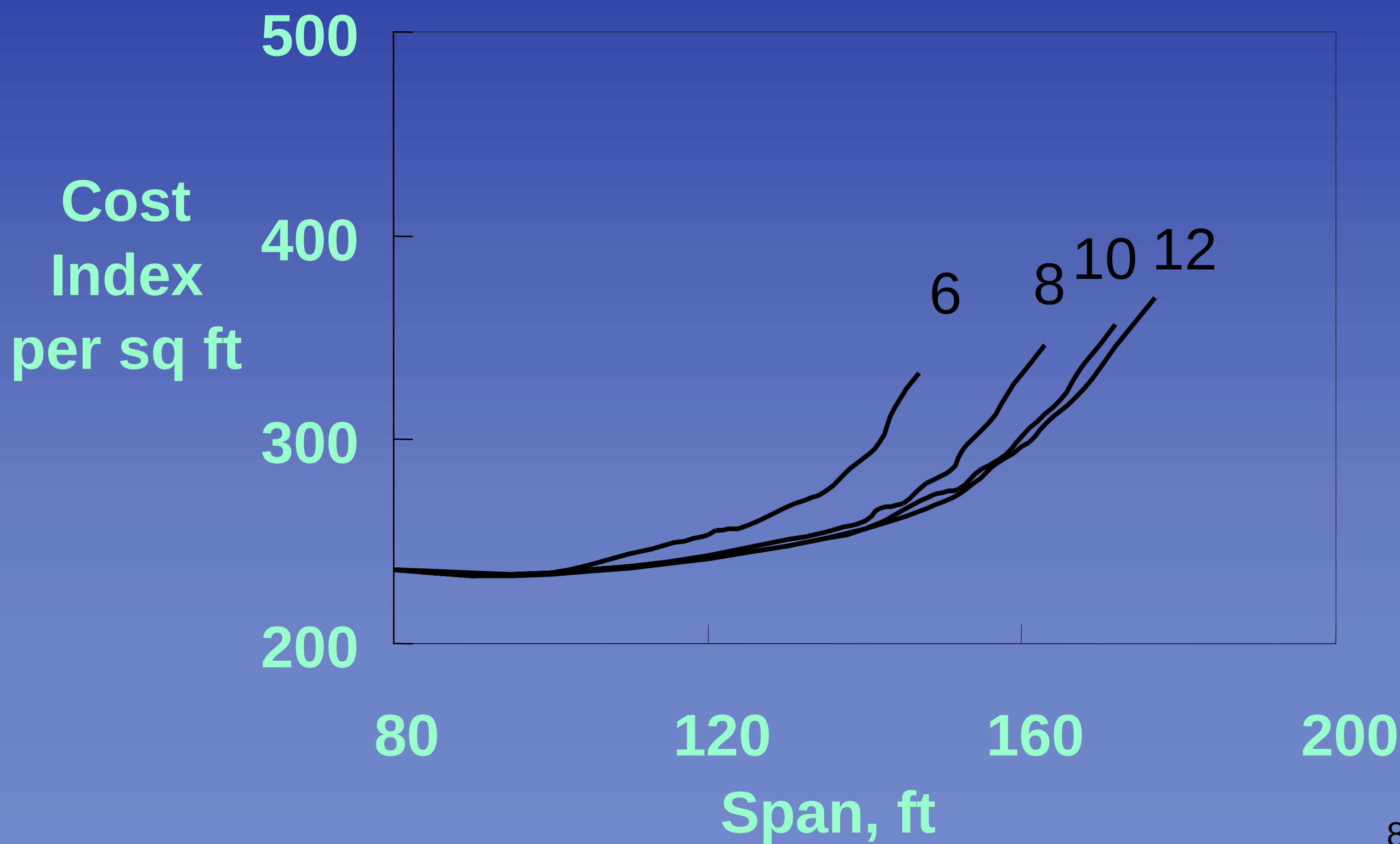
Development Length

Camber

Prestress Losses

Cost Comparison

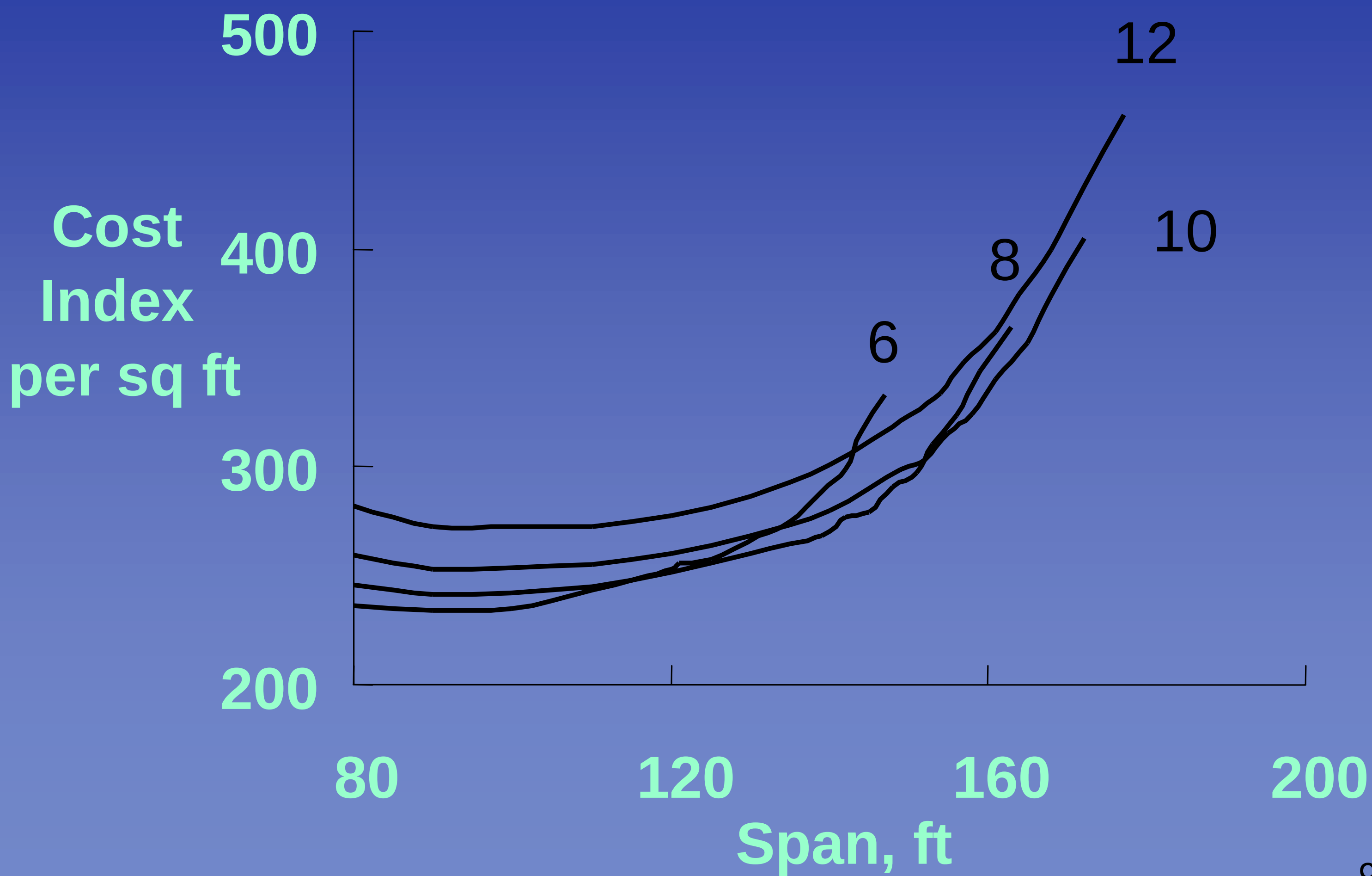
PCI BT-72



Relative Unit Costs

Strength Psi	Min.	Inter.	Max.
6,000	1.00	1.05	1.10
8,000	1.00	1.05	1.10
10,000	1.00	1.13	1.25
12,000	1.00	1.25	1.50

