IOWA STATE UNIVERSITY

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

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Determining Pavement Design Criteria for Recycled Aggregate Base and Large Stone Subbase

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MnDOT Project TPF-5(341)

Monthly Meeting

February 6, 2020

AGENCY MEMBERS

- MnDOT
- Caltrans
- MDOT
- IDOT
- LRRB
- MoDOT
- WisDOT
- NDDOT
- Iowa DOT
- Illinois Tollway

ASSOCIATE MEMBERS

- Aggregate & Ready Mix of MN
- Asphalt Pavement Alliance (APA)
- Braun Intertec
- Infrasense
- Diamond Surface Inc.
- Flint Hills Resources
- International Grooving & Grinding Association (IGGA)
- Midstate Reclamation & Trucking
- MN Asphalt Pavement Association
- Minnesota State University - Mankato
- National Concrete Pavement Technology Center
- Roadscanners
- University of Minnesota - Duluth
- University of New Hampshire
- Mathy Construction Company
- Michigan Tech Transportation Institute (MTTI)
- University of Minnesota
- National Center for Asphalt Technology (NCAT) at Auburn University
- GSE Environmental
- Helix Steel
- Ingios Geotechnics
- WSB
- Cargill
- PITT Swanson Engineering
- University of California Pavement Research Center
- Collaborative Aggregates LLC
- American Engineering Testing, Inc.
- Center for Transportation Infrastructure Systems (CTIS)
- Asphalt Recycling & Reclaiming Association (ARRA)
- First State Tire Recycling
- BASF Corporation
- Upper Great Plains Transportation Institute at North Dakota State University
- 3M
- Pavia Systems, Inc.
- All States Materials Group
- Payne & Dolan, Inc.
- Caterpillar
- The Dow Chemical Company
- The Transtec Group
- Testquip LLC
- Hardrives, Inc.
- Husky Energy
- Asphalt Materials & Pavements Program (AMPP)
- Concrete Paving Association of MN (CPAM)
- MOBA Mobile Automation
- Geophysical Survey Systems
- Leica Geosystems
- University of St. Thomas
- Trimble

OUTLINE

- Follow-up
- Test cells & materials
- Tasks 5 & 6
- Summary
- Discussion
- Future Study

FOLLOW-UP

- **Task 1** – Literature review and recommendations
- **Task 2** – Tech transfer "state of practice"
- **Task 3** – Construction monitoring and reporting
- **Task 4** – Laboratory testing
- **Task 5** – Performance monitoring and reporting
- **Task 6** – Instrumentation
- **Task 7** – Pavement design criteria
- **Task 8 & 9** – Draft/final report

Green – Completed
Red – In Progress

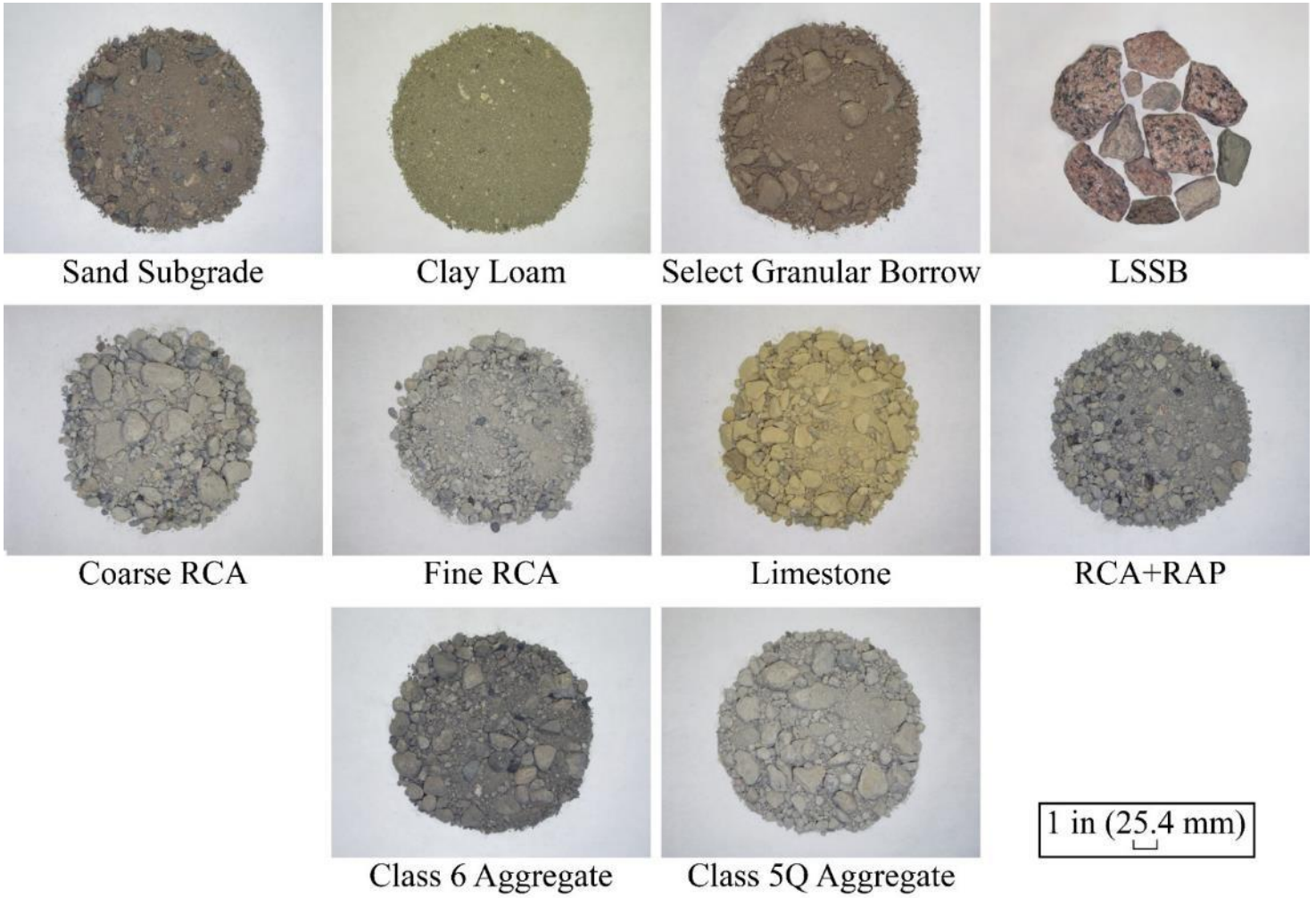
TEST CELLS

Recycled Aggregate Base				Large Stone Subbase		Large Stone Subbase with Geosynthetics				
185	186	188	189	127	227	328	428	528	628	728
3.5 in Superpave	3.5 in Superpave	3.5 in Superpave	3.5 in Superpave	3.5 in Superpave	3.5 in Superpave	3.5 in Superpave	3.5 in Superpave	3.5 in Superpave	3.5 in Superpave	3.5 in Superpave
12 in Coarse RCA	12 in Fine RCA	12 in Limestone	12 in RCA+RAP	6 in Class 6 Aggregate	6 in Class 6 Aggregate	6 in Class 5Q Aggregate	6 in Class 5Q Aggregate	6 in Class 5Q Aggregate	6 in Class 5Q Aggregate	6 in Class 5Q Aggregate
3.5 in S. Granular Borrow	3.5 in S. Granular Borrow	3.5 in S. Granular Borrow	3.5 in S. Granular Borrow	18 in LSSB (1 lift)	18 in LSSB (1 lift)	9 in LSSB TX	9 in LSSB TX+GT	9 in LSSB BX+GT	9 in LSSB BX	9 in LSSB
Sand	Sand	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam

S. Granular Borrow = Select Granular Borrow

TX = Triaxial Geogrid
BX = Biaxial Geogrid
GT = Nonwoven Geotextile

MATERIALS


Sand Subgrade
Clay Loam
Select Granular Borrow
LSSB
Coarse RCA
Fine RCA
Limestone
RCA+RAP
Class 6 Aggregate
Class 5Q Aggregate
1 in (25.4 mm)

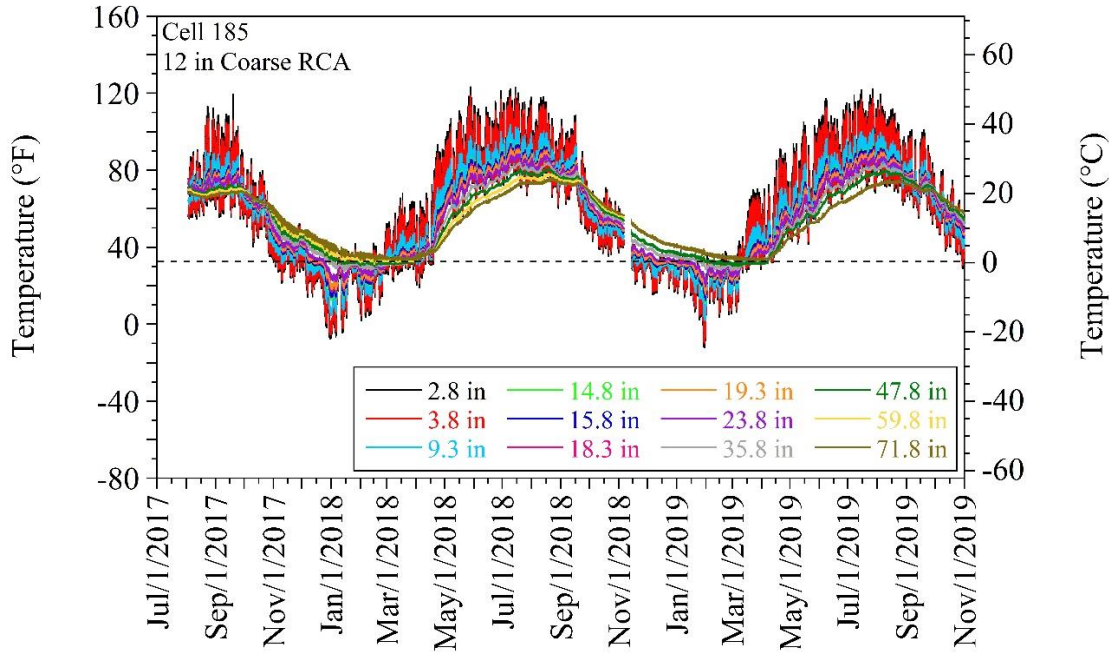
TASKS 5 & 6

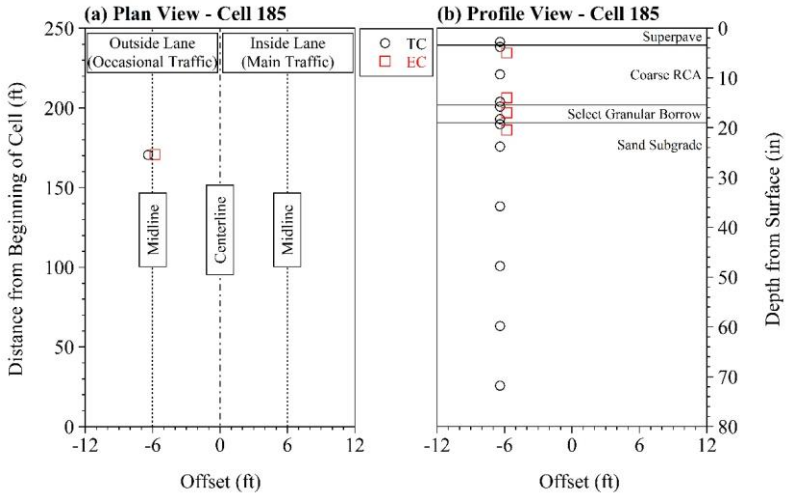
- Falling weight deflectometer (FWD)
- Frost heave
- International roughness index (IRI)
- Rutting
- Environmental monitoring
  - Weather data
  - Temperature sensors
  - Moisture sensors
  - Frost depth
- Pavement distresses

Green – Completed
Red – In Progress

SENSORS

Temperature Profiles





TC = Thermocouple
EC = Moisture probe

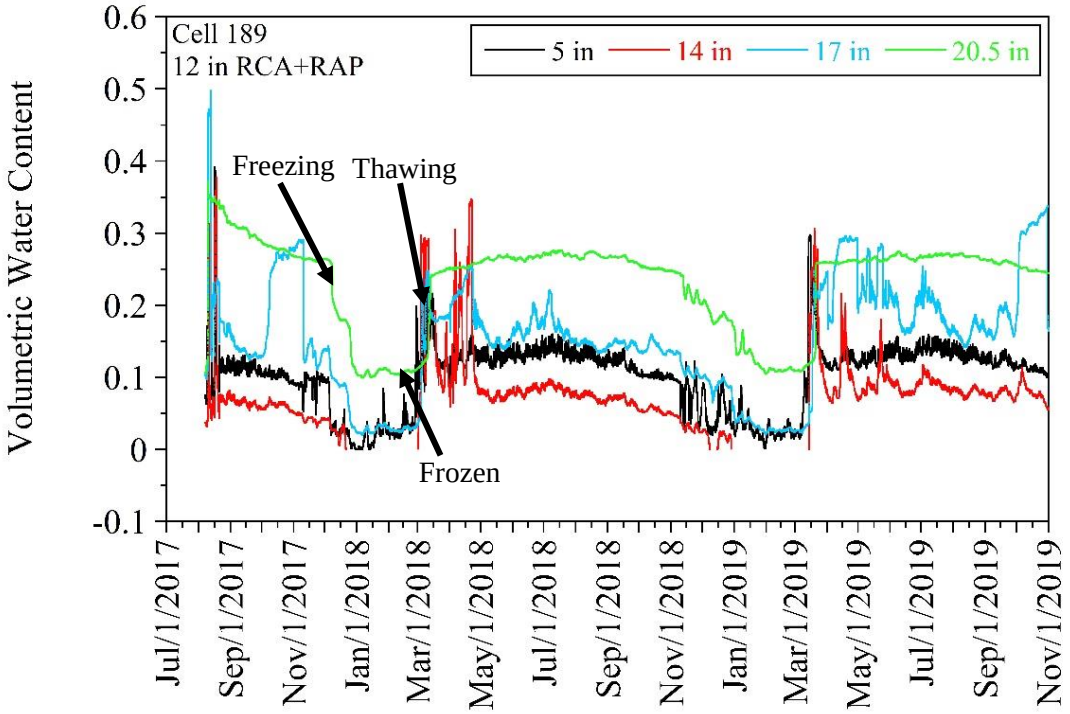
SENSORS

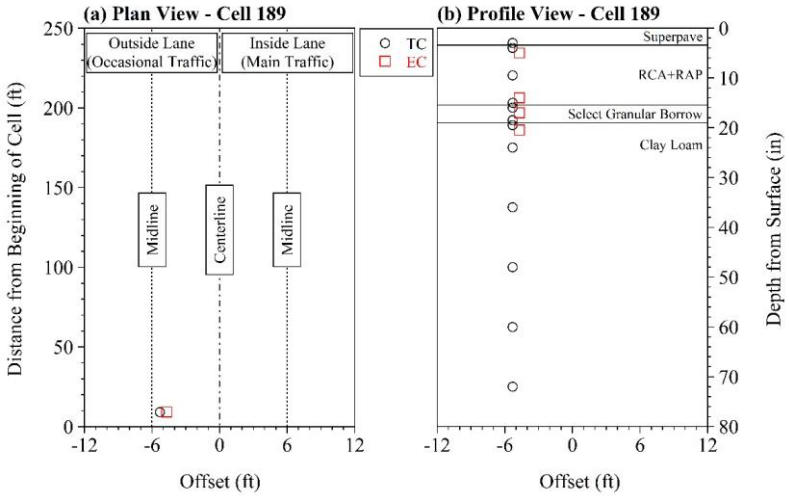
Moisture Profiles

- Moisture probe
  - Dielectric constants → volumetric water content (VWC)
    - Air ≈ 1
    - Dry soil ≈ 4 to 16
    - Water ≈ 80
- Liquid water content ↑ dielectric constant of soil ↑
- Freezing
  - Liquid water content ↓ ice content ↑ dielectric constant of soil ↓
  - Decrease in the VWC
- Thawing
  - Liquid water content ↑ ice content ↓ dielectric constant of soil ↑
  - Increase in the VWC

SENSORS

Temperature Profiles





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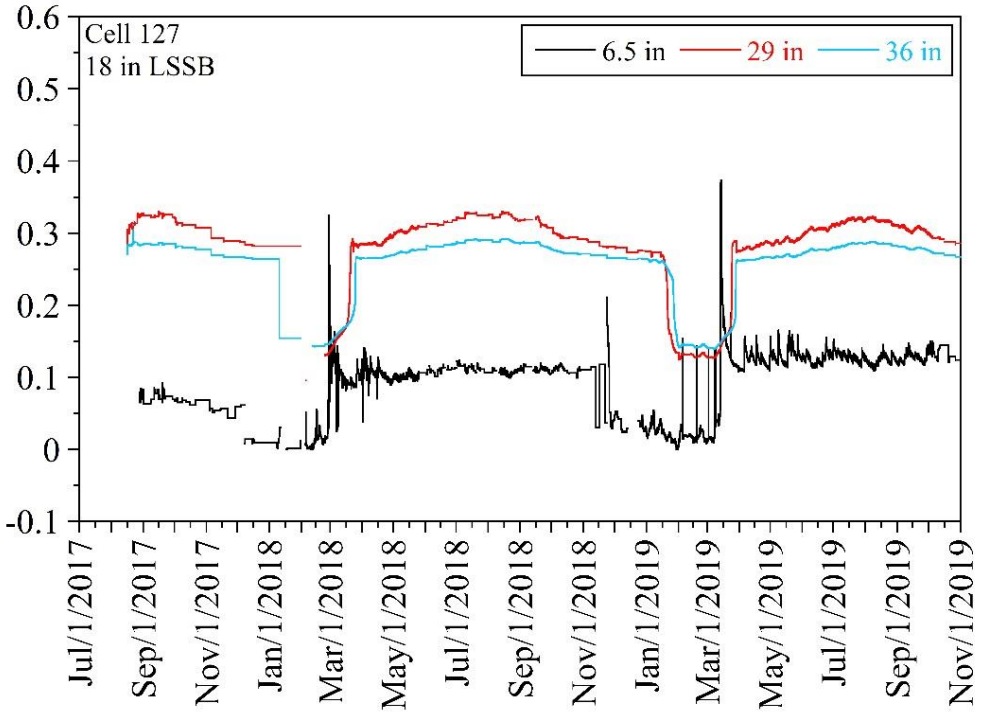
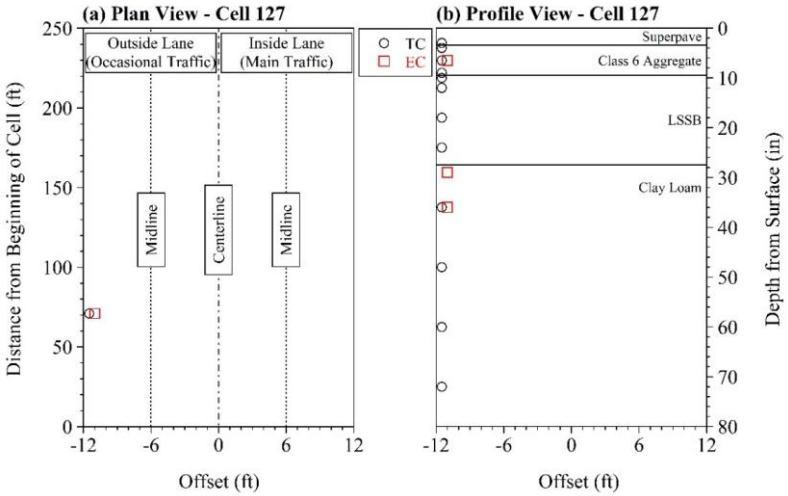
SENSORS

