Quarry By-product Applications for Subgrade and Subbase

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Presented by: Erol Tutumluer, PhD, Professor – UIUC

ICT R27-168 Research Project

Project Team:

Erol Tutumluer, Principal Investigator

Hasan Ozer, Co-Investigator

Issam Qamhia, Graduate Research Assistant

Introduction – *Motivation*

- In 2016, 1.48 billion metric tons of crushed stone were produced from 3,700 operating quarries in 50 States (USGS, 2016)
- 175 million metric tons of quarry by-products are generated in over 3000 quarries in United States each year (NCHRP Synthesis 435, Volume 4)
- Approximately 11.8% of aggregate mined is waste fines!
- Quarrying limestone and dolomite usually produces 20% to 25% fines
- Stockpiling and disposal of quarry by-products (QB) is a major problem facing the aggregate industry

Quarry By-Products (QB)

Blasting

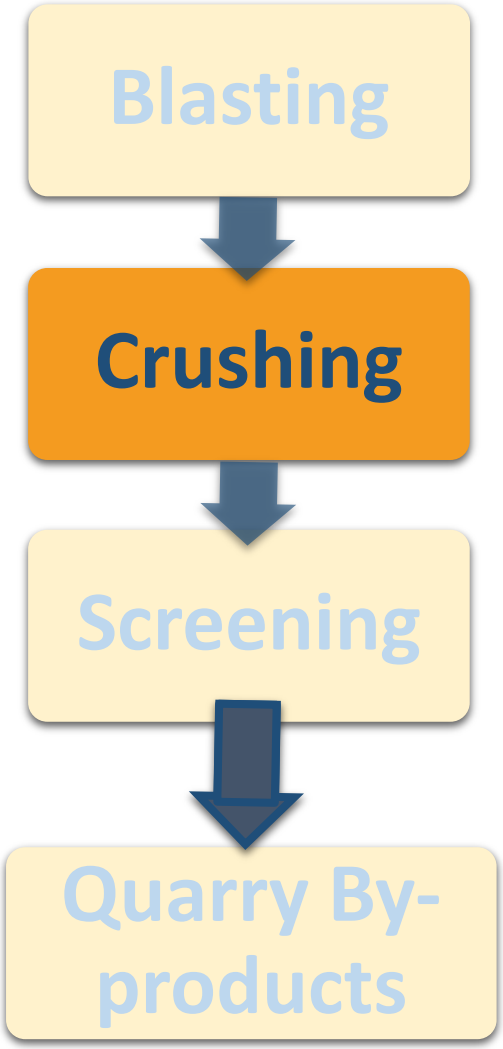
Crushing

Screening

Quarry By-products

Typically less than ¼ in. (6 mm) in size, Produced in quarry processes

Quarry By-Products (QB)



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Quarry By-Products (QB)

Blasting

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Quarry By-products

Approximately 11.8% of aggregate mined is waste fines!

Quarry By-Products (QB)

Blasting

↓

Crushing

↓

Screening

↓

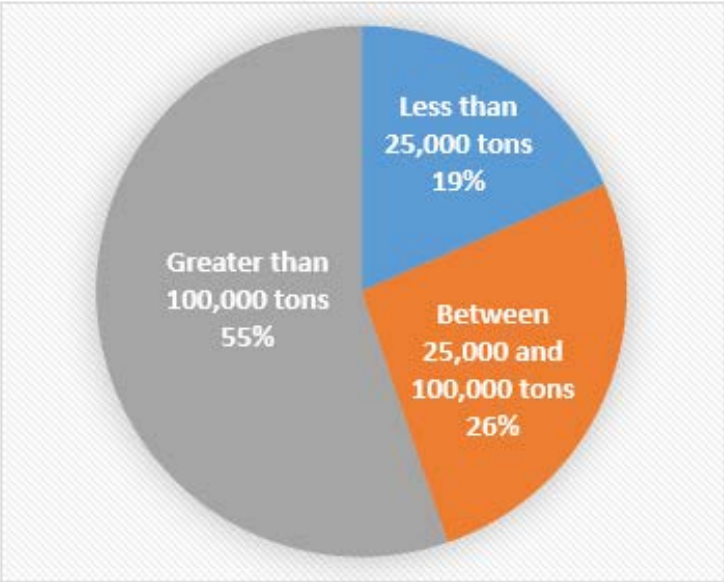
Quarry By-products

A potential to incorporate Excess QB in pavement applications

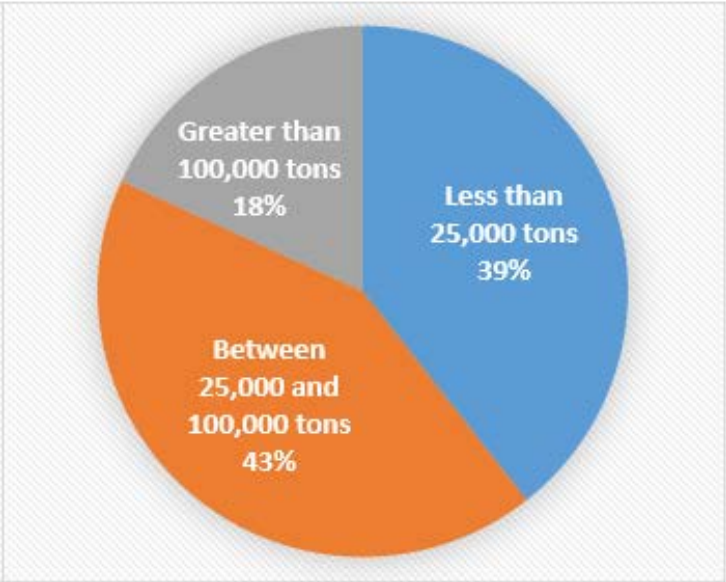
QB Production in Illinois (ICT R27-125)

Survey: Annual Production in Illinois (based on 22 responses)

Typical annual tonnage of total QB production?



Annual tonnage of QB in ***excess*** category? (stockpiled or not being sold for any application)

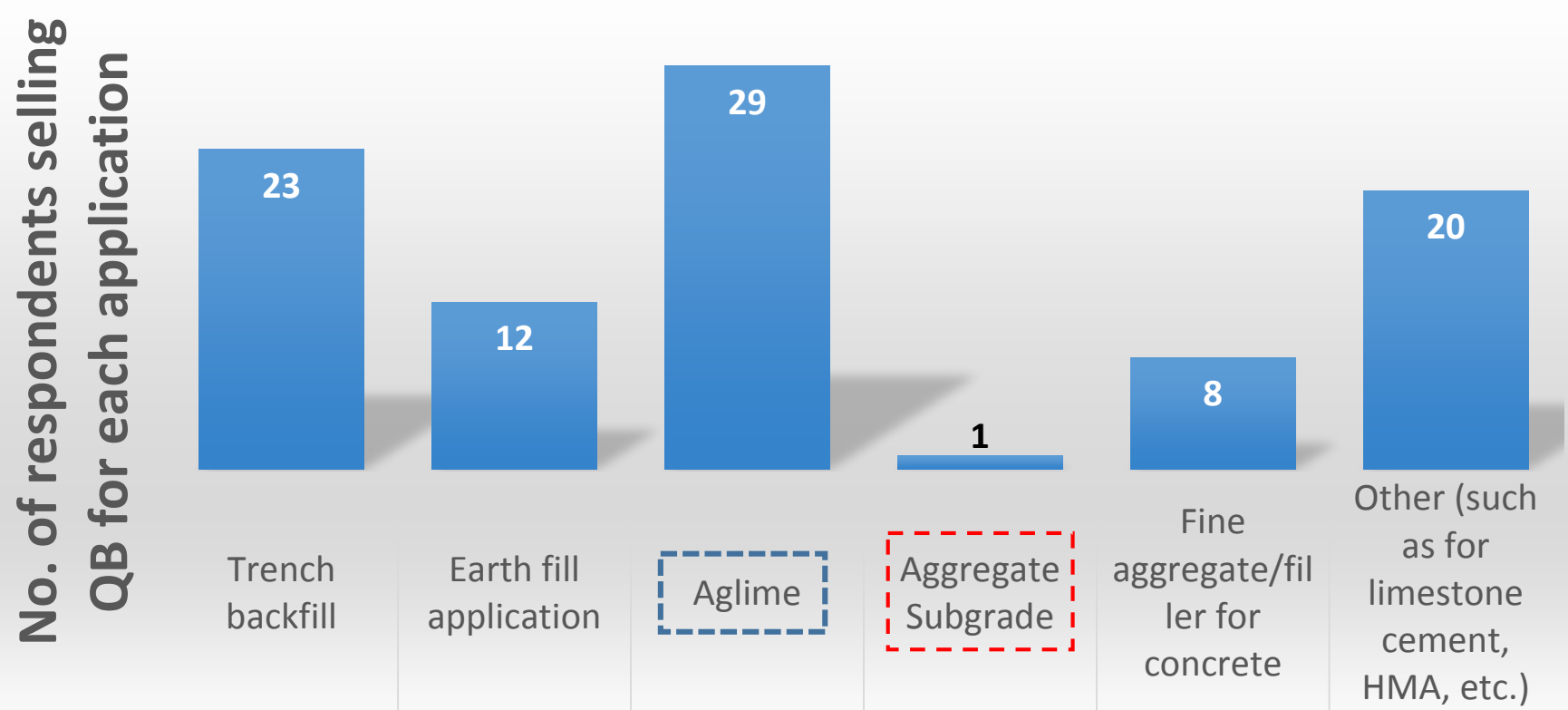


Tutumluer et al., 2013 (ICT R27-125 Project)

The excessive QB produced each year in Illinois can be as high as 950,000 tons!

A potential to incorporate Excess QB in sustainable pavement applications

Survey: Current Applications

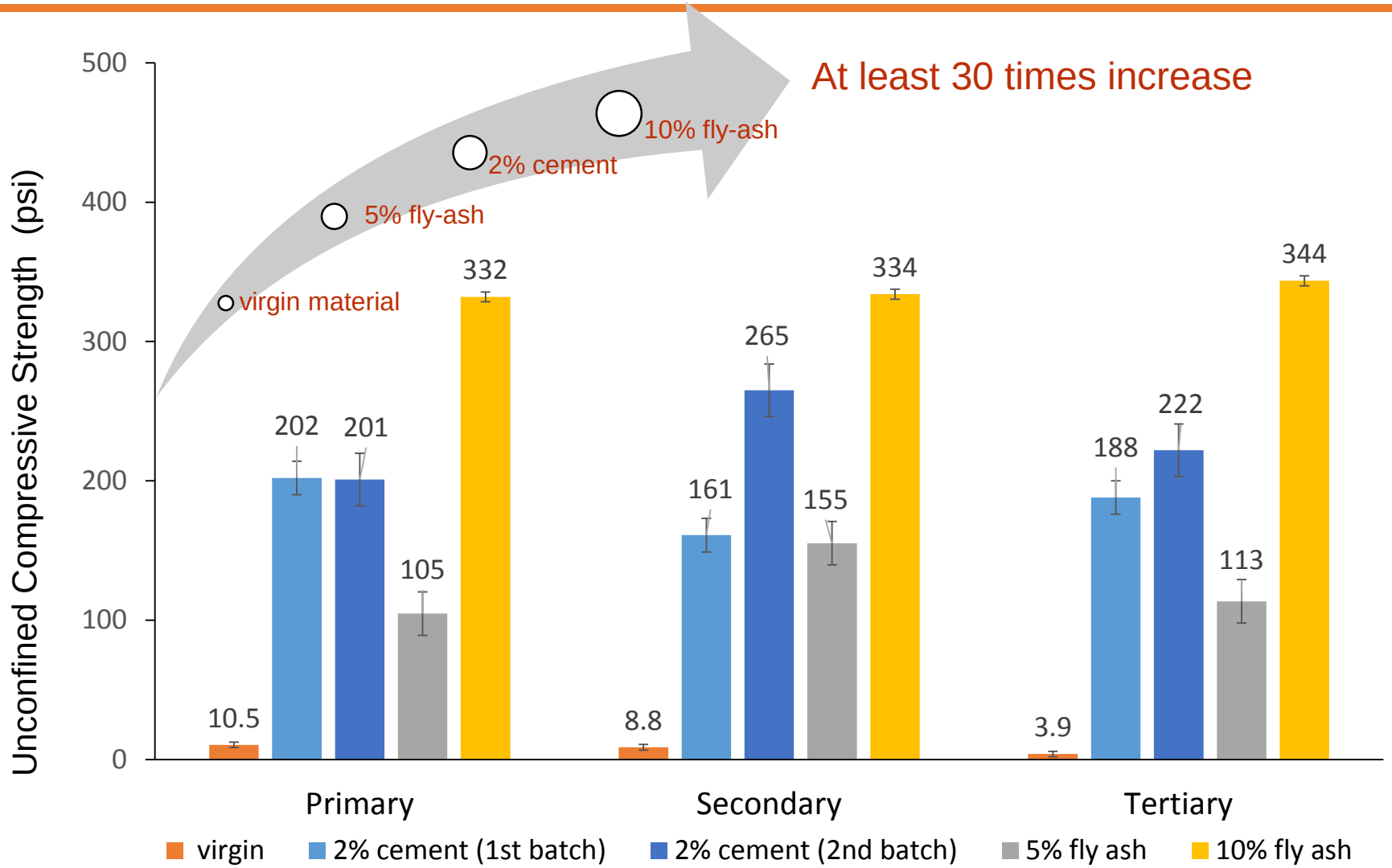


	Trench backfill	Earth fill application	Aglime	Aggregate Subgrade	Fine aggregate/filler for concrete	Other (such as for limestone cement, HMA, etc.)
Percentage	60.5%	31.6%	76.3%	2.6%	21.1%	52.6%

* Total no. of respondents to this question was 38

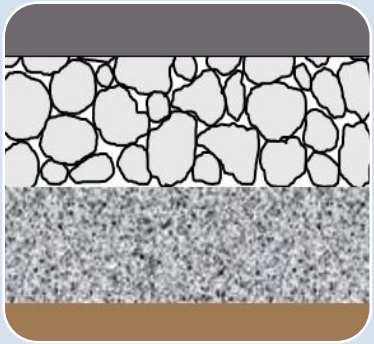
Tutumluer et al., 2013 (ICT R27-125 Project)

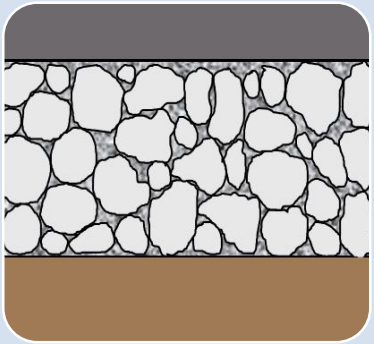
Unconfined Compressive Strength Results



Tutumluer et al., 2013 (ICT R27-125 Project)

Proposed Pavement Applications





High Fine (QB) Aggregate for Subgrade Remediation

- IDOT CA06 materials with higher fines contents, up to 15%, by utilizing QB (Plastic vs NP fines)

Stabilized Base with QB

- Stabilized with cement or Type C Fly ash, and consider mixing with recycled materials (FRAP, FRCA)

Stabilized Subbase with QB

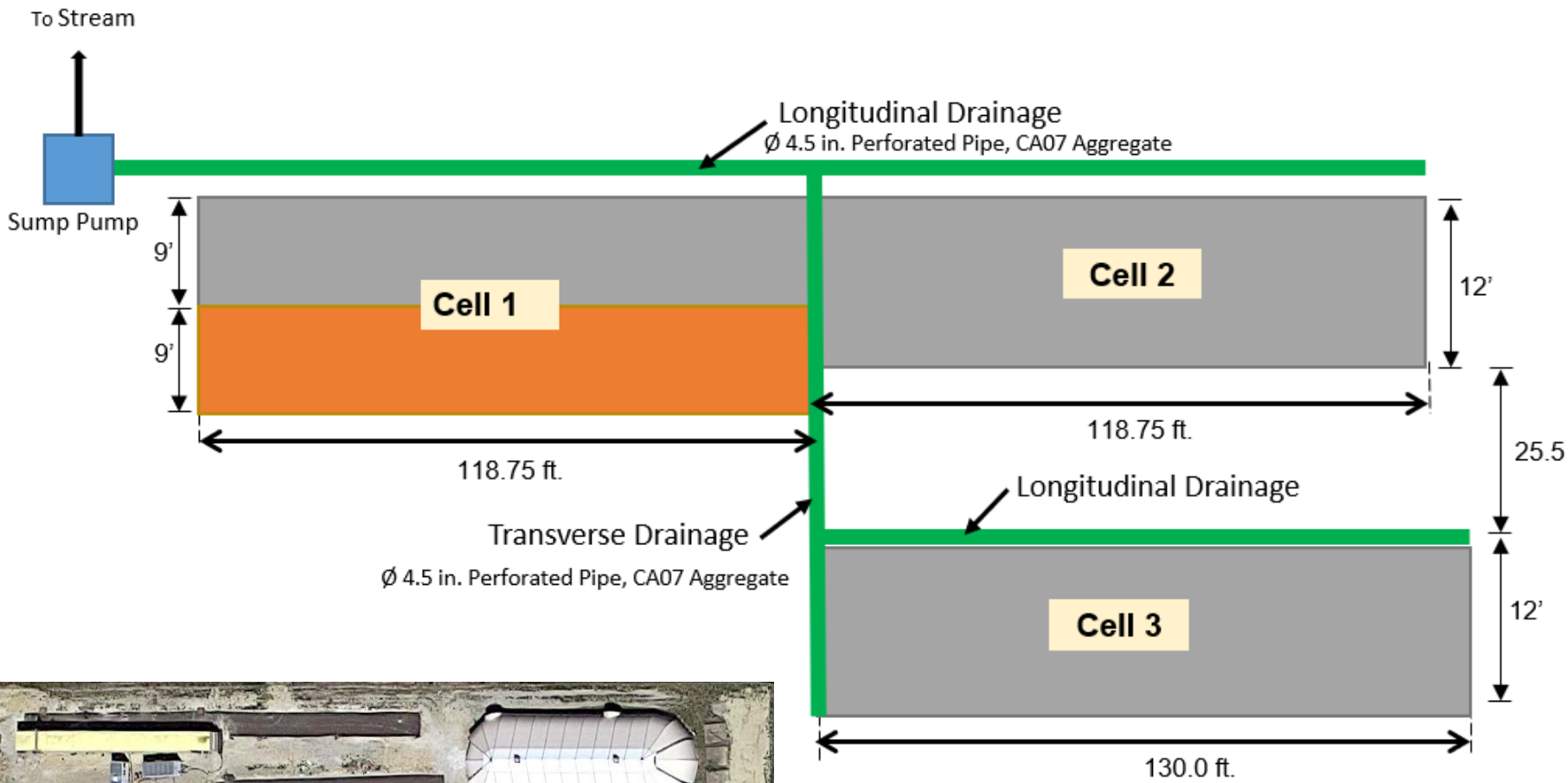
- Inverted Pavement
- Better compaction of aggregate placed over stabilized base layer

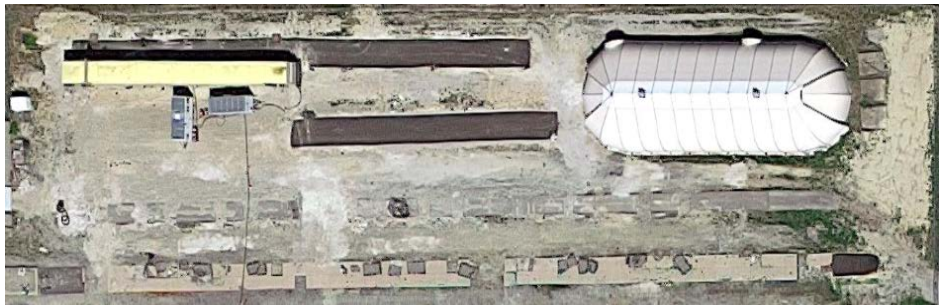
Aggregate Subgrade + QB

- Aggregate subgrade materials on very weak (CBR = 1) subgrades blended with QB
- Fill gaps/voids between large stones

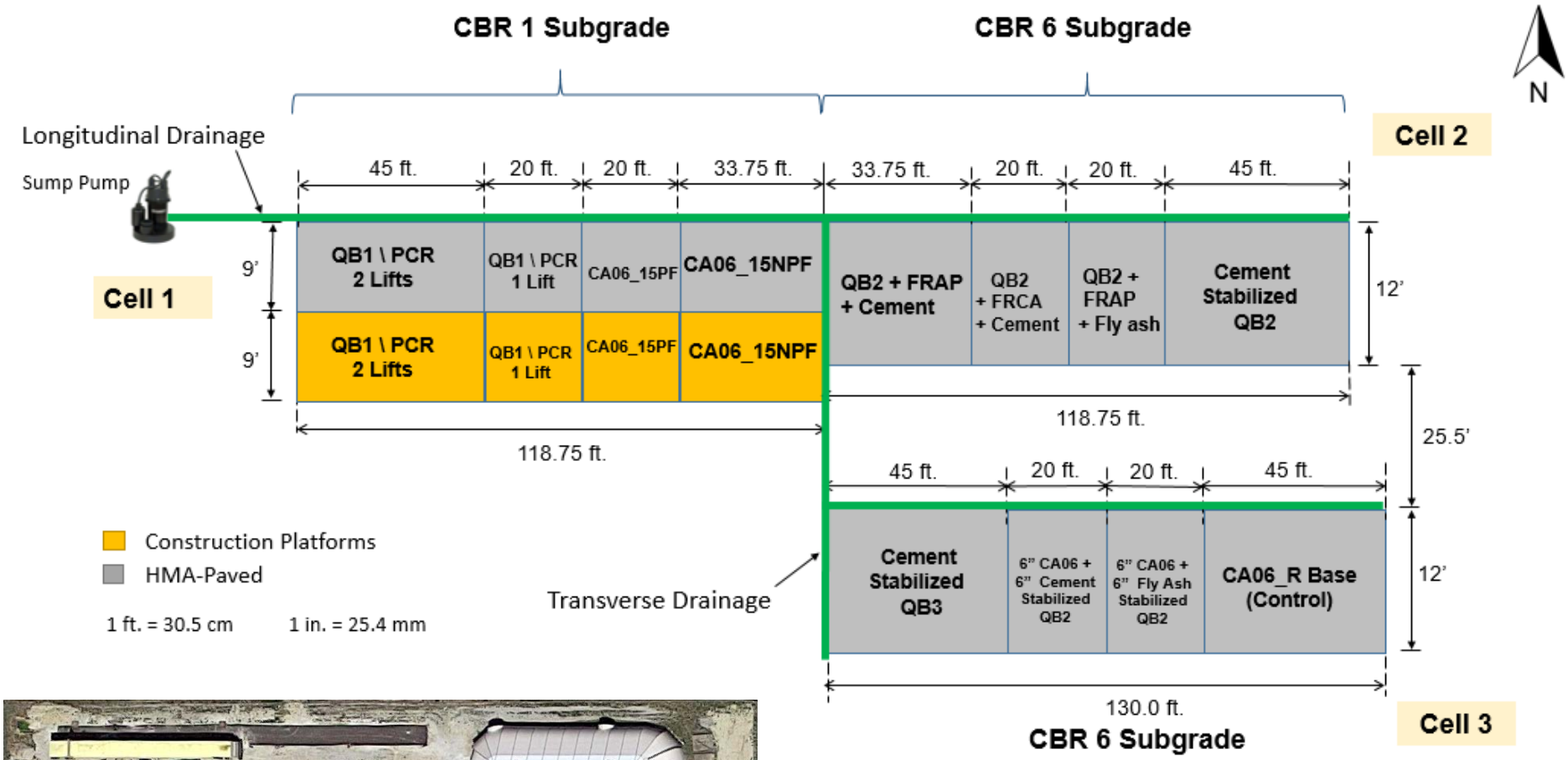
Tutumluer et al., 2013 (ICT R27-125 Project)