Cost Comparison with Premium



Sections Analyzed

Bulb-Tee PCI BT-72,
FL BT-72

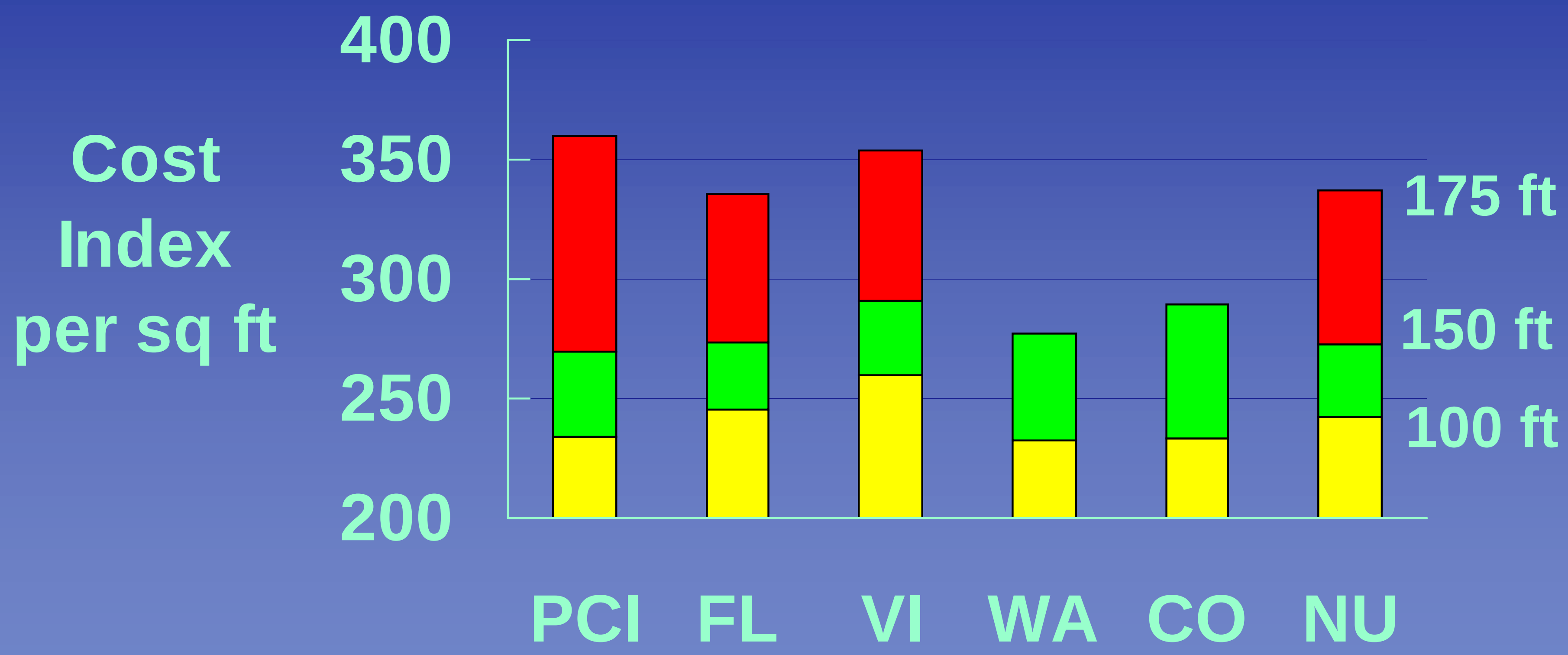
AASHTO VI/6

Washington 14/6

Colorado G 68/6

Nebraska NU 1800 `

Cost Comparison -
12,000 psi



Optimum Cross Sections

Optimum Cross Sections:

- Up to 120 ft - PCI BT-72, WA 14/6, CO 68/6
- Up to 150 ft - PCI BT-72
- 150 to 200 ft - FL BT-72, NU 1800