Temperature Profiles





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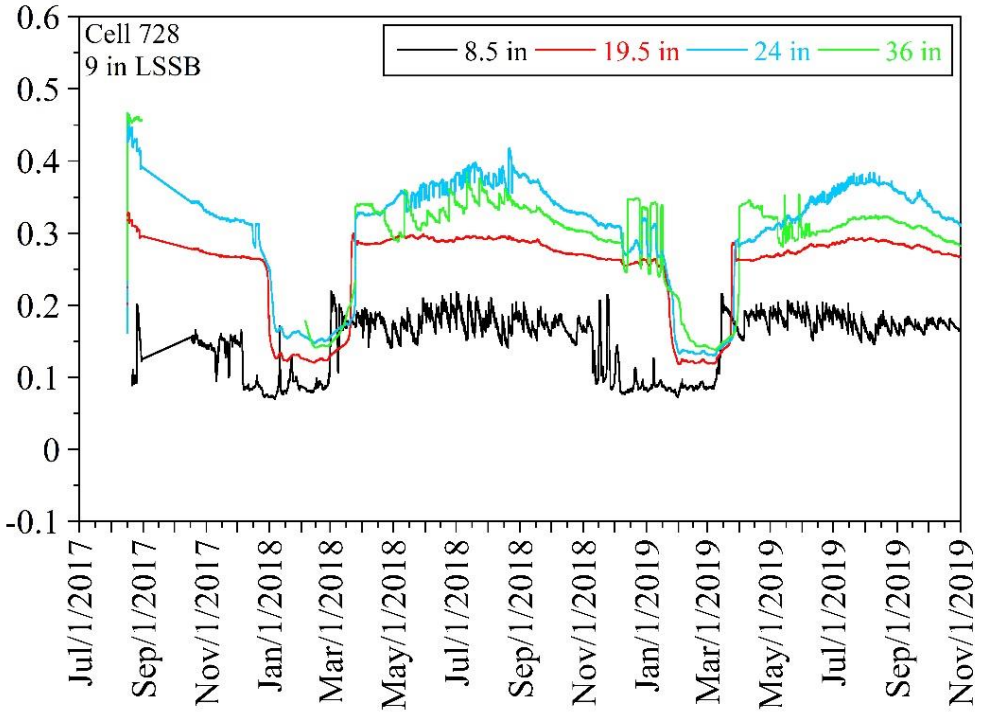
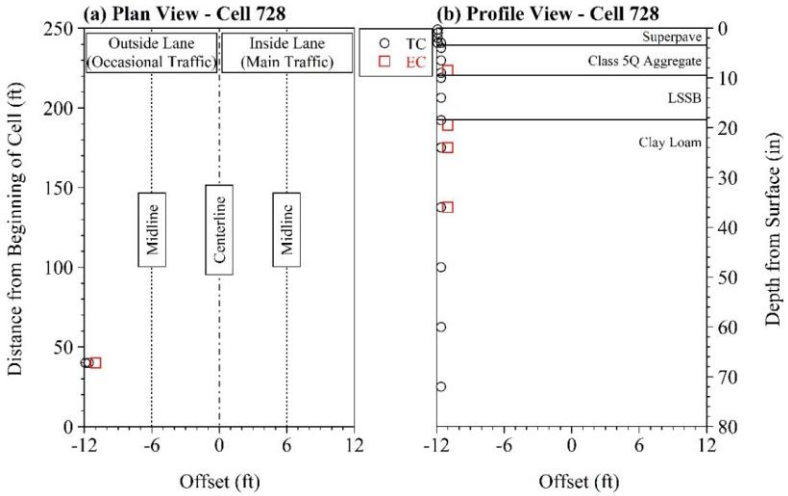
SENSORS

Temperature Profiles





TC = Thermocouple
EC = Moisture probe

FROST PENETRATION DEPTH

Laboratory and field performance of recycled aggregate base in a seasonally cold region

Tuncer B. Edil, Bora Cetin, Ali Soleimanbeigi (2017)

- Freeze-point depression
  - Temperature at which water would begin to freeze in the materials
- Complete freezing
  - Lower temperature than the freeze-point depression

Table 2 Freezing-point depressions and freezing temperatures of materials (Rosa *et al.*, 2016).

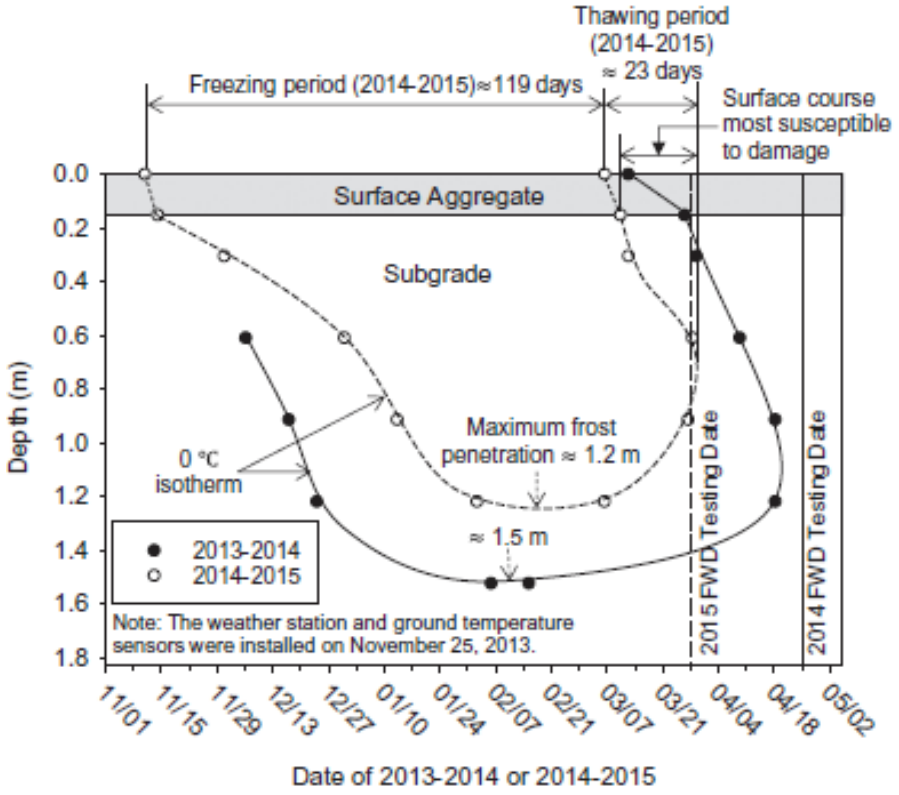
Materials	Freezing-point depression (°C)	Freezing temperature (°C)
RCA	–	−12
50% RCA~50% Aggregate	–	−12
RAP	−10	−15
Natural aggregate	−5.2	−12

FROST PENETRATION DEPTH

Mechanistic-based comparisons for freeze-thaw performance of stabilized unpaved roads

Cheng Li, Pavana K.R. Vennapusa, Jeramy Ashlock, David J. White (2017)

- 0°C isotherm lines

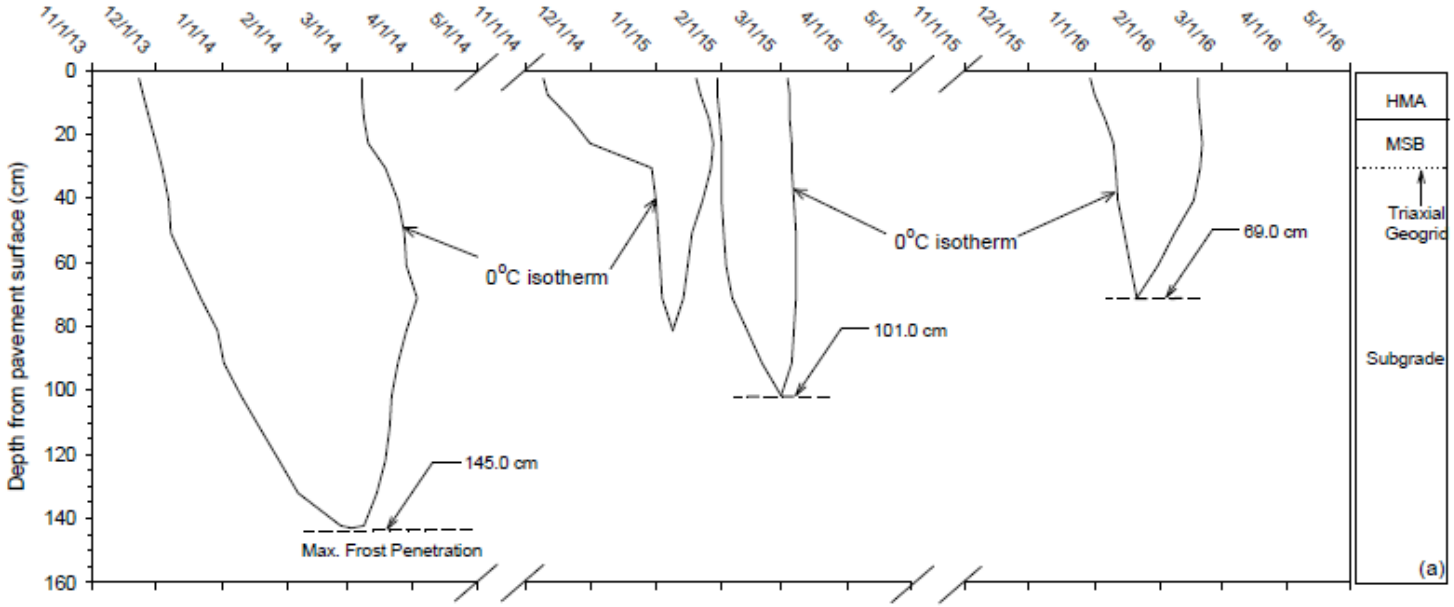


FROST PENETRATION DEPTH

Assessing seasonal performance, stiffness, and support conditions of pavement foundations

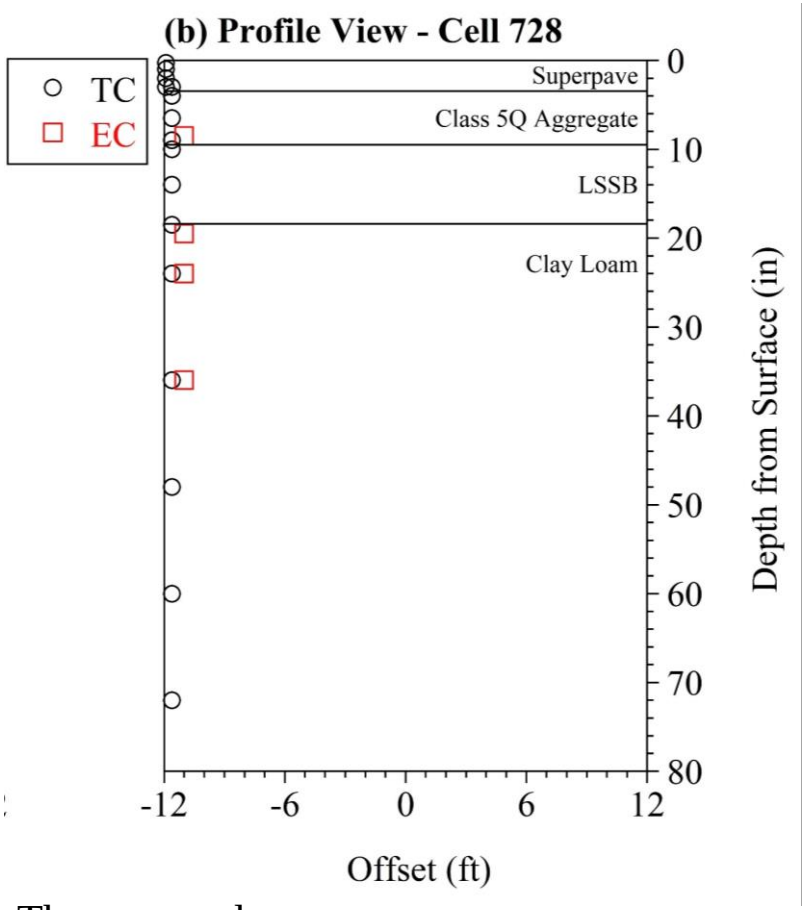
Yang Zhang (2016)

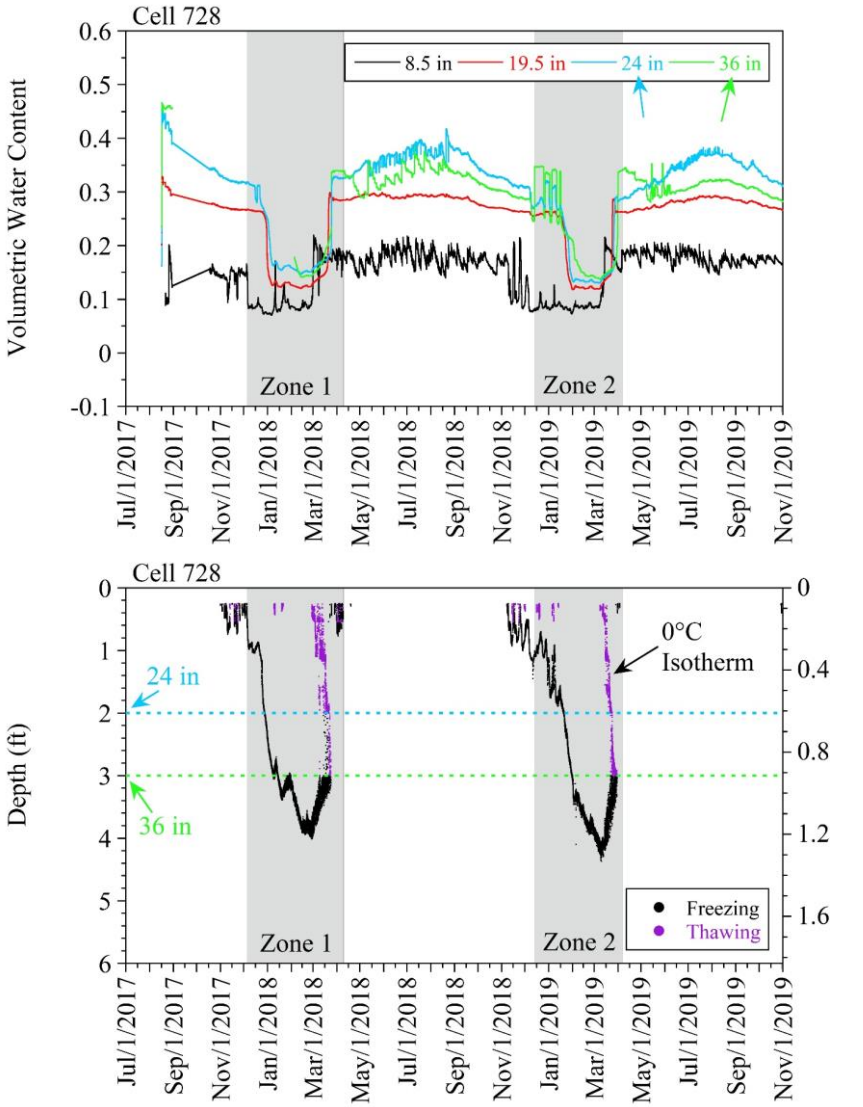
- 0°C isotherm lines (Andersland and Ladanyi 2004)