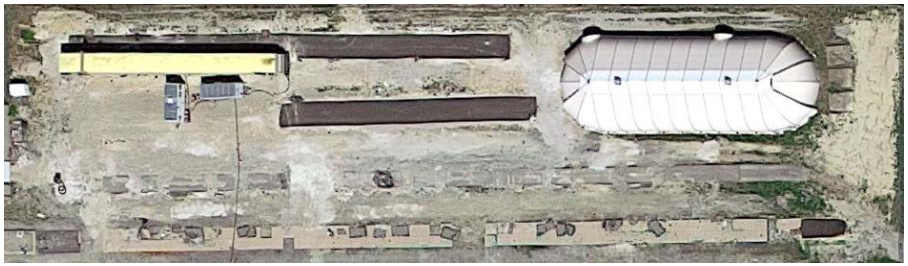
Layout of Test Cells – ICT R27-168



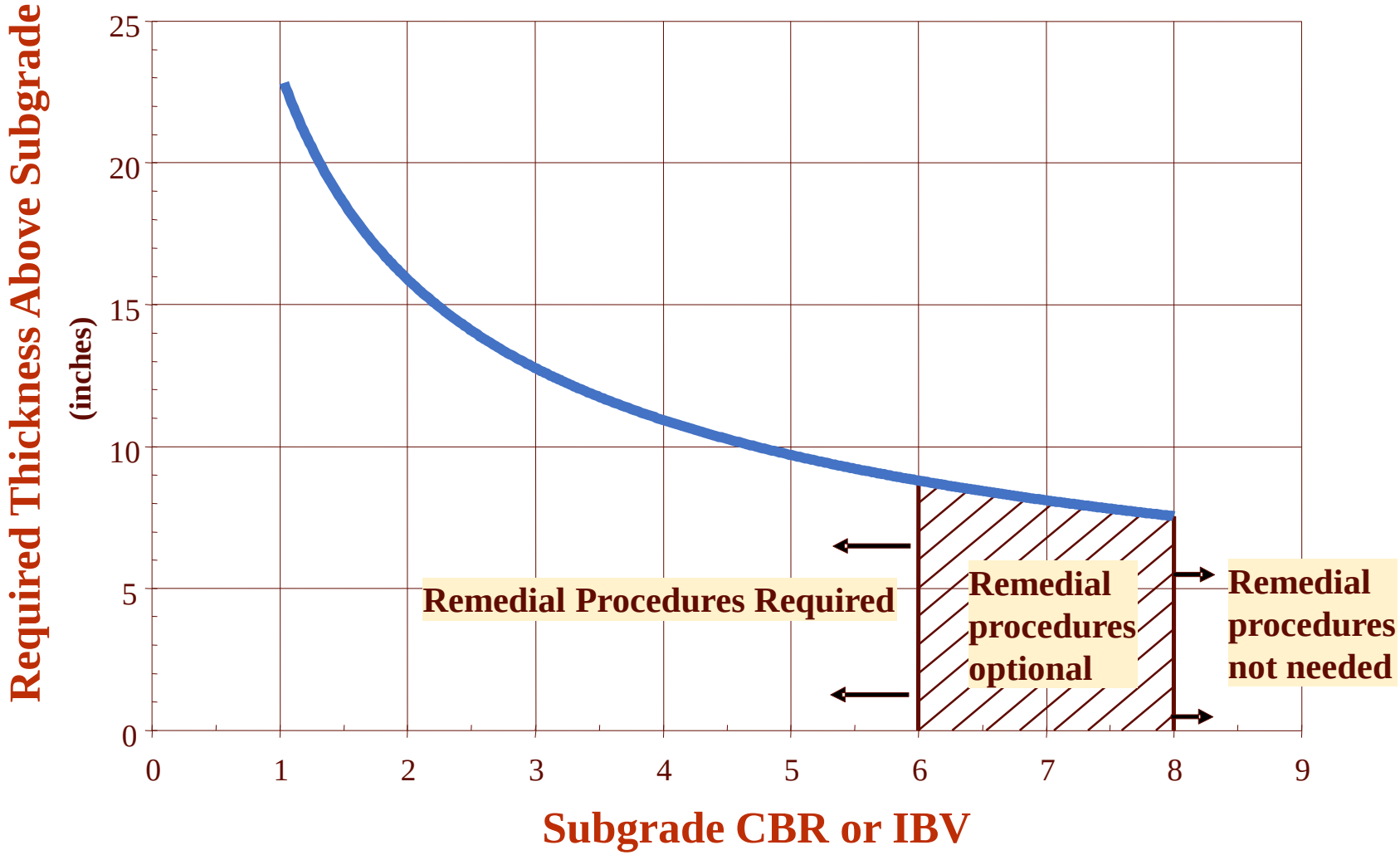


Layout of Test Cells – ICT R27-168



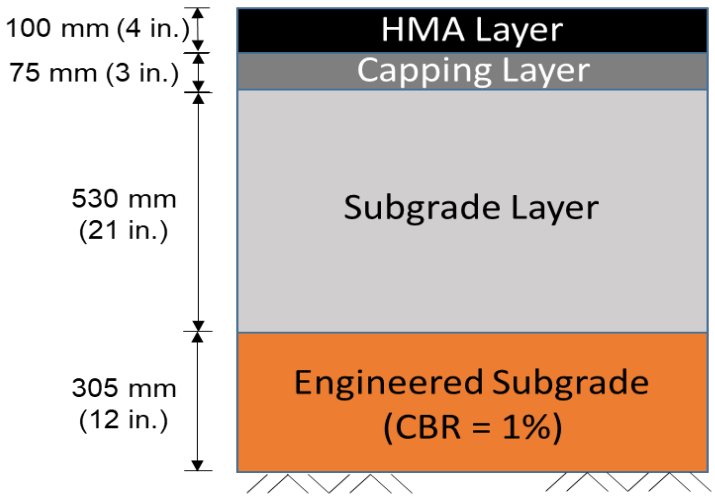


IDOT Granular Backfill Cover Requirements

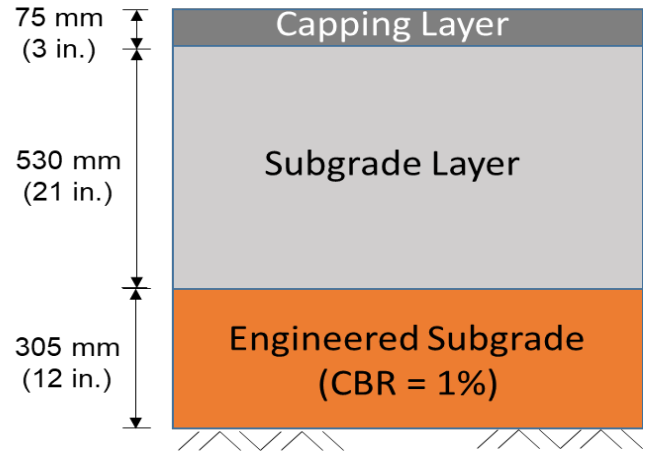


Subgrade Stability Manual, 2005

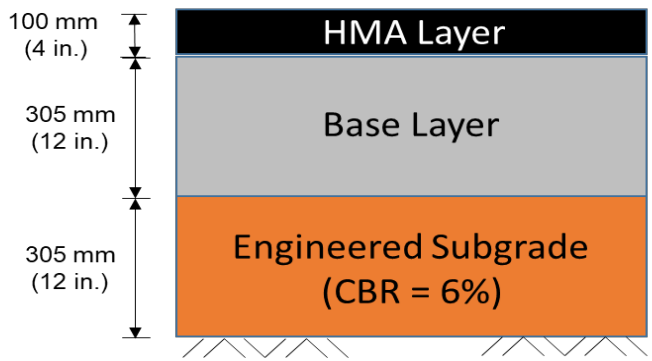
Cross Sections of Test Sections



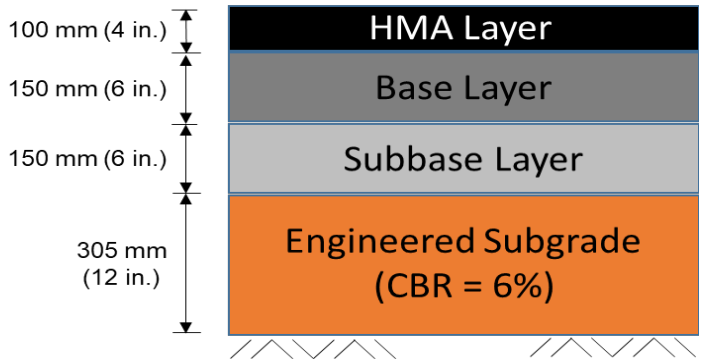
(Cell 1N)



(Cell 1S)



(Cells 2 and 3)



(C3S2 and C3S3)

IDOT Gradation Bands

CS02

CA06

QB

Grad No.	Coarse Aggregate Subgrade Gradations							
	Sieve Size and Percent Passing							
	8”	6”	4”	3”	2”	1 ½”	#4	#200
CS 02		100	80 ± 10		25 ± 15			

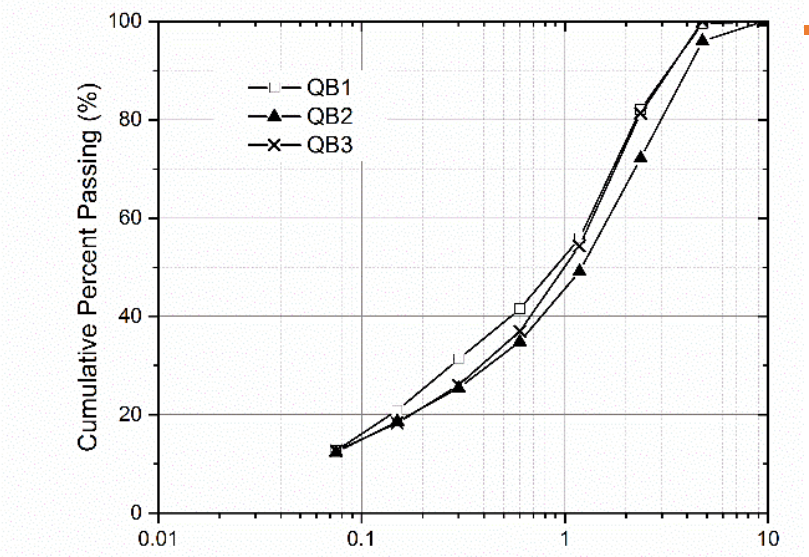
Grad No.	Coarse Aggregate Gradations												
	Sieve Size and Percent Passing												
	3"	2 ½"	2"	1 ½"	1"	3/4"	1/2"	3/8"	# 4	# 8	# 16	# 50	# 200
CA 06				100	95±5		75±15		43±14		25±15		8±4

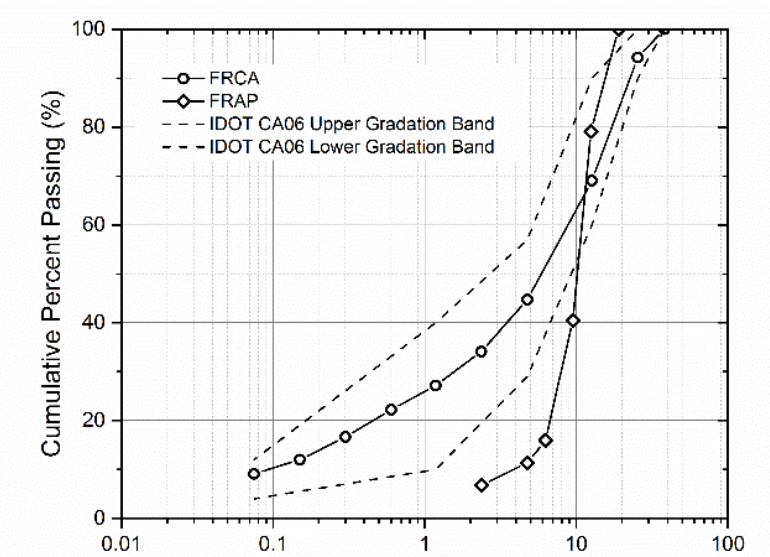
Materials Selection

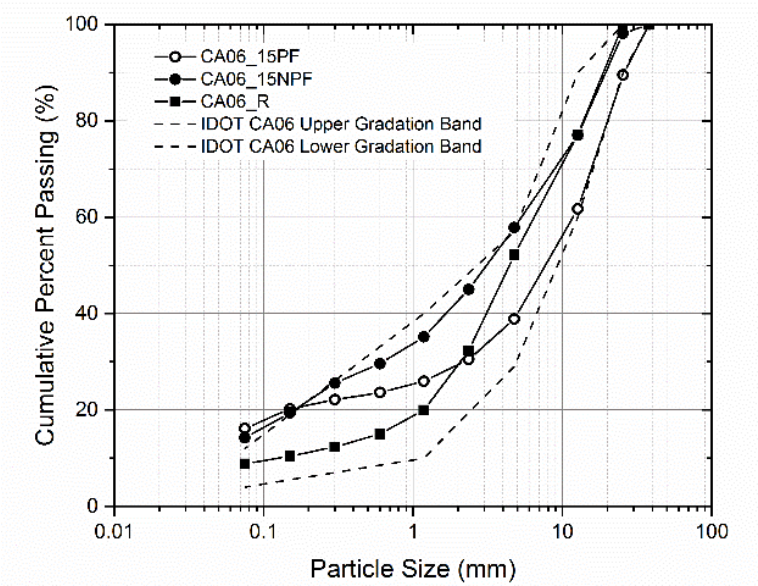
Materials List

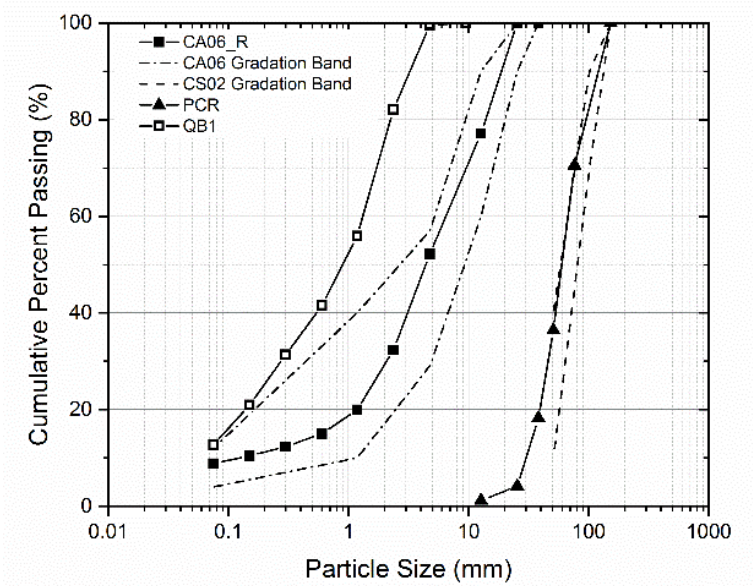
- **Cell 1**:
  - QB1
  - CS02 (PCR)
  - CA06 – R
  - CA06 – 15NPF
  - CA06 – 15PF
- **Cell 2:**
  - QB2
  - FRAP
  - FRCA
- **Cell 3:**
  - QB2
  - QB3
  - CA06 – R

Particle Size Distributions

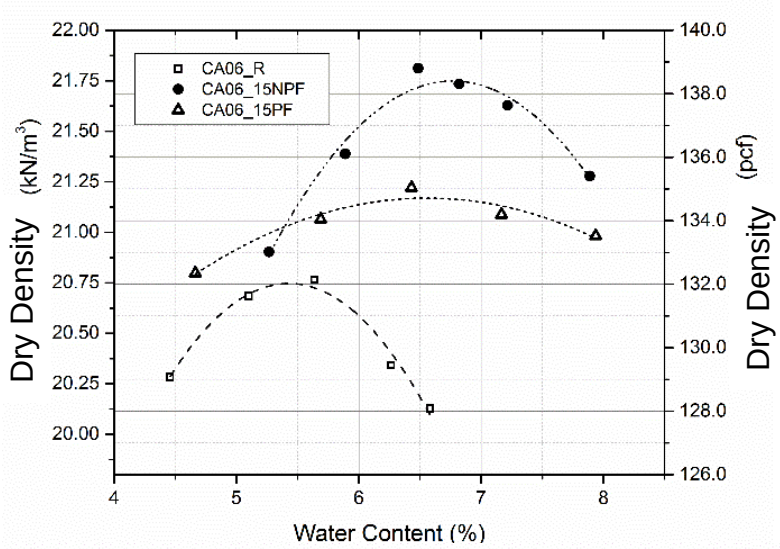


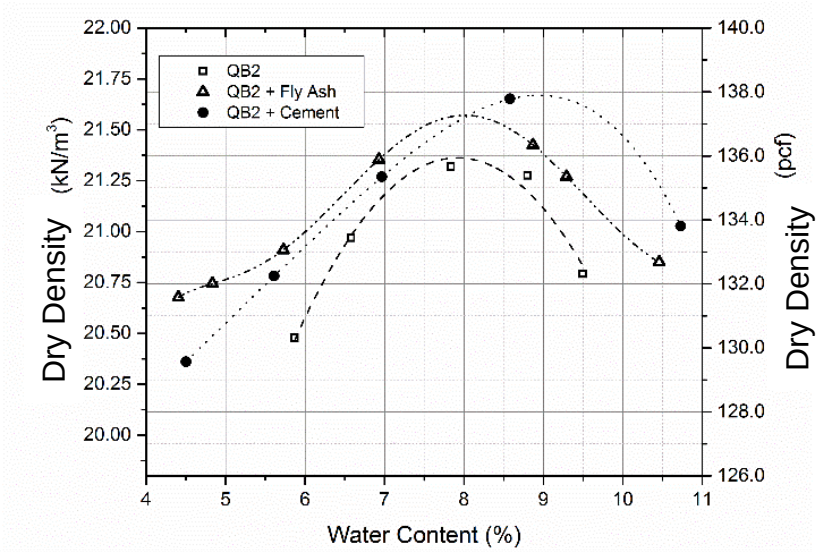


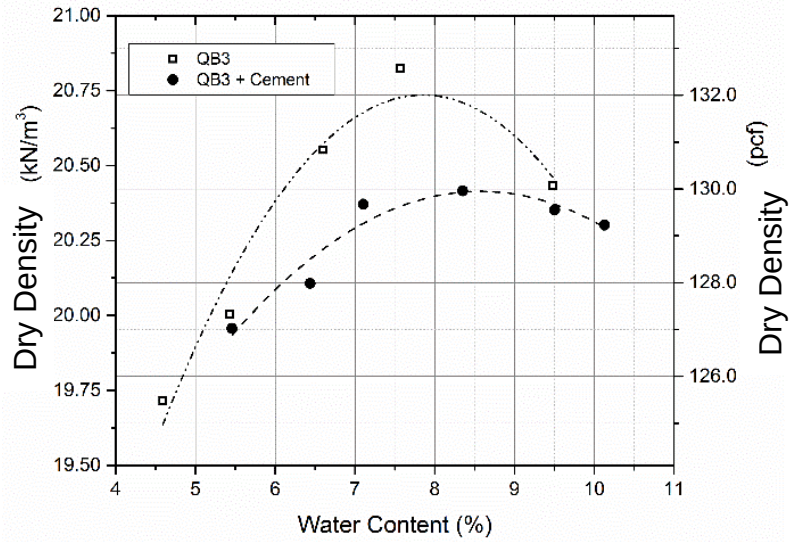


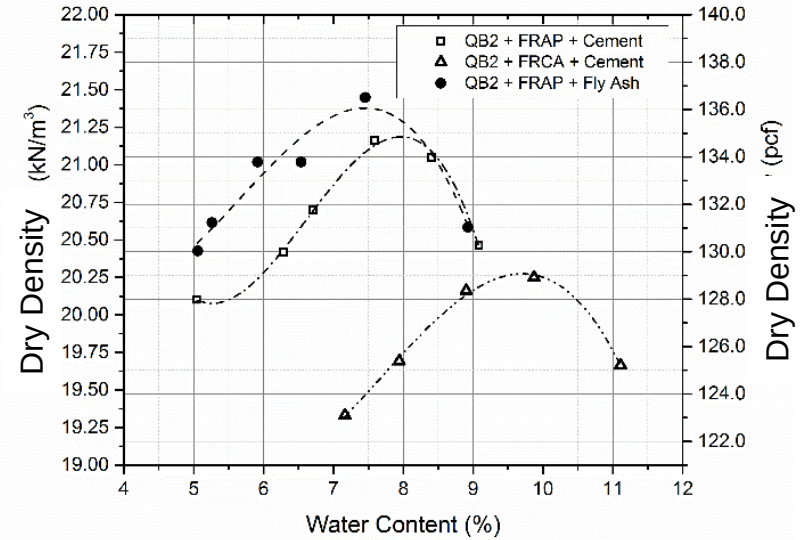


Moisture-Density Relationships

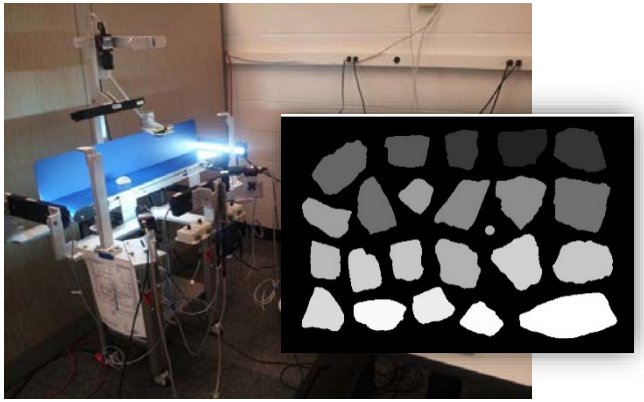








Laboratory Testing



Field and Lab Imaging

UIUC Box Packing Study

Unconfined Compressive Strength

PCR Packing Study

Test 1: PCR compacted in 1 lift
Average Density: 90.1 pcf

Test 2: PCR compacted in 2 lifts
Average Density: 91.9 pcf

$$Void\ Ratio = e = \frac{V_v}{V_s} = 77.5\ \%\ (\mathbf{2lifts})\ and\ 83.1\%\ (\mathbf{1\ lift})$$

$$Porosity = \emptyset = \frac{V_v}{V_T} = \mathbf{43.6}\ \%\ (\mathbf{2\ lifts})\ and\ \mathbf{45.4}\%\ (\mathbf{1\ lift})$$

$$V_s = \frac{M_s}{G_s * \rho_w}$$

Packing and Compaction Studies

- Test #1 CS02 only, compacted in 2 lifts
- Test #2 CS02 only, compacted in 2 lifts
- Test #3 CS02 only, compacted in 1 lift
- Test #4 CS02 only, compacted in 1 lift
- Test #5 CS02 + **20% QB** by weight, compacted in 2 lifts
- Test #6 CS02 + **40% QB** by weight, compacted in 2 lifts
- Test #7 CS02 + **30% QB** by weight, compacted in 2 lifts
- Test #8 CS02 + **30% QB** by weight, compacted in 1 lift
- Test #9 CS02 + **30% QB** by weight, compacted in 2 lifts
- Test #10 CS02 + **40% QB** by weight, compacted in 2 lifts
- Test #11 CS02 + **35% QB** by weight, compacted on top of subgrade
- Test #12 CS02 + **30% Wet QB** by weight, compacted in 2 lifts
- Test #13 CS02 + **25% Wet QB** by weight, compacted in 2 lifts
- Test #14 CS02 + **25% Wet QB** by weight, compacted on subgrade

Packing Box Study: 25% WET QB in 1 lift

1. Uncompacted Subgrade

2. Compacted Subgrade

3. CS02 on Top of Subgrade

4. 25% QB Before compaction

5. 25% QB After compaction

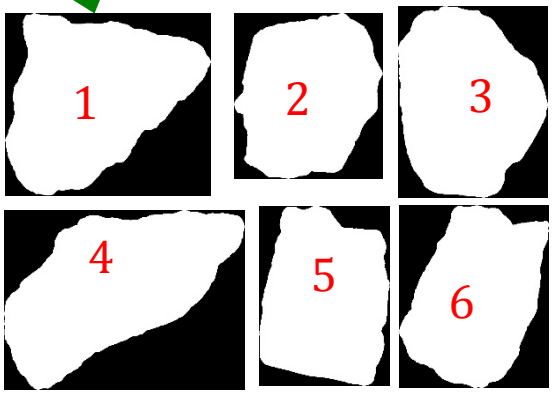
6. After compaction (front view)

With Wet QB (w=2.7%), **25%** by weight is recommended for a single lift and 2 lifts!

Field Imaging

Image Acquisition

Grayscale Image Conversion



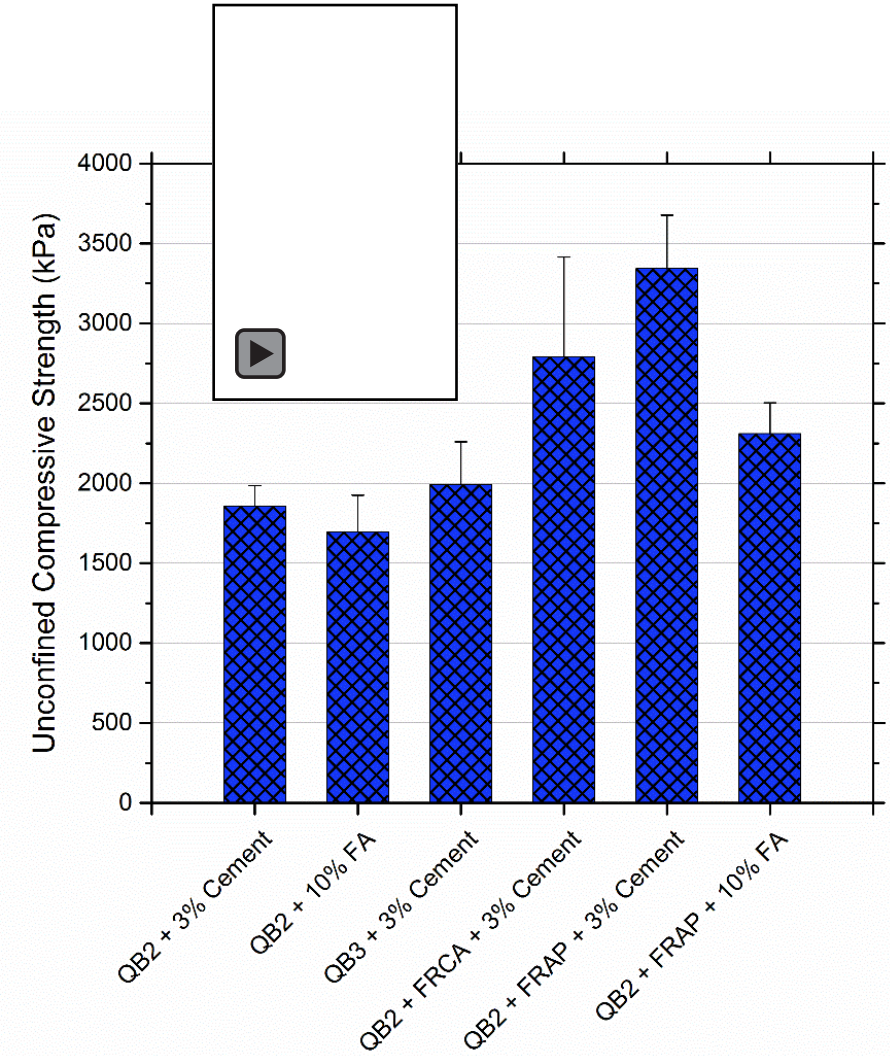
Thresholding/Segmentation

Shape Property Indices for PCR

			Angularity	FE Ratio	Surface Texture
Field Imaging	Retained on 3” sieve	Average	447.84	1.36 **(Cubical)**	2.37
		Max	840.00	2.28	4.03
		Min	230.00	1.06	1.38
			Angularity	**FE Ratio**	**Surface Texture**
Lab Imaging Using the Enhanced University of Illinois Aggregate Image Analyzer (E-UIAIA)	Retained on 2” sieve	Average	488.37	2.11	1.54
		Max	707.83	3.81	2.75
		min	318.46	1.30	0.77
			Angularity	**FE Ratio**	**Surface Texture**
	Retained on 1.5” sieve	average	452.87	2.01	1.38
		max	686.06	2.69	2.17
		min	327.33	1.40	0.84
			Angularity	**FE Ratio**	**Surface Texture**
	Retained on 1” sieve	Average	401.69	2.37	1.44
		max	619.58	3.92	3.46
		min	280.78	1.47	0.43
			Angularity	**FE Ratio**	**Surface Texture**
	Retained on 0.5” sieve	Average	462.61	2.48	2.29
		max	663.09	2.98	3.59
		min	370.44	1.61	1.27