Limitations

Prestressing Force

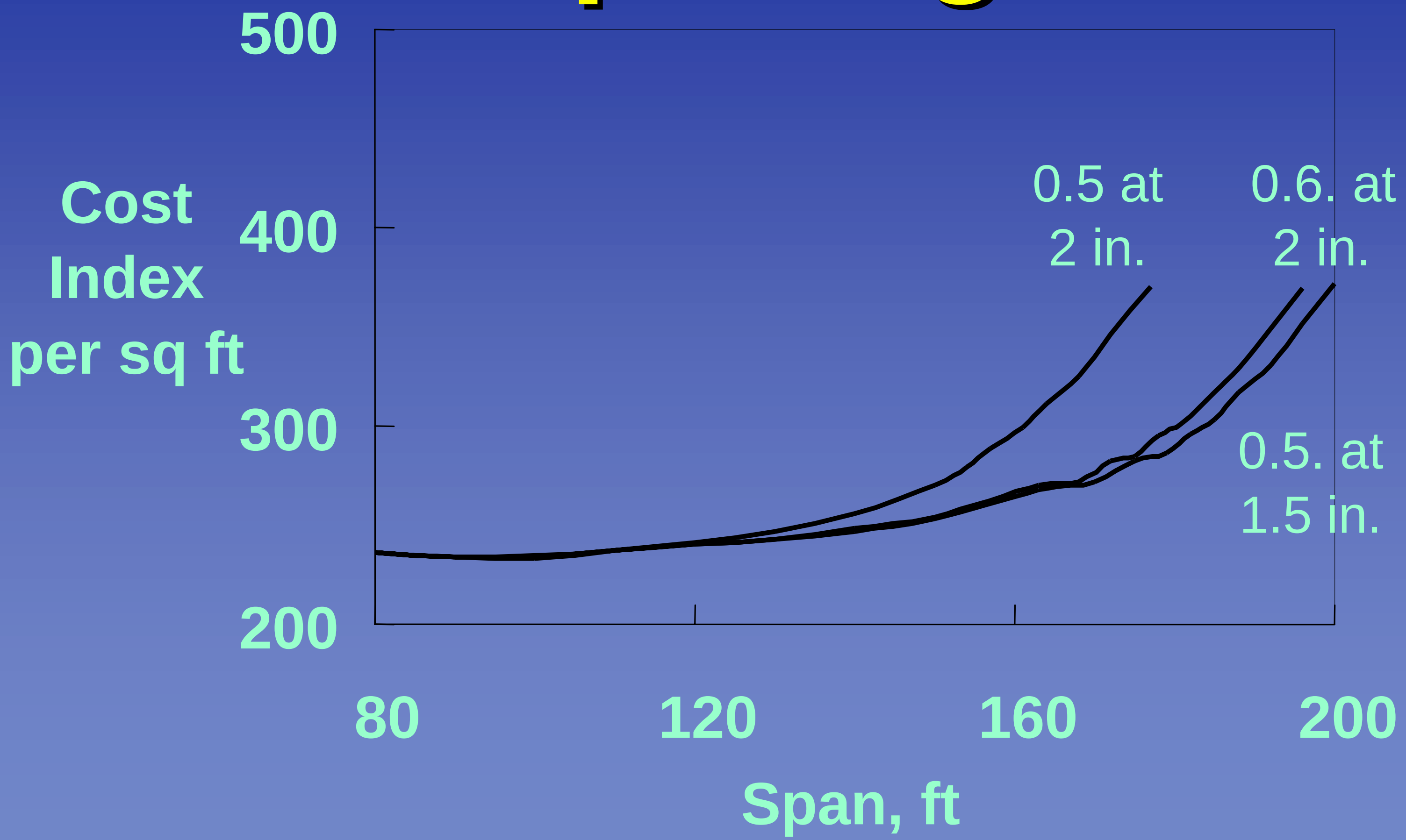
Strand Spacing

Strand Size

Strand Grade

Flange Size

Strand Size and Spacing



Structural Design - Serviceability

Optimized Sections

Tensile Stress Limits

Transfer Length

Development Length

Camber

Prestress Losses

Modulus of Rupture

ACI / AASHTO Equation

$MOR = 7.5\ (f'_c)^{0.5}$

Cornell Equation

$MOR = 11.7\ (f'_c)^{0.5}$

Texas Design

At release: $10.0\ (f'_{ci})^{0.5}$ vs $7.5\ (f'_{ci})^{0.5}$

At service: $8.0\ (f'_c)^{0.5}$ vs $6.0\ (f'_c)^{0.5}$

Structural Design - Serviceability

Optimized Sections

Tensile Stress Limits

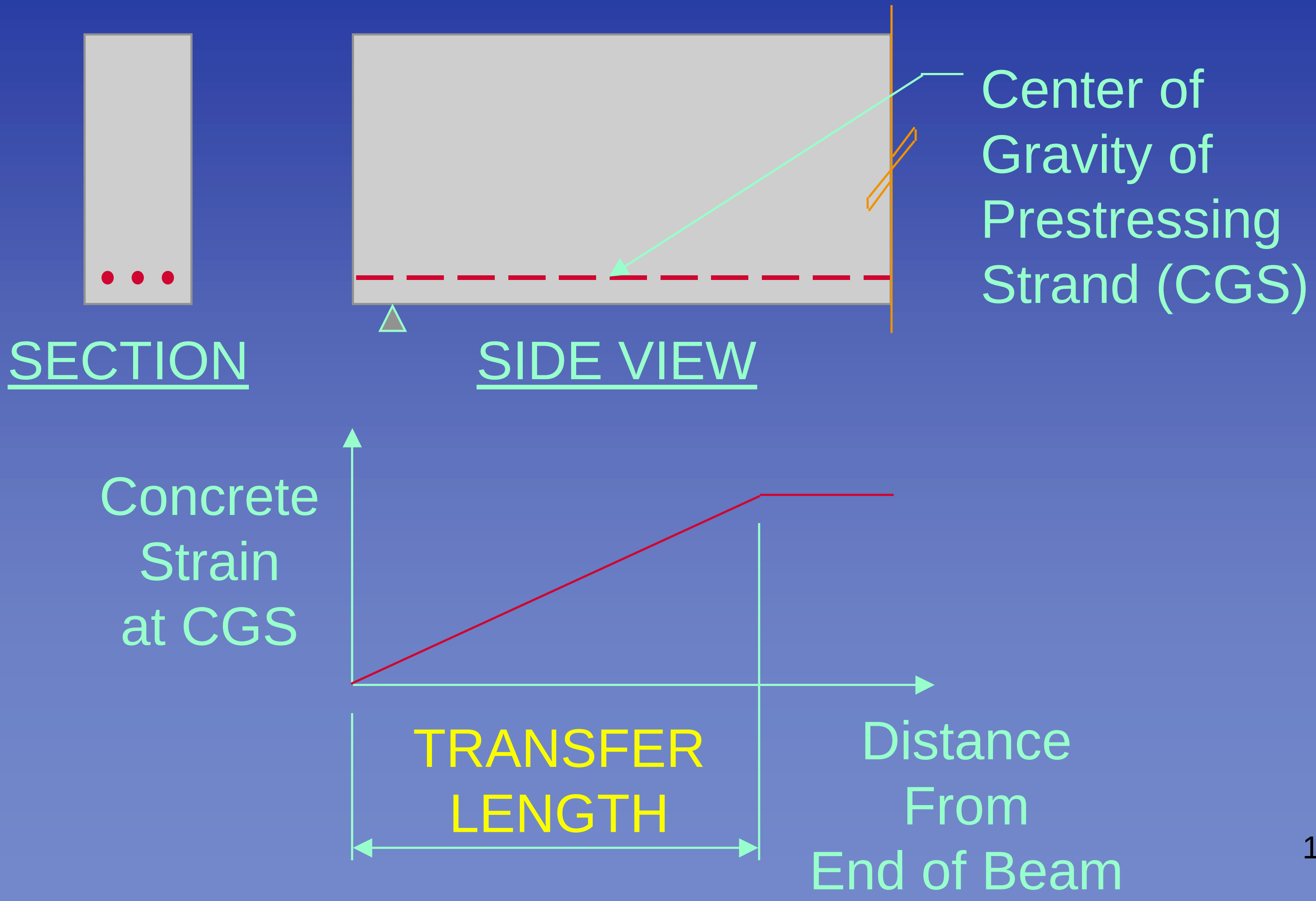
Transfer Length

Development Length

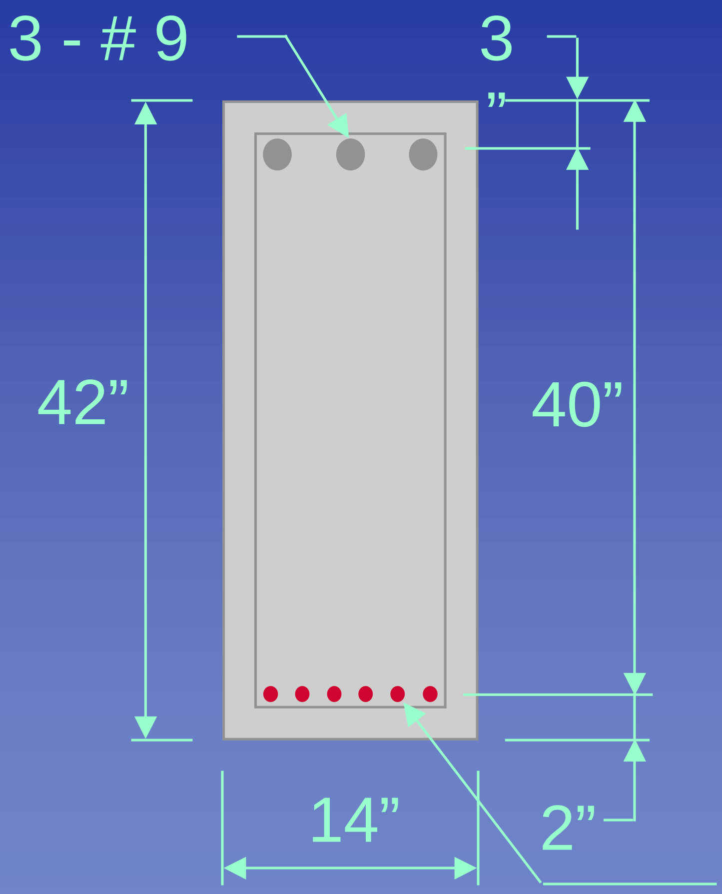
Camber

Prestress Losses

TRANSFER LENGTH (l_t) DEFINITION



HOBLITZELL - BUCKNER HPC BEAMS



TRANSFER AND DEVELOPMENT LENGTH TESTS

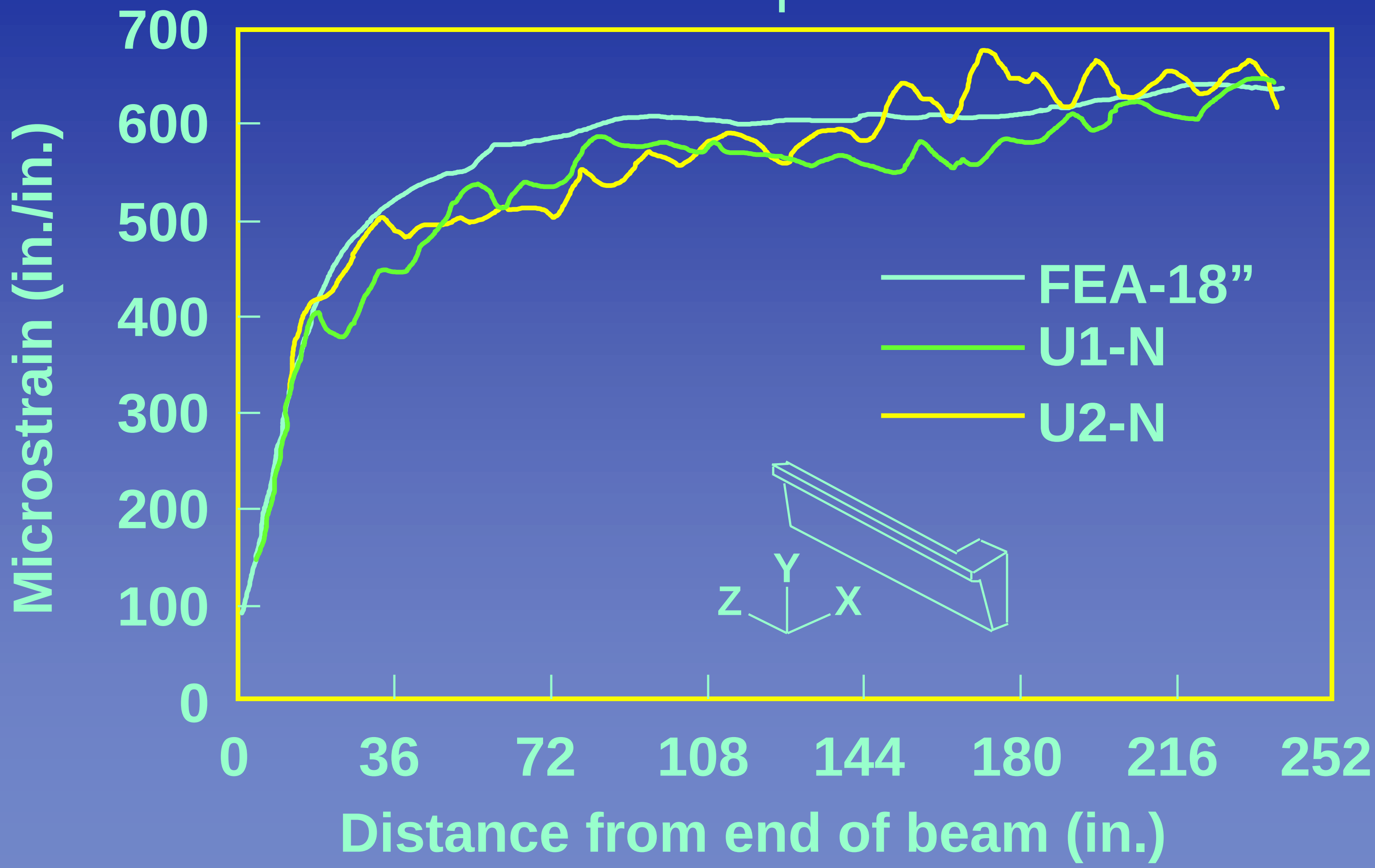
f'ci = 7,000 psi

f'c = 11,800 psi

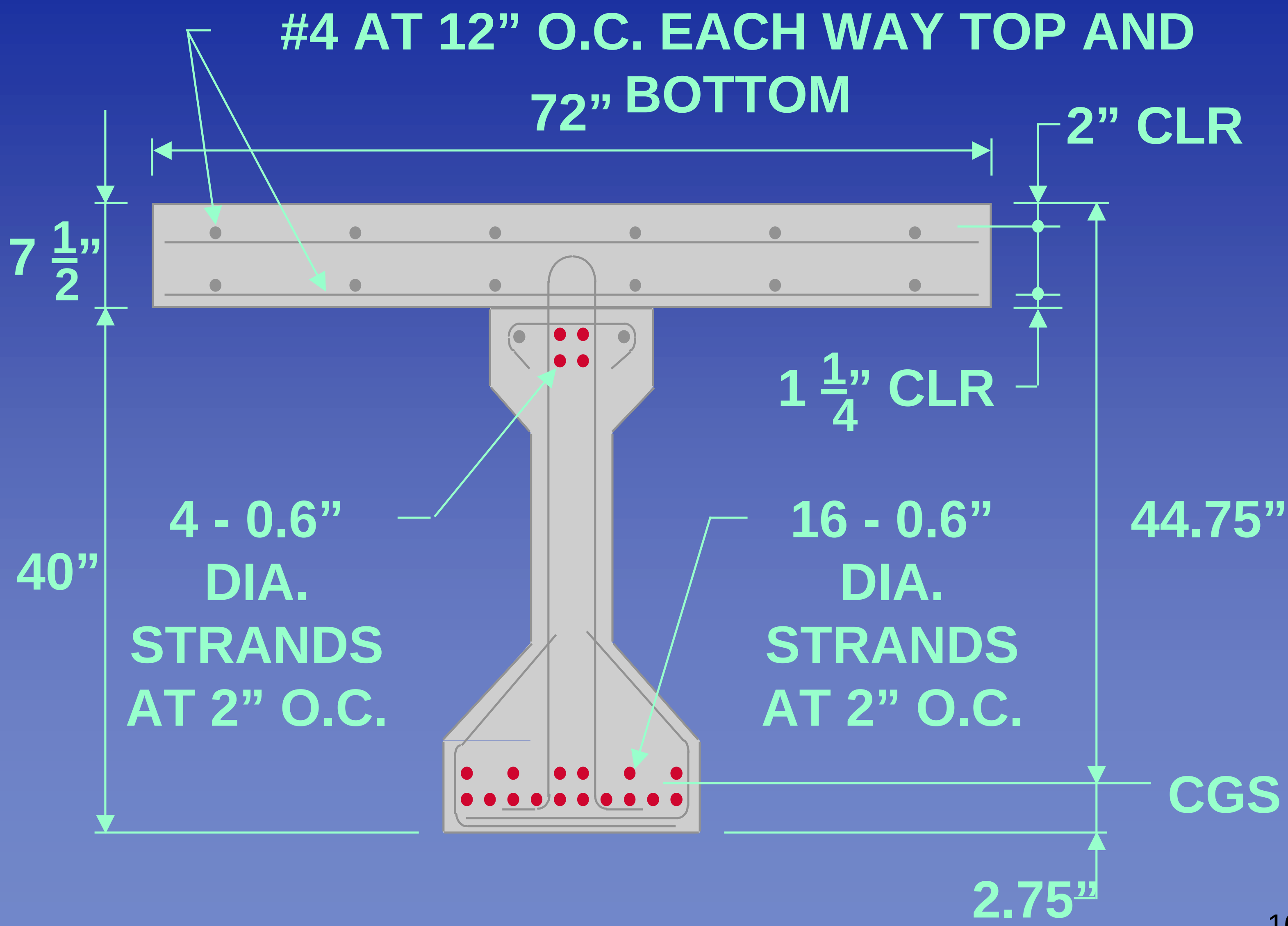
6 - 0.6" DIA STRANDS AT 2" O.C.