FROST PENETRATION DEPTH

Cell 728 – 0°C Isotherm

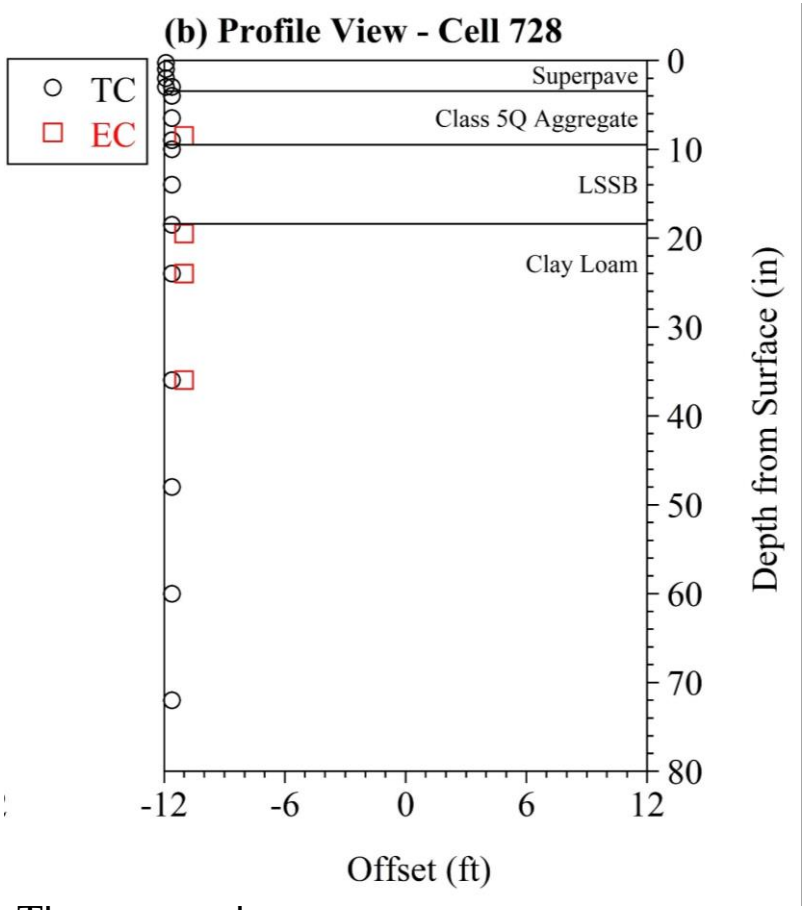


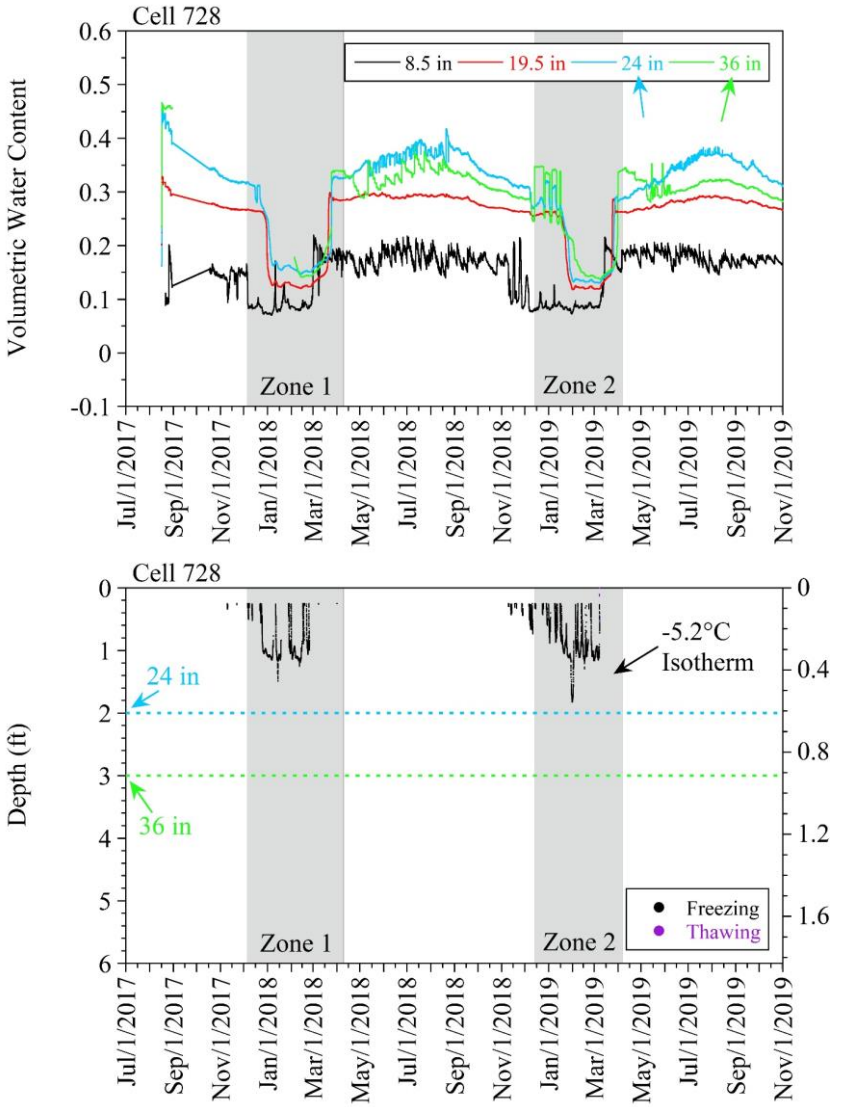


TC = Thermocouple
EC = Moisture probe

FROST PENETRATION DEPTH

Cell 728 – -5.2°C Isotherm





TC = Thermocouple
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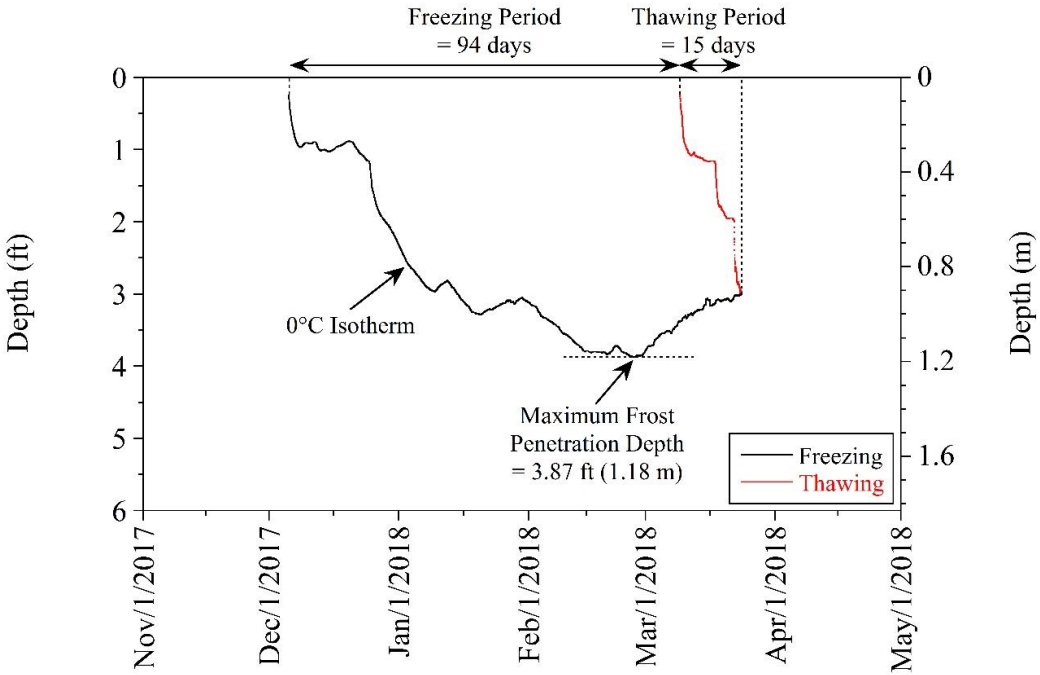
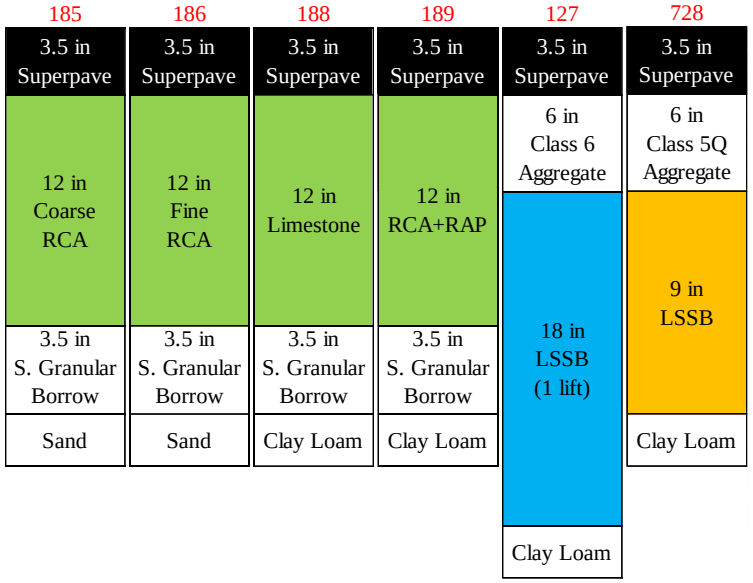
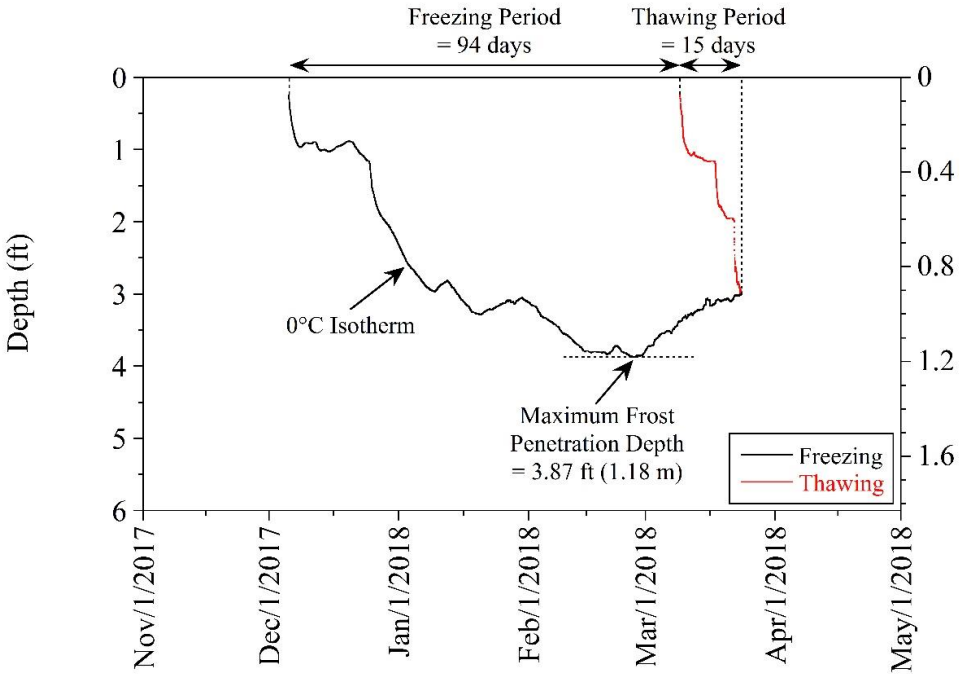
FROST PENETRATION DEPTH

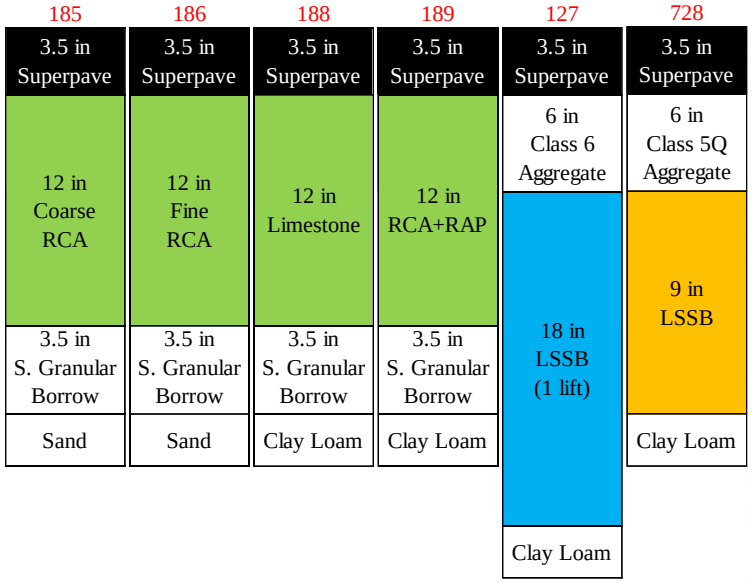




Cell Number	Cell Description	2017-2018		2018-2019	
		Freezing Period (days)	Thawing Period (days)	Freezing Period (days)	Thawing Period (days)
185	12 in Coarse RCA	83	25	116	27
186	12 in Fine RCA	84	28	116	27
188	12 in Limestone	84	18	121	18
189	12 in RCA+RAP	84	16	120	23
127	18 in LSSB	84	28	121	22
728	9 in LSSB	94	15	124	17

FROST PENETRATION DEPTH





Cell Number	Cell Description	2017-2018 Maximum Frost Penetration Depth		2018-2019 Maximum Frost Penetration Depth	
		(ft)	(m)	(ft)	(m)
185	12 in Coarse RCA	4.44	1.35	4.75	1.45
186	12 in Fine RCA	4.24	1.29	4.39	1.34
188	12 in Limestone	4.9	1.49	5.52	1.68
189	12 in RCA+RAP	4.47	1.36	5.09	1.55
127	18 in LSSB	4.29	1.31	4.81	1.47
728	9 in LSSB	3.87	1.18	4.17	1.27

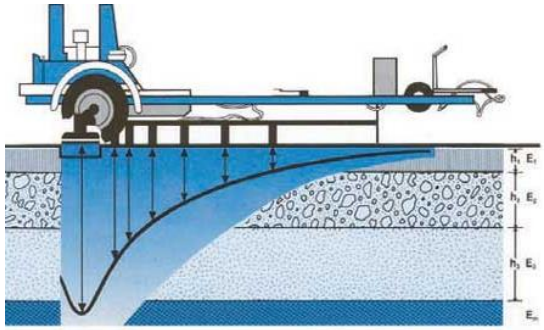
FWD

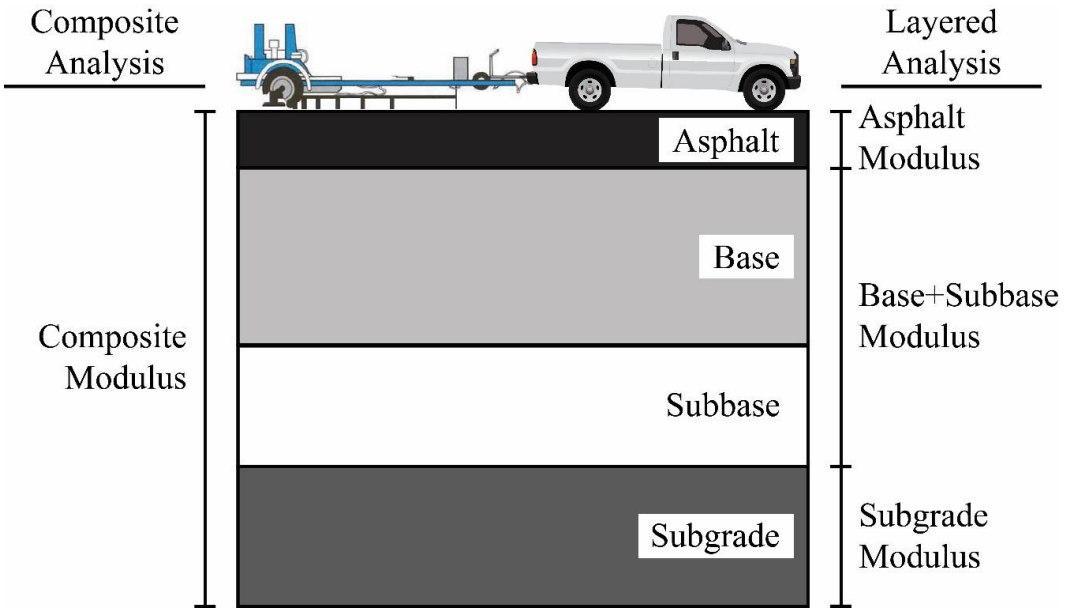
- Composite analysis
  - Maximum deflections

$$E = \frac{(1-\nu^2)\sigma_0 a}{d_0} f$$

where:
E=elastic modulus (MPa),
d_0=measured settlement (mm),
ν=Poisson's ratio,
σ_0=applied stress (MPa),
a=radius of the plate (mm), and
f=shape factor depending on stress distribution

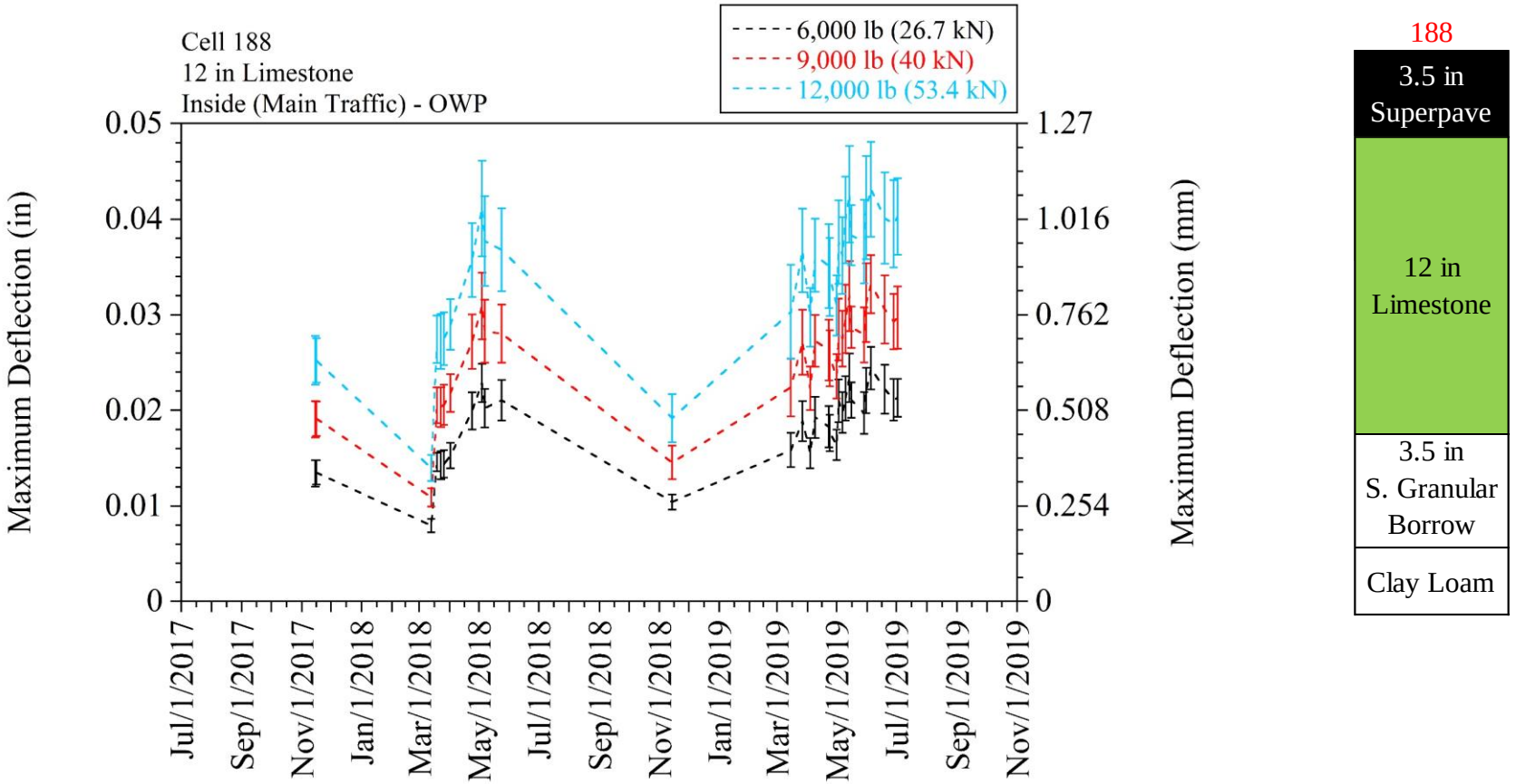
- Layered analysis
  - Deflection basins
  - MODULUS 7.0