Unconfined Compressive Strength (UCS)

- QB samples stabilized with
  - 3% Portland cement
  - 10% class 'C' fly ash
- Observations
  - [FRAP/QB2/Cement] achieved highest UCS
  - [FRAP/QB2/Cement] strength is statistically different from other combinations except [FRCA/QB2/Cement]
  - Mean UCS for [FRAP/QB2/ FA] and [FRCA QB2/Cement] are statistically different from all stabilized QB2 and QB3 samples
  - Strength of stabilized QB2 and QB3 samples are not statistically different



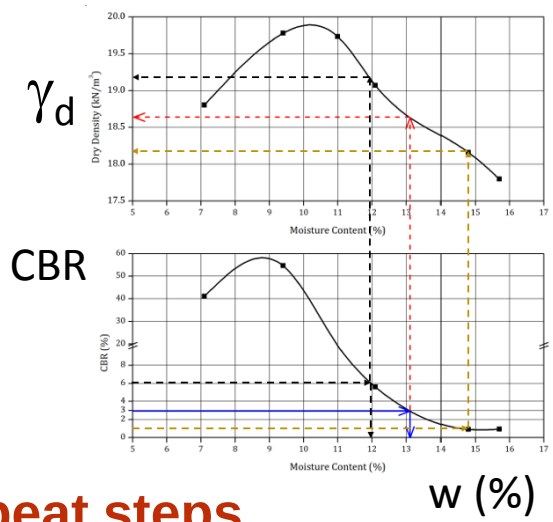
Field Construction & QA/QC

- Subgrade Engineering and Preparation (CBR = 1 and CBR = 6)
- Subgrade, Subbase, and Base Construction
  - Uniform Mixing
  - Compaction at Optimum Moisture Content (MDD)
- Quality Checks
  - Nuclear Density Gauge, GeoGauge, Lightweight Deflectometer LWD

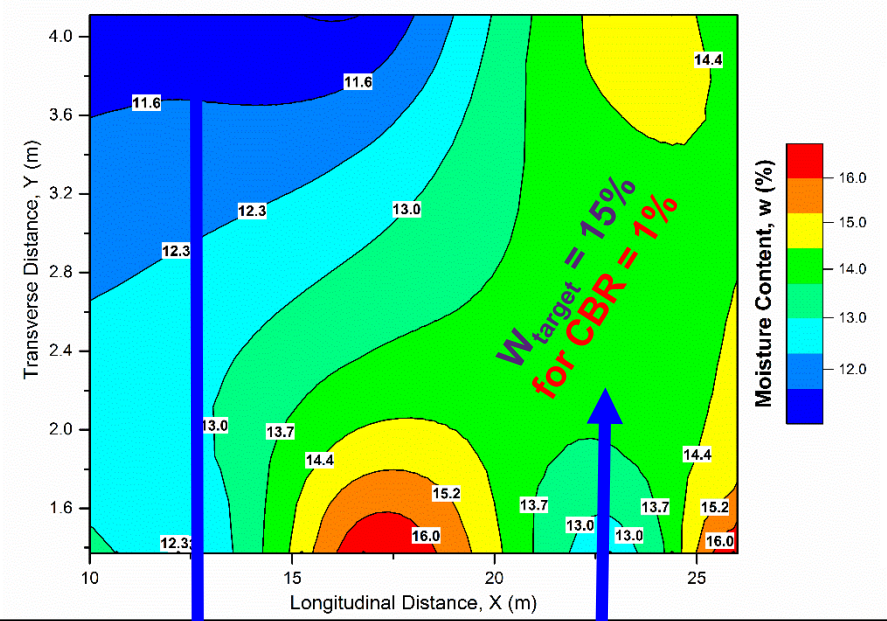
Cell 1 Subgrade Engineering & Preparation

Procedure:

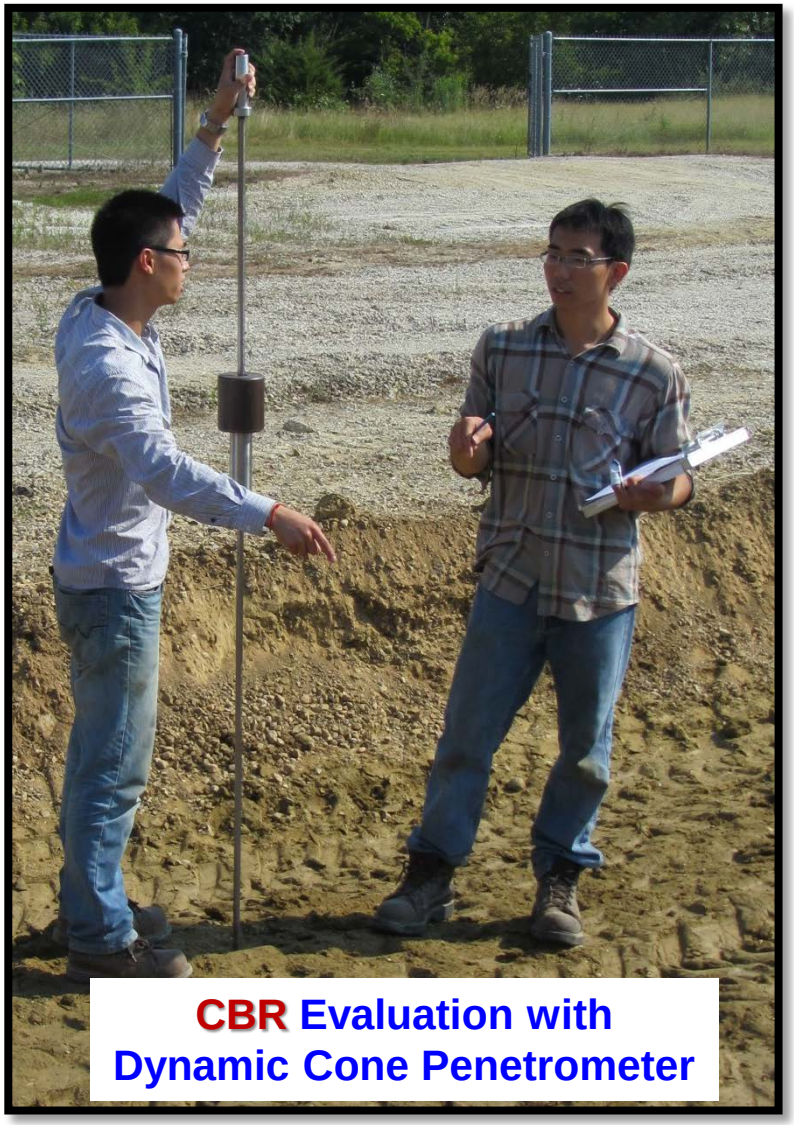
1. **Till top 35.5 cm (14 in.) with a Tiller**
2. **Collect samples to estimate w(%) using a Microwave (ASTM D4643)**
3. **Roll Subgrade with a Sheepsfoot Roller**
4. **Get CBR Profile from field DCP testing**
   - **Satisfactory → Seal Surface with Tack Coat**
   - **Unsatisfactory → Moisture Adjustment / Repeat steps**



Moisture Adjustment for Engineered CBR



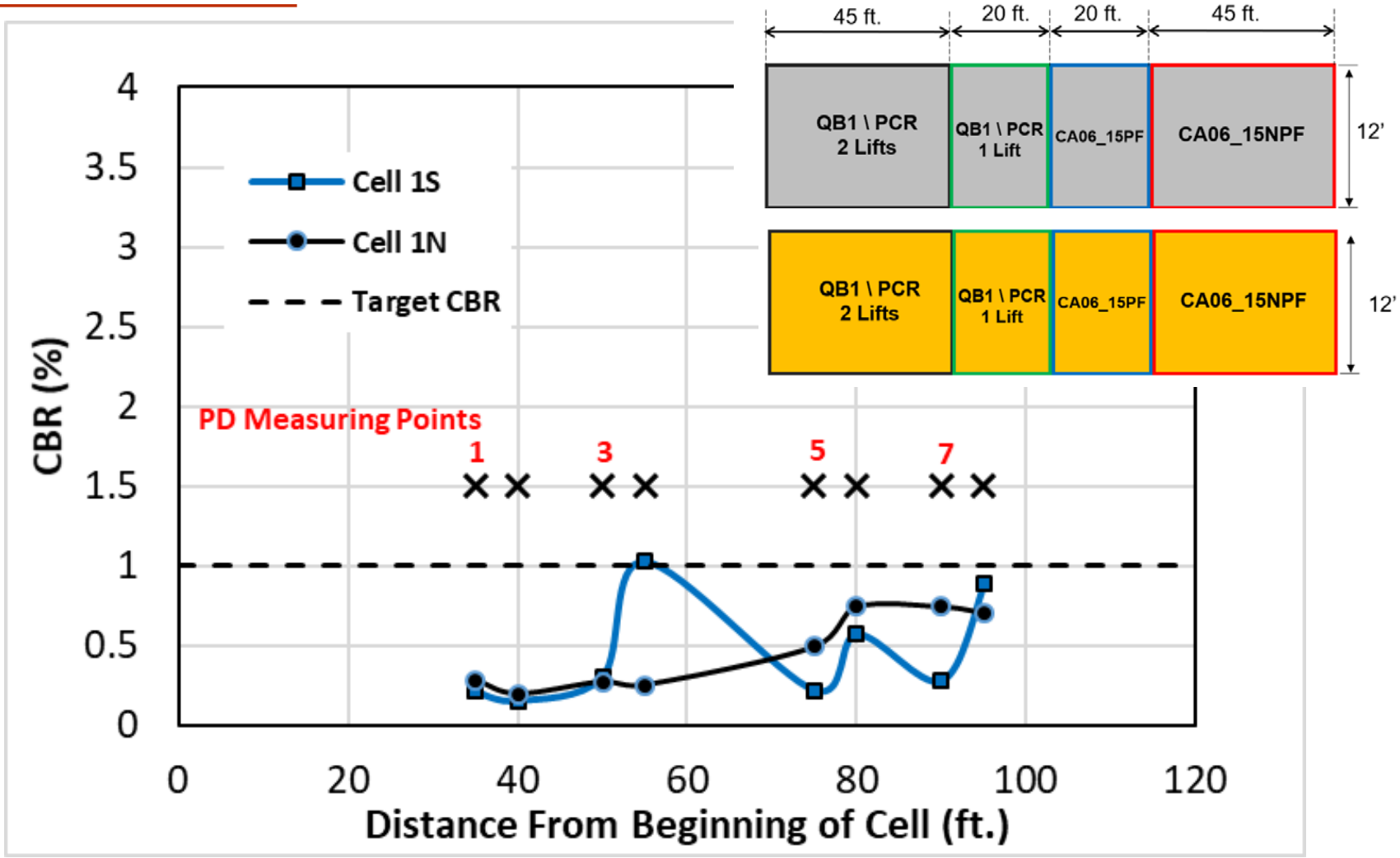
Subgrade tilling to a depth of 30.5 cm (12-in)