TRANSFER LENGTH

Measurements vs. Finite Element Analysis for 54-Inch Deep U-Beam



TxDOT TYPE "C" TEST BEAMS



TASK 2: STRUCTURAL TESTING

Two full-scale prestressed beams with:

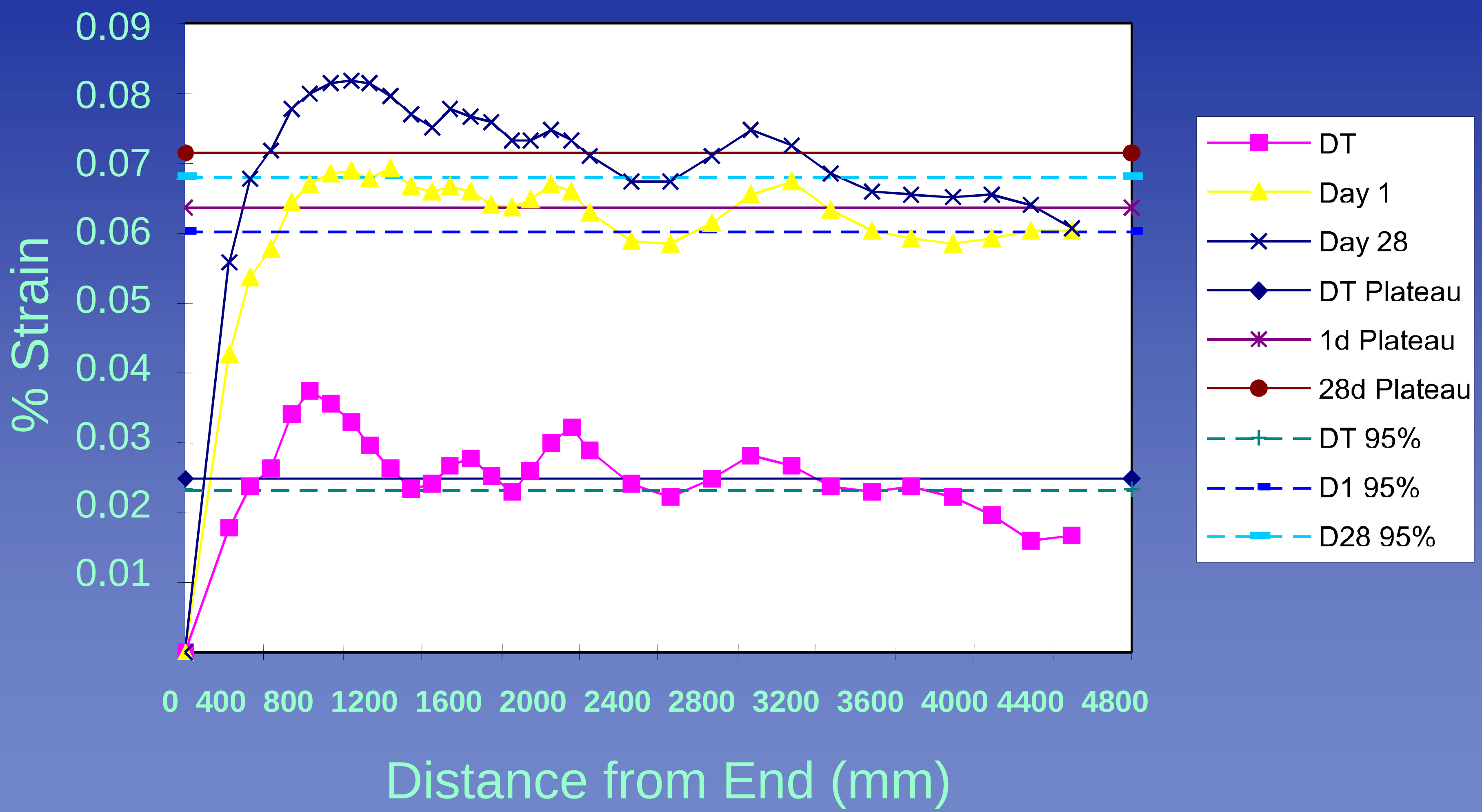
- 0.6-inch strands at 2-inch spacing
- composite deck slabs

Test beams for flexural strength, transfer length, end slippage, and development length

Separate pull-out test to further evaluate bond strength


A1 A3 A5 A6 A4 A2

TRANSFER LENGTH



Measured Transfer Lengths

Girder End	Release in.	28-days in.
1-E	24.2	28.3
1-W	24.4	26.4
2-E	22.0	22.0
2-W	23.8	25.6
3-E	23.8	25.6
3-W	21.9	21.7