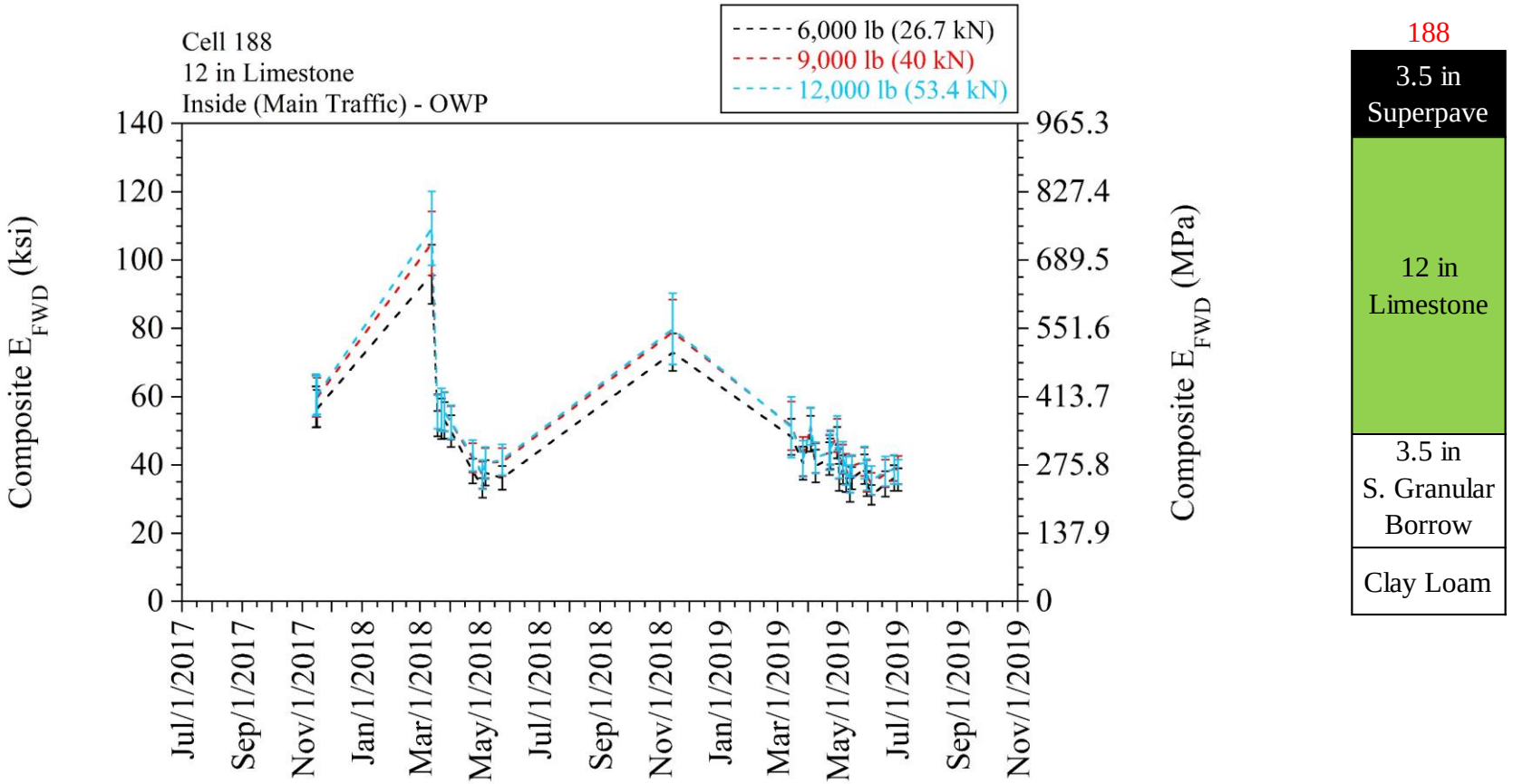
FWD

- Different loads
  - Maximum deflection



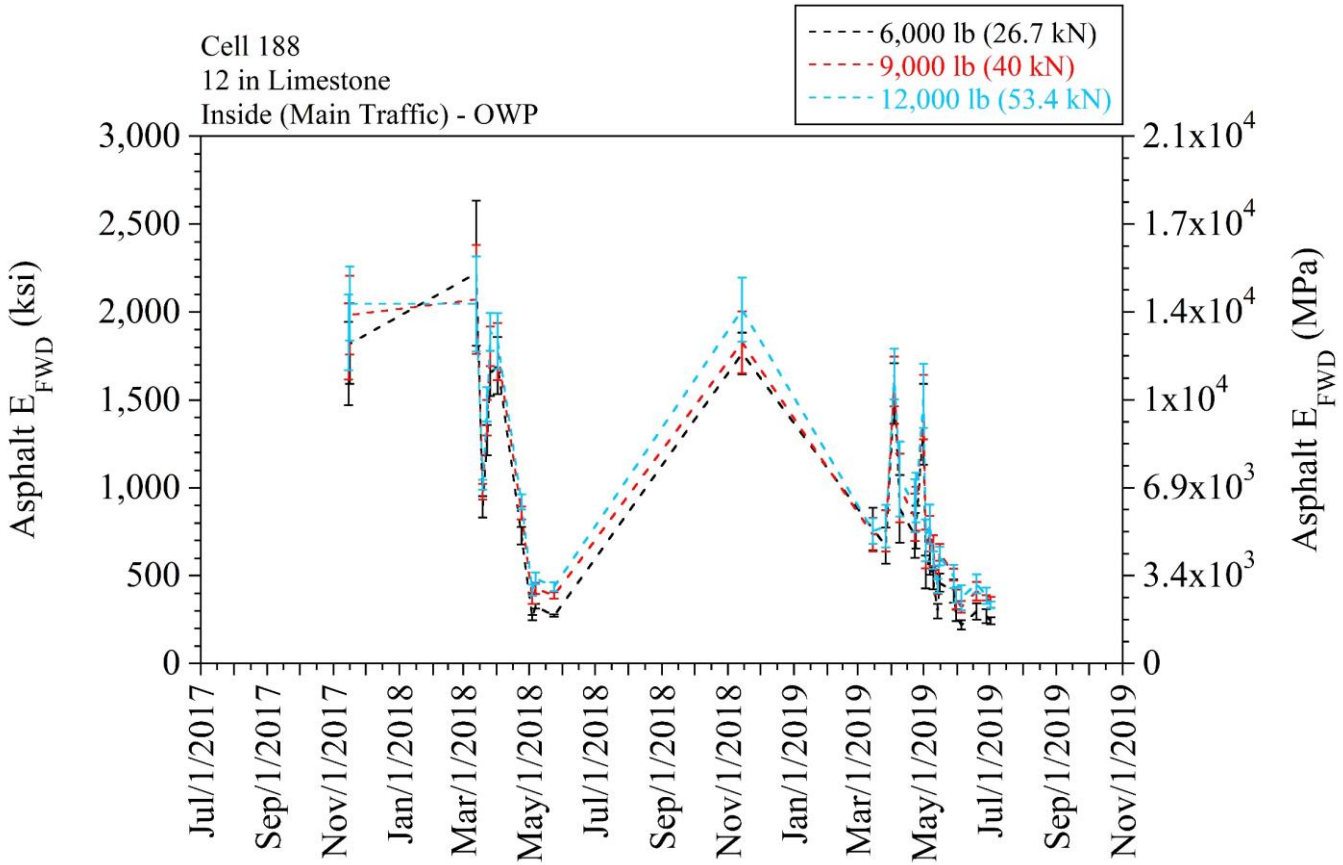
FWD

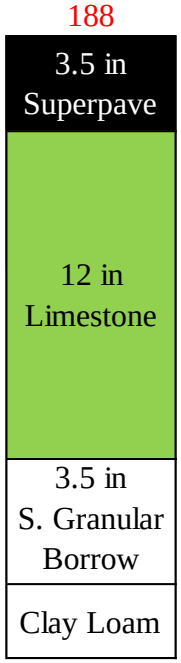
- Different loads
  - Composite E_{FWD}



FWD

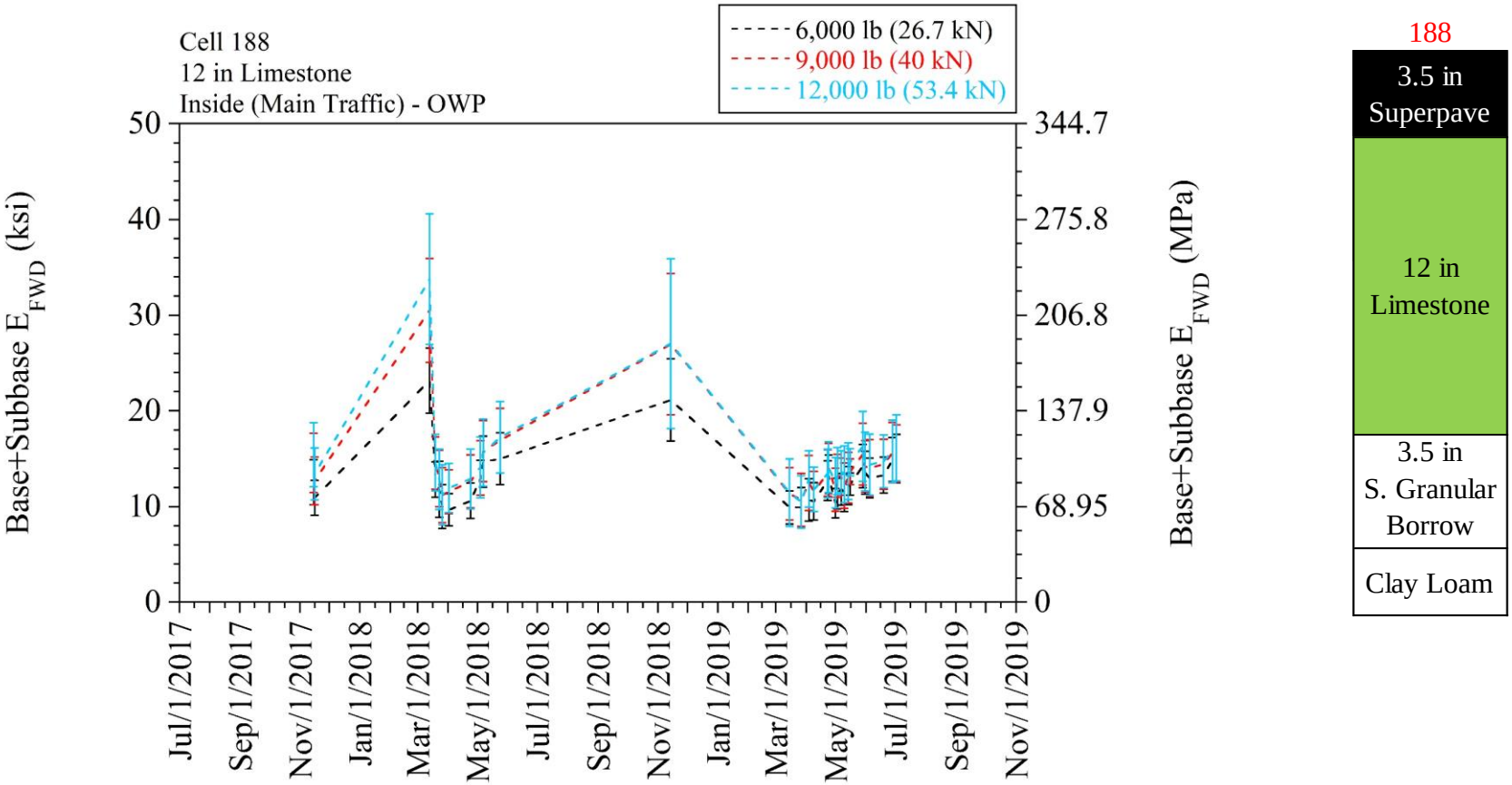
- Different loads
  - Asphalt E_{FWD}





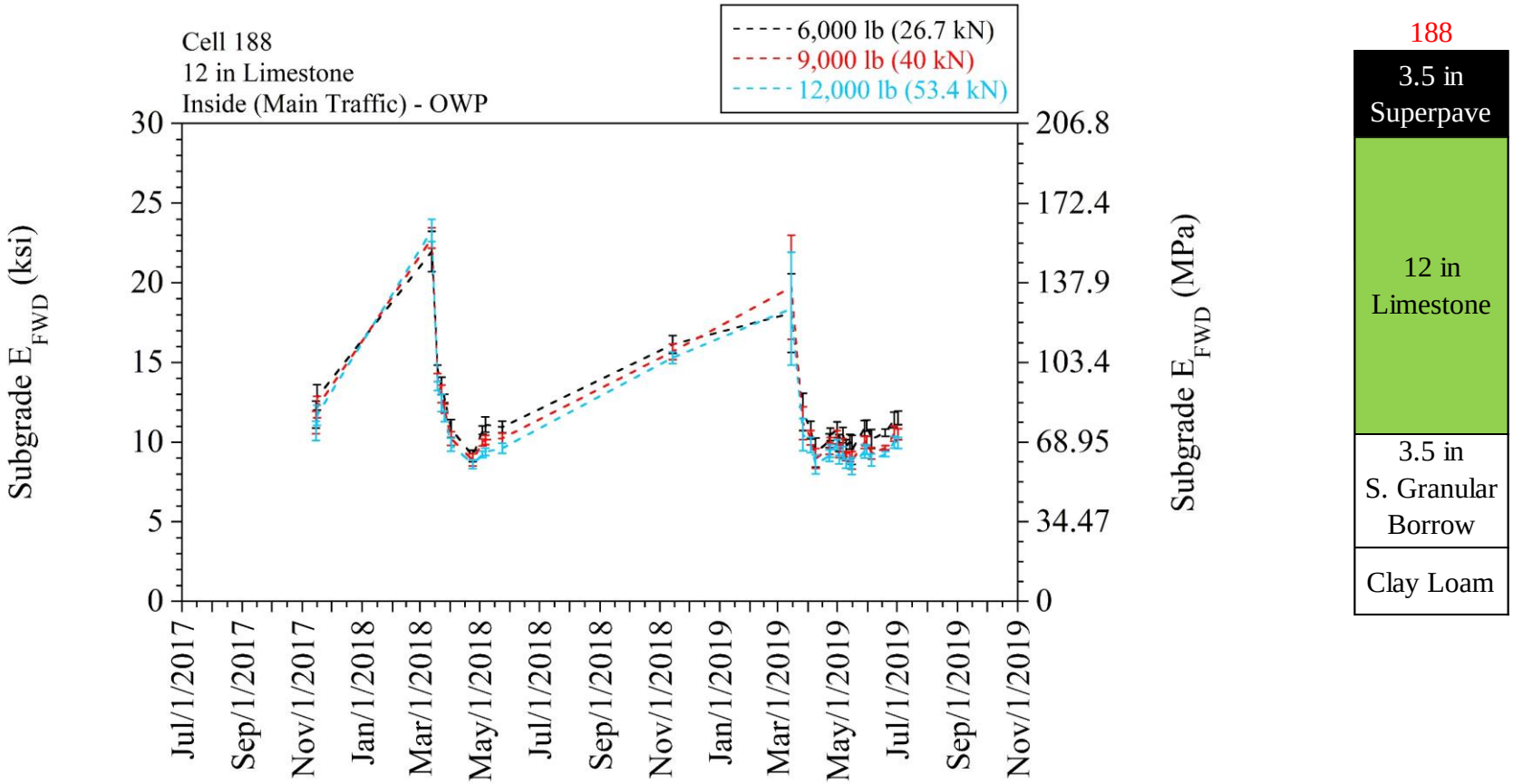
FWD

- Different loads
  - Base+subbase E_{FWD}



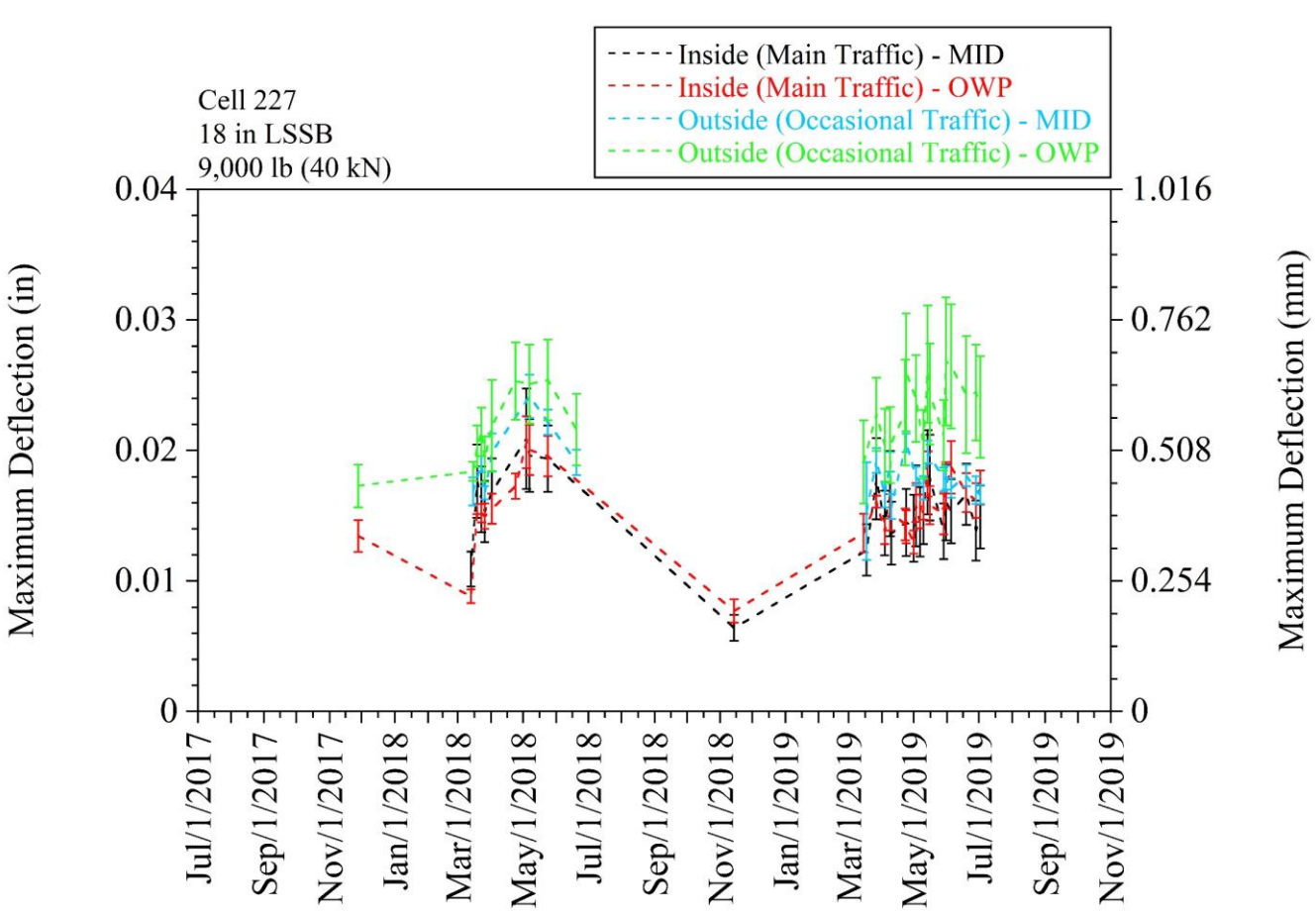
FWD

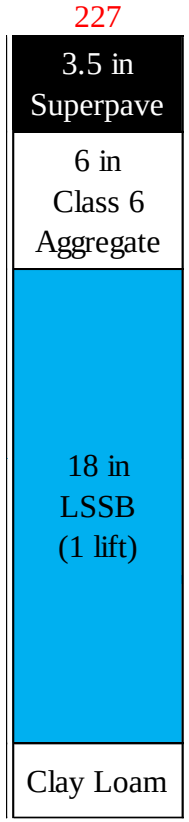
- Different loads
  - Subgrade E_{FWD}



FWD

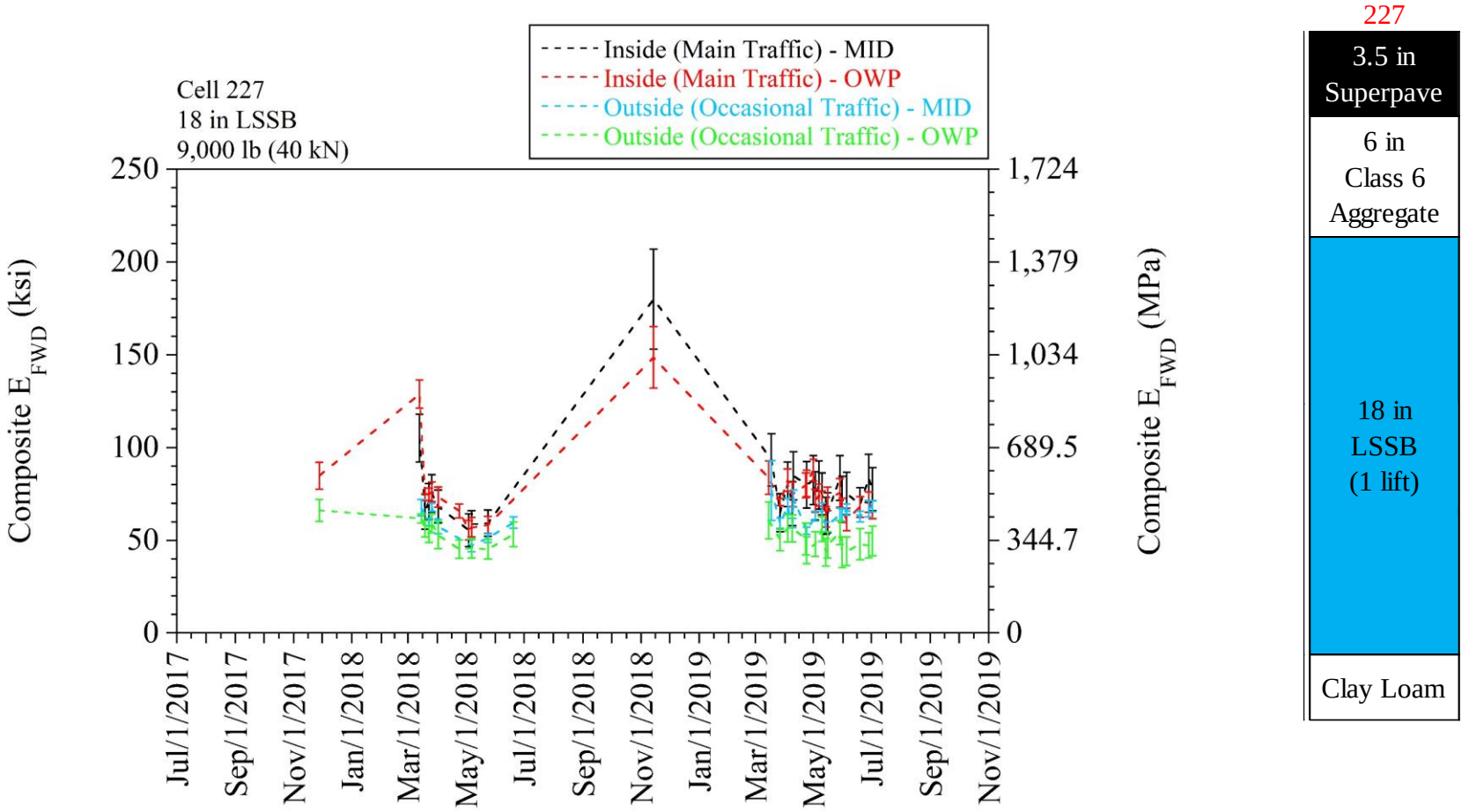