Kleyn (1975) → DCP – CBR Correlation

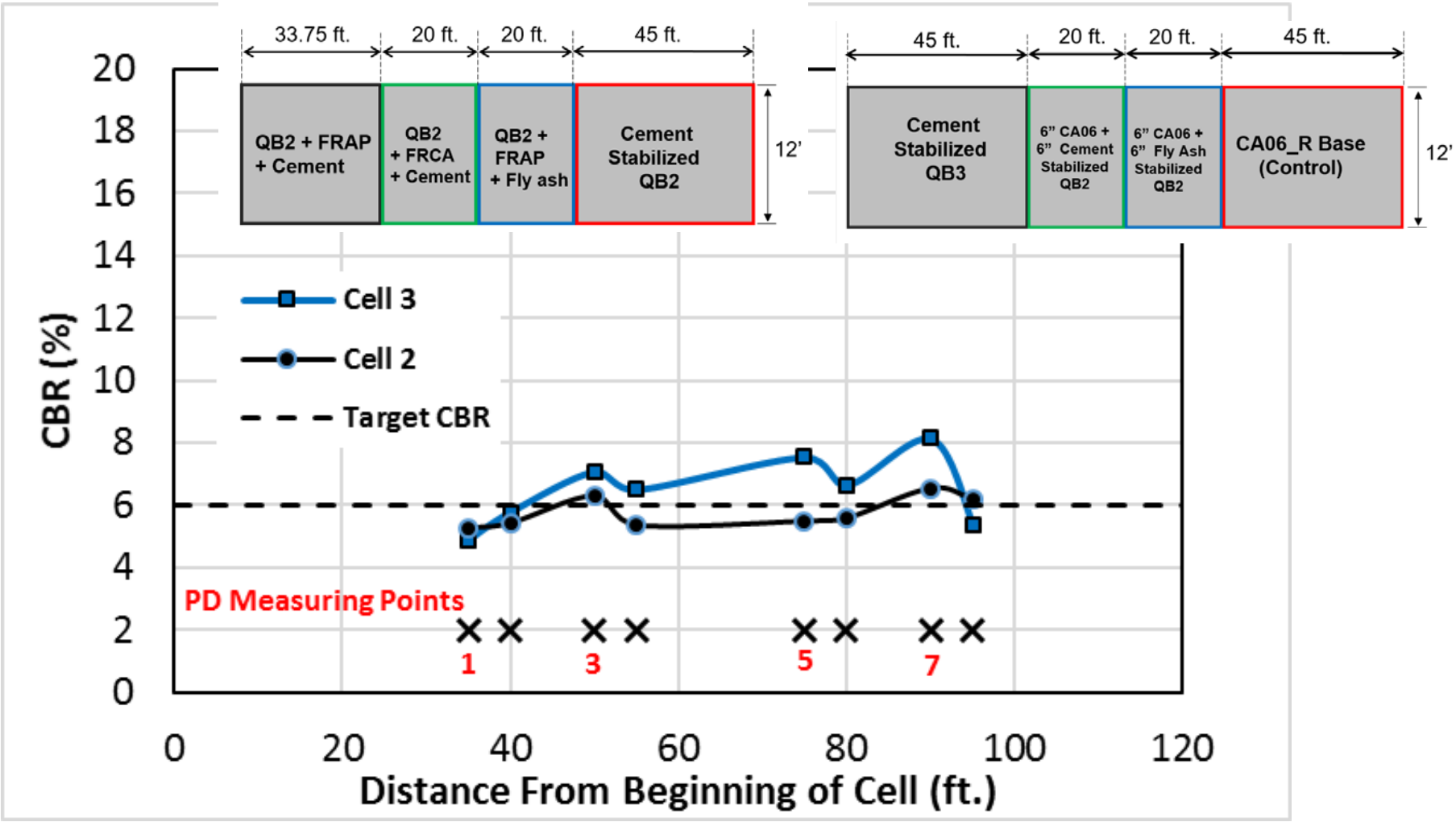
Subgrade Engineering and Preparation

Cell 1S and Cell 1N



Subgrade Engineering and Preparation

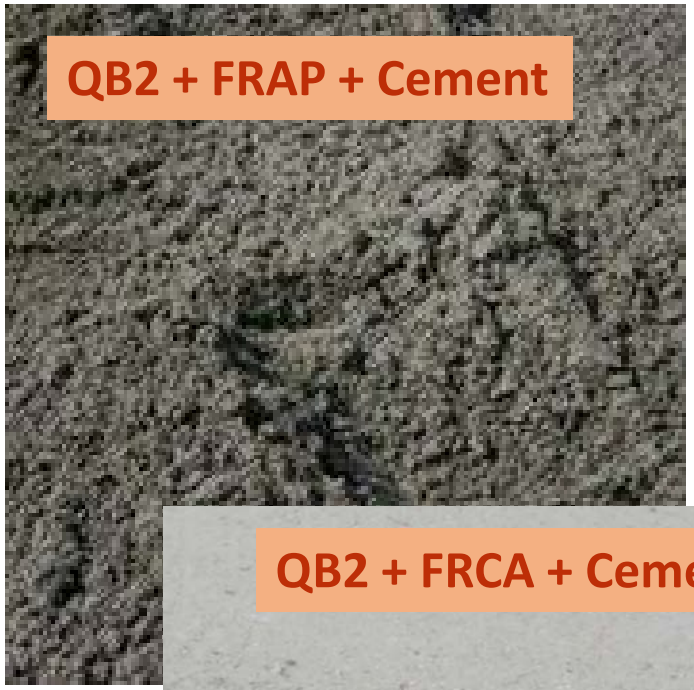
Cell 2 and Cell 3



Field Construction & QA/QC

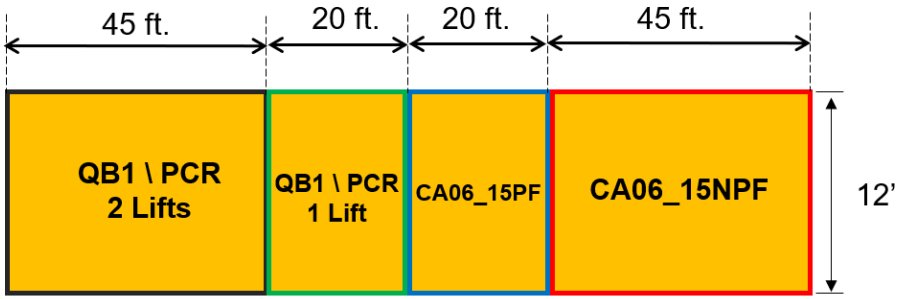
Construction of Stabilized Layers

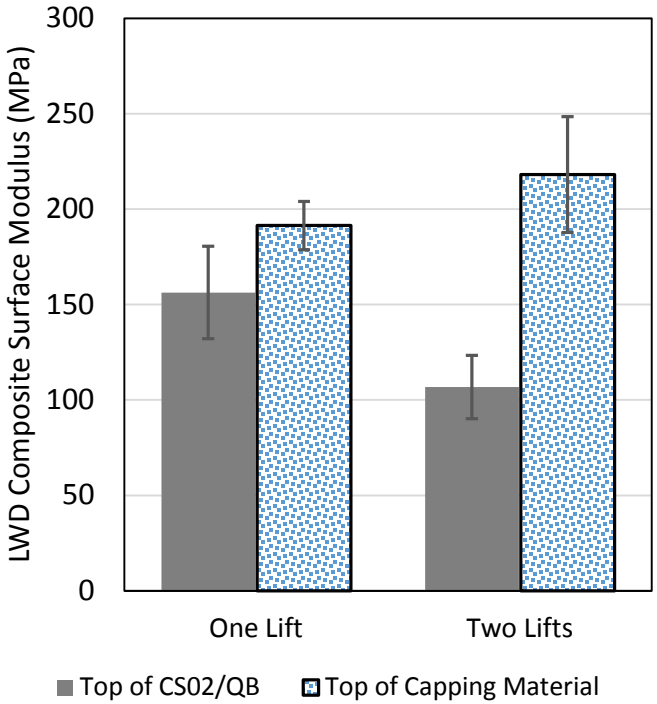
Construction of Stabilized Layers

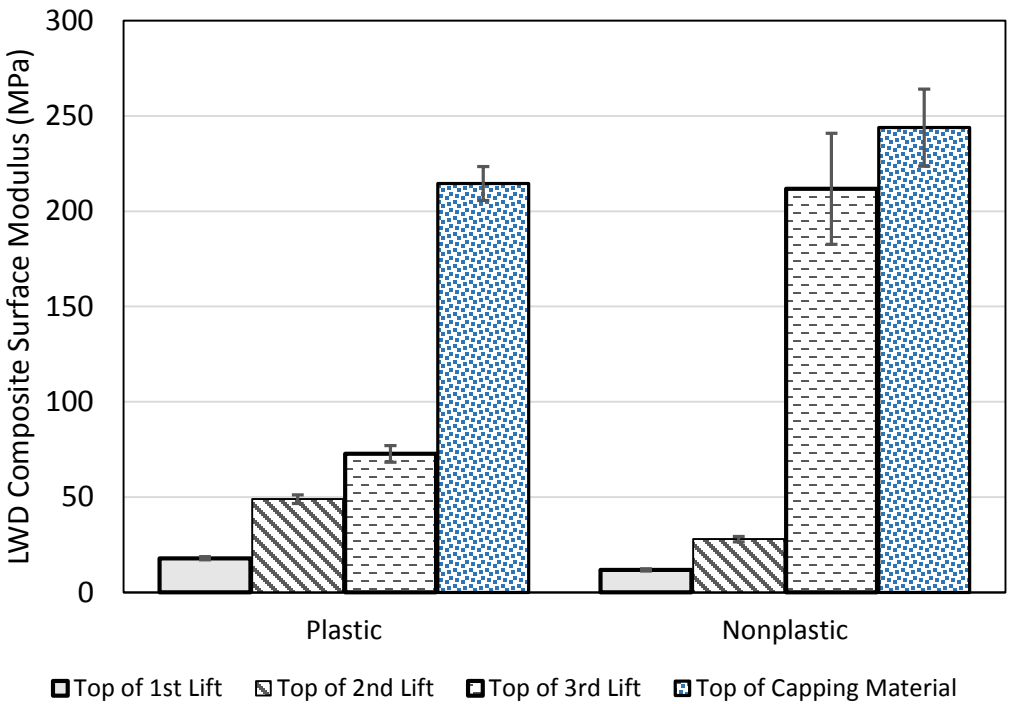


Cell 1S LWD Backcalculated Moduli

Cell 1S: Construction Platforms

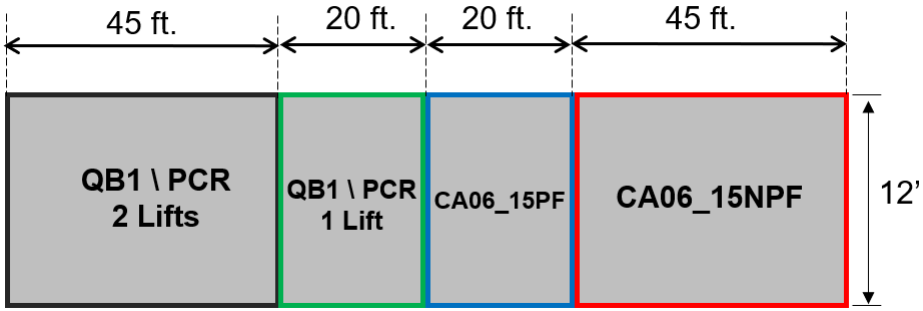


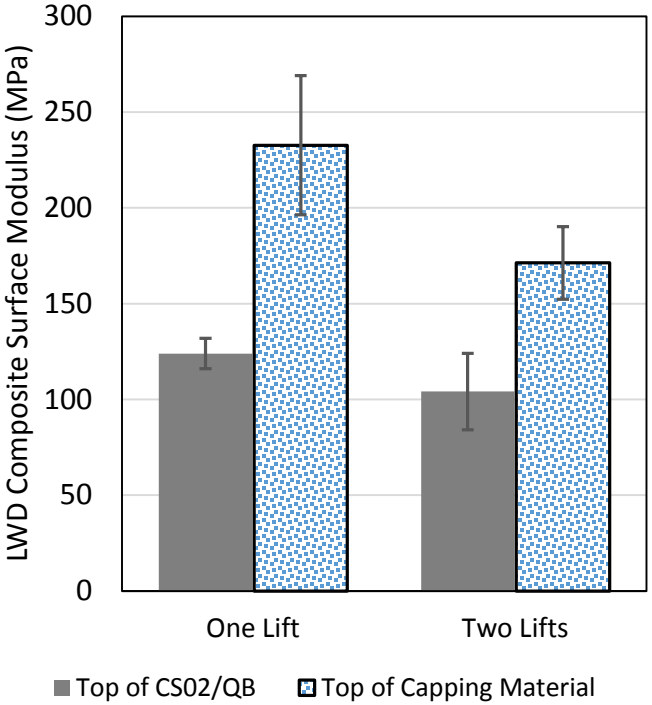


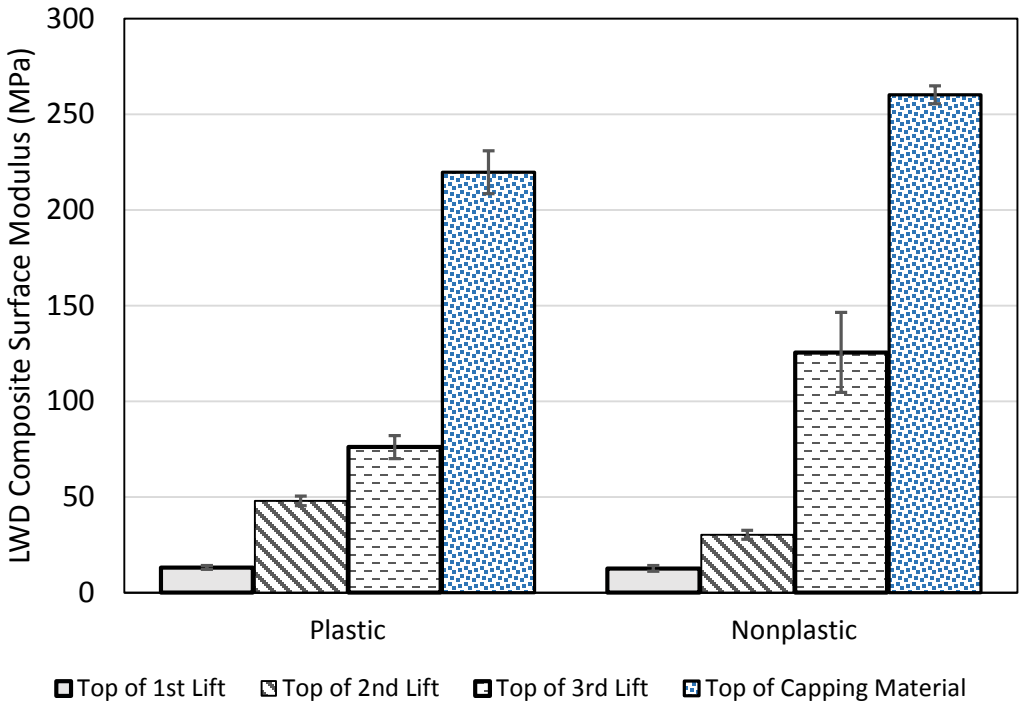


Cell 1N LWD Backcalculated Moduli

Cell 1N: Low Volume Roads

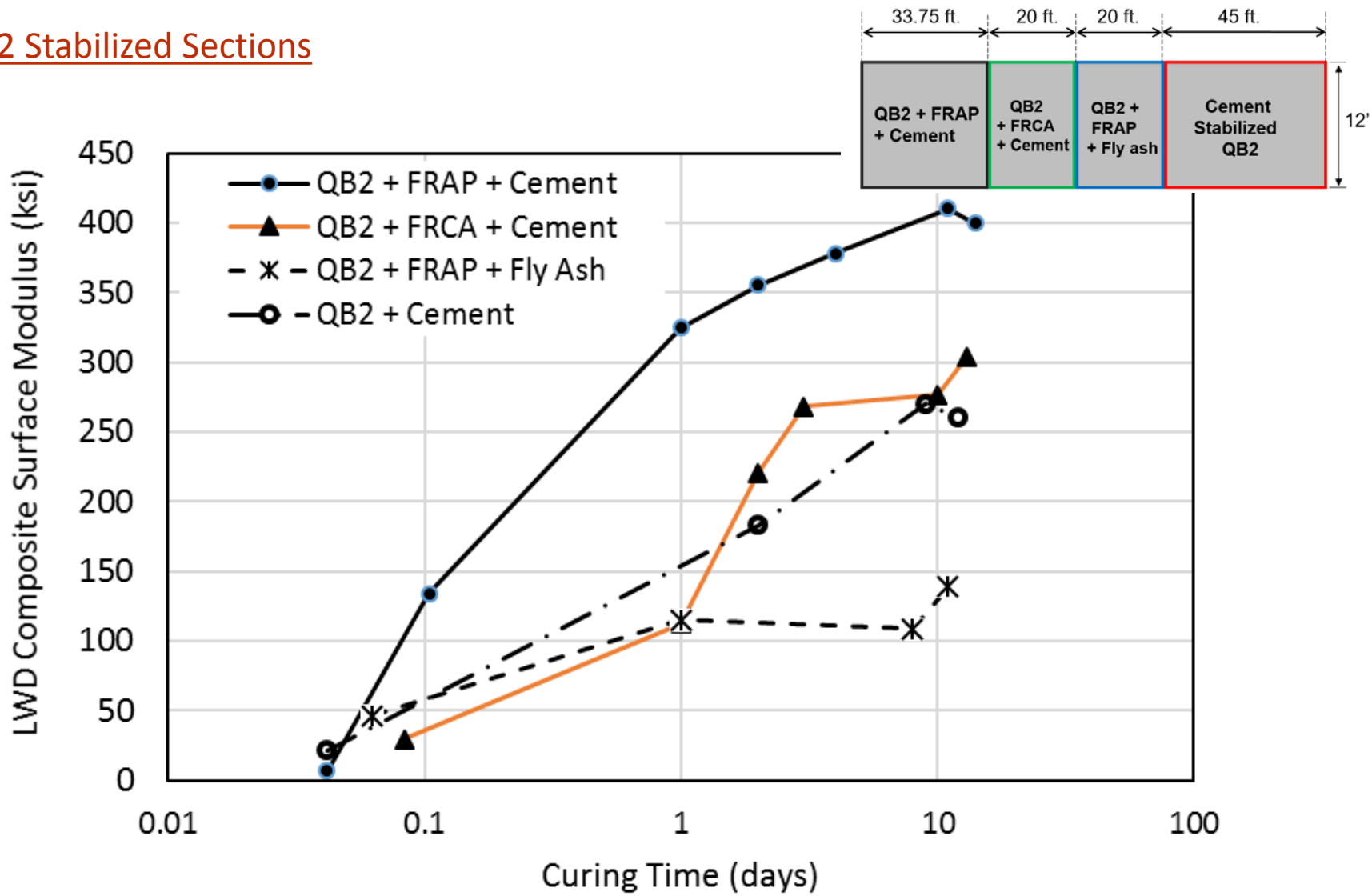




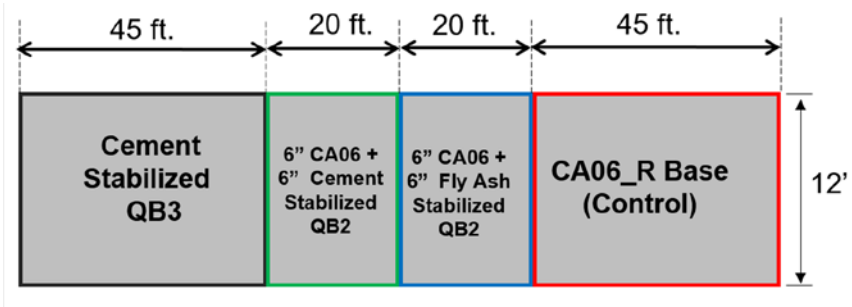


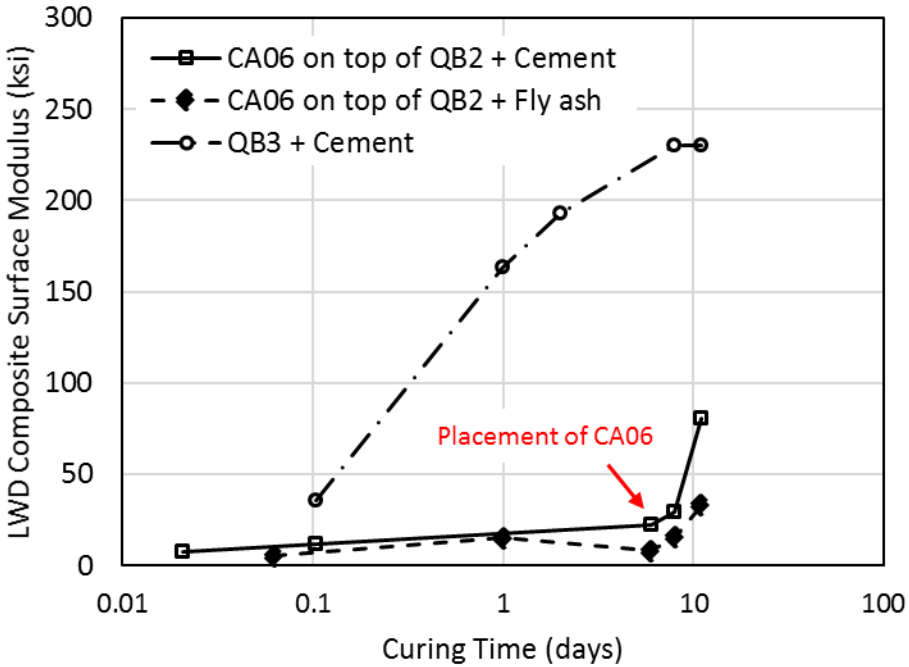
Cell 2 LWD Backcalculated Moduli

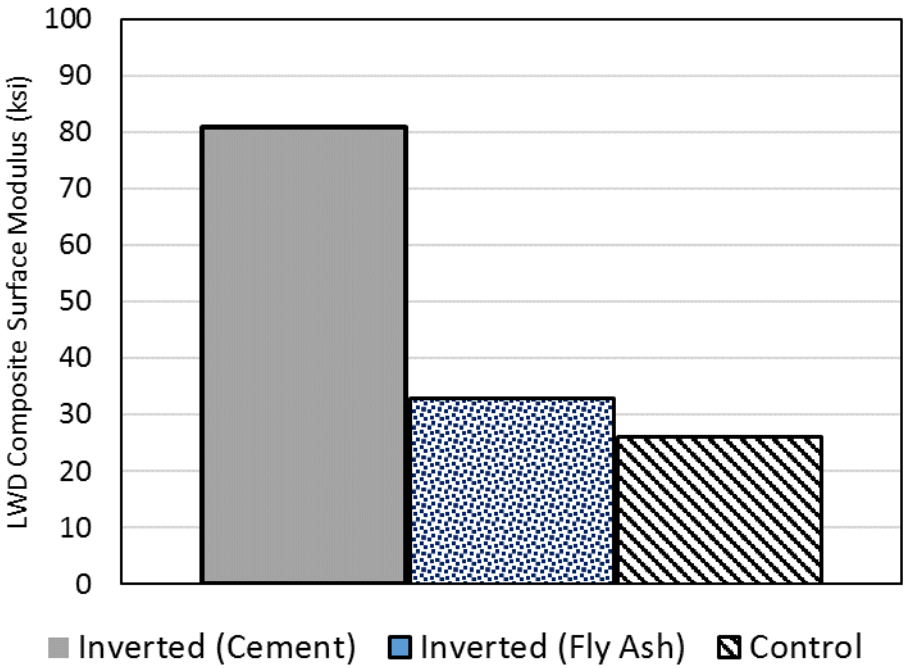
Cell 2 Stabilized Sections



Cell 3 LWD Backcalculated Moduli



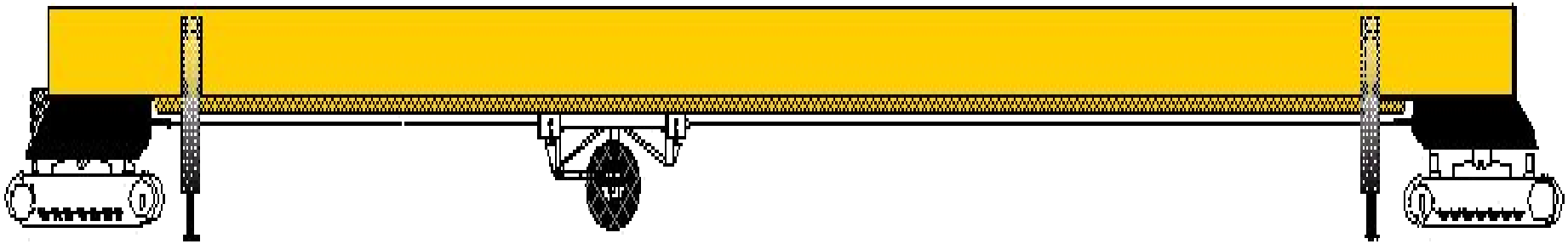




Final LWD Readings Before Placement of HMA

Re-worked CA06 was placed 8-days after Stabilized QB Subbase Layers

UIUC ATLAS



22.5’

Wheel Span = 85 feet
(constant Speed Achieved for 65 feet)

22.5’

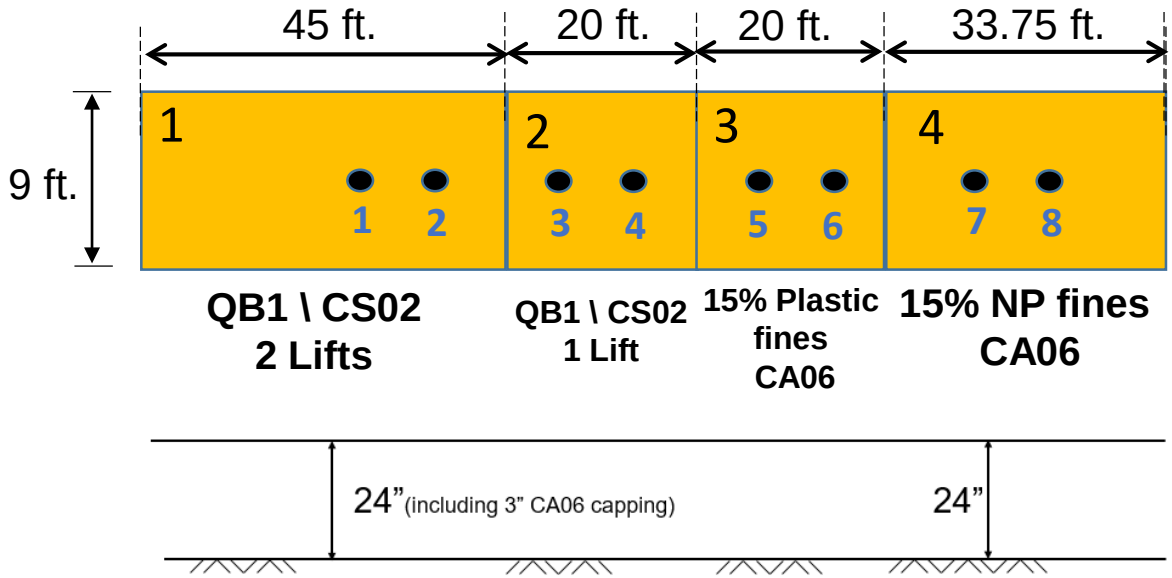
Performance Monitoring

- Super-single tire (455/55R22.5) wide-base tire with constant speed of 8 km/h (5 mph)
- Tire Load and Pressure
  - Pass 1 – Pass 100,000
    - Unidirectional tire load of 44.5 kN (10 kip)
    - Tire pressure of 760 kPa (110 psi)
  - Pass 100,001 – Pass 135,000
    - Unidirectional tire load of 62.5 kN (14 kip)
    - Tire pressure of 860 kPa (125 psi)
- Pressure Cell Locations (2 in each section)
  - Cell 2_Sec1: [70% QB 2 + 30% FRAP] + 3% Cement
  - Cell 2_Sec4 : [100% QB 2] + 3% Cement
  - Cell 3_Sec2 : Inverted Pavement, (QB2 + 3 % Cement) Subbase & CA06 Base
  - Cell 3_Sec4 : CA06_R (Control)

Cell 1 South QB Applications

Construction platforms on weak subgrade

- QB for filling voids/gaps between large stones as aggregate subgrade on soft subgrades
- Increased fines content in dense-graded subgrade replacement (e.g. 15% passing No. 200)

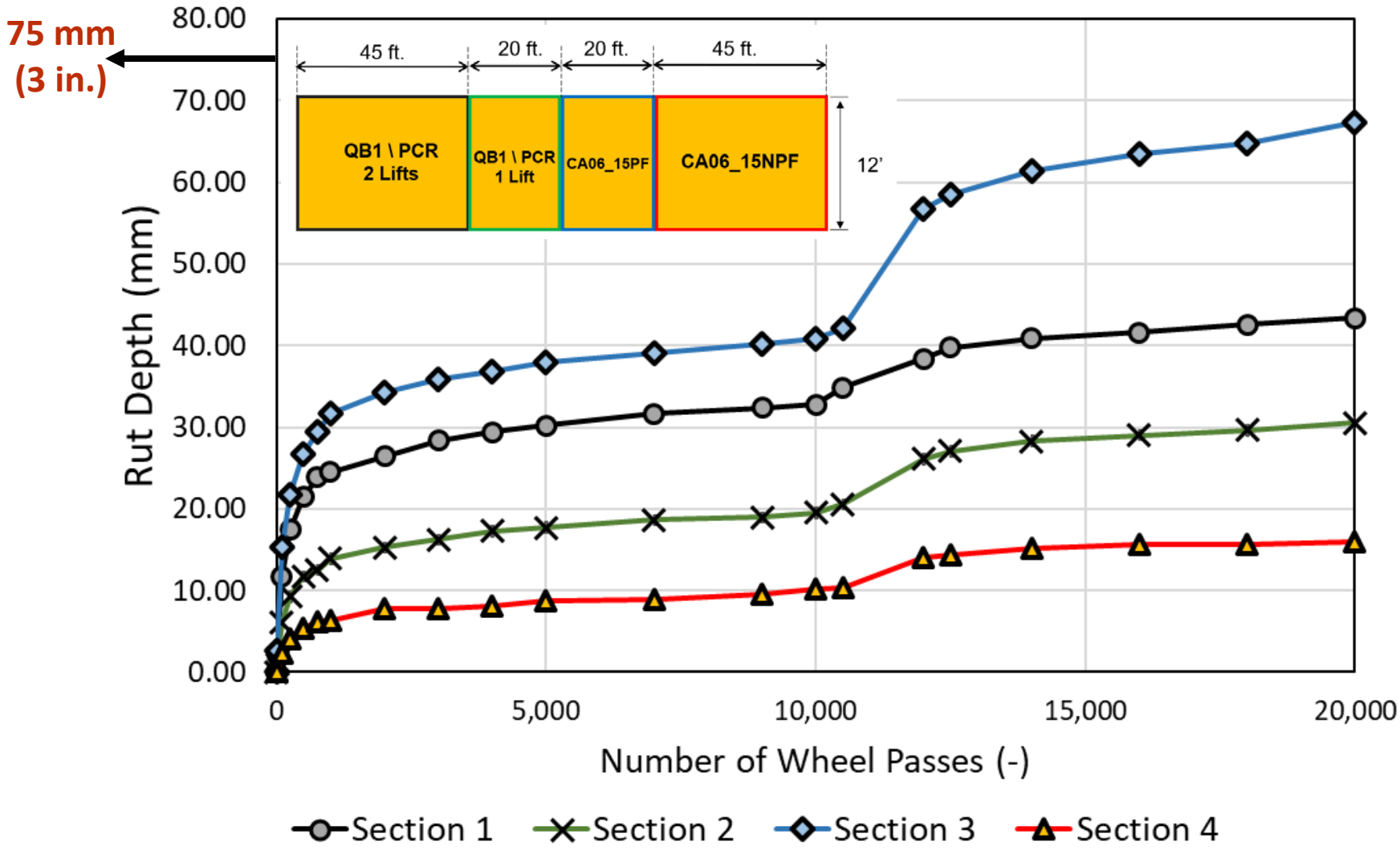


Subgrade CBR = 1%

Subgrade **Top 12"** tilled & compacted

1 ft. = 0.30 m
1 in. = 2.54 cm

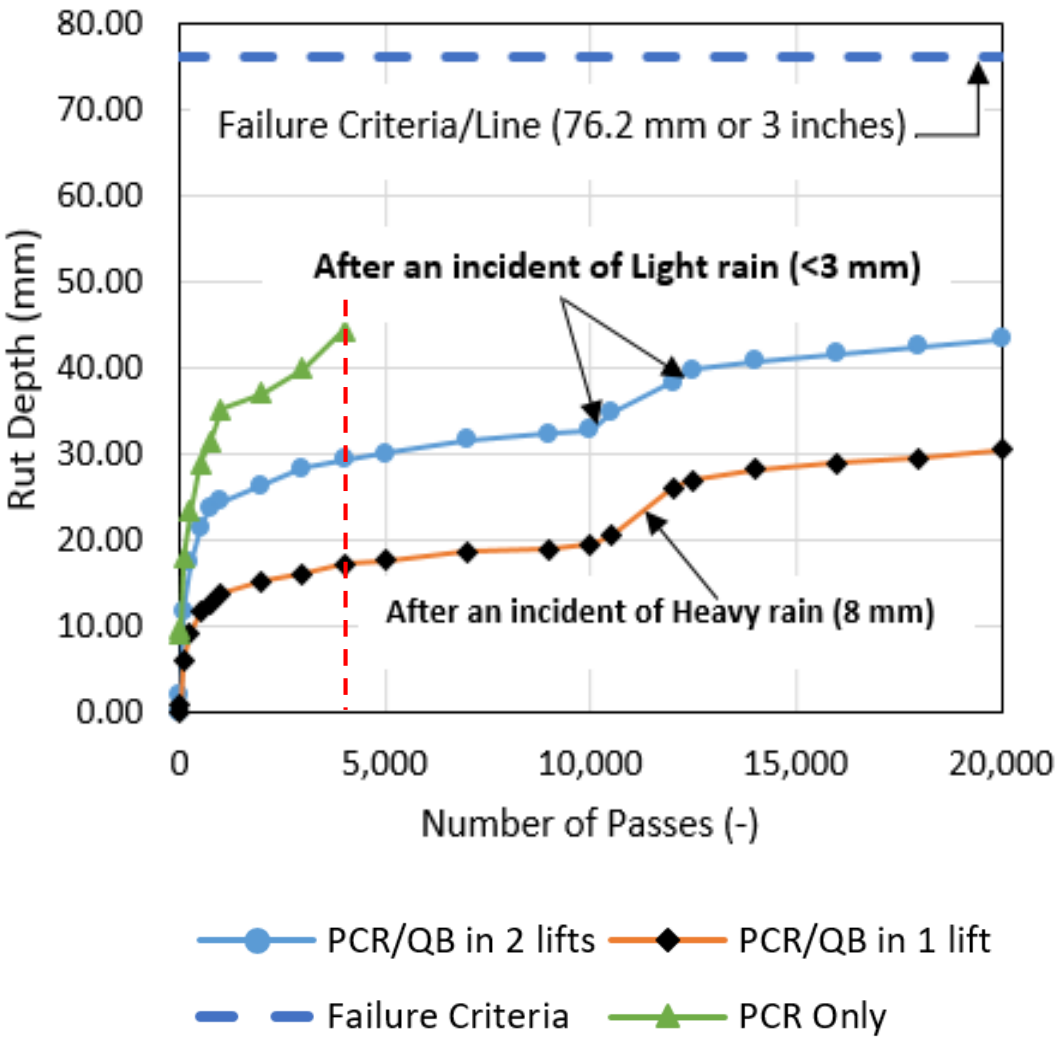
Performance Monitoring (Cell 1S)



Average of each Section

Cell 1S: Performance Compared to No QB

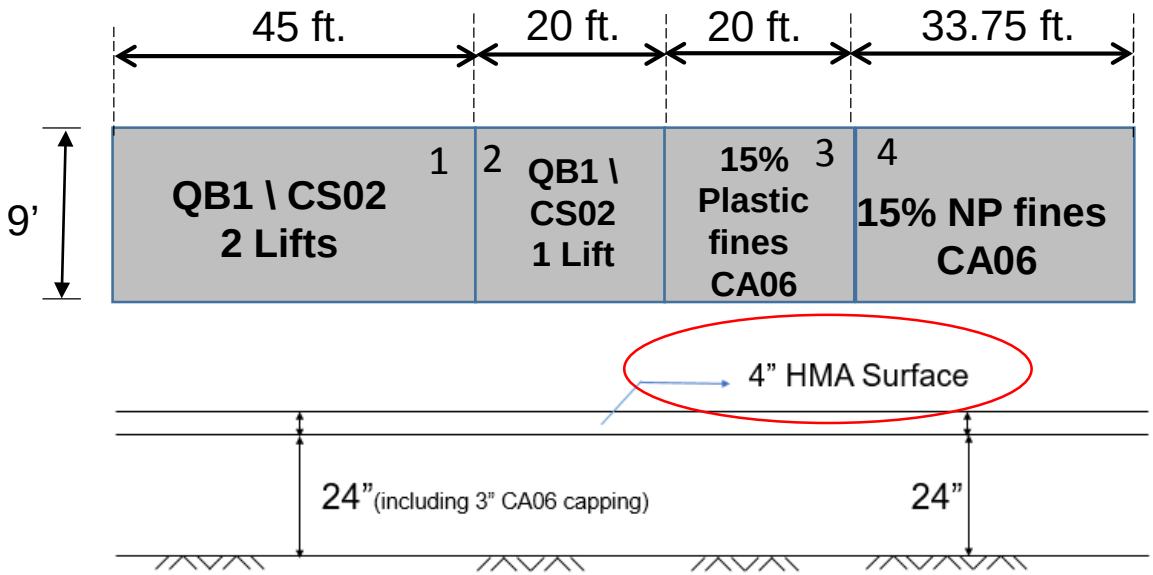
- Results compared with the previous study (Kazmee et al., 2016) using **only large PCR aggregates with no QB**
  - ✓ Same large rocks
  - ✓ Same subgrade capping materials
  - ✓ Same layer thicknesses
  - ✓ Similar subgrade strength
- This test section was loaded with 4,000 load passes.
- **Significantly higher permanent deformation/ lower stability for the section with PCR only**



Cell 1 North QB Applications

Low volume roads on weak subgrade

- QB for filling voids/gaps between large stones as aggregate subgrade on soft subgrades
- Increased fines content in dense-graded subgrade replacement (e.g. 15% passing No. 200)



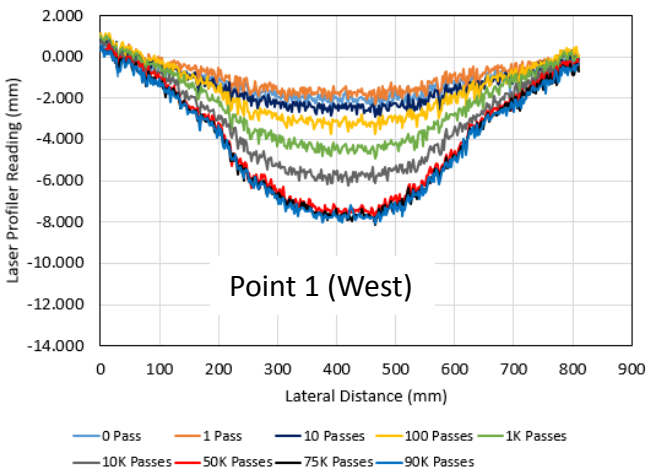
Subgrade CBR = 1%

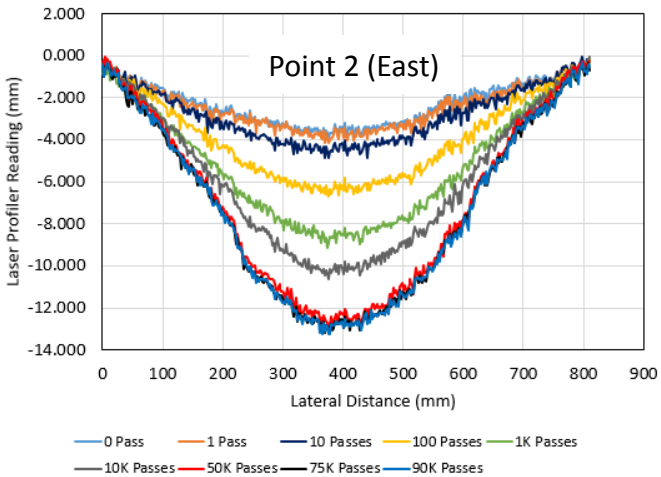
Subgrade **Top 12"** tilled & compacted

1 ft. = 0.30 m
1 in. = 2.54 cm

Cell 1N: Performance Monitoring

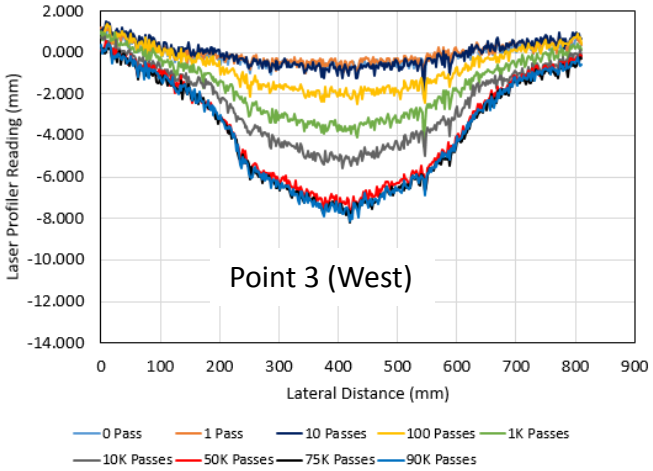
Section 1: Primary Crusher Run/QB constructed in TWO lifts