Structural Design - Serviceability

Optimized Sections

Tensile Stress Limits

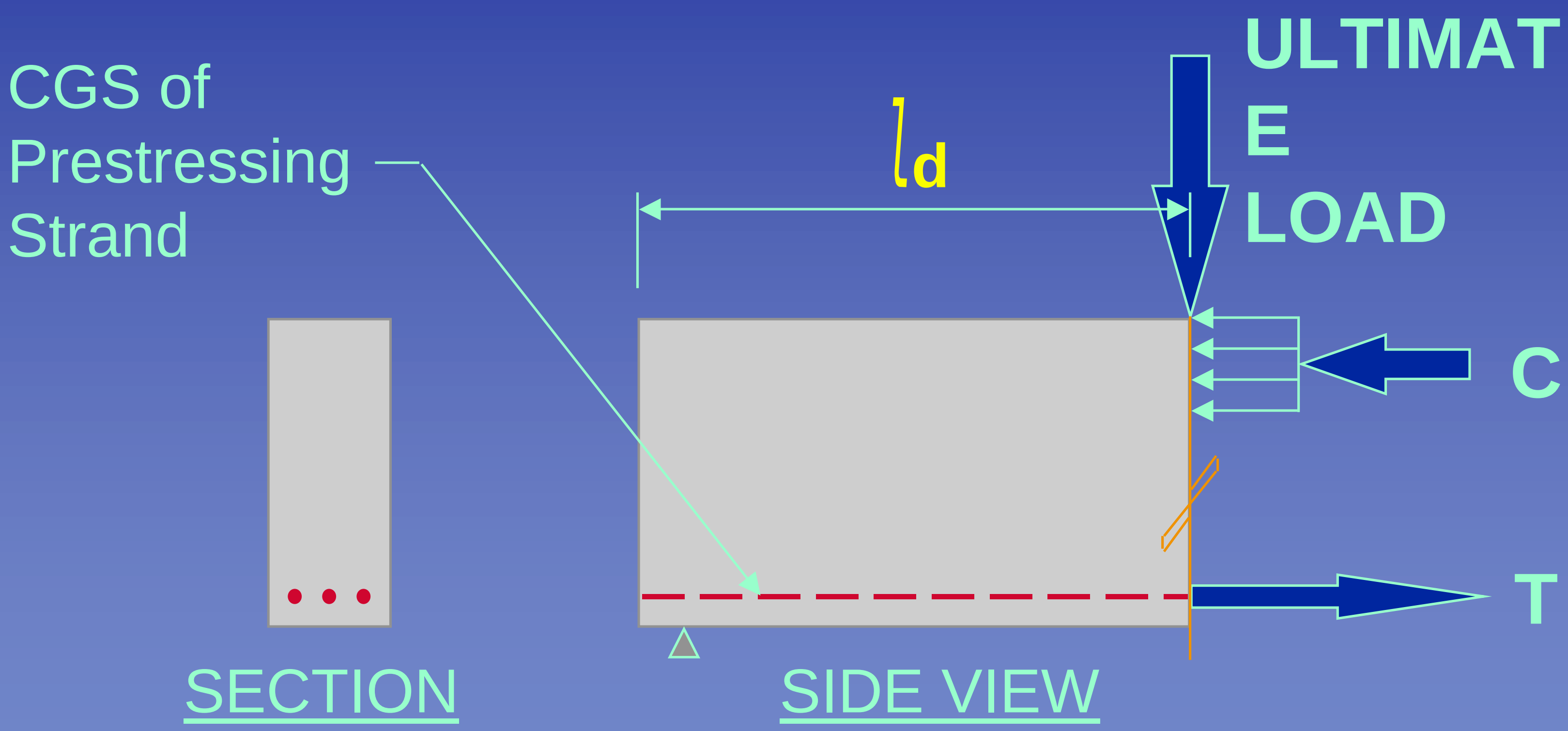
Transfer Length

Development Length

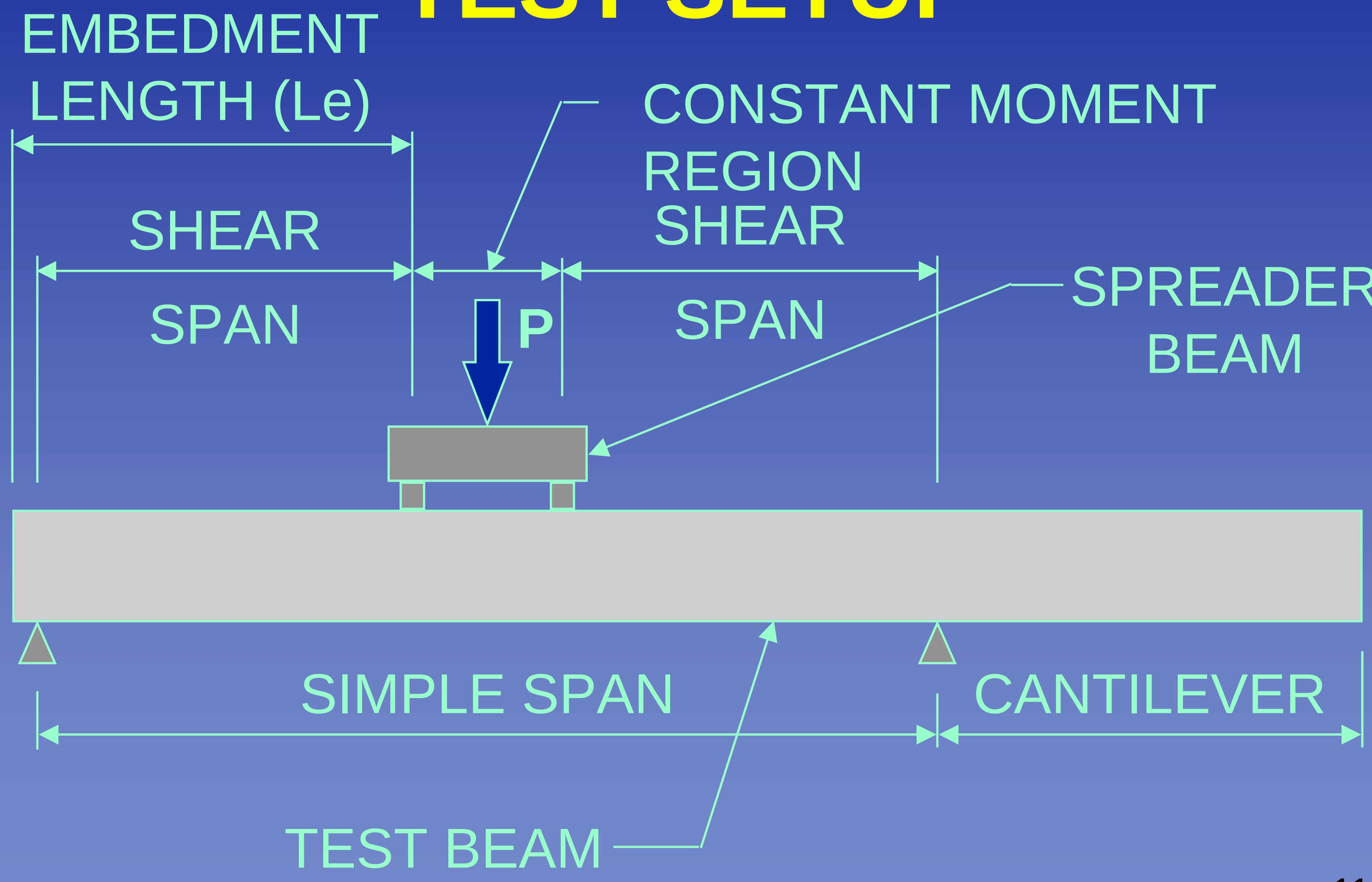
Camber

Prestress Losses

DEVELOPMENT LENGTH (l_d)
(DEFINITION)



DEVELOPMENT LENGTH TEST SETUP



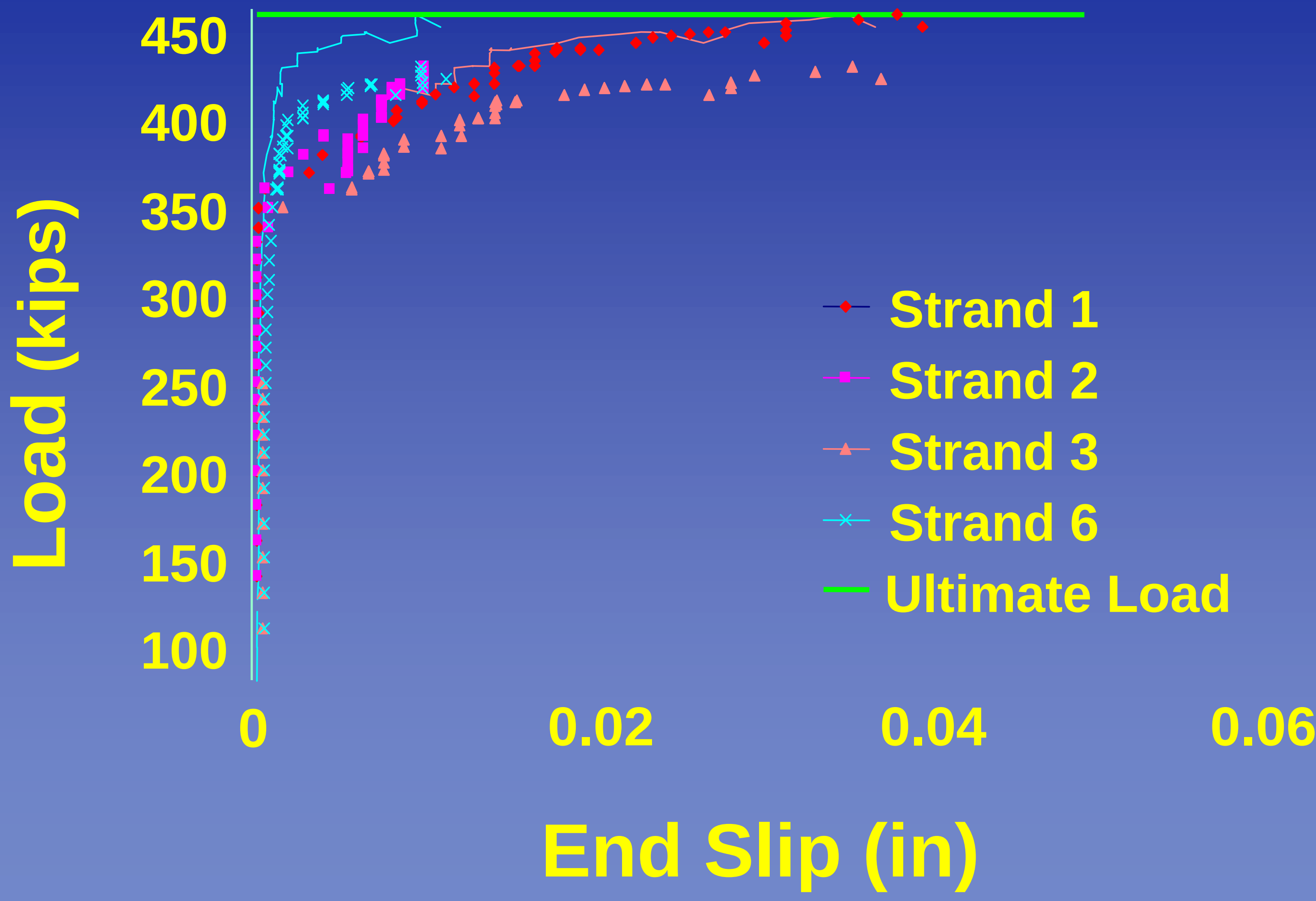
HOBLITZELL-BUCKNER BEAMS
Development Length Test Results

Test	Embedment Length, in.	Failure Type
1	163	Flexural
2	119	Flexural
3	102	Flexural
4	78	Flexural

TxDOT TYPE "C" TEST BEAMS
Development Length Test Results

Test	Embedment Length, in.	Failure Type
1	120	Flexural
2	93	Flexural
3	78	Flexural
4	72	Flexural

BALANCED FAILURE



CONCLUSIONS

Transfer and development lengths were successfully measured.

0.6-inch strands at 2-inch spacing can be used.