- Different lanes & wheel paths
  - Maximum deflection





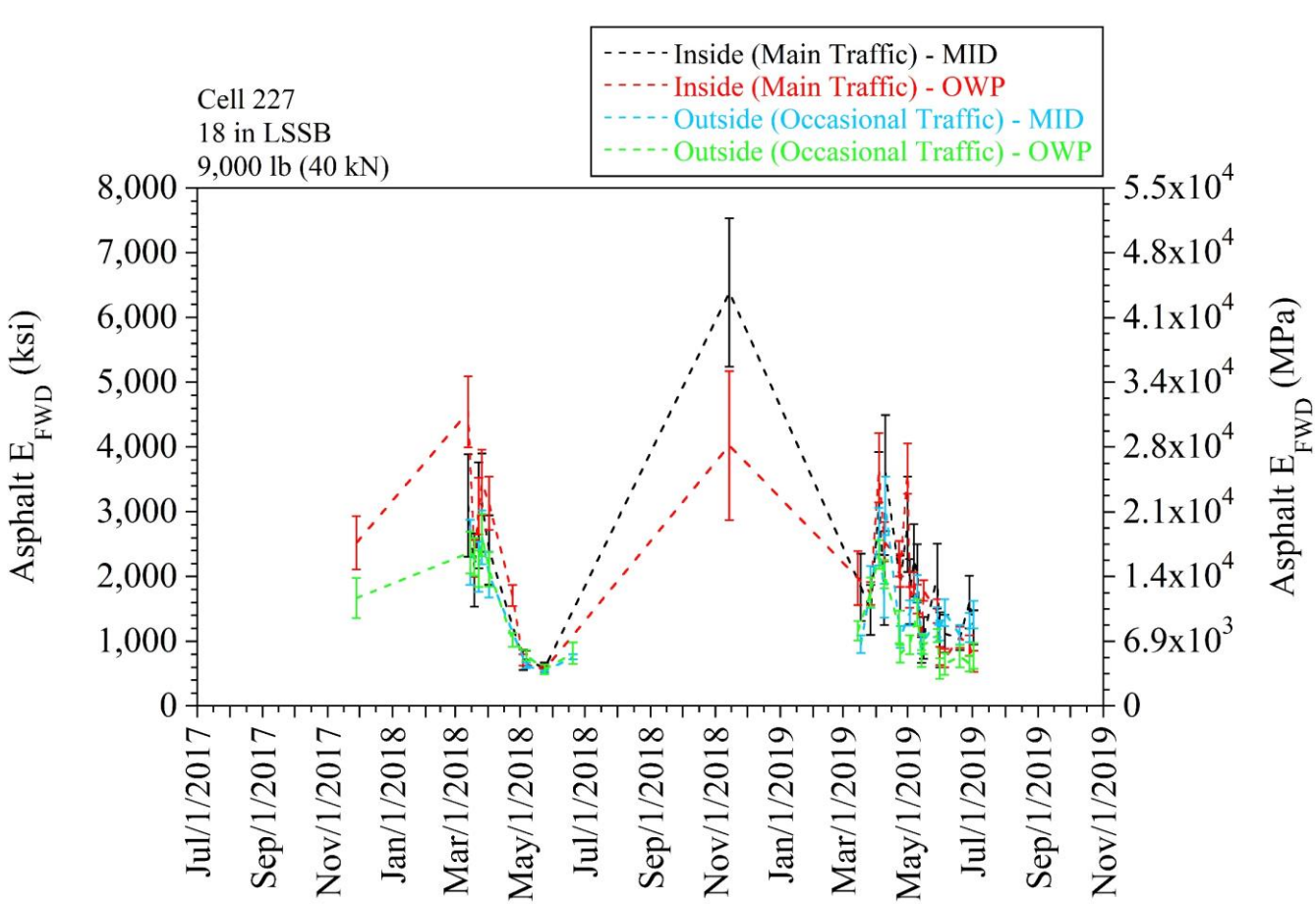
FWD

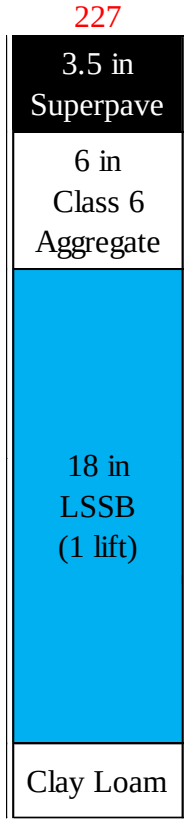
- Different lanes & wheel paths
  - Composite E_{FWD}



FWD

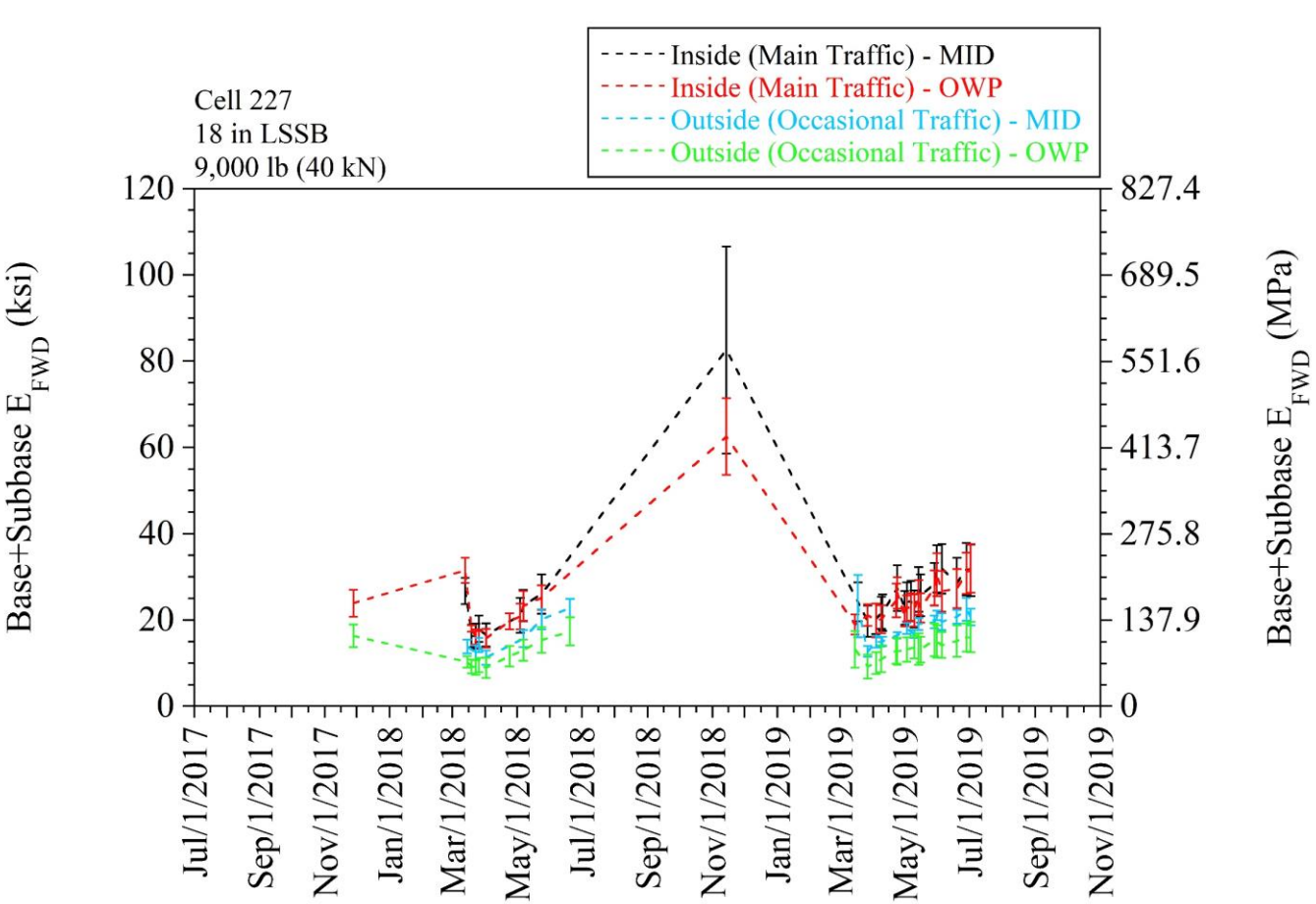
- Different lanes & wheel paths
  - Asphalt E_{FWD}

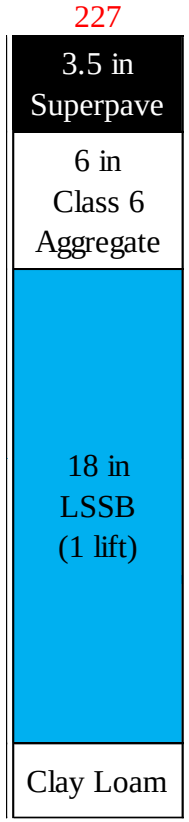




FWD

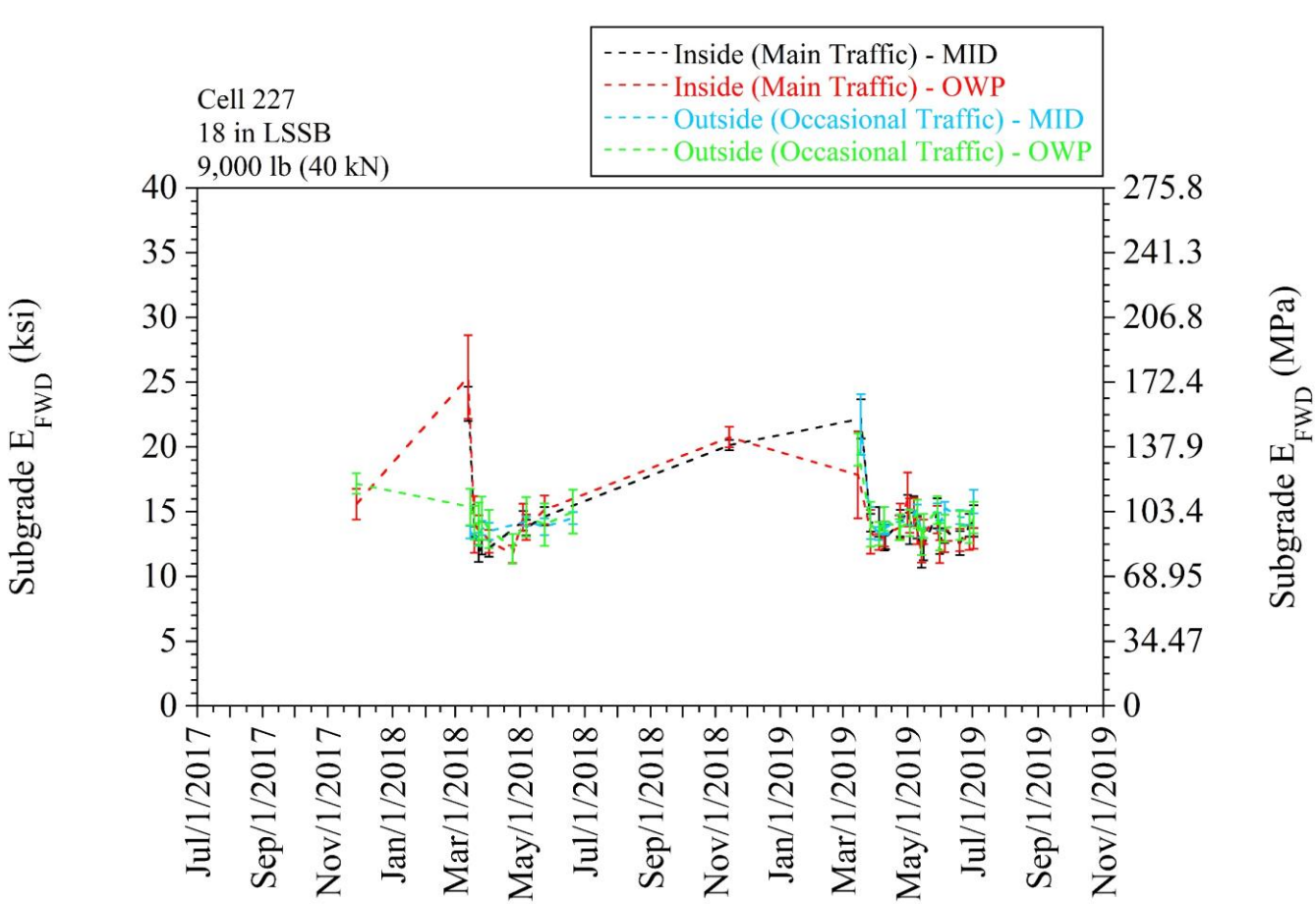
- Different lanes & wheel paths
  - Base+subbase E_{FWD}

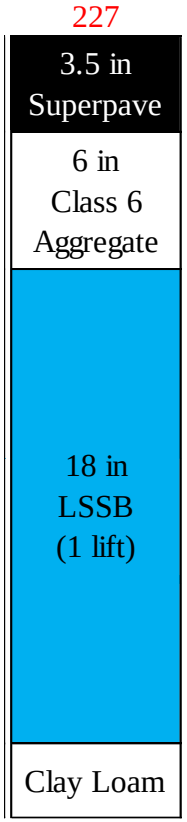




FWD

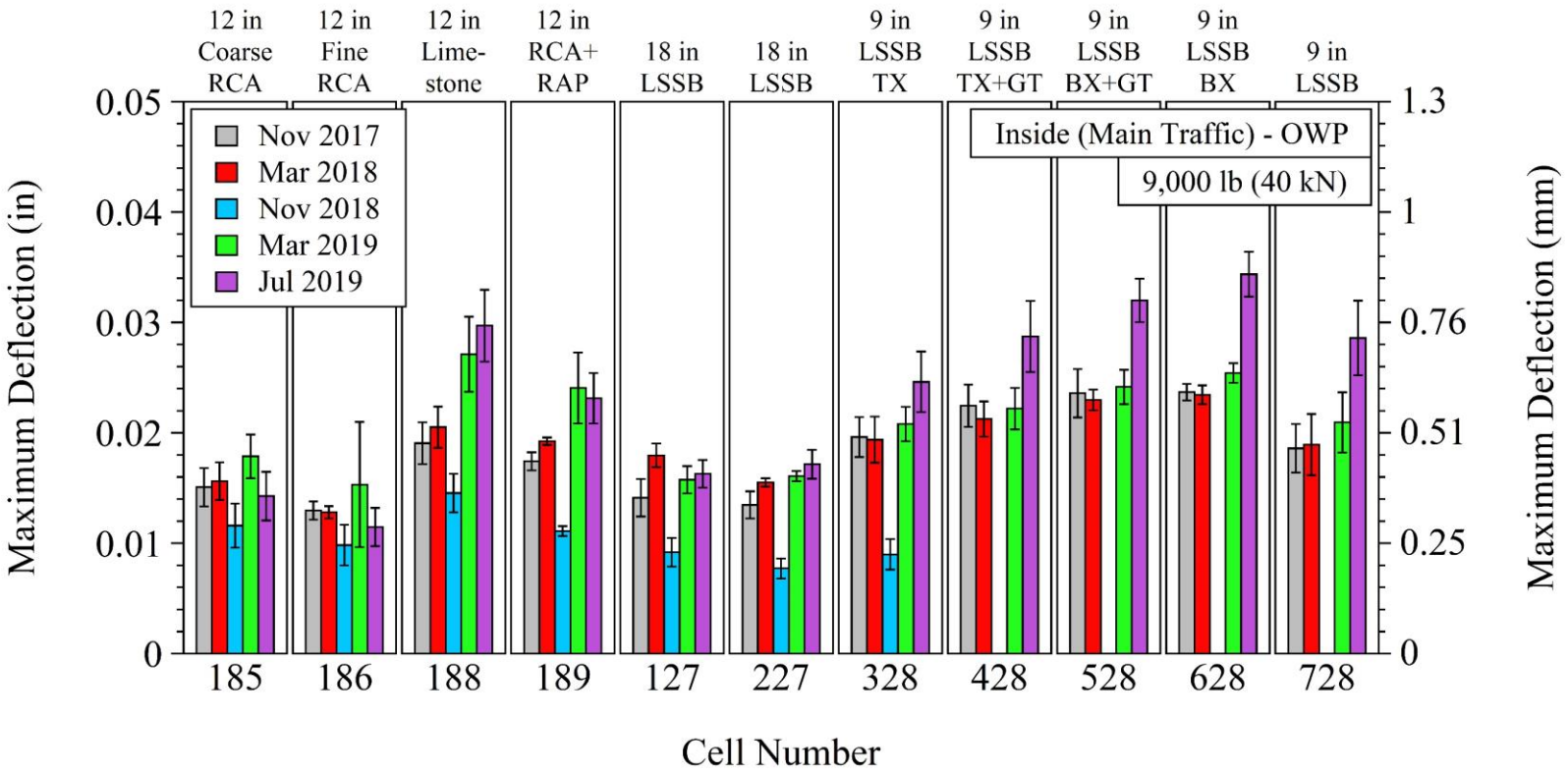
- Different lanes & wheel paths
  - Subgrade E_{FWD}