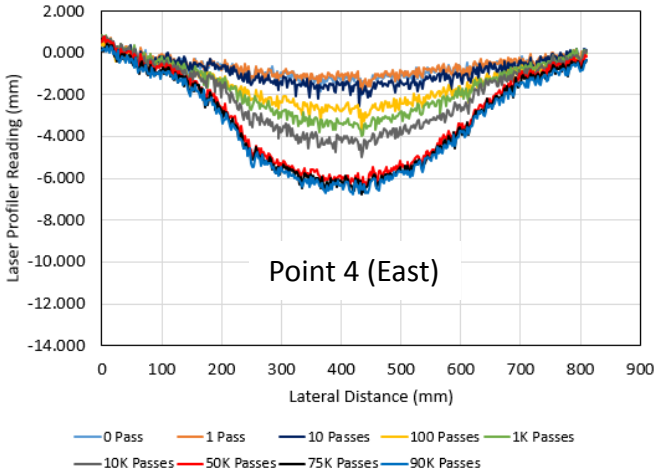




Up to 90,000 passes

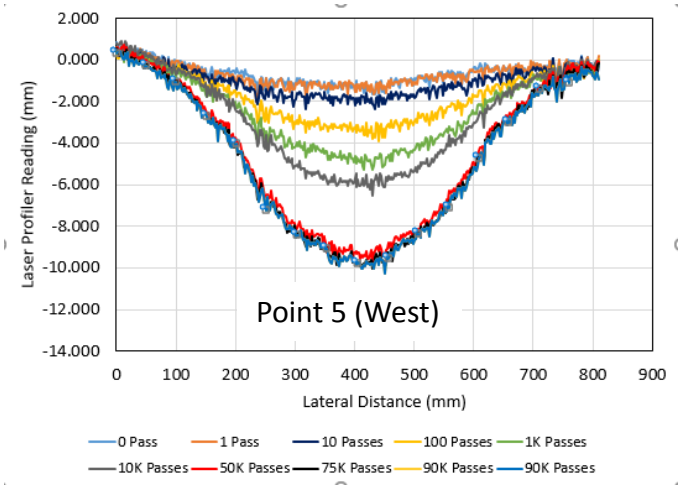
Section 2: Primary Crusher Run/QB constructed in ONE lift

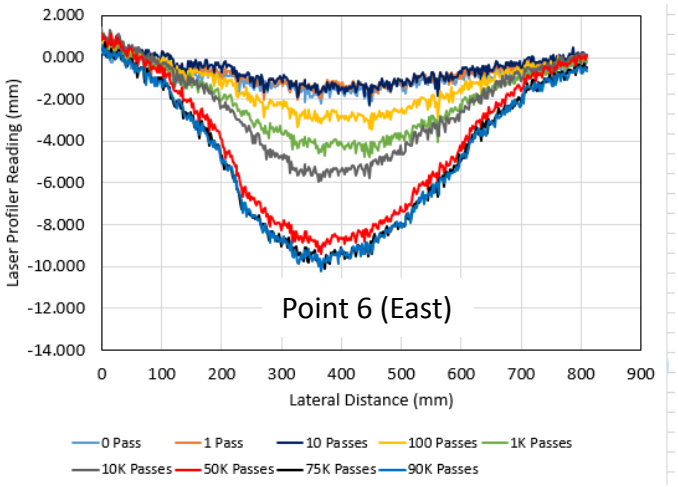




Cell 1N: Performance Monitoring

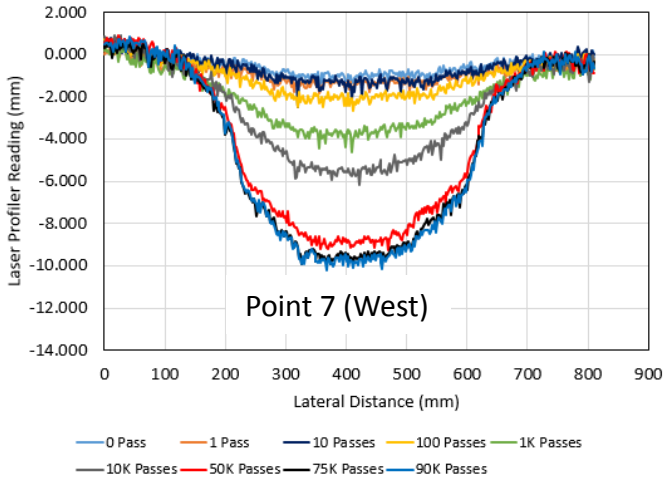
Section 3: CA06 with 15% PLASTIC fines

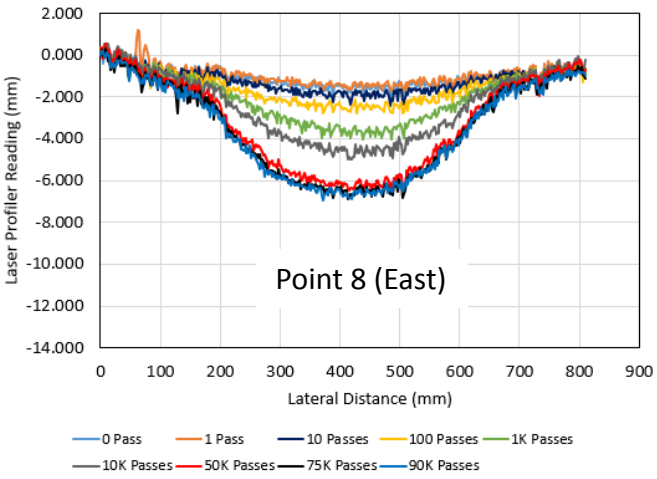




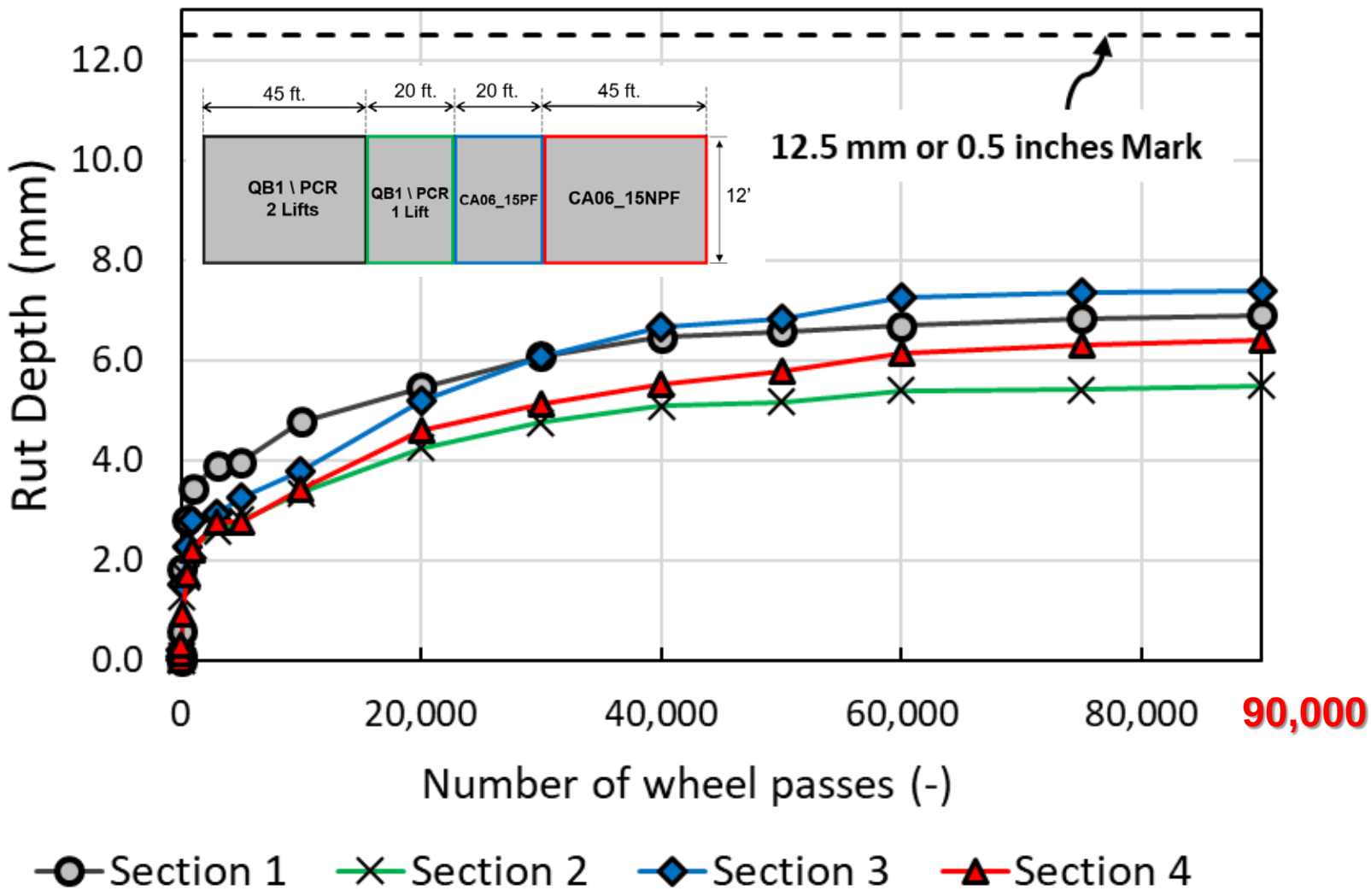
Up to 90,000 passes

Section 4: CA06 with 15% NON-PLASTIC fines





Performance Monitoring (Cell 1N)

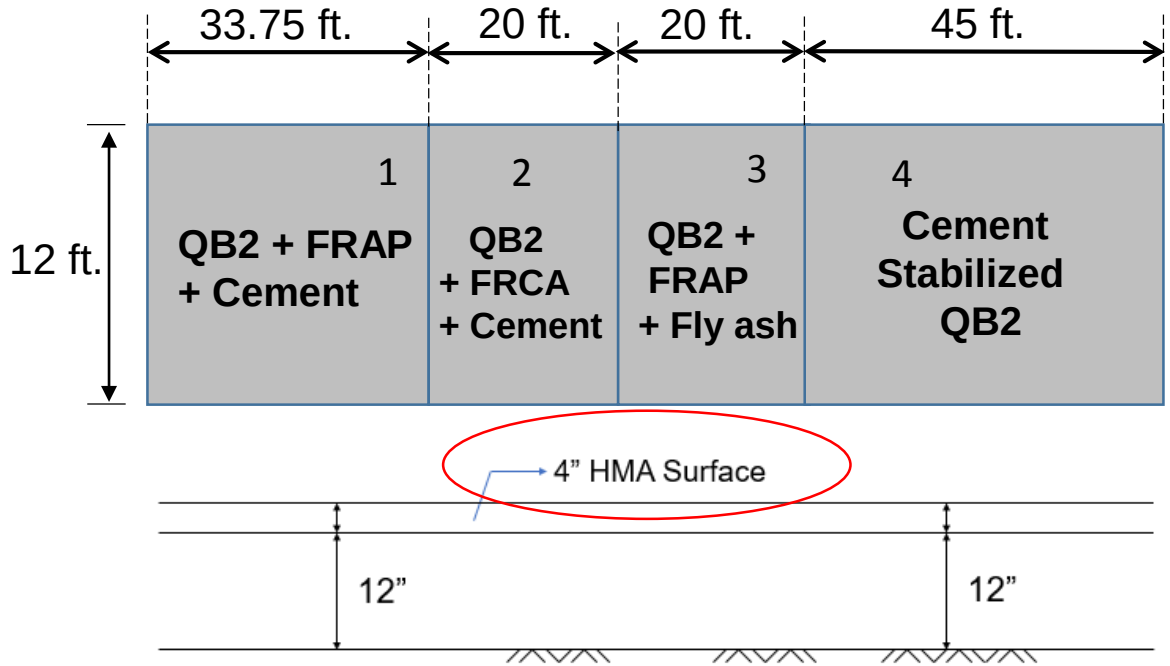


Average of each Section

Cell 2 QB Base Applications

Low volume road base applications

- Blending QB with coarse aggregate fractions of recycled materials (FRAP or FRCA) and other additives for use as base materials
- Using QB as a cement-treated base material

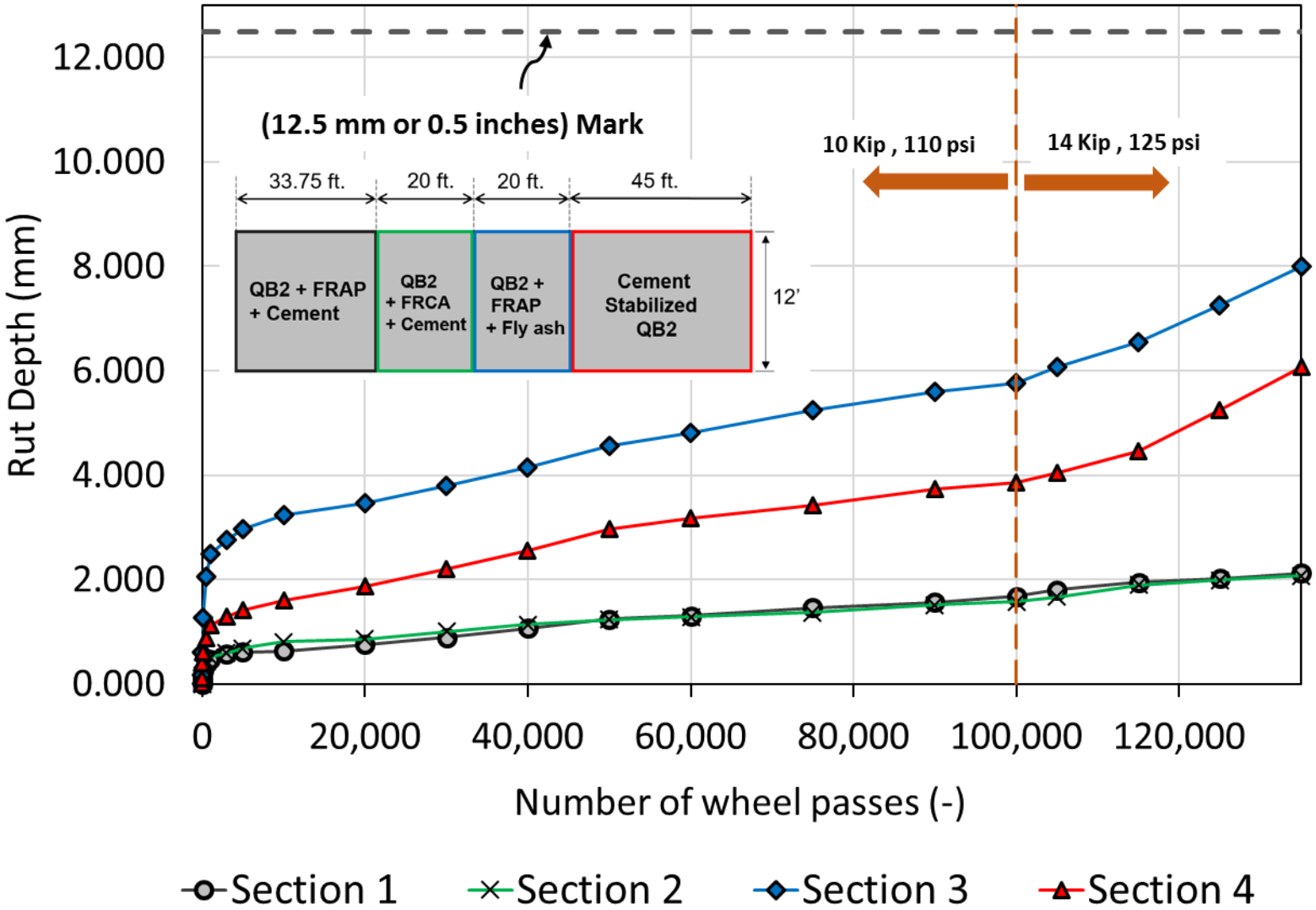


Subgrade CBR = 6%

Subgrade **Top 12"** tilled & compacted

1 ft. = 0.30 m
1 in. = 2.54 cm

Performance Monitoring (Cell 2)

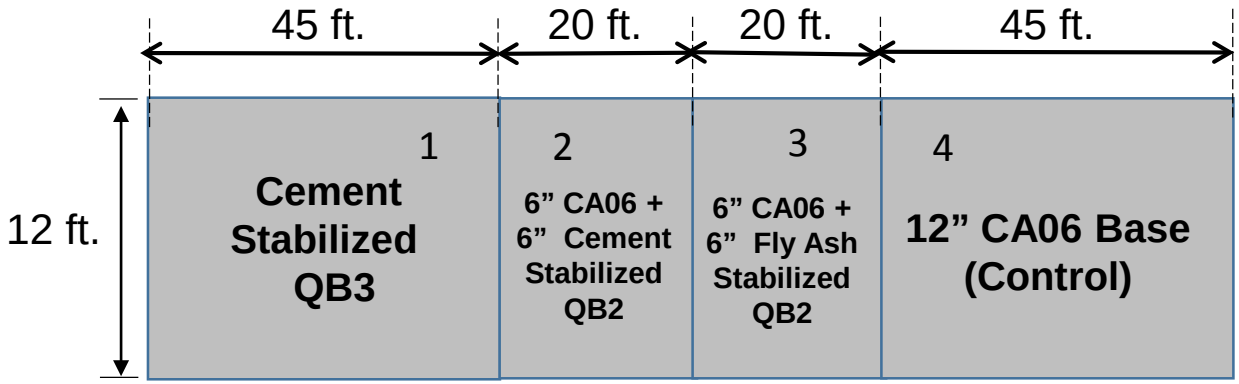


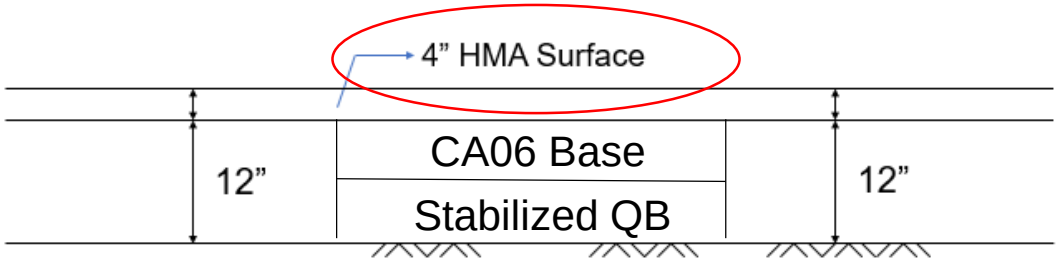
Average of each Section

Cell 3 QB Base/Subbase Applications

Proposed Applications: Low volume roads

- Using QB as a cement or fly ash-treated subbase (i.e., in inverted pavements).
- Using QB as a cement-treated base material



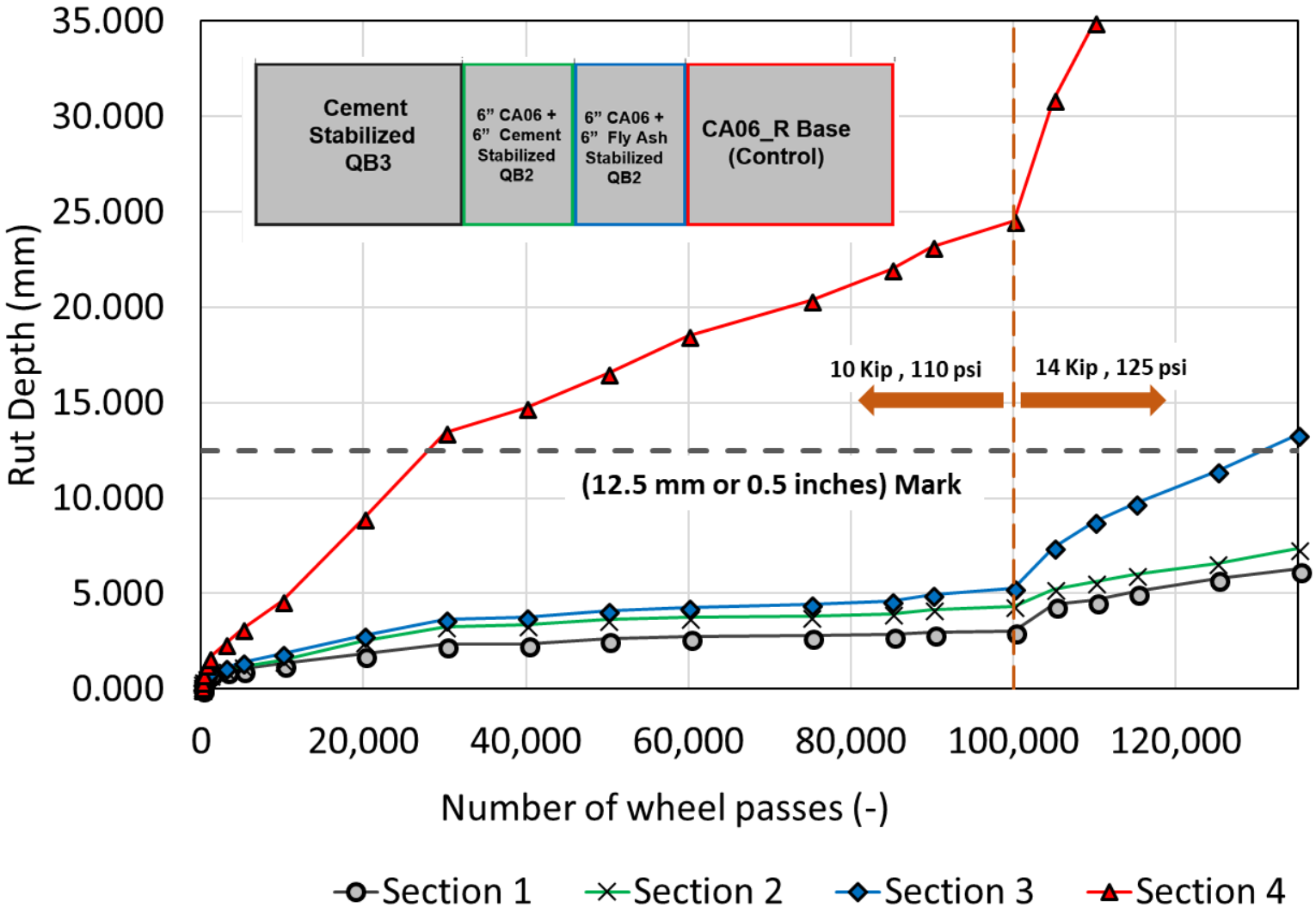


Subgrade CBR = 6%

Subgrade **Top 12"** tilled & compacted

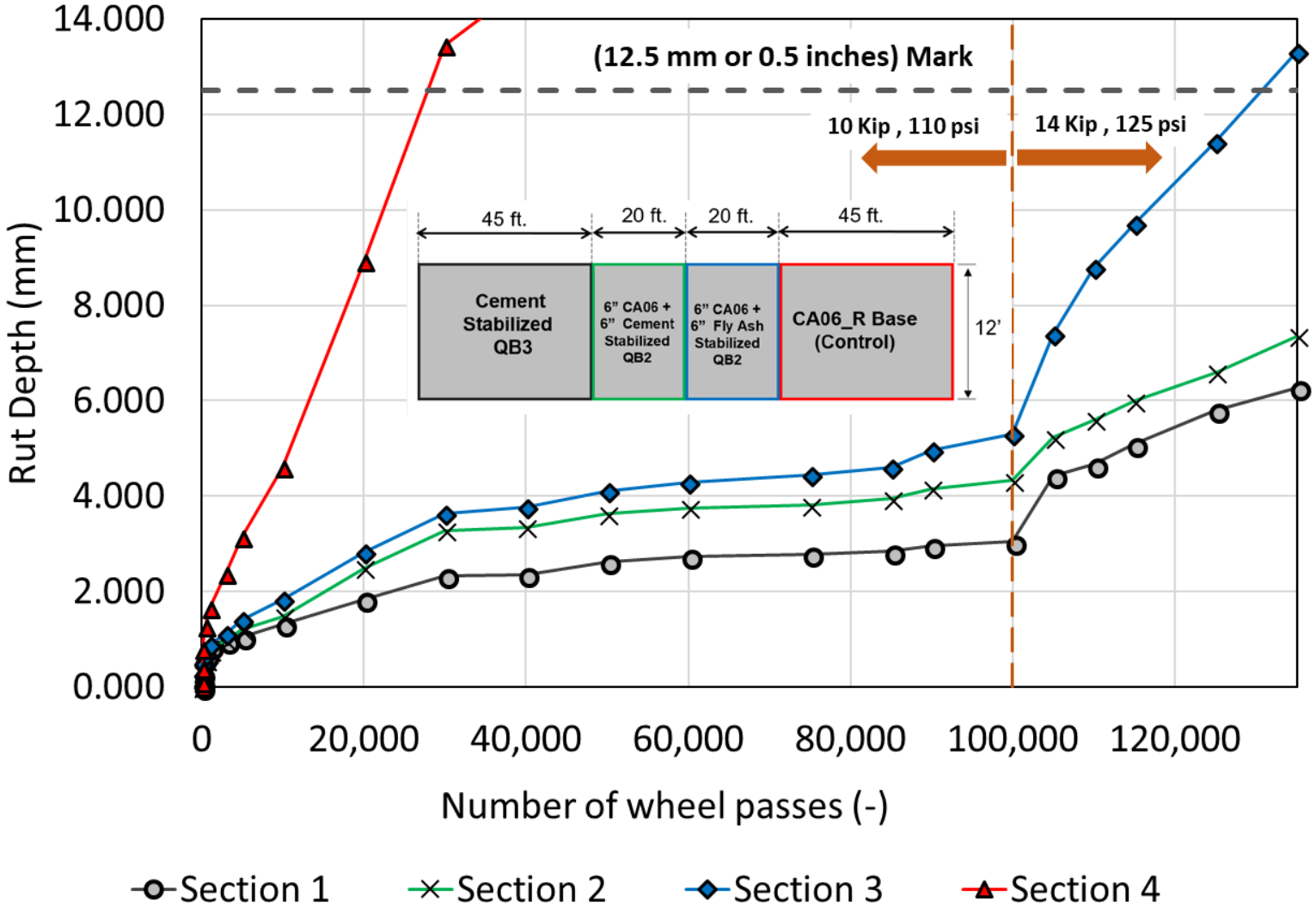
1 ft. = 0.30 m
1 in. = 2.54 cm

Performance Monitoring (Cell 3)