Development Lengths

Girder End	Length in.
1-E	85
1-W	81
2-W	76
2-E	65
3-E	60
3-W	59

Structural Design - Serviceability

Optimized Sections

Tensile Stress Limits

Transfer Length

Development Length

Camber

Prestress Losses

Beam Camber

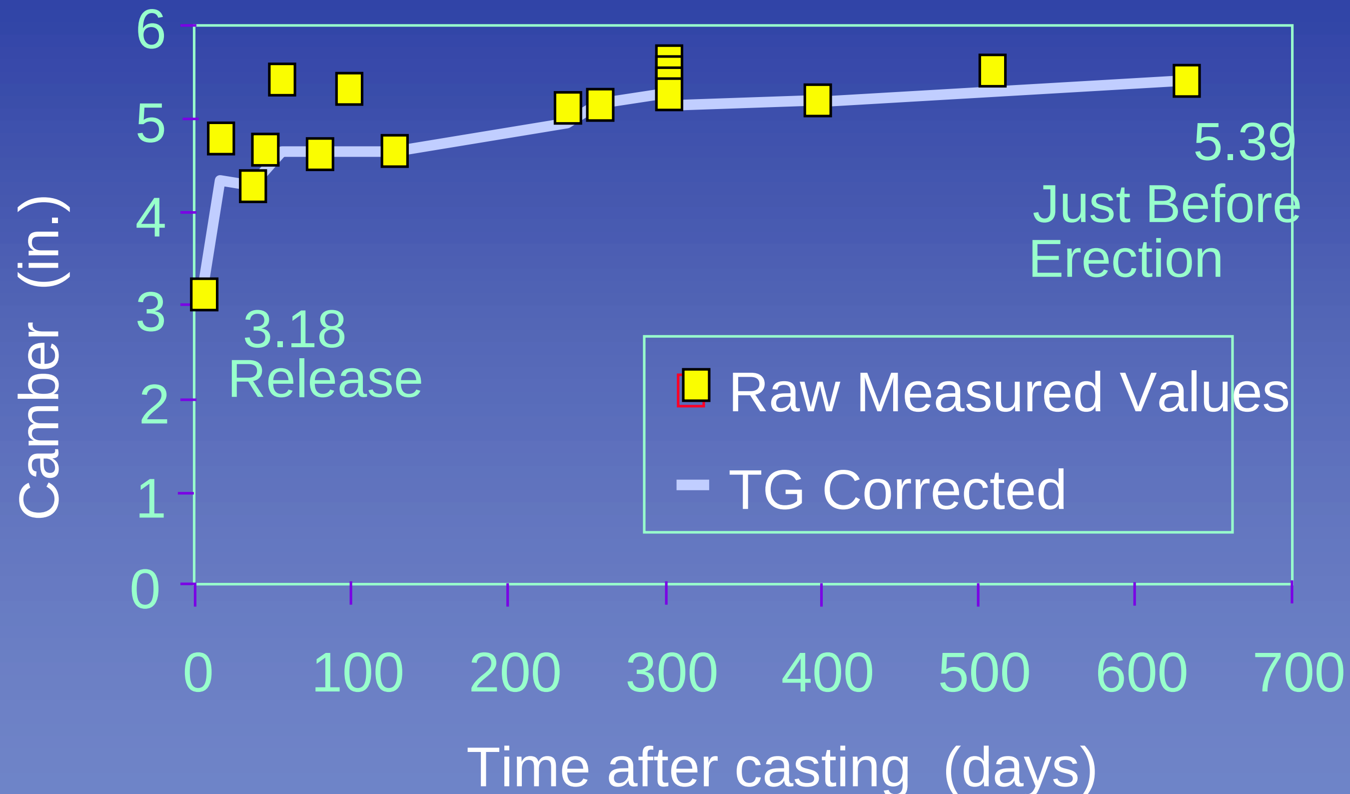
Beam S16 / AA-6 Cast 9/30/94

68 0.6-in. diameter strands

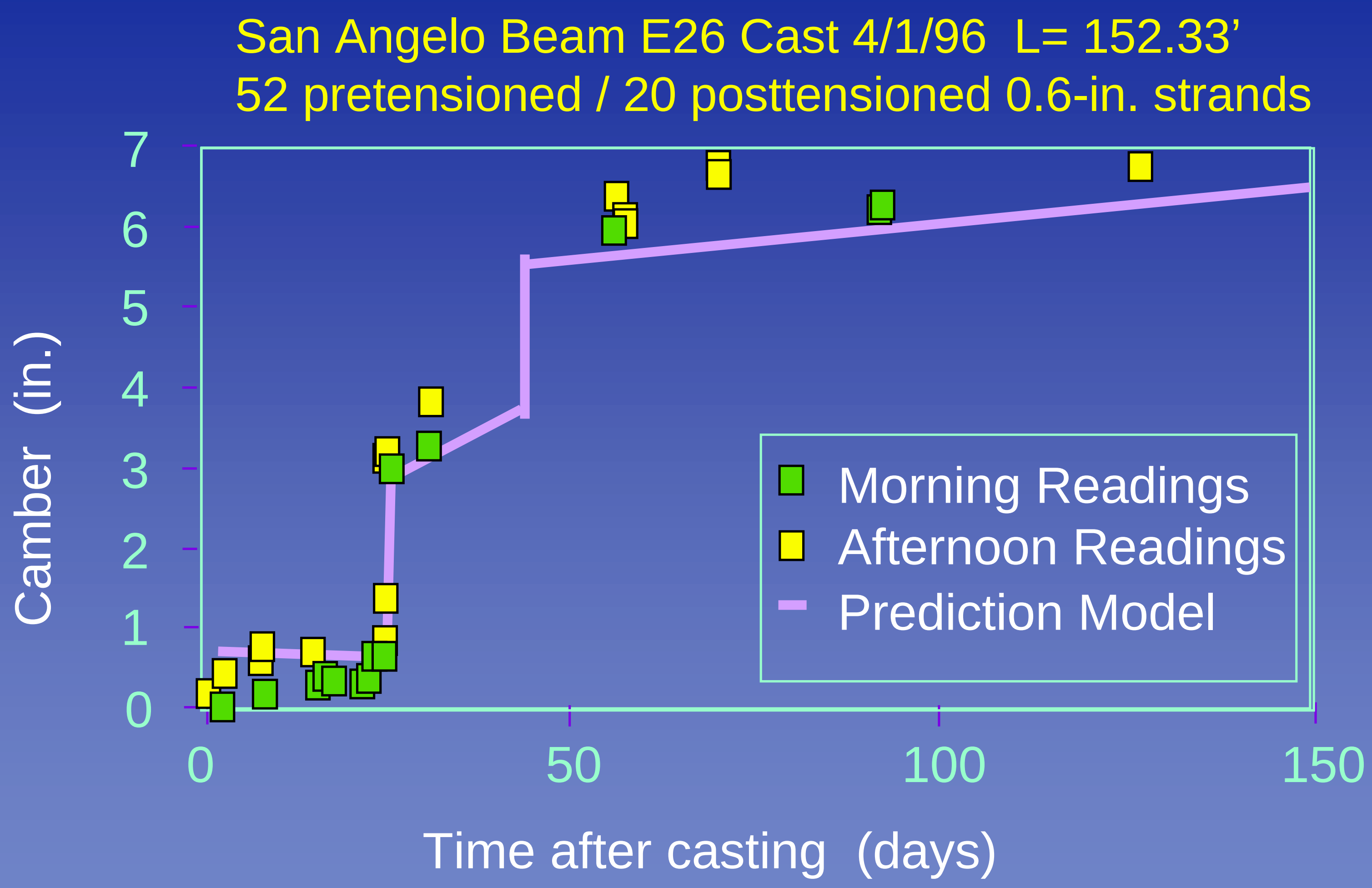
Beam Camber

Beam N21 / AA-24 Cast 10/28/94

87 0.6-in. diameter strands



Beam Camber



San Angelo Beam E26 Cast 4/1/96 L= 152.33'
52 pretensioned / 20 posttensioned 0.6-in. strands
Camber (in.)
7
6
5
4
3
2
1
0
0
50
100
150
Time after casting (days)
Morning Readings
Afternoon Readings
Prediction Model

Initial Elastic Camber

Measured immediately after release

Corrected for thermal gradients (small)

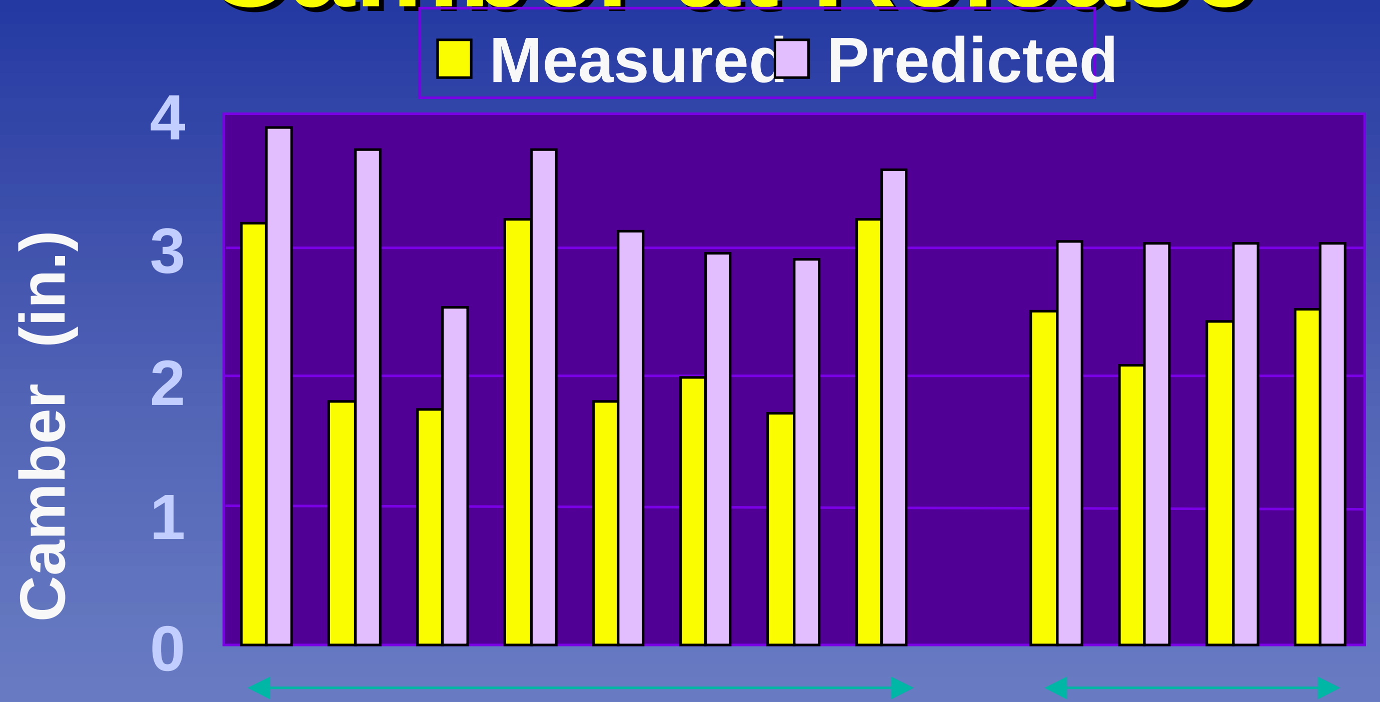
Theoretical prediction:

(Prestress Camber) *upward*

\- (Self-weight deflection)___________ *downward*

$$\Delta = \frac{P_o e L^2}{8EI} - \frac{5wL^4}{384EI}$$

Measured vs. Predicted Camber at Release



Fall '94
Avg. Ratio = 0.70
Avg. Diff. = 0.96"

Spring '96
Avg. Ratio = 0.79
Avg. Diff. = 0.64"

Time-Dependent Camber

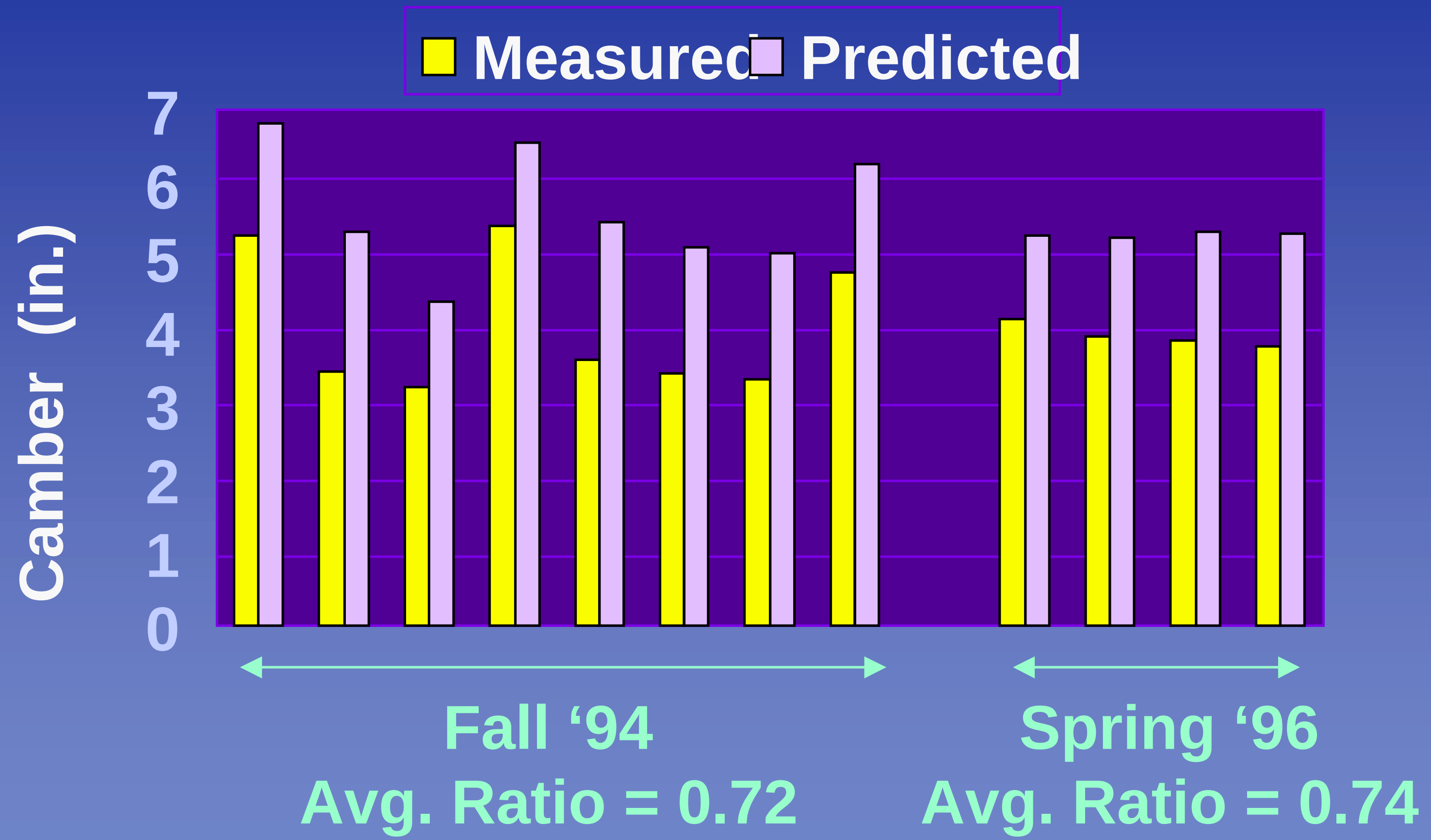
Prestress losses *decrease* camber
Creep *increases net* camber

Multiplier Method:

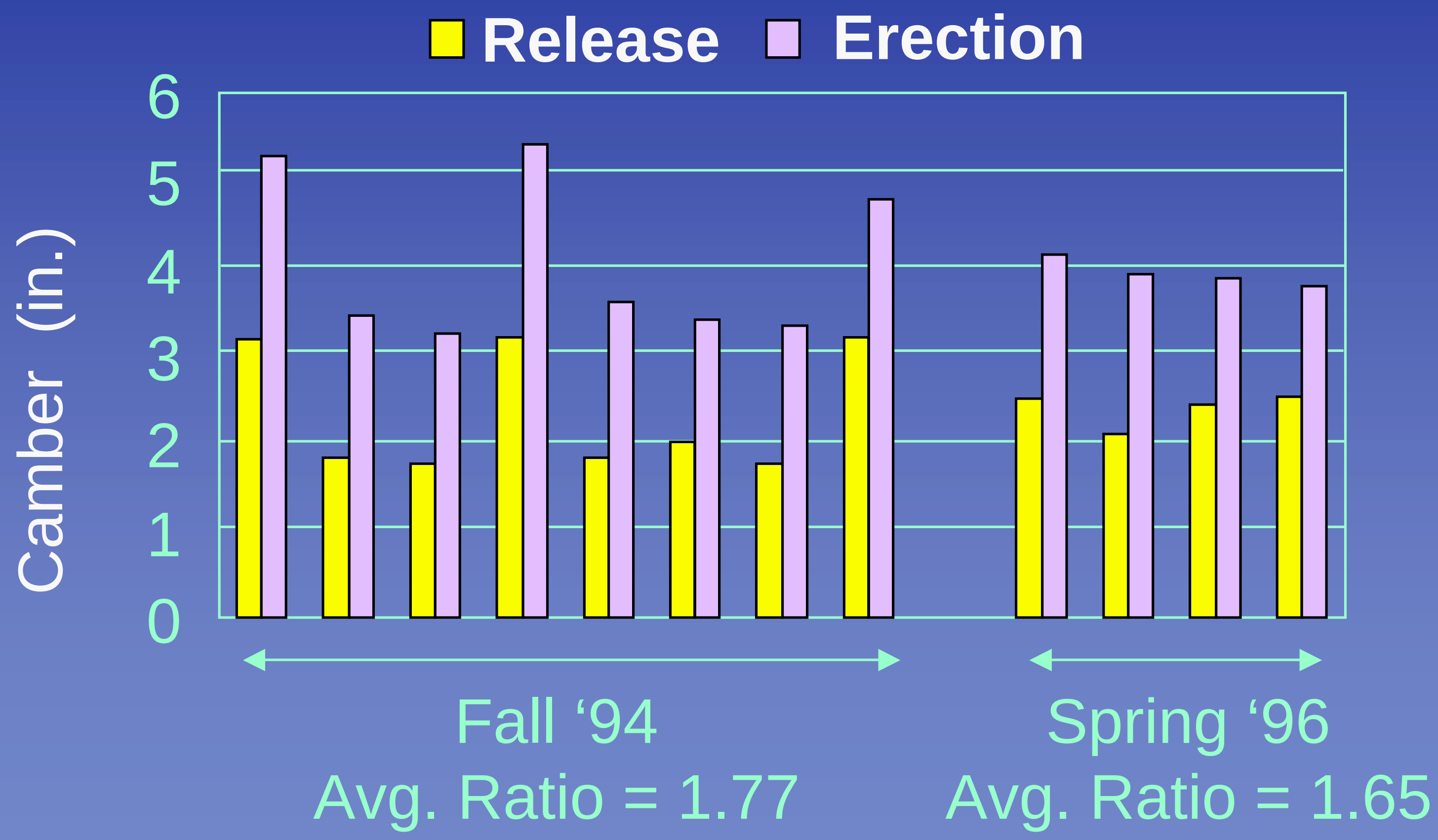
$$) = \lambda_1)_{prestress} - \lambda_2)_{self\ weight}$$

PCI (Erection): $\lambda_1 = 1.80$ $\lambda_2 = 1.85$

Measured vs. Predicted Camber Immediately Prior to Erection



Measured Camber Immediately Prior to Erection vs. Measured Camber at Release



Structural Design - Serviceability

Optimized Sections

Tensile Stress Limits

Transfer Length

Development Length

Camber

Prestress Losses

Prestress Losses

Sources of Loss:

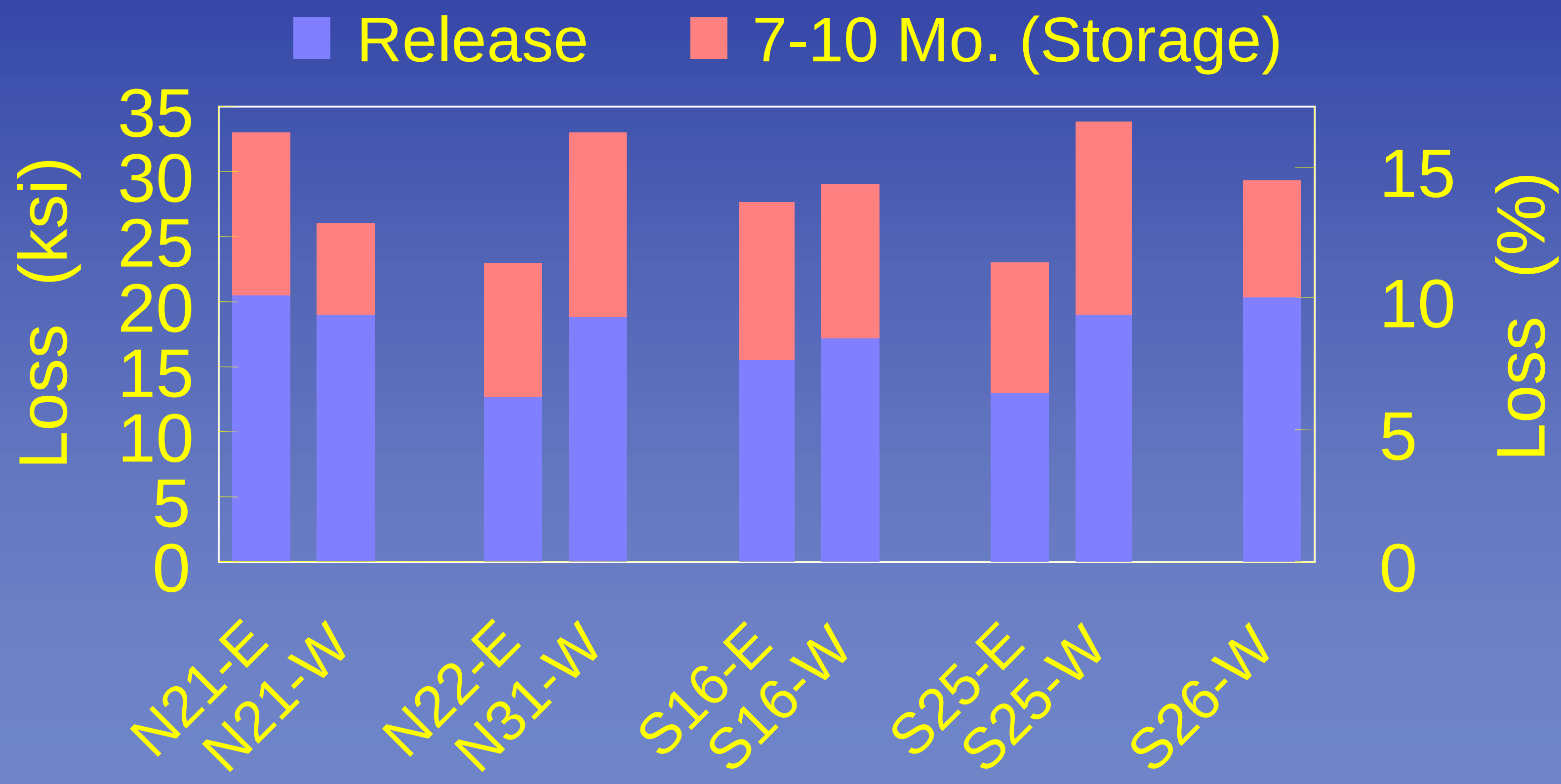
Elastic Shortening	*immediate*
Creep	*time-dependent*
Shrinkage	*time-dependent*
Relaxation	*time-dependent*

Change in concrete strain at cgs (measured)

= Change in strand strain at cgs

$\times E_{ps}$ = Prestress loss at cgs *(ksi)*

Measured Prestress Loss



Structural Design - Strength

Flexural Strength

Shear Strength

Flexural Strength

Girder	Cracking Moment, k-ft Measured	Cracking Moment, k-ft AASHTO	Ultimate Moment, k-ft Measured	Ultimate Moment, k-ft AASHTO
BT-1	3192	3066	6977	6575
BT-3	3031	3190	6996	6596
BT-5	2730	3016	6594	6491

Structural Design - Strength

Flexural Strength

Shear Strength

Shear Cracking

	Flexural Shear, kips		Web Shear, kips	
Girder	Measured	AASHTO	Measured	AASHTO
BT-1	160	159	423	261
BT-2	136	129	328	213
BT-3	158	164	-	-
BT-5	163	157	-	-

Load Tests

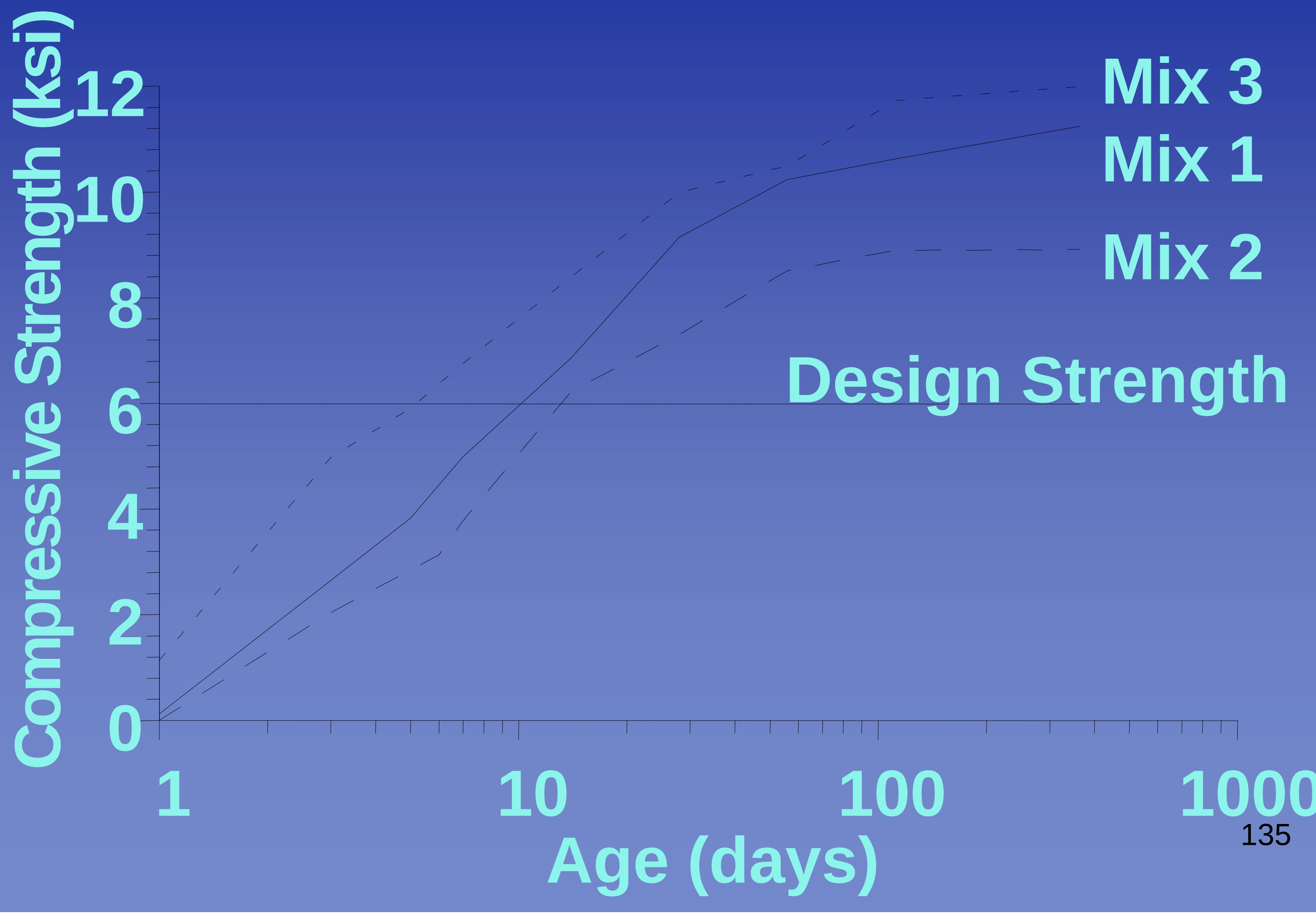
New Hampshire

UNIVERSITY OF NEW HAMPSHIRE BRIDGE DECK TESTING FACILITY

Mix Designs

Mix	w/cm	Slag	Silica Fume	Air
1	0.35	50 %	-	6 %
2	0.35	50%	2 %	6 %
3	0.35	-	8 %	6 %

STRENGTH VERSUS TIME



Mix Performance

Mix	Scaling	Slump (in)	Chloride Permeability (C)	28-Day Strength (psi)
1	3.7	2.5	1016	8910
2	2.9	4.4	625	7220
3	2.1	3.0	641	9700

POST SERVICE STRENGTH TESTING

- Concrete Compressive Strength
- Concrete Tensile Strength
- Concrete Modulus of Elasticity
- Steel Tensile Strength
- Slab Flexural Strength

Lessons Learned

Washington State

General

- **Design**
- **Concrete Materials**
- **Construction**

Purpose of HPC - WA

Economy

Longer Spans

Fewer Girders

Durability

Define Durability

Is Strength Related to Durability

What Have We Learned - WA

Develop Mix Designs under a Separate Contract

Coordinate Research during Construction

- Scheduling
- Communication

Girders vs Deck Concrete

Deck Concrete - WA

Water Cure

Fly Ash

High Strength

Lessons Learned - Design

- 0.6 in. (15.2 mm) Diameter Strands
- Permissible Tensile Stress
- Lateral Stability

Lessons Learned - Concrete Materials

- Concrete Mix Proportions
- Mineral Admixtures
- Chemical Admixtures
- Trial Mixes
- Full-Scale Tests

Lessons Learned - Construction

- Girder Lengths
- Bed Capacities
- Match Curing and Maturity
- Heat Curing
- Deck Curing

THANK YOU