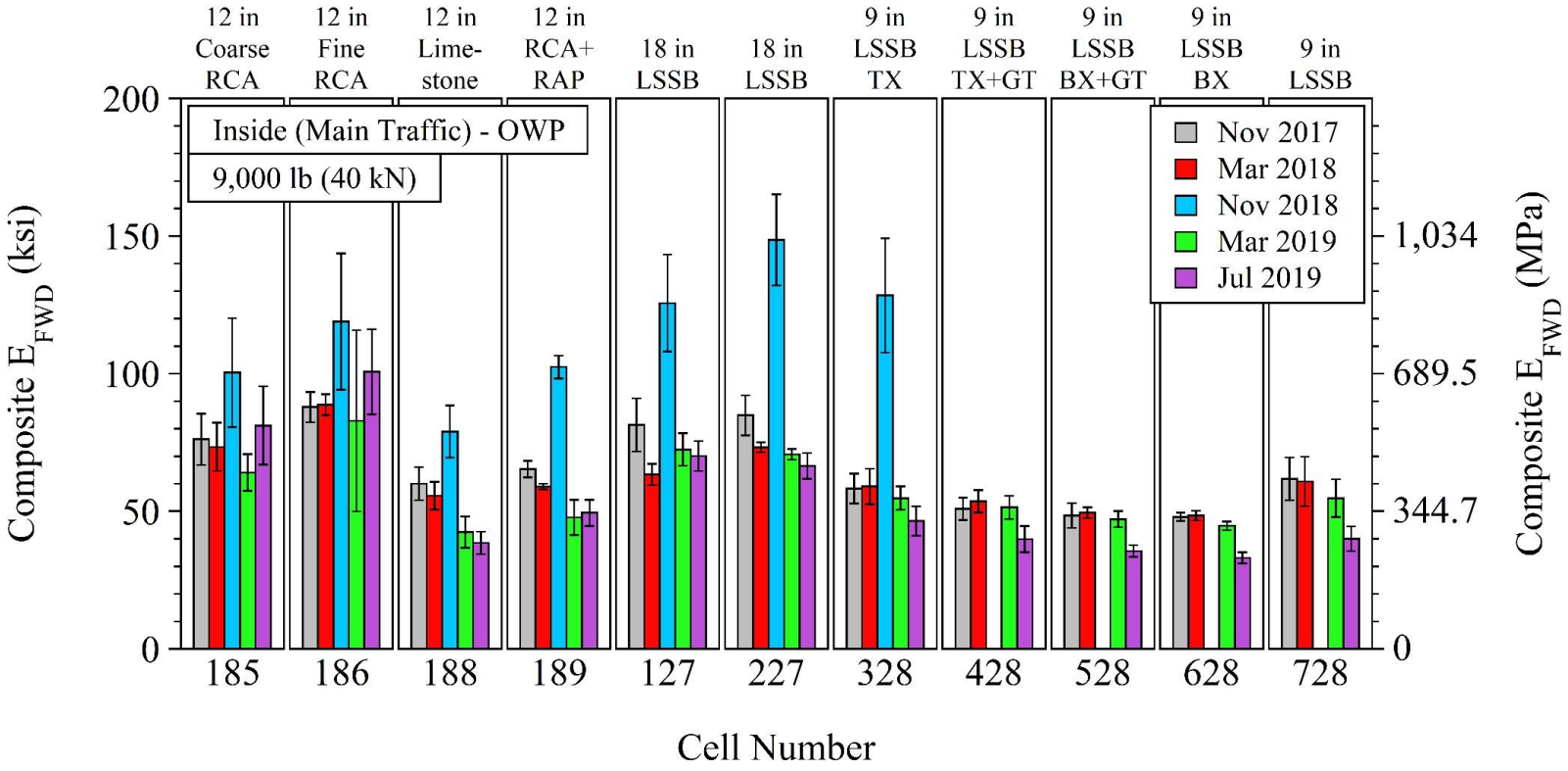
FWD

- Long-term performance
  - Maximum deflection



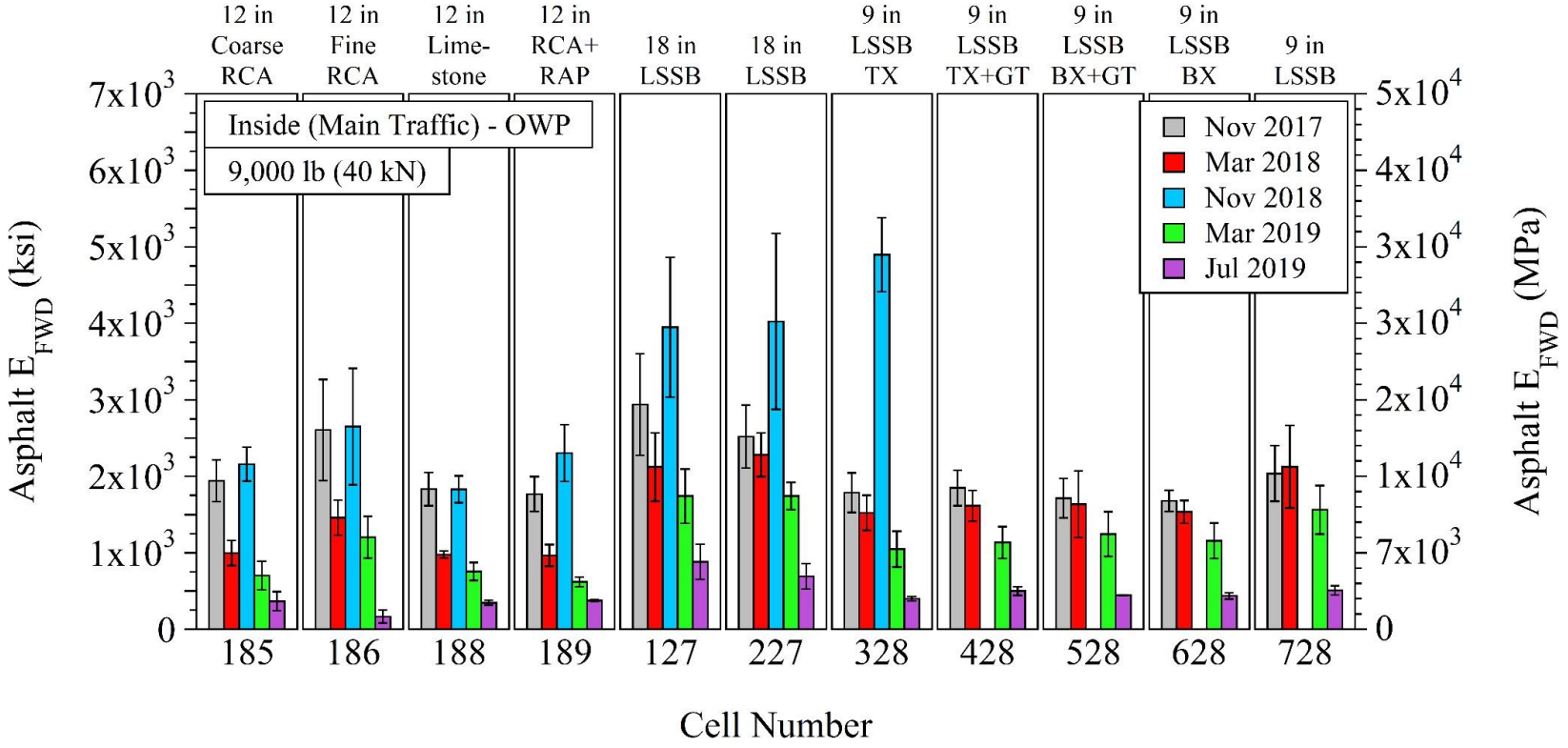
FWD

- Long-term performance
  - Composite E_{FWD}



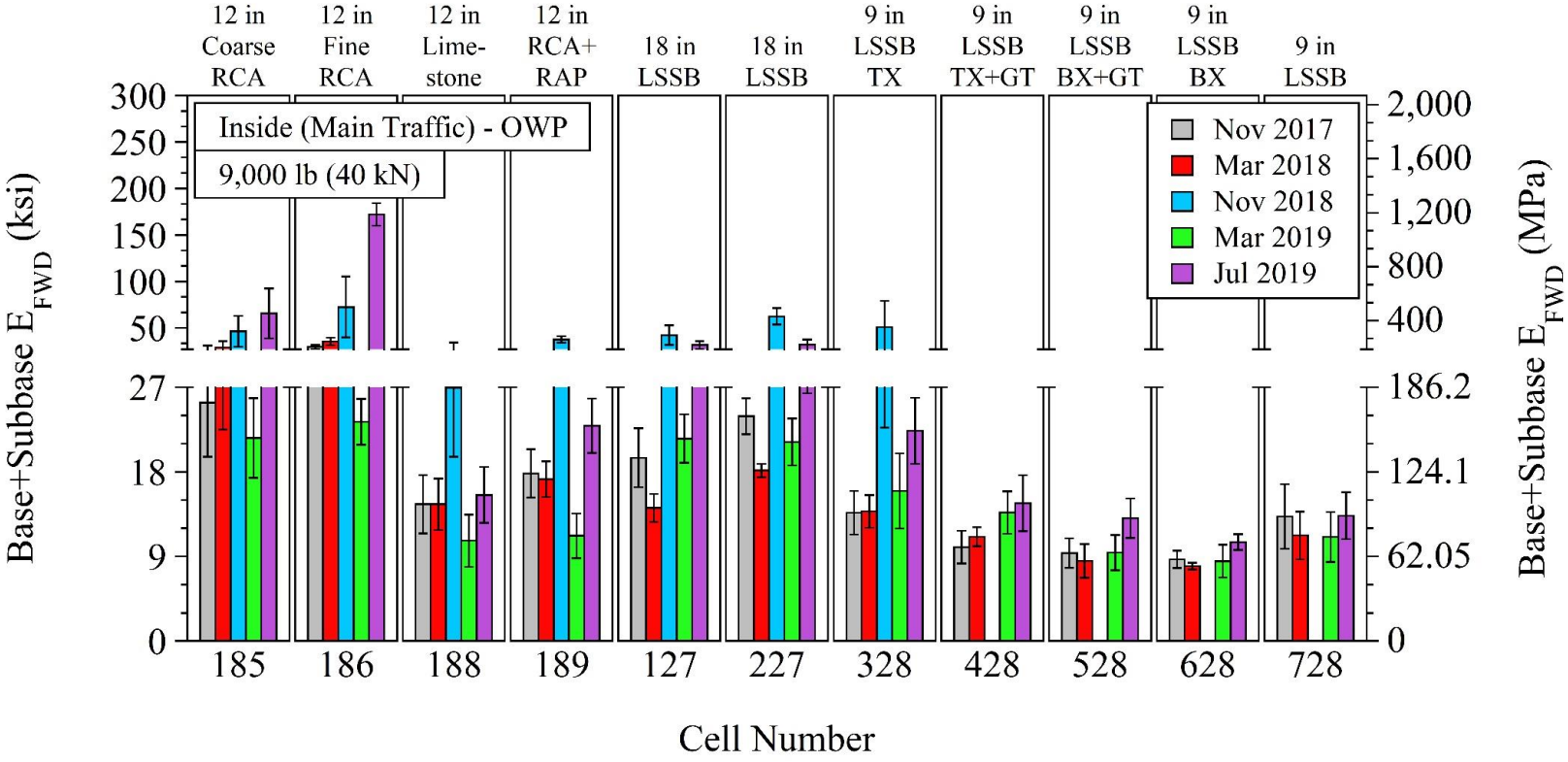
FWD

- Long-term performance
  - Asphalt E_{FWD}



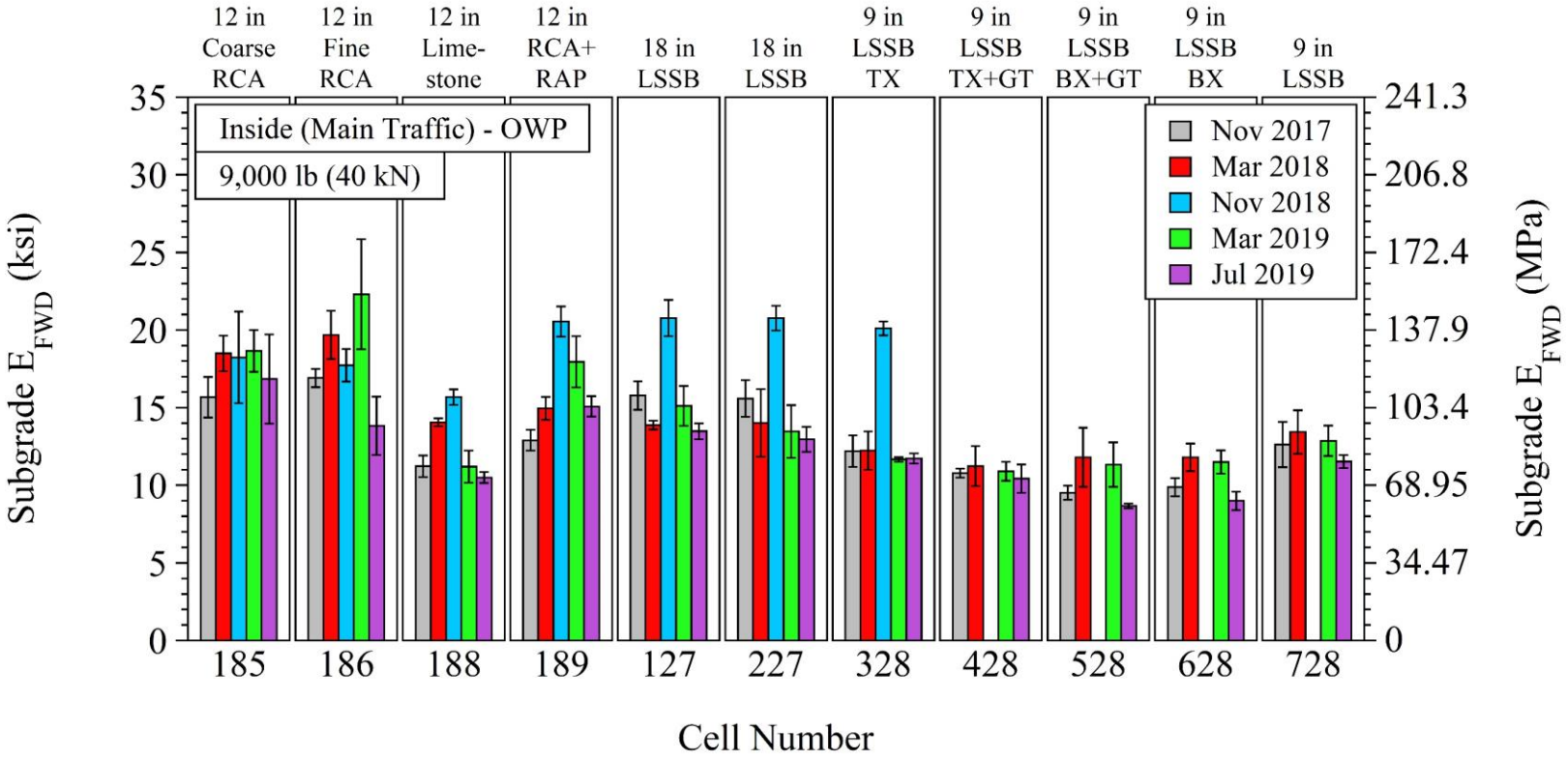
FWD

- Long-term performance
  - Base+subbase E_{FWD}



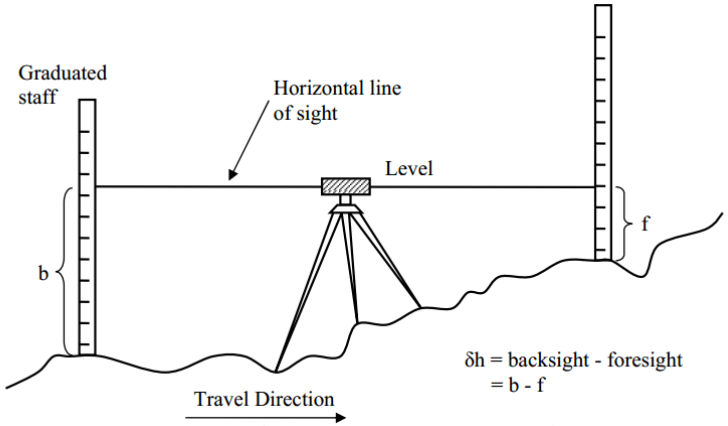
FWD

- Long-term performance
  - Subgrade E_{FWD}

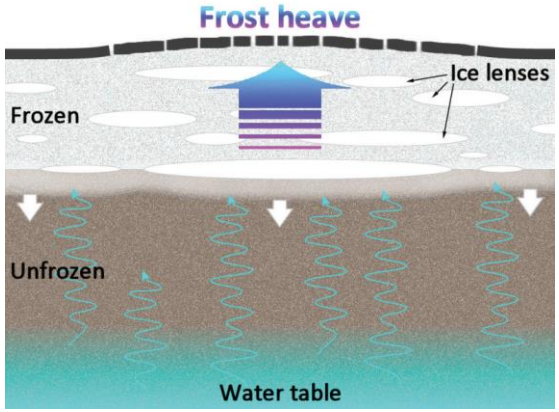


ELEVATION CHANGE IN F-T

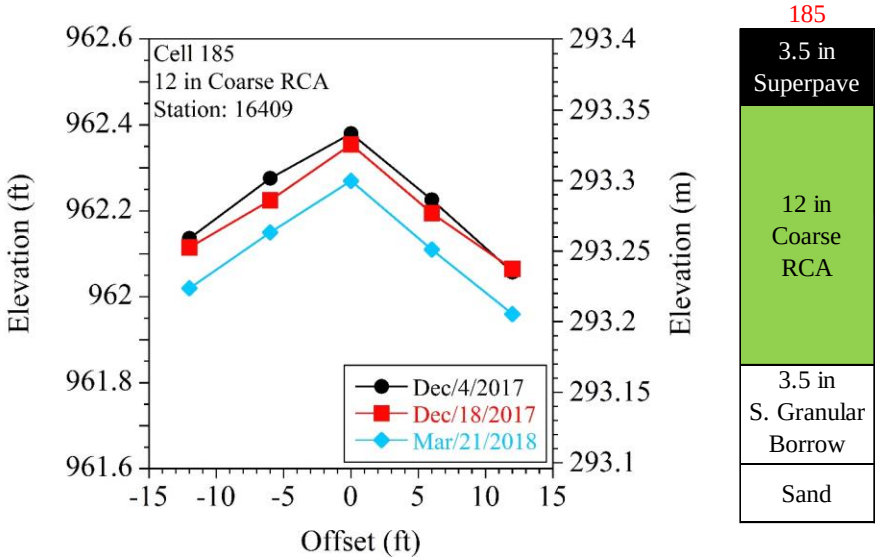
- Leveling