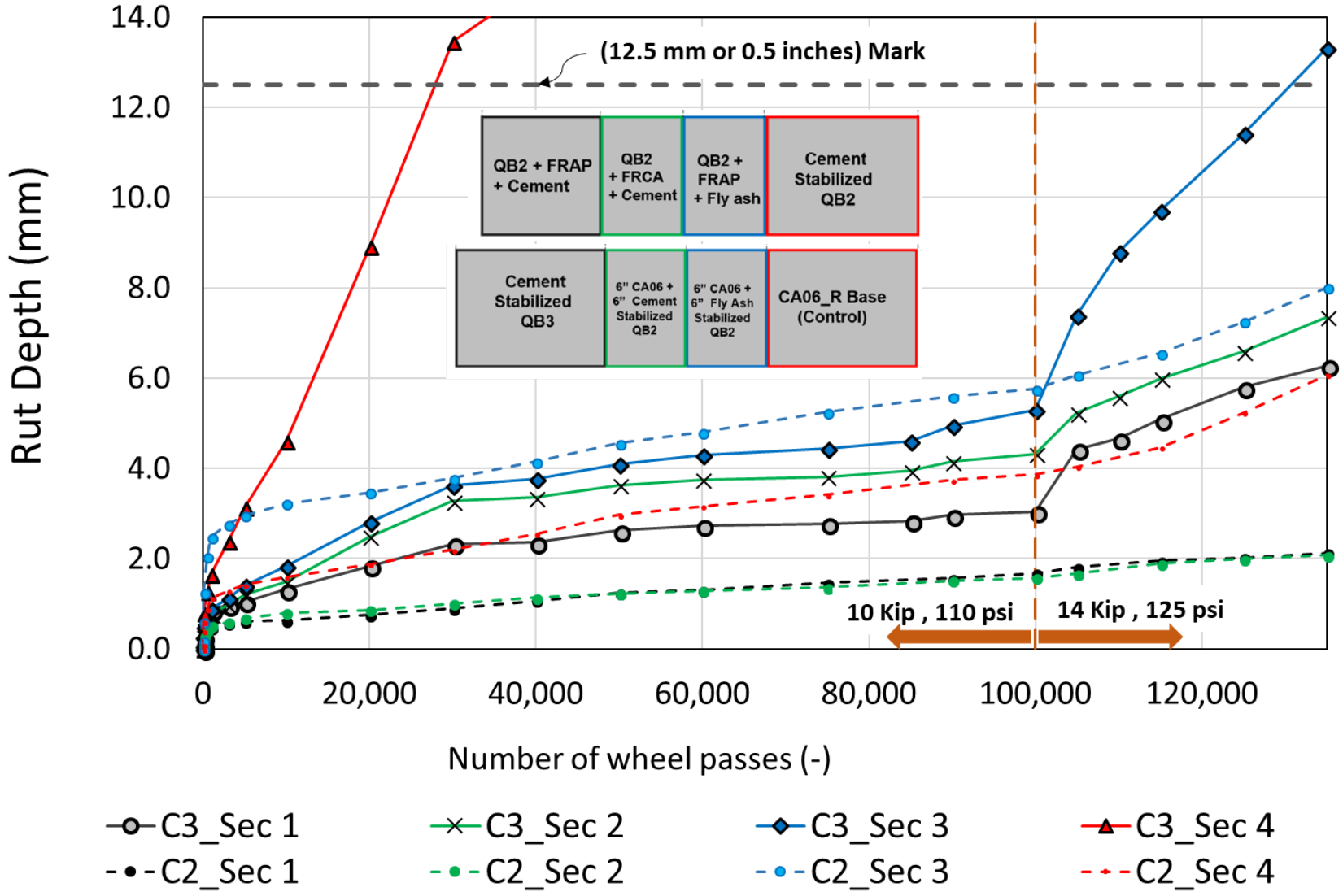
Average of each Section

Performance Monitoring (Cell 3)



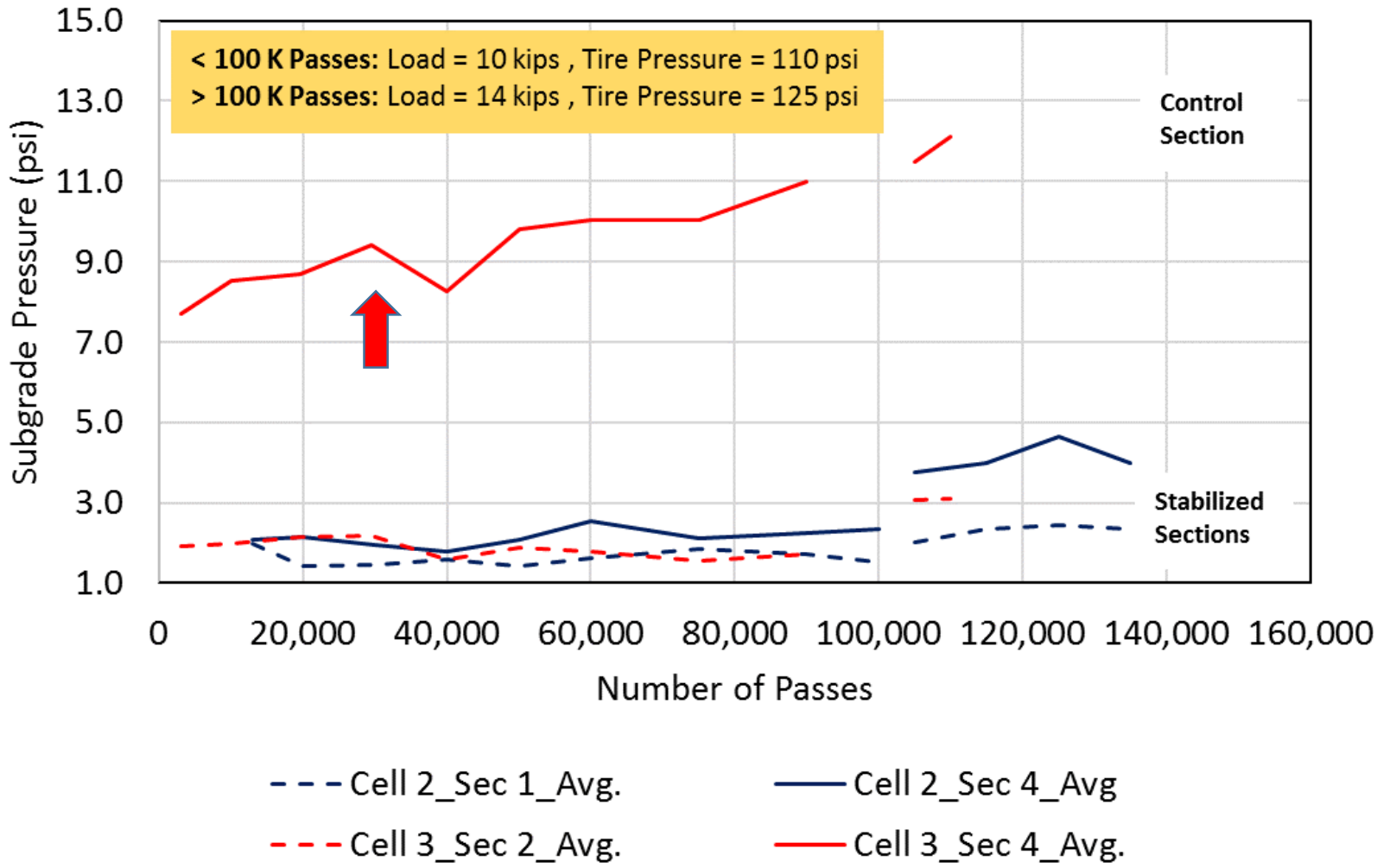
How Do Cell 2 and Cell 3 Compare?

(Zoom-in)



Soil Pressure Cell Results

Combined Results of Cell 2 and Cell 3



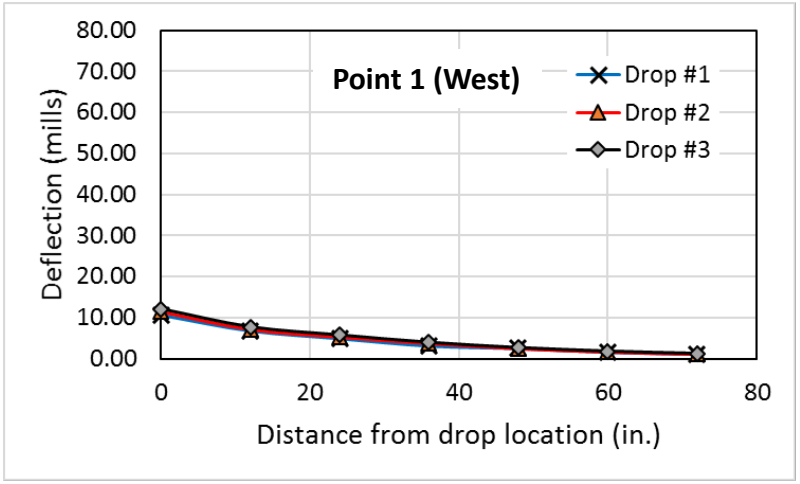
Key Findings on Performance

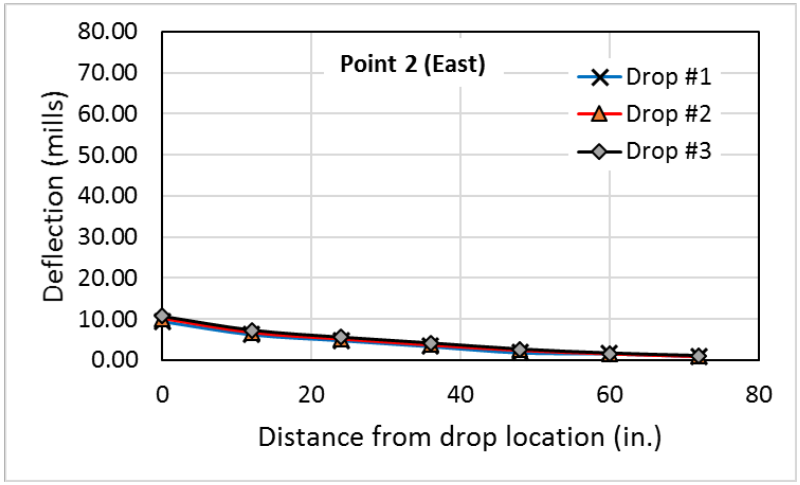
- QB sections stabilized with cement showed better performance and less variability than similar sections stabilized with Class 'C' fly ash
  - C3S3 (QB2 + fly ash subbase) accumulated >0.5 in. rutting after 135k passes
- QB blends with recycled coarse aggregates (FRAP / FRCA) performed **the best!**
- Two different QB sources (QB2 vs. QB3) stabilized with 3% cement had similar rutting performance
- Rutting rate increased when the wheel load was increased in Cells 2 and 3
- Significant increase in pressure on top of the subgrade when wheel load was increased
- Premature failure of the control section (Rutting and fatigue cracks)
  - Subgrade pressure in the control section was significantly higher than those in the stabilized sections (9 psi vs. 2 psi)

Falling Weight Deflectometer

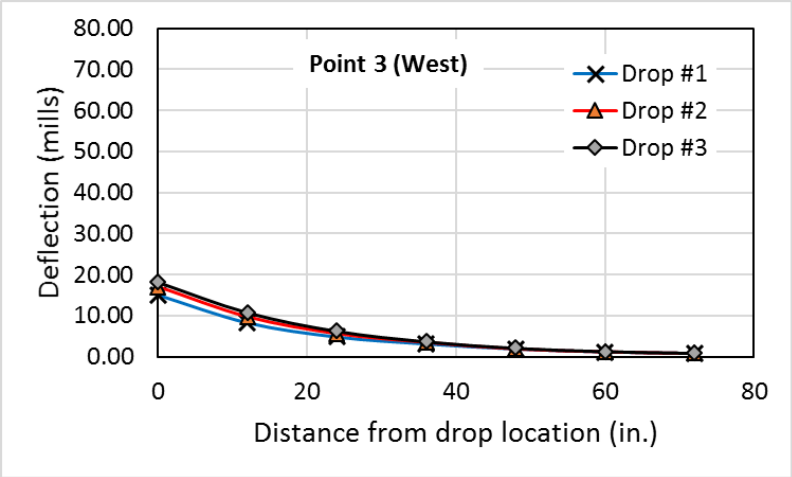
FWD Deflections (Sample Results)

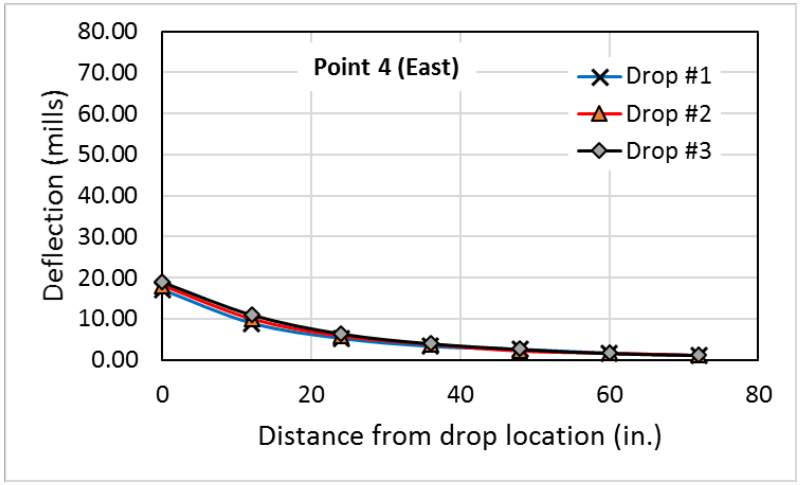
Cell 3 Section 1: QB3 + 3% Cement Base



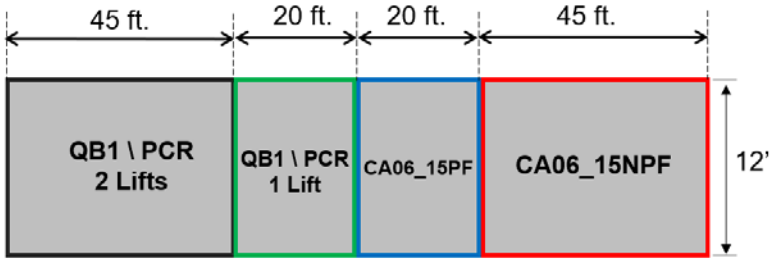


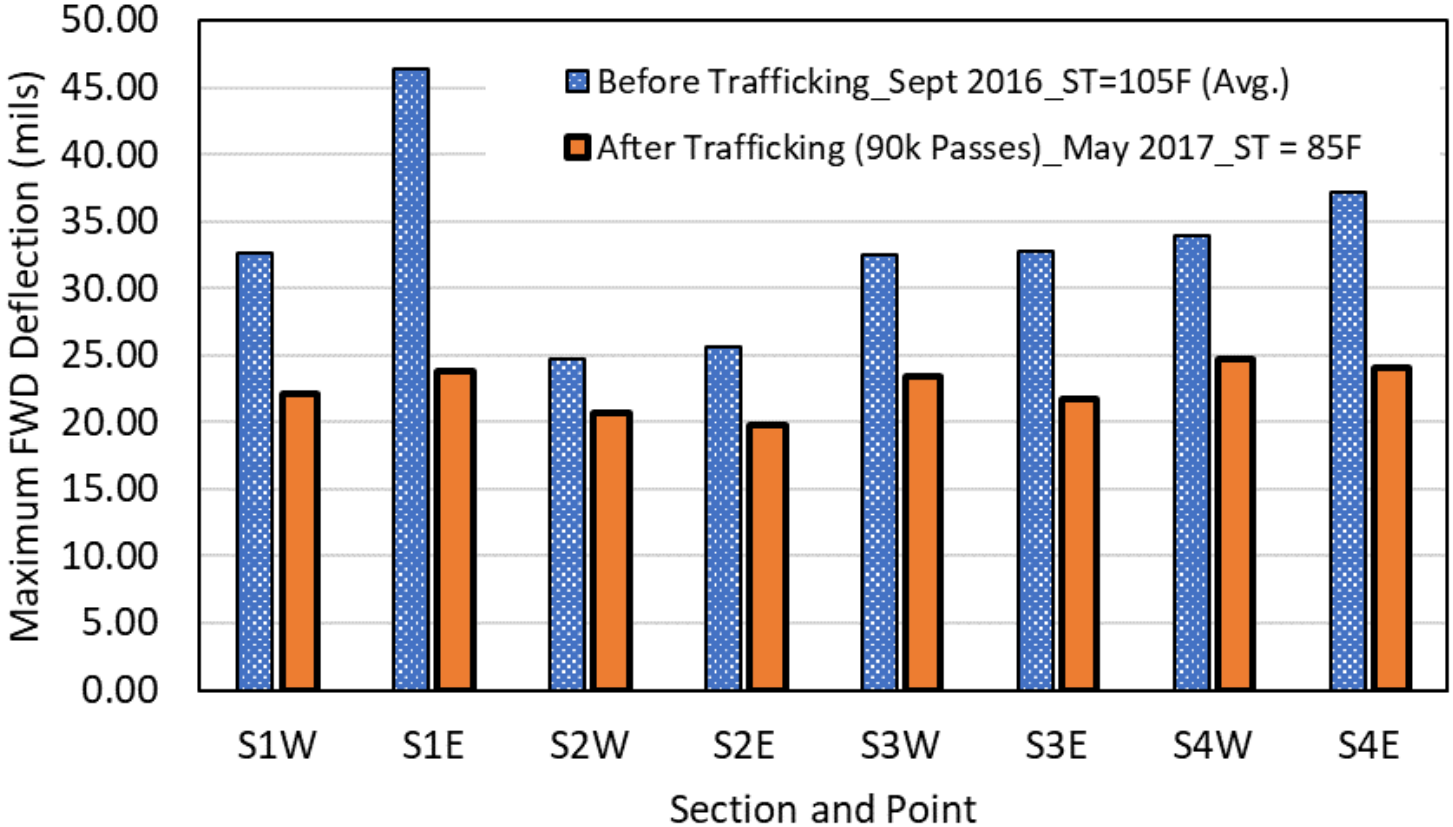
Cell3 Section 2: (QB2 + 3% Cement) Subbase & CA06 Base



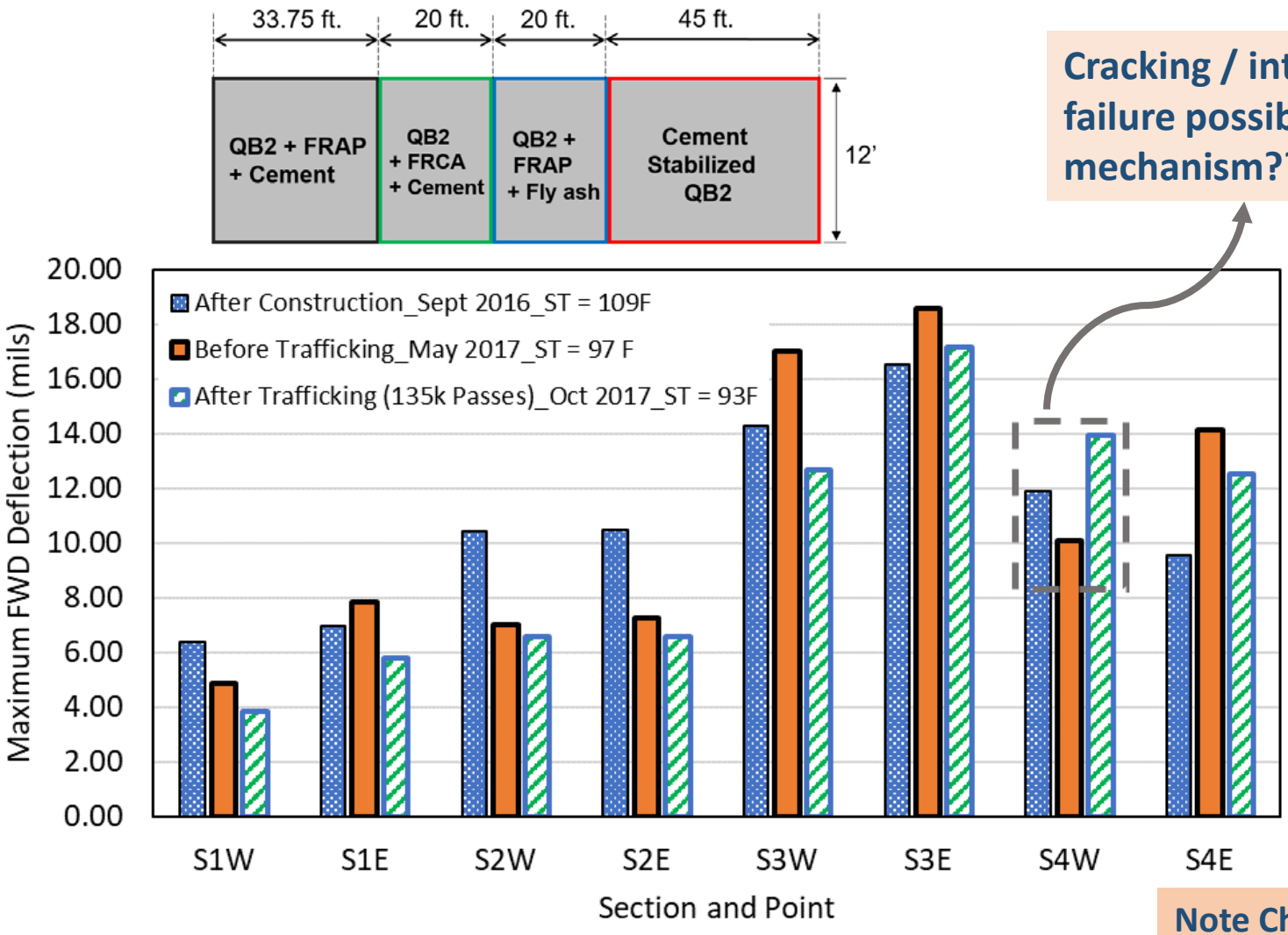


Center FWD Deflections (Cell 1N)





Center FWD Deflections (Cell 2)

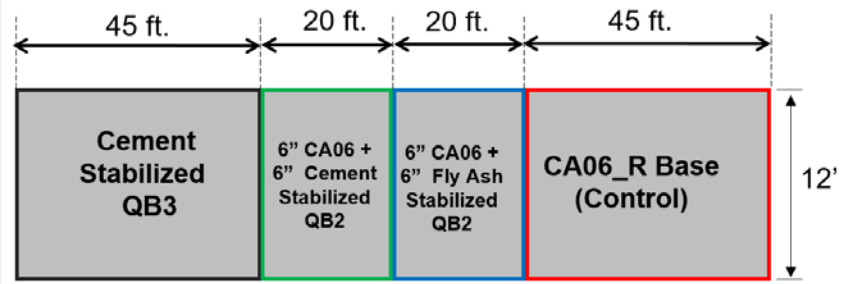


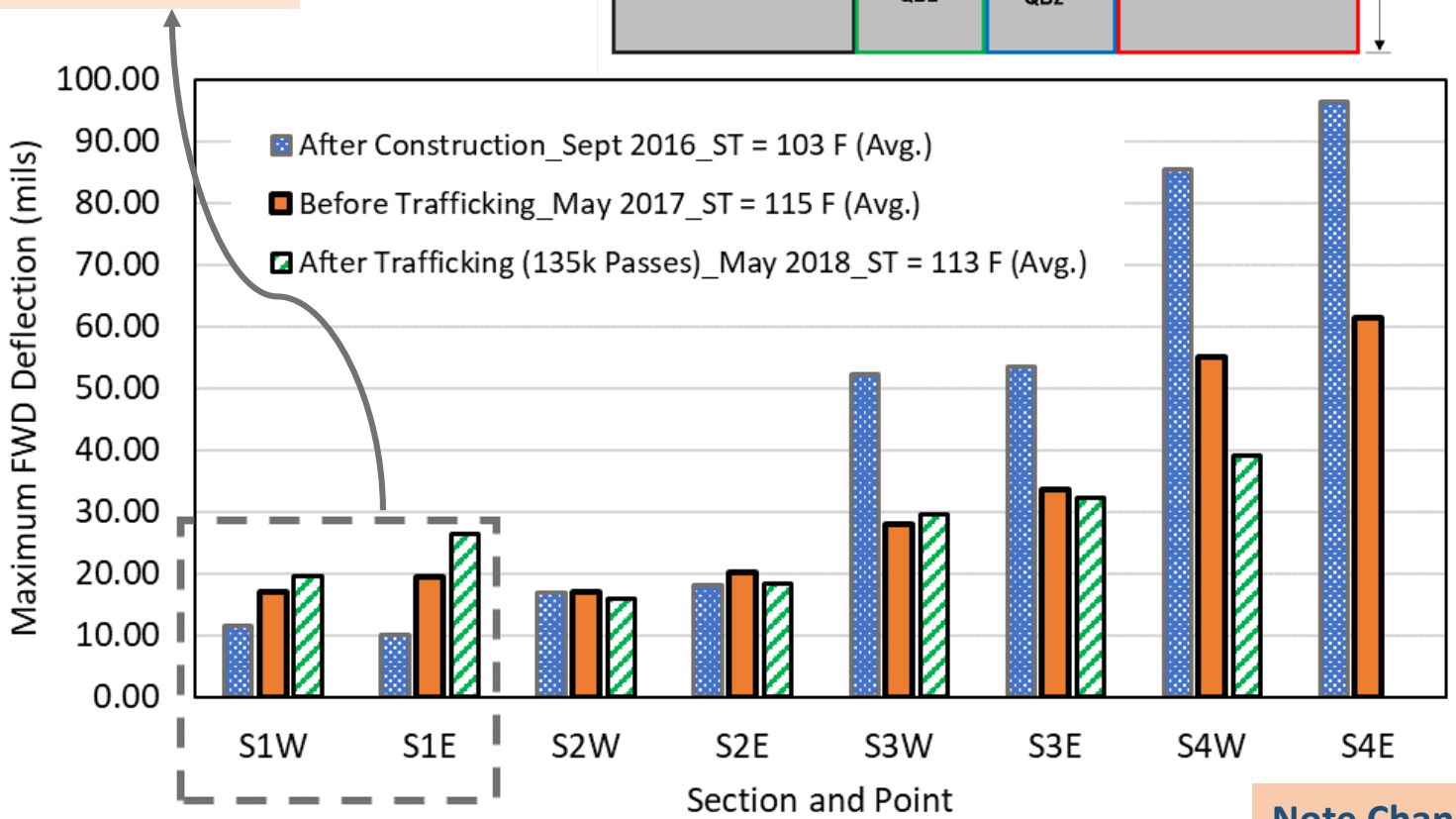
Cracking / internal failure possible mechanism??

Note Change in Scale

Center FWD Deflections (Cell 3)

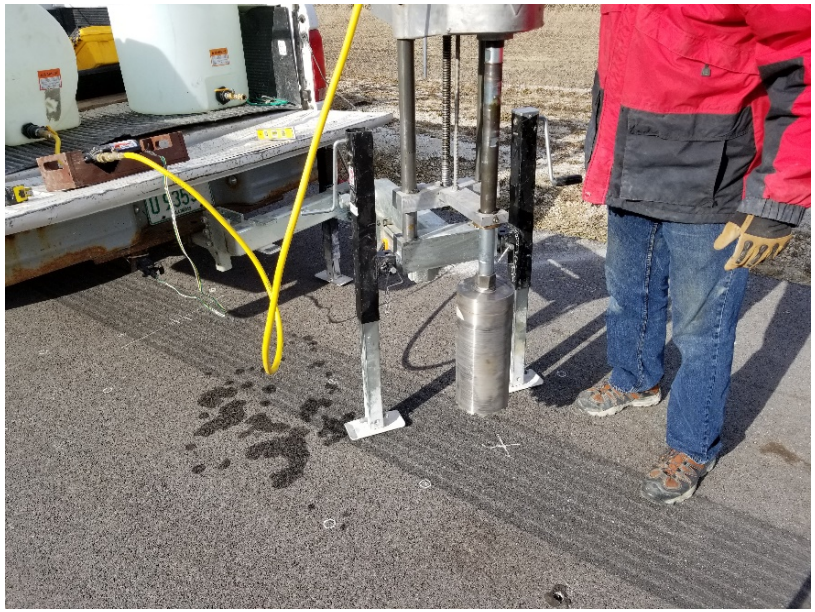
Cracking / internal failure possible mechanism??

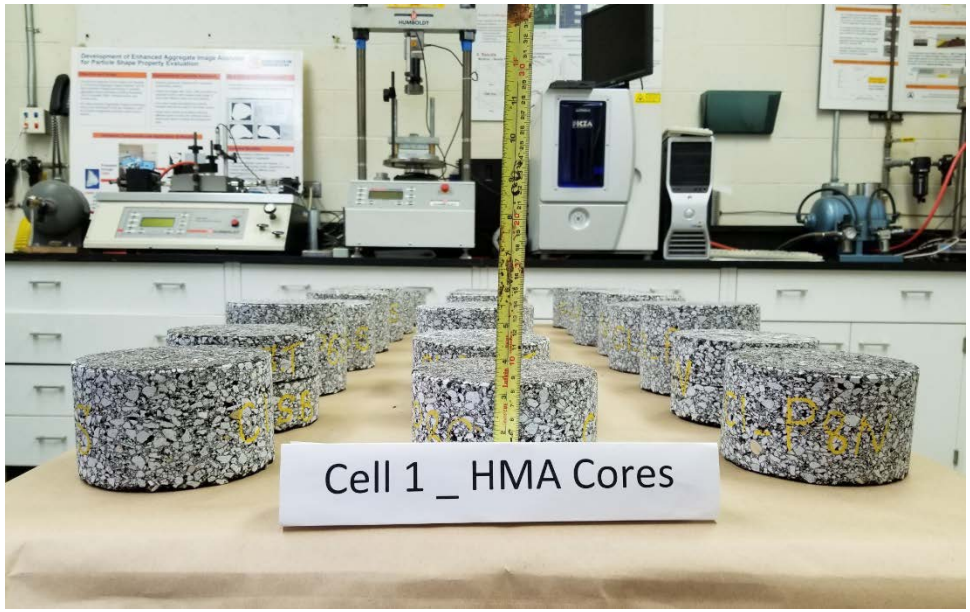




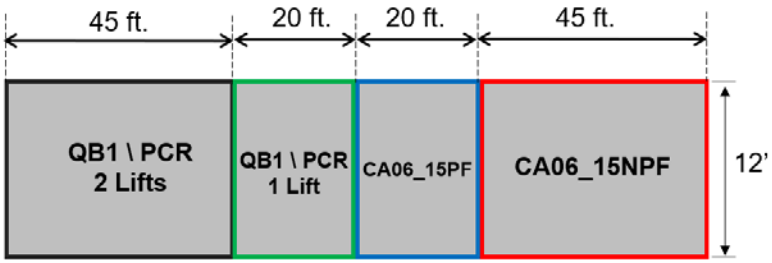
Note Change in Scale

HMA Coring





HMA Coring (Cell 1)

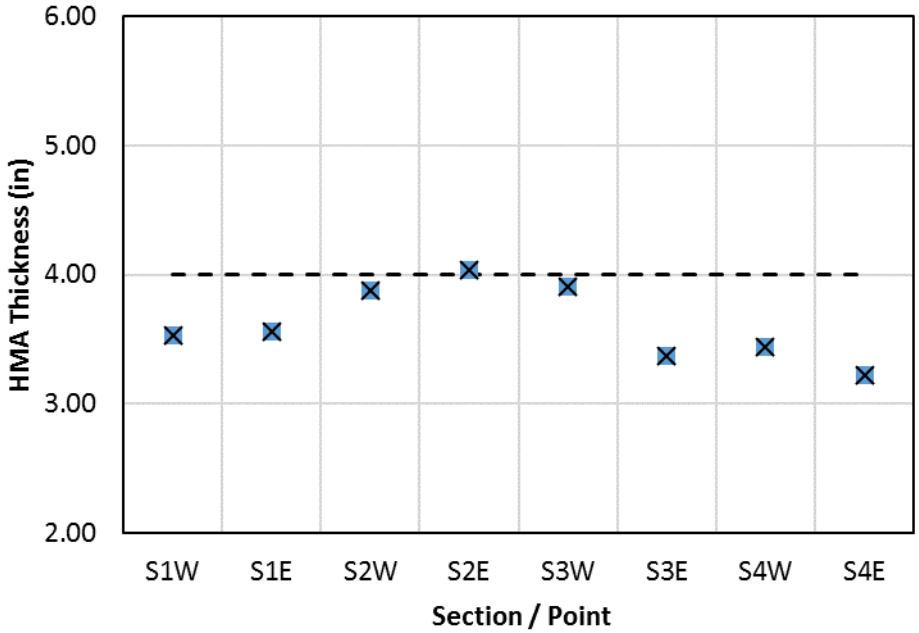


Section #	Point #	North Points	Centerline	South Points
1	S1W	3.875	3.531	3.344
1	S1E	4.094	3.563	3.719
2	S2W	4.156	3.875	4.188
2	S2E	4.219	4.031	4.219
3	S3W	3.969	3.906	3.969
3	S3E	3.500	3.375	3.500
4	S4W	3.375	3.438	3.750
4	S4E	3.469	3.219	3.531

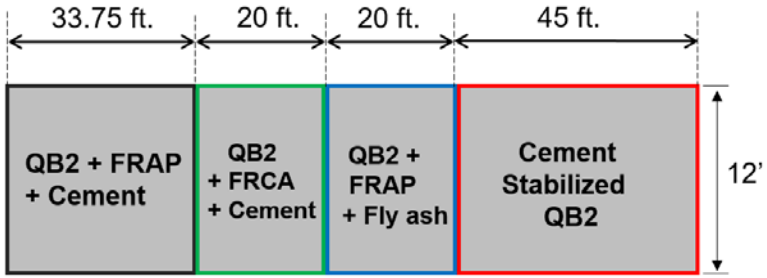
- Range of Cores Thickness (Center):

  3.22 – 4.03 inches
- North and South Cores are 16 inches from wheel path centerline
- Highest Thickness: Section 2
- Lowest Thickness: Section 4

Plot indicates centerline core thickness



HMA Coring (Cell 2)

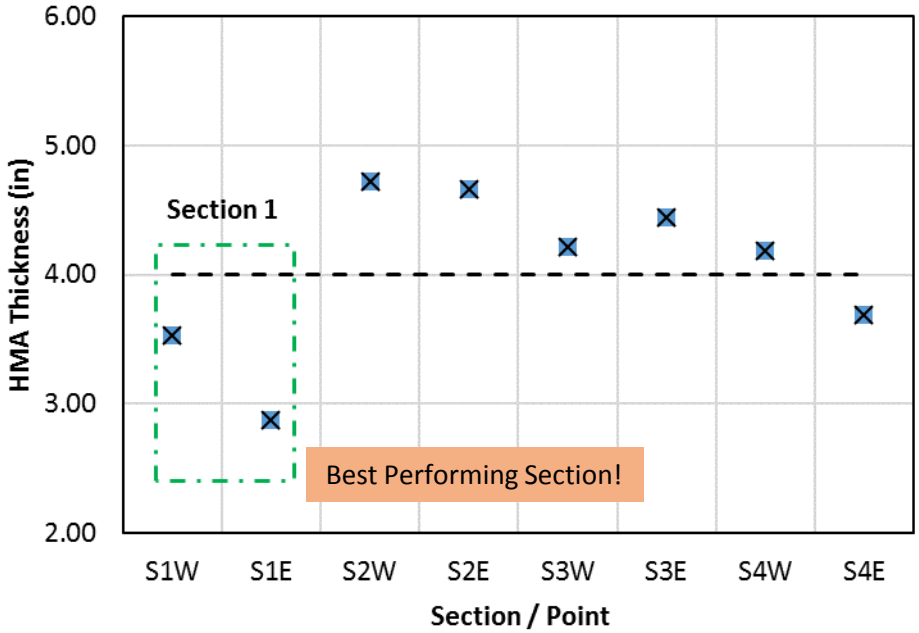


Section #	Point #	North Points	Centerline	South Points
1	S1W	3.688	3.531	3.781
1	S1E	3.594	2.875	3.125
2	S2W	4.156	4.719	4.813
2	S2E	4.469	4.656	4.563
3	S3W	5.156	4.219	4.313
3	S3E	4.938	4.438	4.563
4	S4W	3.750	4.188	4.250
4	S4E	3.875	3.688	3.750

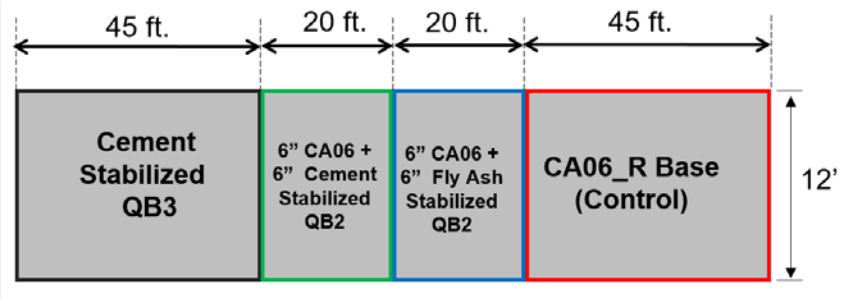
- Range of Cores Thickness (Center):

  2.88 – 4.72 inches
- North and South Cores are 20 inches from wheel path centerline
- Highest Thickness: Section 2
- Lowest Thickness: Section 1

Plot indicates centerline core thickness



HMA Coring (Cell 3)

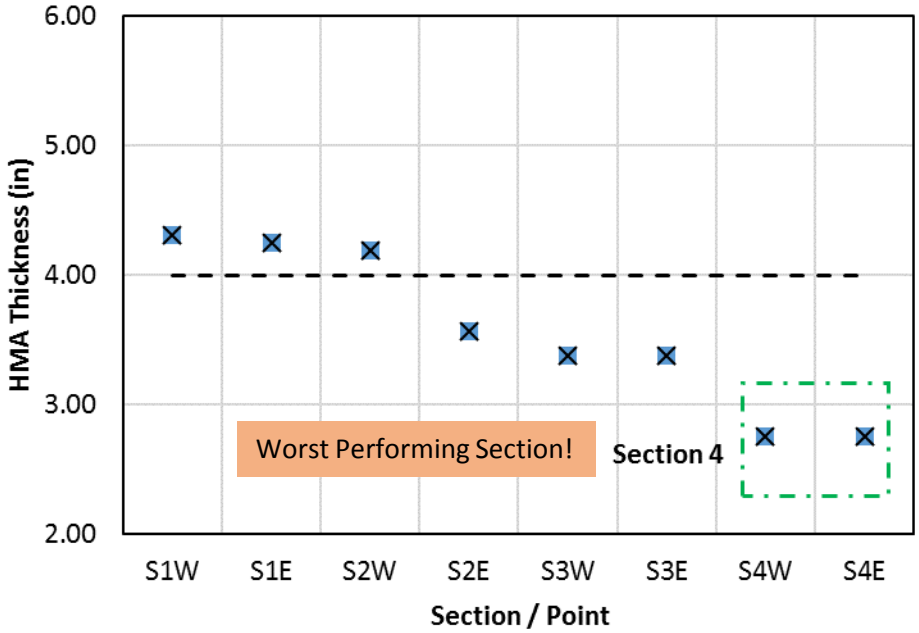


Section #	Point #	North Points	Centerline	South Points
1	S1W	4.500	4.313	4.313
1	S1E	4.625	4.250	4.438
2	S2W	4.125	4.188	4.250
2	S2E	3.688	3.563	3.500
3	S3W	3.688	3.375	3.375
3	S3E	3.625	3.375	3.438
4	S4W	3.563	2.750	3.563
4	S4E	3.313	2.750	3.313

- Range of Cores Thickness (Center):

  2.75 – 4.31 inches
- North and South Cores are 20 inches from wheel path centerline
- Highest Thickness: Section 1
- Lowest Thickness: Section 4

Plot indicates centerline core thickness



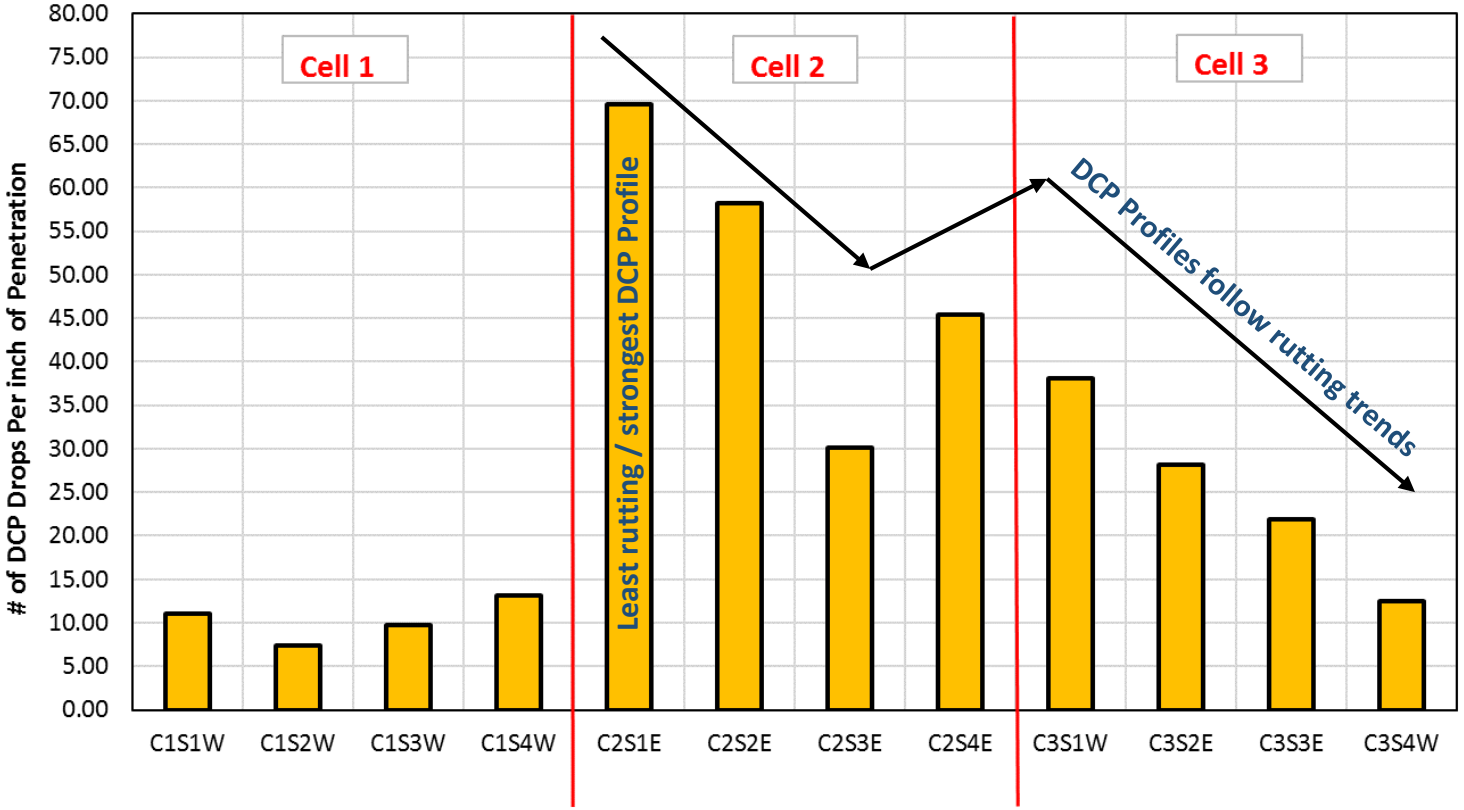
DCP Testing

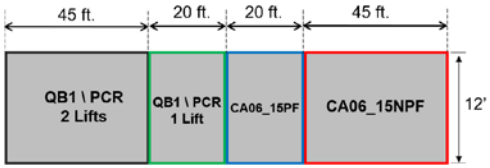
- **Strength profiles** (DCP penetrations) **follow the rutting trends** for Cells 2 and 3 (i.e. chemically stabilized sections)
- Heat map shows the number of DCP drops per 1 inch penetration (i.e. normalized results)

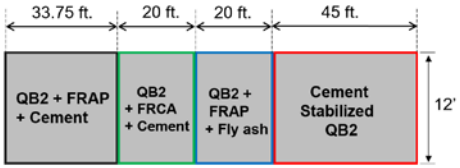
Section	Depth of DCP	Number of Drops	# of Drops / inch
C1S1W	21	231	11.0
C1S2W	22	163	7.4
C1S3W	18	176	9.8
C1S4W	17.5	230	13.1
C2S1E	12.25	852	69.6
C2S2E	11	741	58.3
C2S3E	11.1	334	30.1
C2S4E	10.1	458	45.3
C3S1W	11	419	38.1
C3S2E	11.5	324	28.2
C3S3E	11.5	251	21.8
C3S4W	10.5	131	12.5

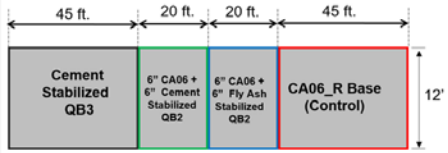
DCP results for Base / Subbase Only

DCP Testing



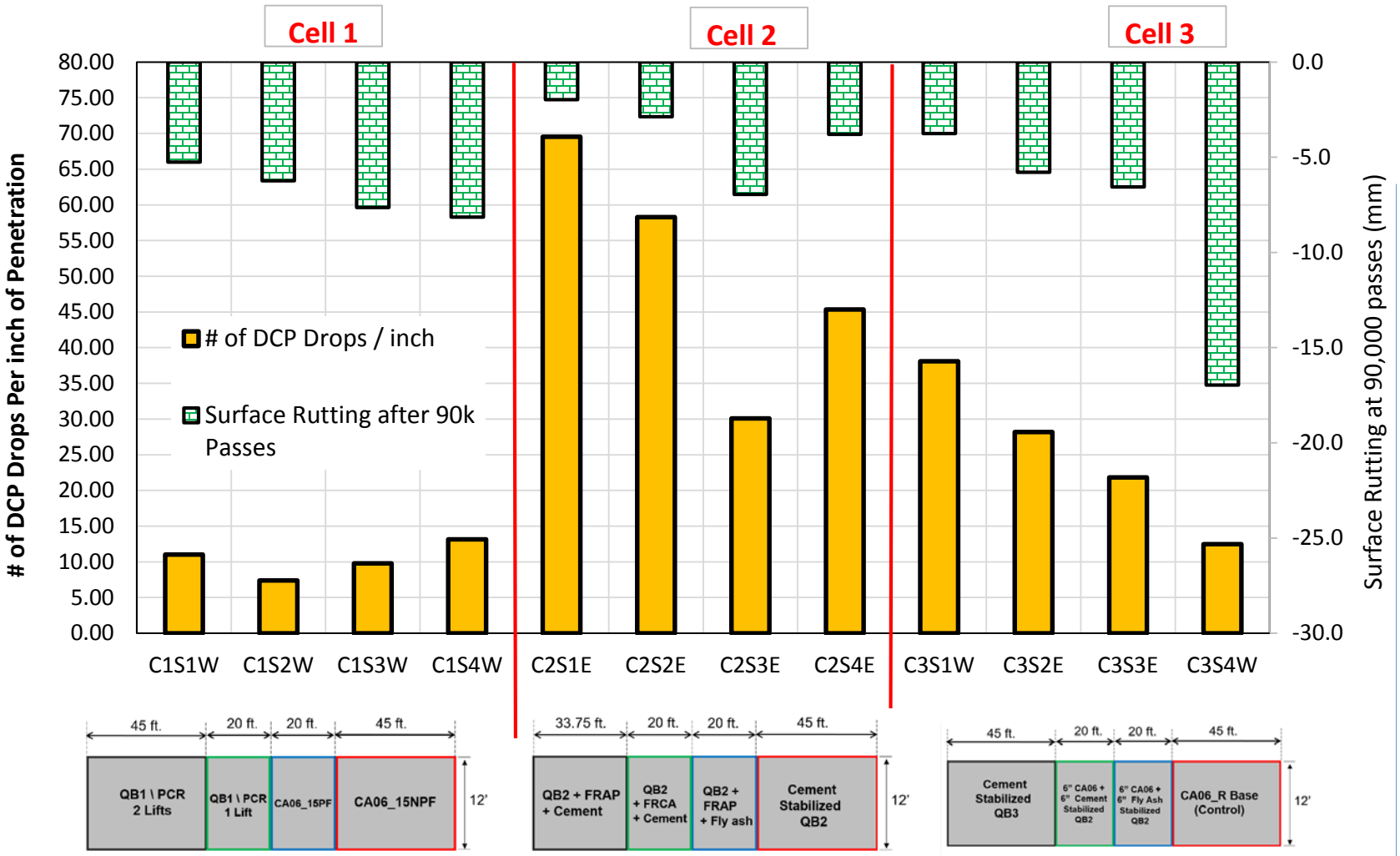






DCP results for Base / Subbase Only

DCP Testing



DCP results for Base / Subbase Only

Trenching

Trenching (Cell 1)

Section 1W: PCR /QB constructed in TWO lifts

Aggregate Subgrade (AS) Thickness: 19.7

Capping Thickness: 3.5

HMA Thickness: 3.53

Water Table Level: 52

All are inches.

- **Remarks:**

Good (Uniform) Intermixing between QB and PCR

Little penetration into the subgrade (3 in. max)

Trenching (Cell 1)

Section 2W: PCR /QB constructed in One lift

AS Thickness: 21.1

Capping Thickness: 3.0

HMA Thickness: 3.88

Water Table Level: 56

All are inches.

- **Remarks:**

Good (Uniform) Intermixing between QB and PCR

Little Penetration into the subgrade

Trenching (Cell 1)

Section 3W: CA06 with 15% PLASTIC fines

AS Thickness: 20.1

Capping Thickness: 3.5

HMA Thickness: 3.91

Water Table Level: 55

All are inches.