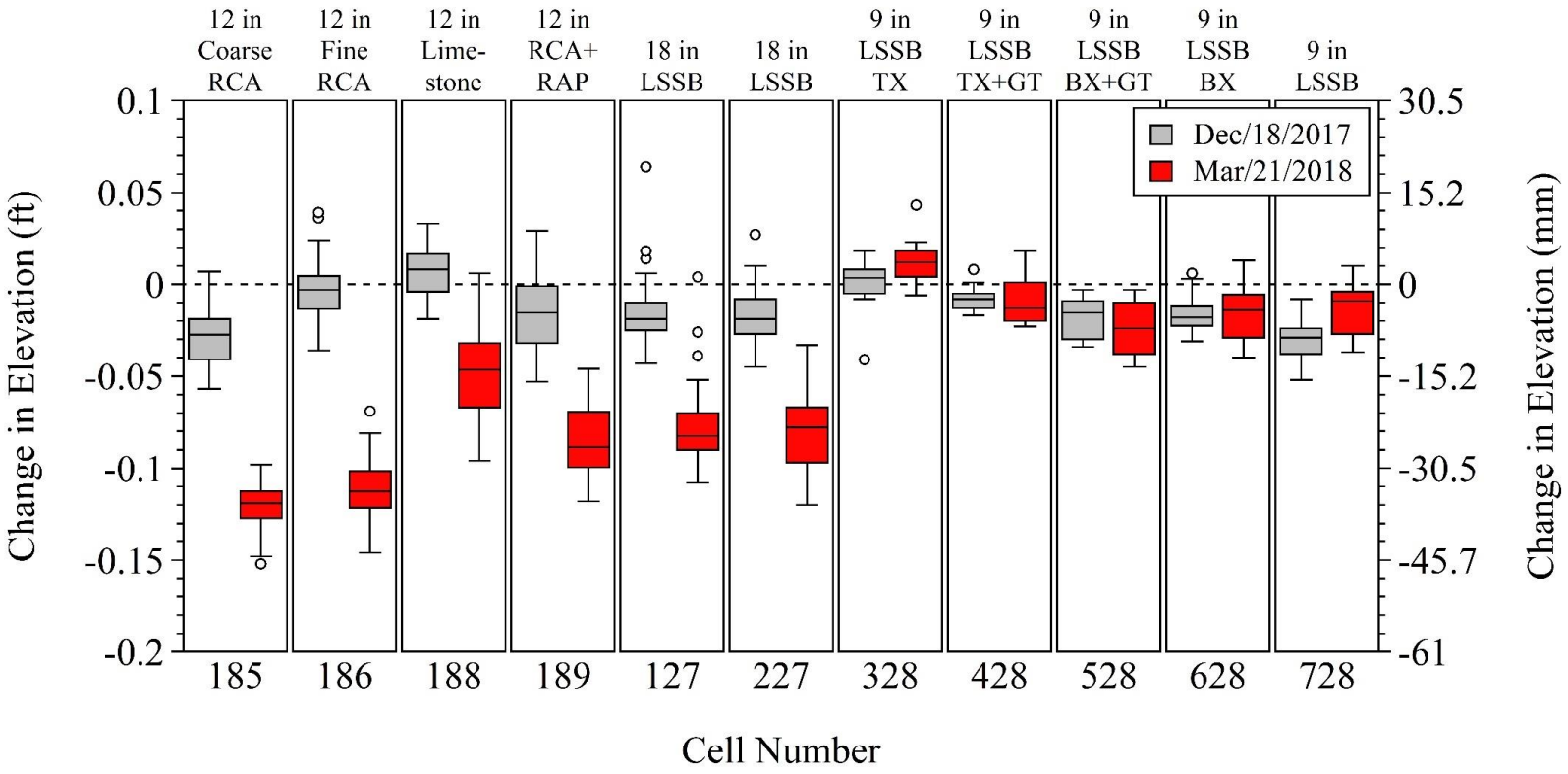
https://www.researchgate.net/figure/Spirit-levelling-procedure_fig1_312031900



https://www.dmr.nd.gov/ndgs/documents/newsletter/2011Summer/FrostHeave.pdf

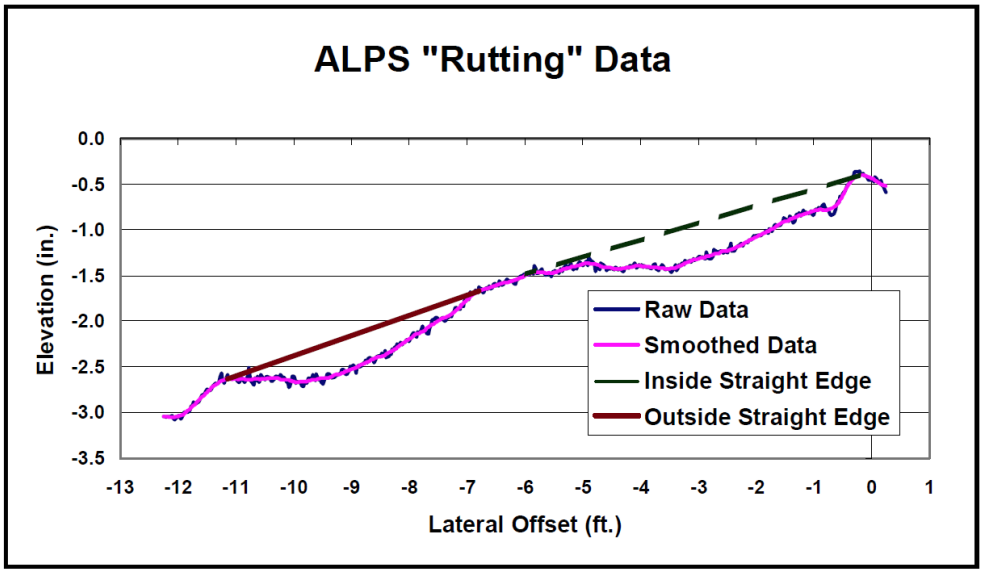


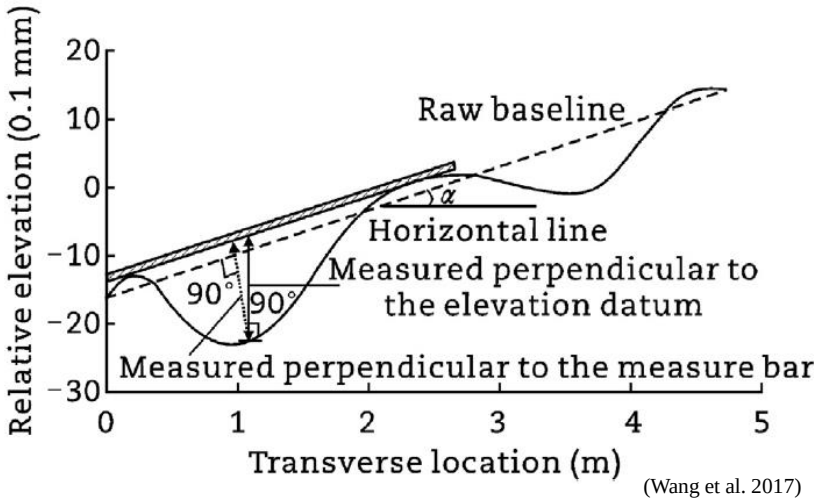
ELEVATION CHANGE IN F-T



RUTTING

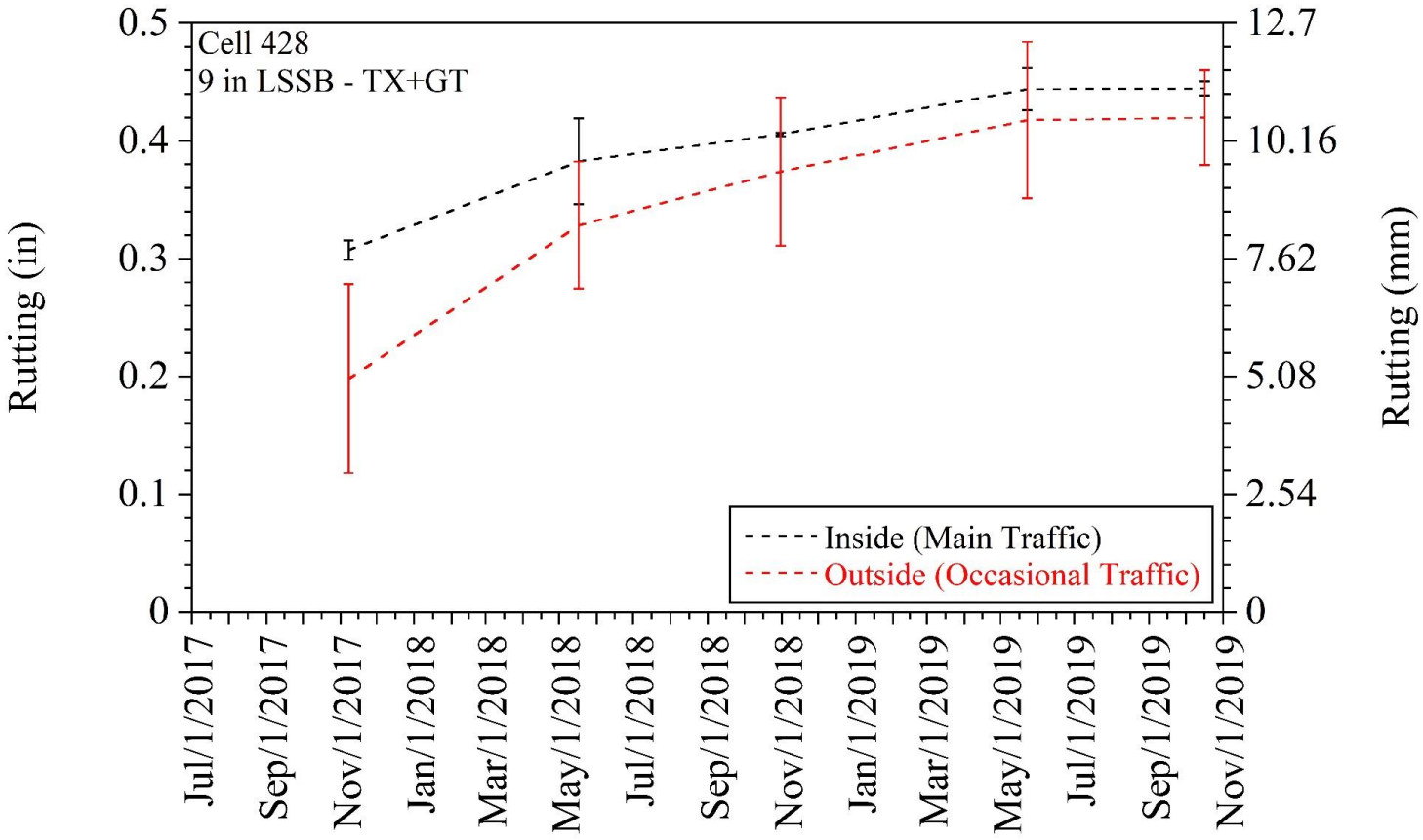
- Automated laser profile system (ALPS)

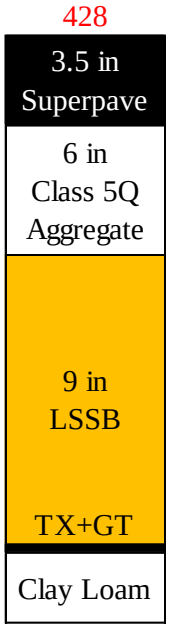




(Wang et al. 2017)

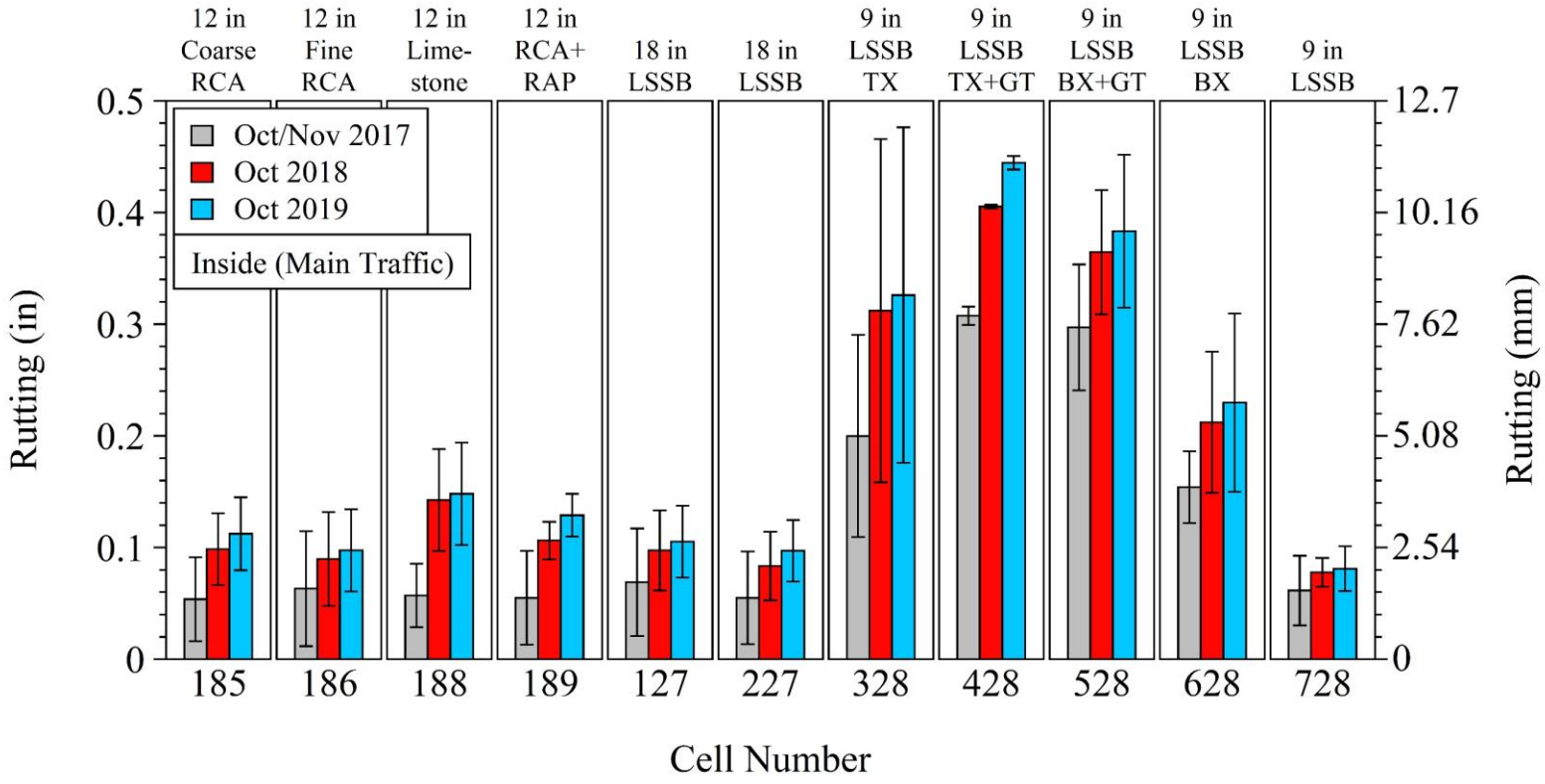
RUTTING





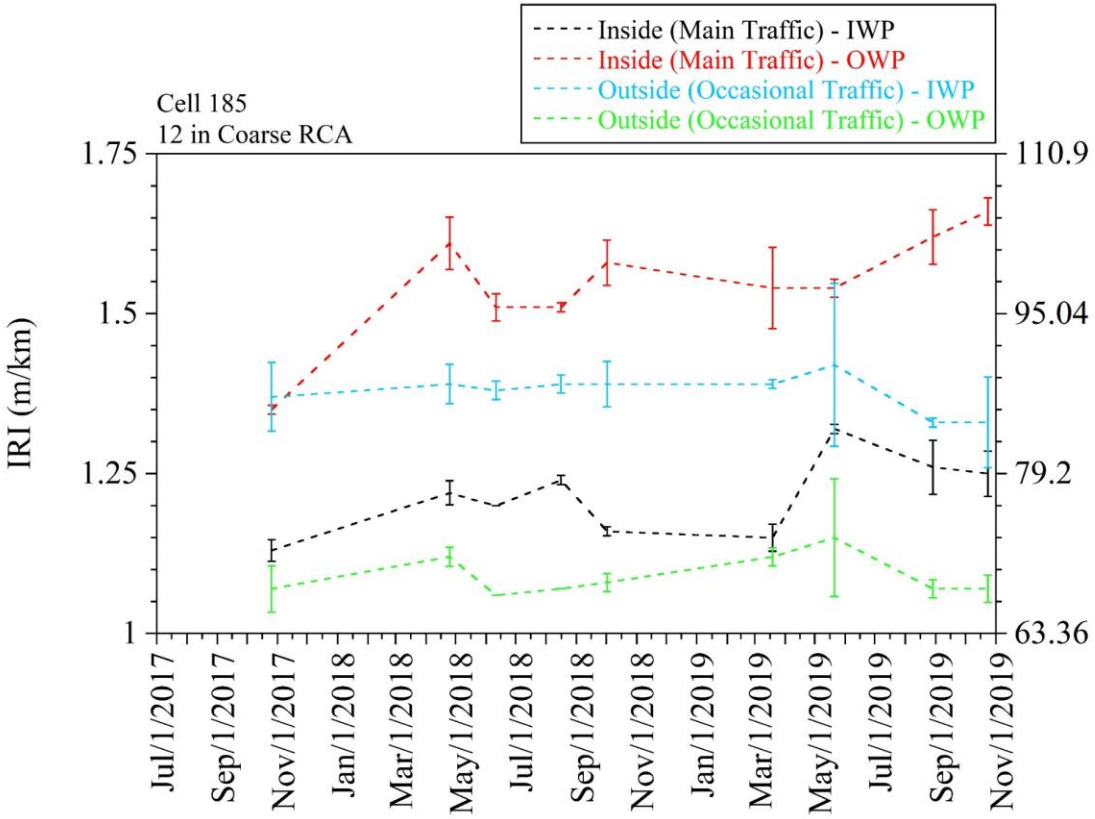
TX = Triaxial Geogrid
GT = Nonwoven Geotextile