- **Remarks:**

Coarser gradation visible compared to Section 4 (nonplastic fines)

Trenching (Cell 1)

Section 4W: CA06 with 15% NONPLASTIC fines

AS Thickness: 21.8

Capping Thickness: 3.0

HMA Thickness: 3.44

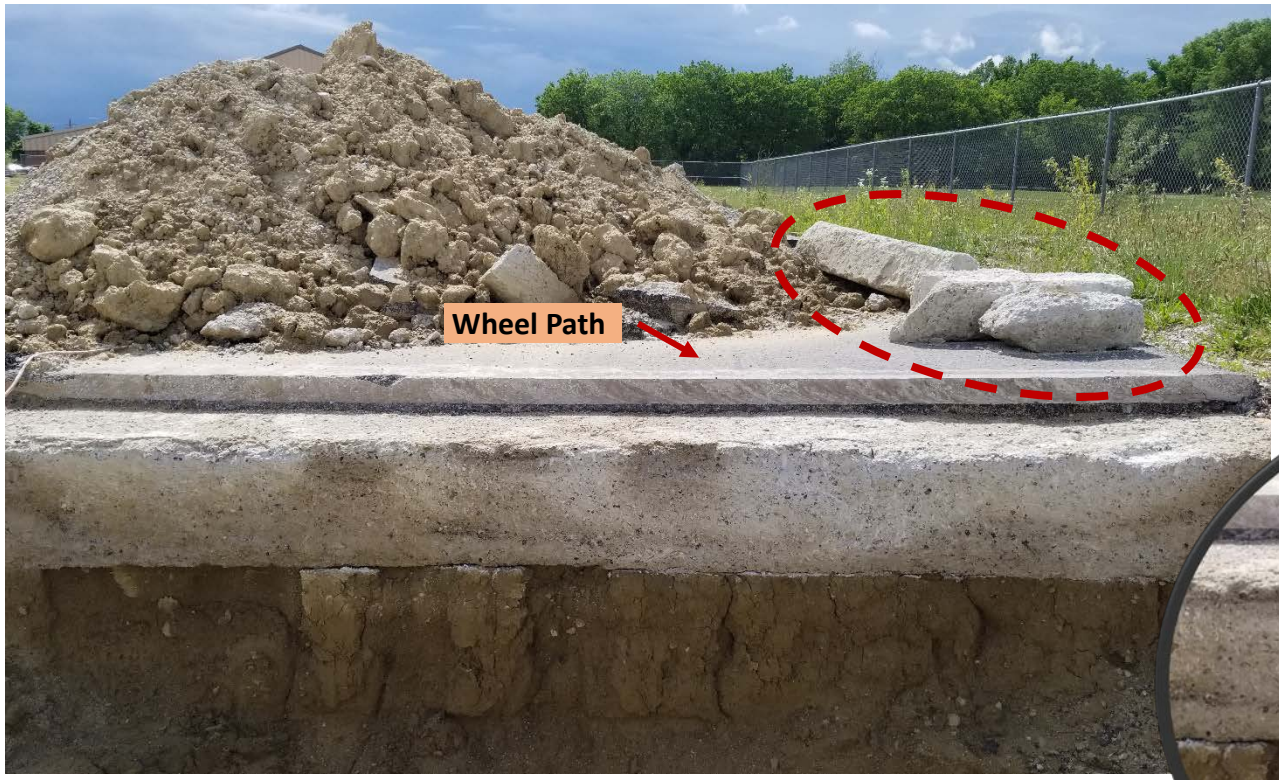
Water Table Level: 57.5

- **Remarks:**

Finer gradation visible compared to Section 3 (plastic fines)

Trenching (Cell 2)

Section 1W: QB2 + FRAP + 3% Cement Base



Base Thickness: 12.7

HMA Thickness: 3.5

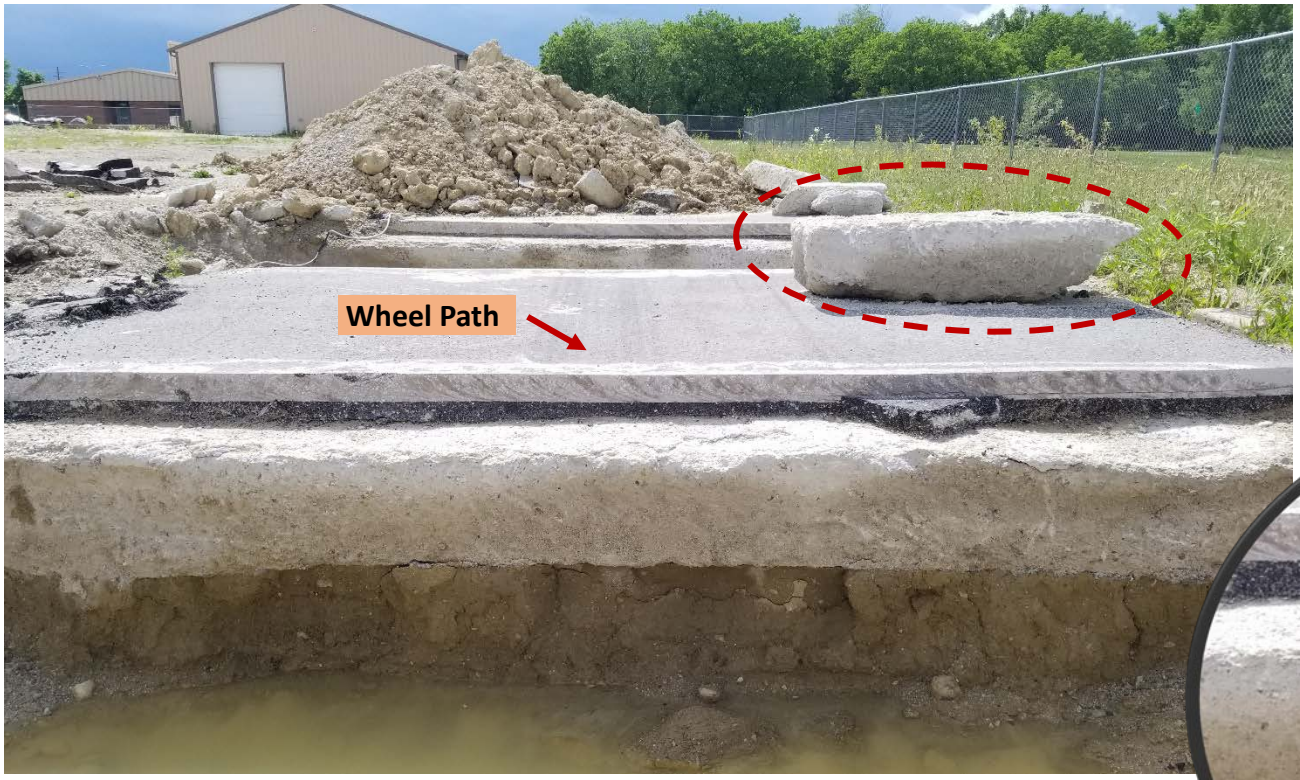
Water Table Level: 53

- **Remarks:**

Strongest section to dig through.

Trenching (Cell 2)

Section 2W: QB2 + FRCA + 3% Cement Base



Base Thickness: 11.3

HMA Thickness: 4.7

Water Table Level: 50 (Interpolation)

- **Remarks:**

Strong section to dig through.

Trenching (Cell 2)

Section 3W: QB2 + FRAP + 10% Fly Ash Base

Base Thickness: 13.3

HMA Thickness: 4.2

Water Table Level: 47

- **Remarks:**

The weakest section to dig through in Cell 2

Trenching (Cell 2)

Section 4W: QB2 + 3% Cement Base

Base Thickness: 11.3

HMA Thickness: 4.2

Water Table Level: 47

- **Remarks:**

Relatively weaker section to dig through compared to Section 3

Trenching (Cell 3)

Section 1W: QB3 + 3% Cement Base

Base Thickness: 12.9

HMA Thickness: 4.3

Water Table Level: 52.5

- **Remarks:**

Relatively similar strength to C2S4 (QB2 + Cement)

Trenching (Cell 3)

Section 2W: [QB2 + 3% Cement] Subbase & CA06_R Base

Subbase Thickness: 7.5

Base Thickness: 5.8

HMA Thickness: 4.2

Water Table Level: 51

- **Remarks:**

Cement-treated subbase was significantly stronger the fly ash-treated subbase

Trenching (Cell 3)

Section 3W: [QB2 + 10% Fly Ash] Subbase & CA06_R Base

Subbase Thickness: 6.0

Base Thickness: 6.0

HMA Thickness: 3.4

Water Table Level: 49.5

Trenching (Cell 3)

Section 4W: CA06_R Base

Base Thickness: 12.3

HMA Thickness: 2.8

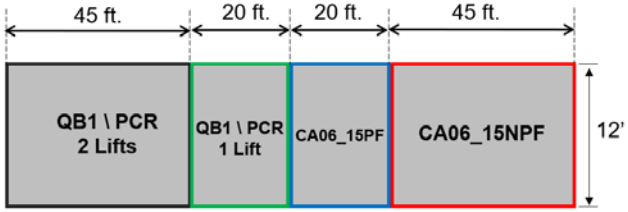
Water Table Level: 43

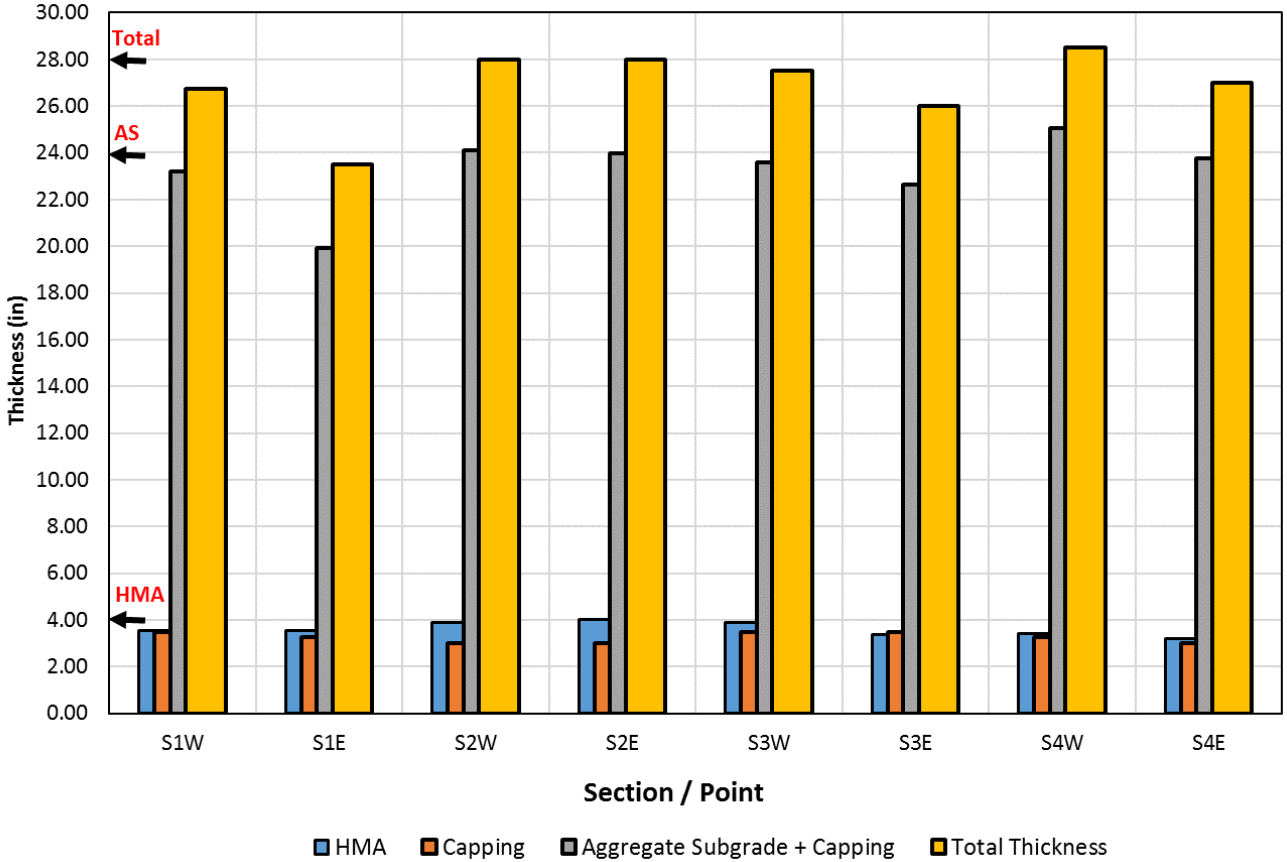
- **Remarks:**

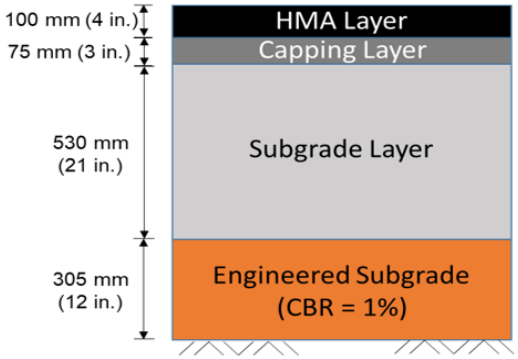
Shallowest water table level of all sections

Coring & Trenching Results (Cell 1)

- Nominal Thicknesses:
  - HMA: 4 in.
  - Capping: 3 in
  - AS: 21 in.
  - Total: 28 in.

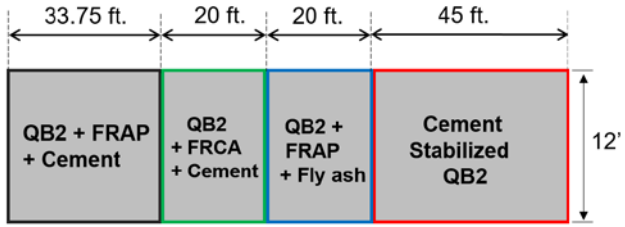


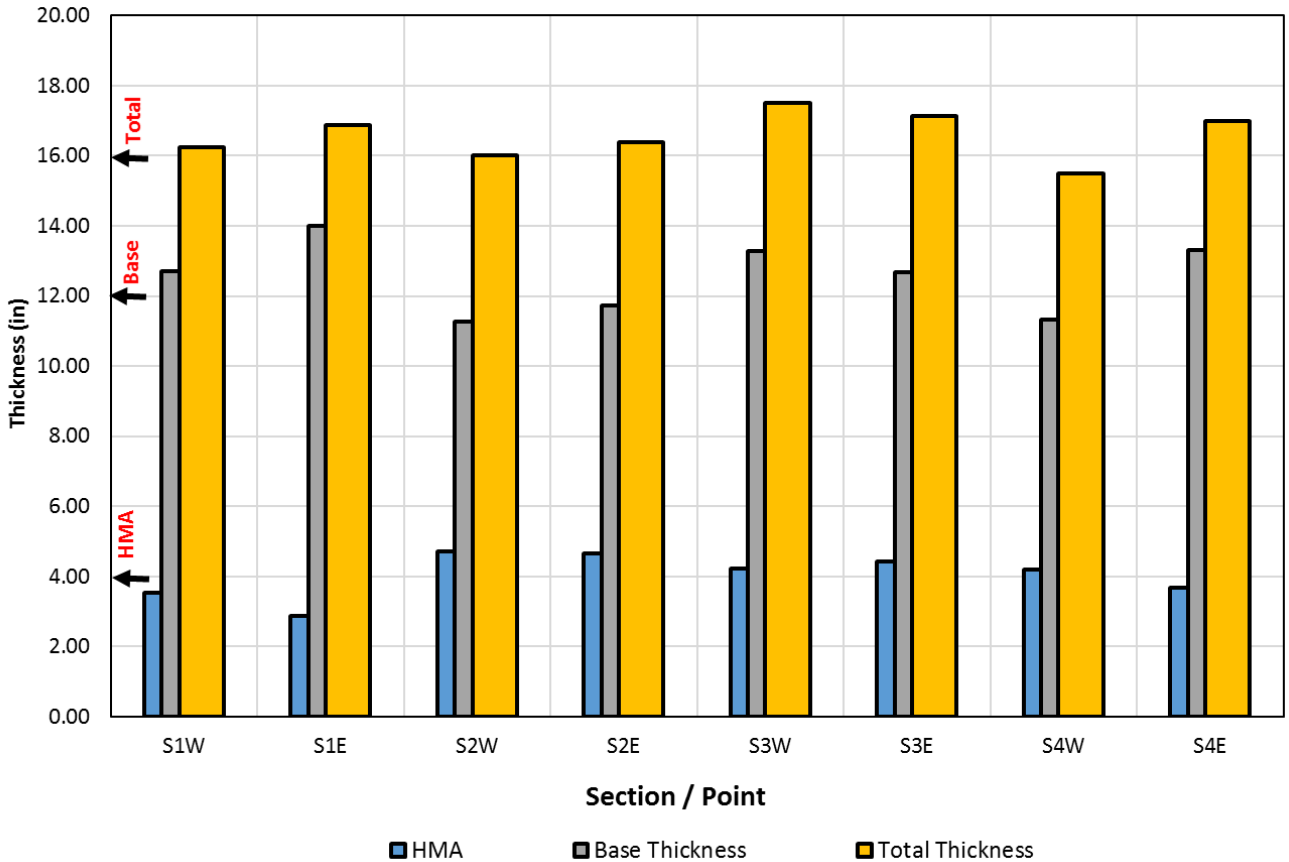


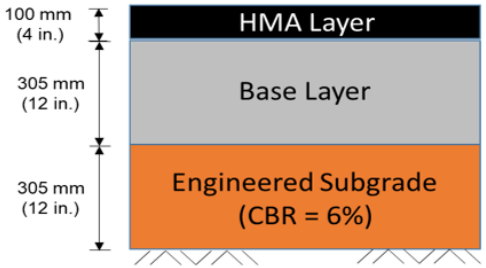


Coring & Trenching Results (Cell 2)

- Nominal Thicknesses:
  - HMA: 4 in.
  - Base: 12 in.
  - Total: 16 in.

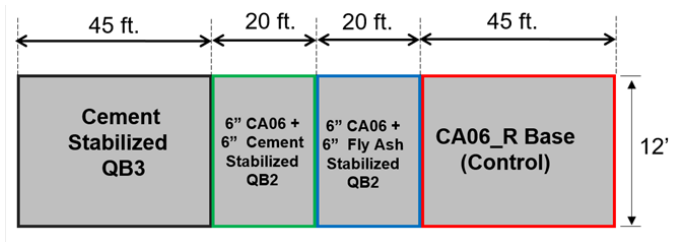


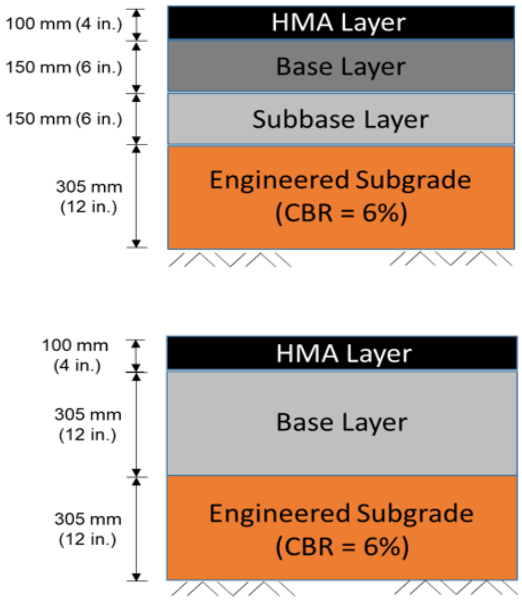


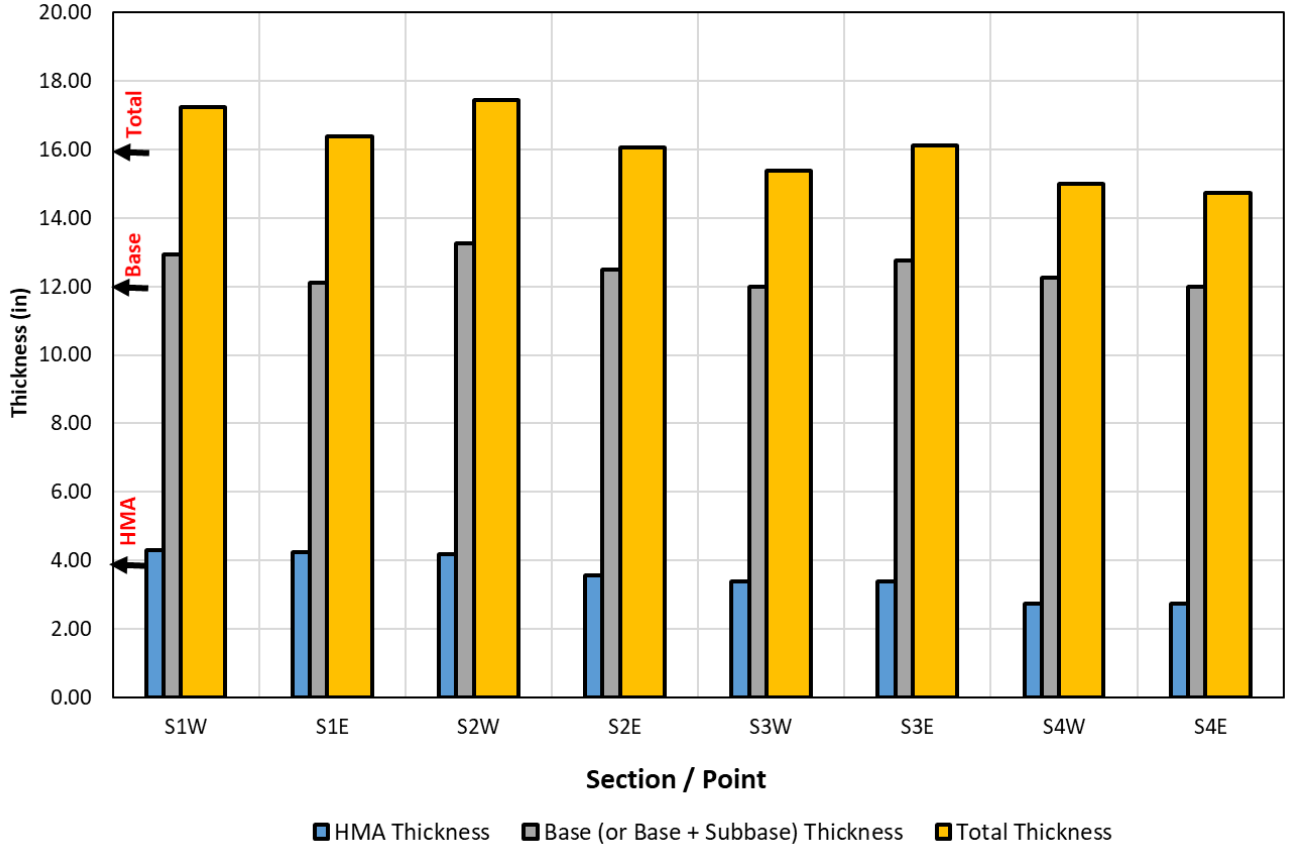


Coring & Trenching Results (Cell 3)

- Nominal Thicknesses:
  - HMA: 4 in.
  - Base: 12 in.
  - Total: 16 in.

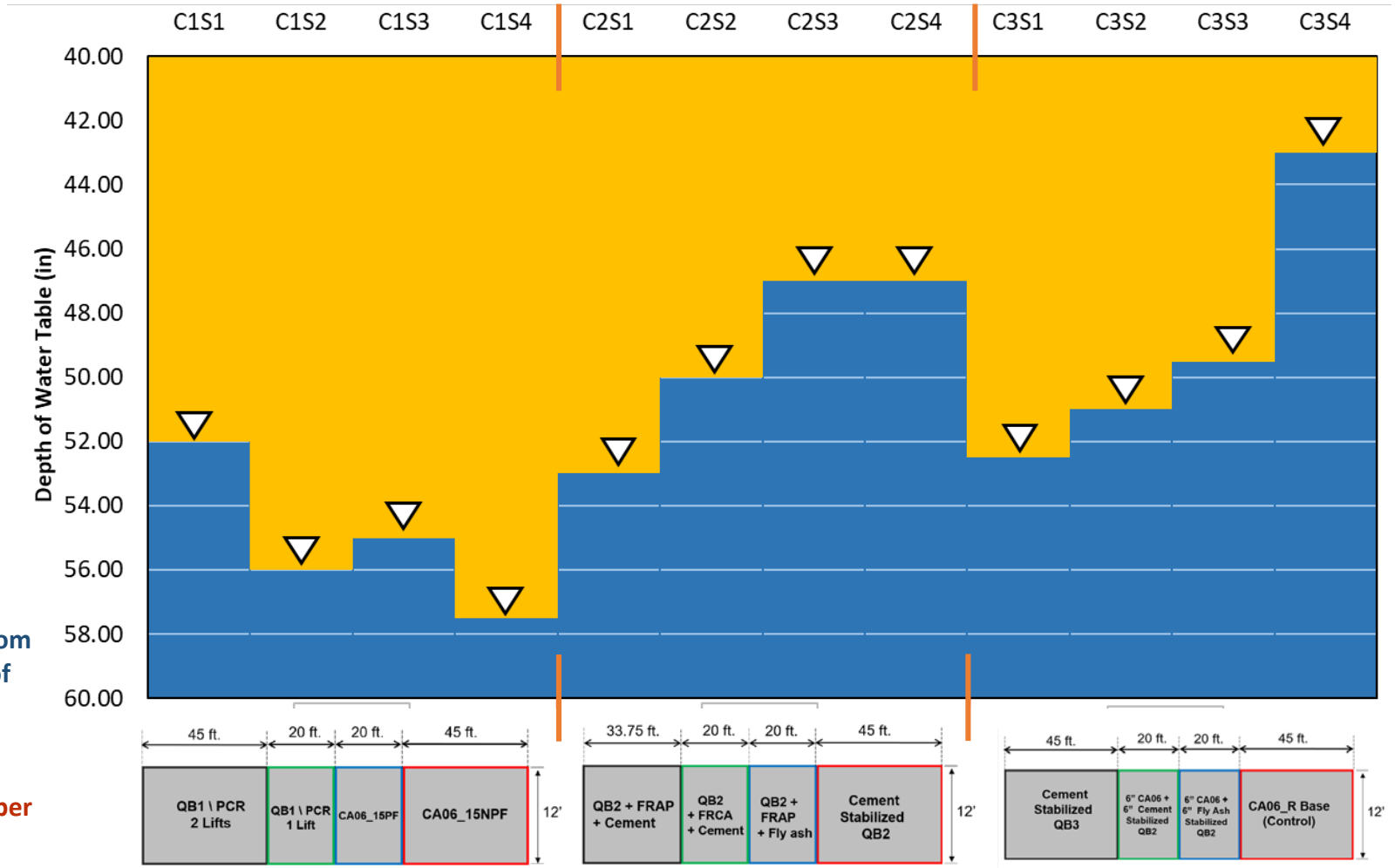






Trenching Results (Cell 1, 2 and 3)

- Depth of Water Table Level: Shallowest for C3S4



Measured from the surface of HMA

Higher value indicate deeper WTL

Findings and Conclusions

- Quarry By-products (QB) were successfully used as a filler material in the voids of large, unconventional, uniformly graded "***aggregate subgrade***" materials to improve strength and reduce potential settlement over soft CBR=1% subgrade
- Construction platform section with 15% plastic fines accumulated the most rutting, indicating the detrimental effect of plastic fines on performance, especially when they were exposed to moisture
- Sections with QB blended with FRAP / FRCA showed the best performance.
    - No significant difference in performance between FRAP & FRCA
- Premature failure of control section can be attributed to lowest HMA thickness, as-constructed low HMA density, and shallowest ground water table

Findings and Conclusions

- Thickness of subsurface and HMA has a significant effect on performance
- Sections stabilized with cement consistently showed better performance than section stabilized with fly ash
- Cement-stabilized layers of two QB sources (QB2 and QB3) showed similarly good performance
- Inverted pavement sections (especially cement stabilized section) showed good performance

Sustainable QB applications need to be brought into IDOT ME design framework

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Thank You

Any Questions?