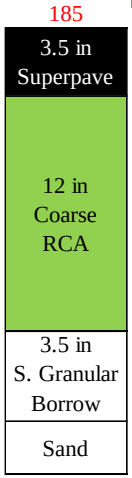
RUTTING


12 in Coarse RCA
12 in Fine RCA
12 in Lime-stone
12 in RCA+ RAP
18 in LSSB
18 in LSSB
9 in LSSB TX
9 in LSSB TX+GT
9 in LSSB BX+GT
9 in LSSB BX
9 in LSSB
Oct/Nov 2017
Oct 2018
Oct 2019
Inside (Main Traffic)
Rutting (in)
0
0.1
0.2
0.3
0.4
0.5
Rutting (mm)
0
2.54
5.08
7.62
10.16
12.7
185
186
188
189
127
227
328
428
528
628
728
Cell Number

IRI

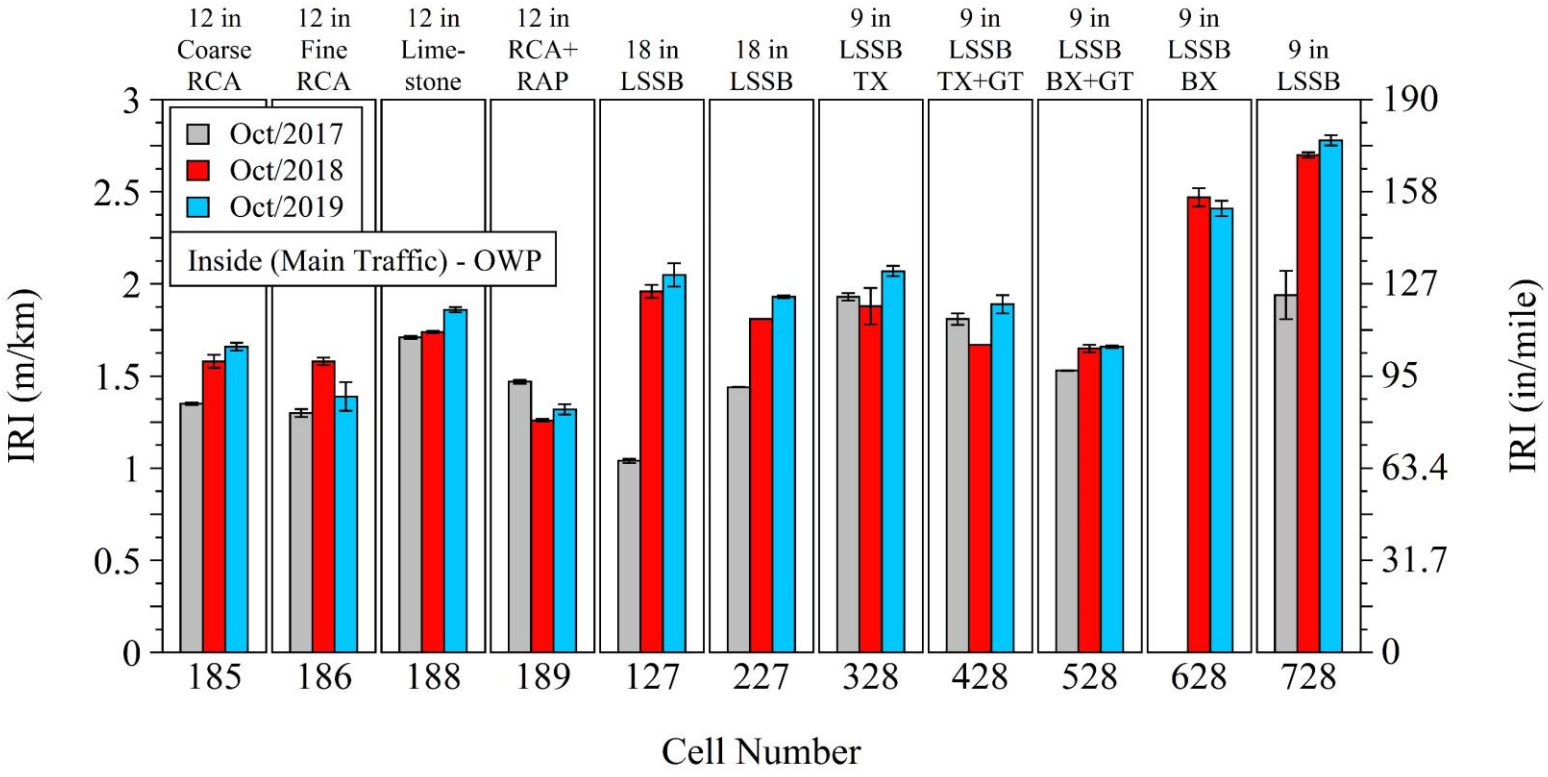
- Lightweight internal surface analyzer (LISA)





Condition Term	IRI	Ride Quality
Very Good	< 0.95 m/km	Acceptable 0 – 2.68 m/km
Good	0.95 – 1.49 m/km	
Fair	1.50 – 1.88 m/km	
Poor	1.89 – 2.68 m/km	
Very Poor	> 2.68 m/km	Unacceptable

IRI



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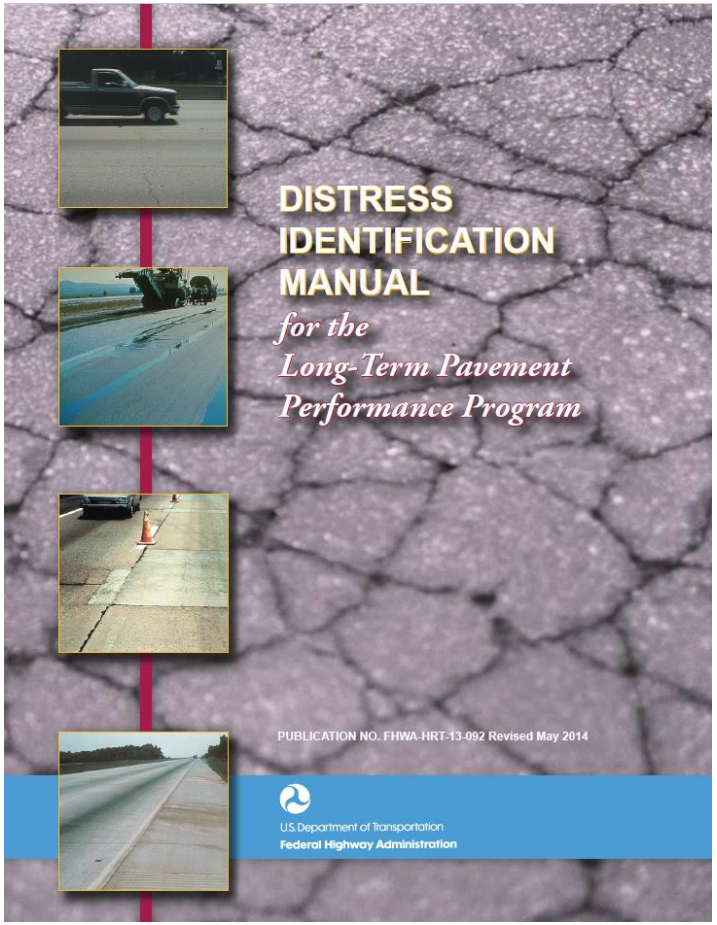
Poor	1.89 – 2.68 m/km	
Very Poor	> 2.68 m/km	Unacceptable

PAVEMENT DISTRESSES

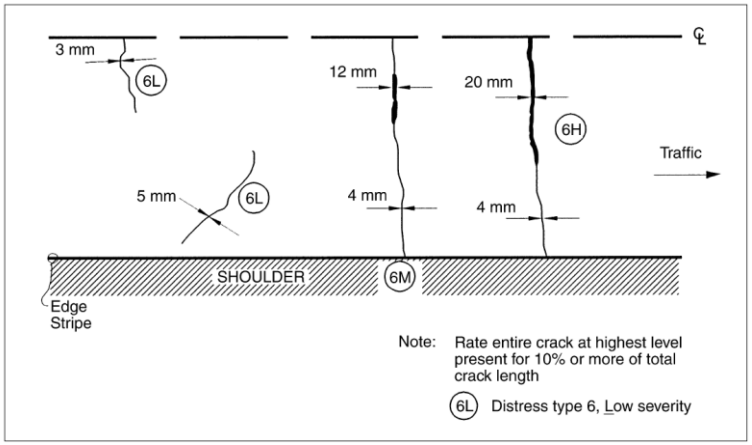
- Transverse cracking
- Longitudinal cracking
- Raveling (related to asphalt)
- Fatigue cracking
- Block cracking
- Edge cracking
- Patch
- Potholes
- Shoving
- Bleeding
- Polished aggregate
- Pumping

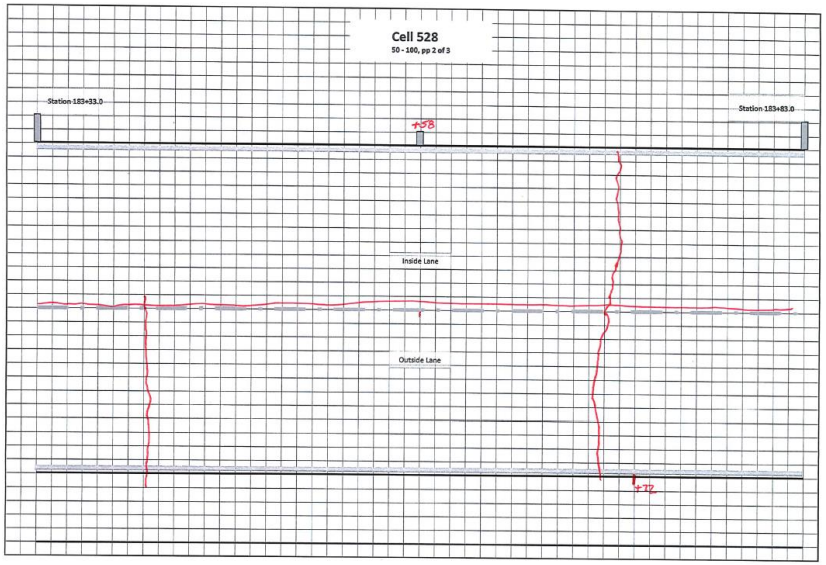
Red – Observed
Red – Not Observed

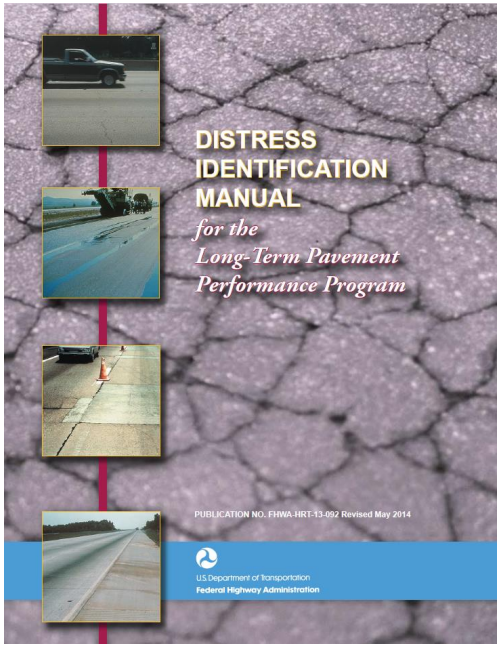


PAVEMENT DISTRESSES

- Transverse cracking

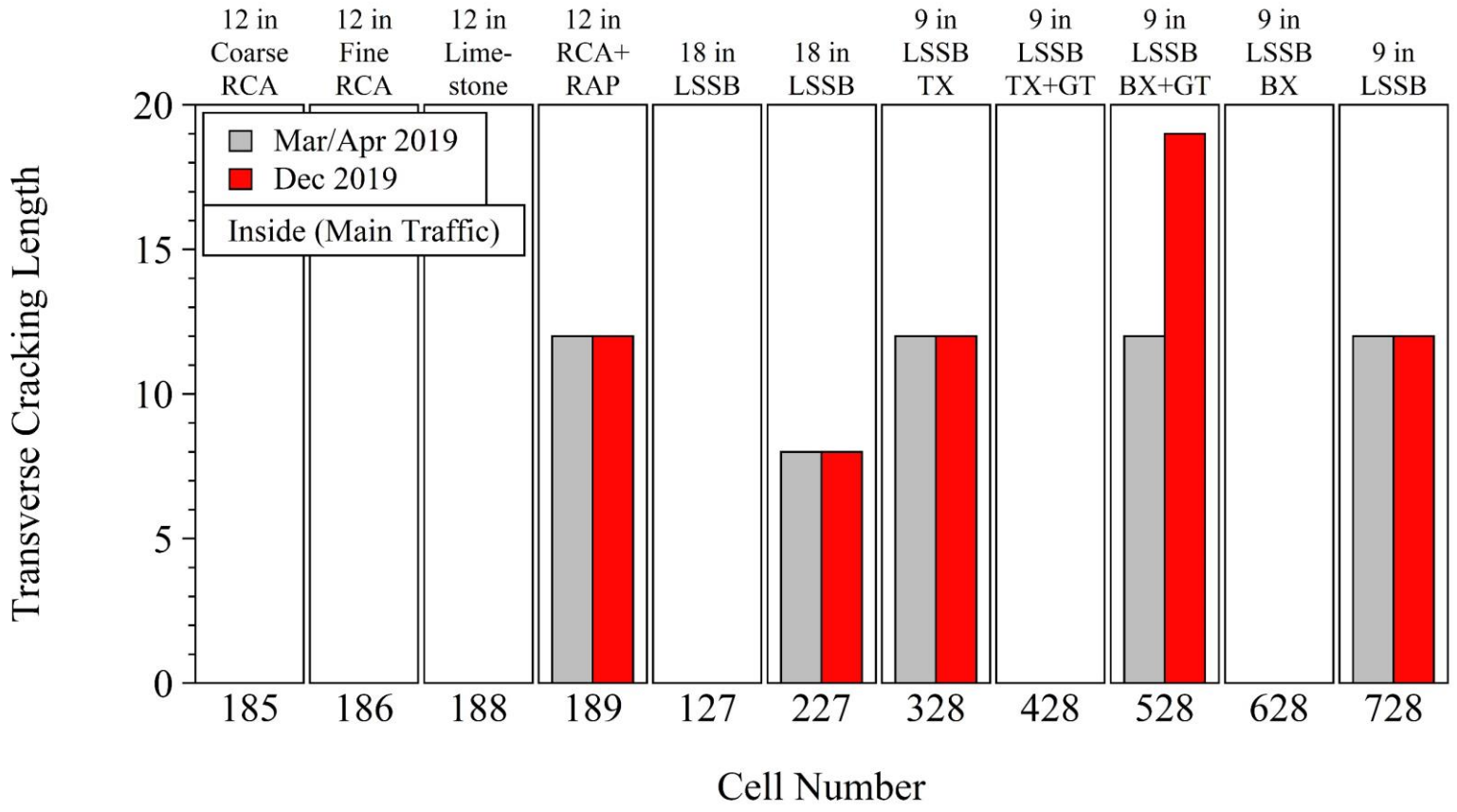






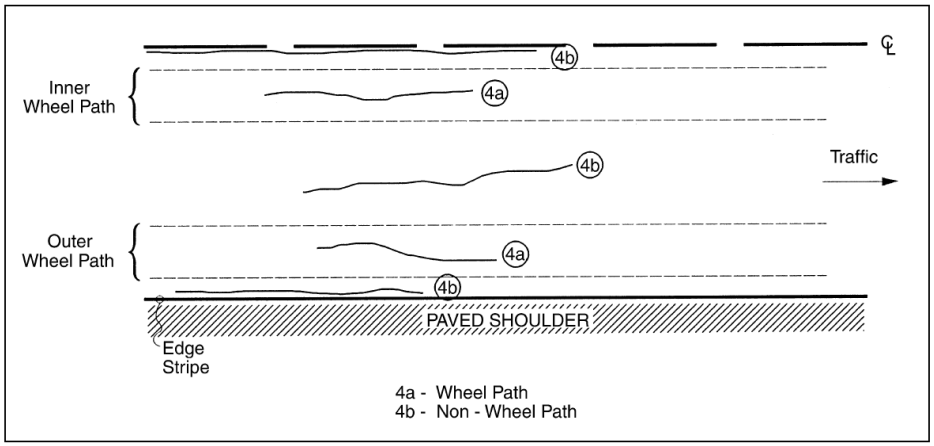
PAVEMENT DISTRESSES

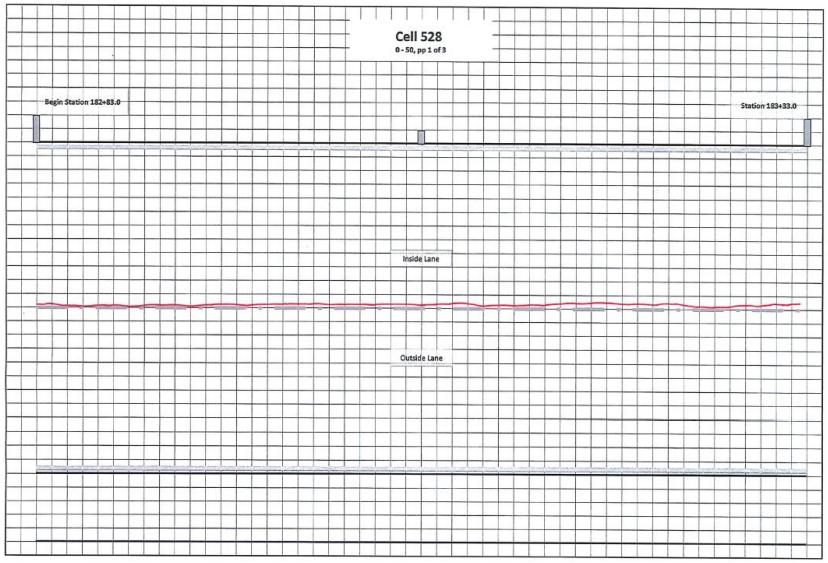
- Transverse cracking
  - Low severity (an unsealed crack with a mean width ≤ 6 mm)

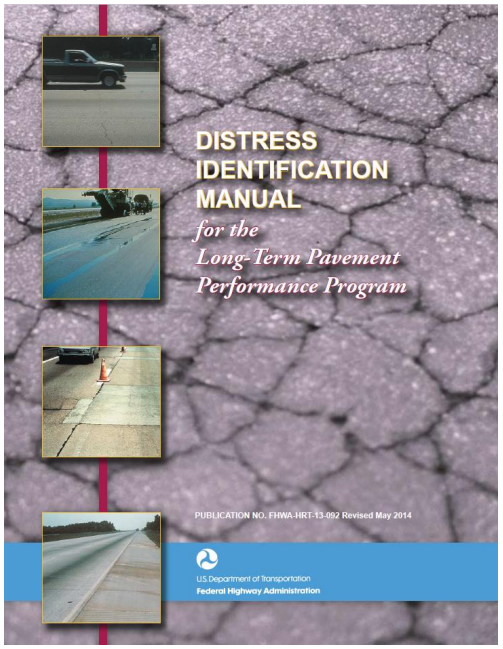


PAVEMENT DISTRESSES

- Longitudinal cracking

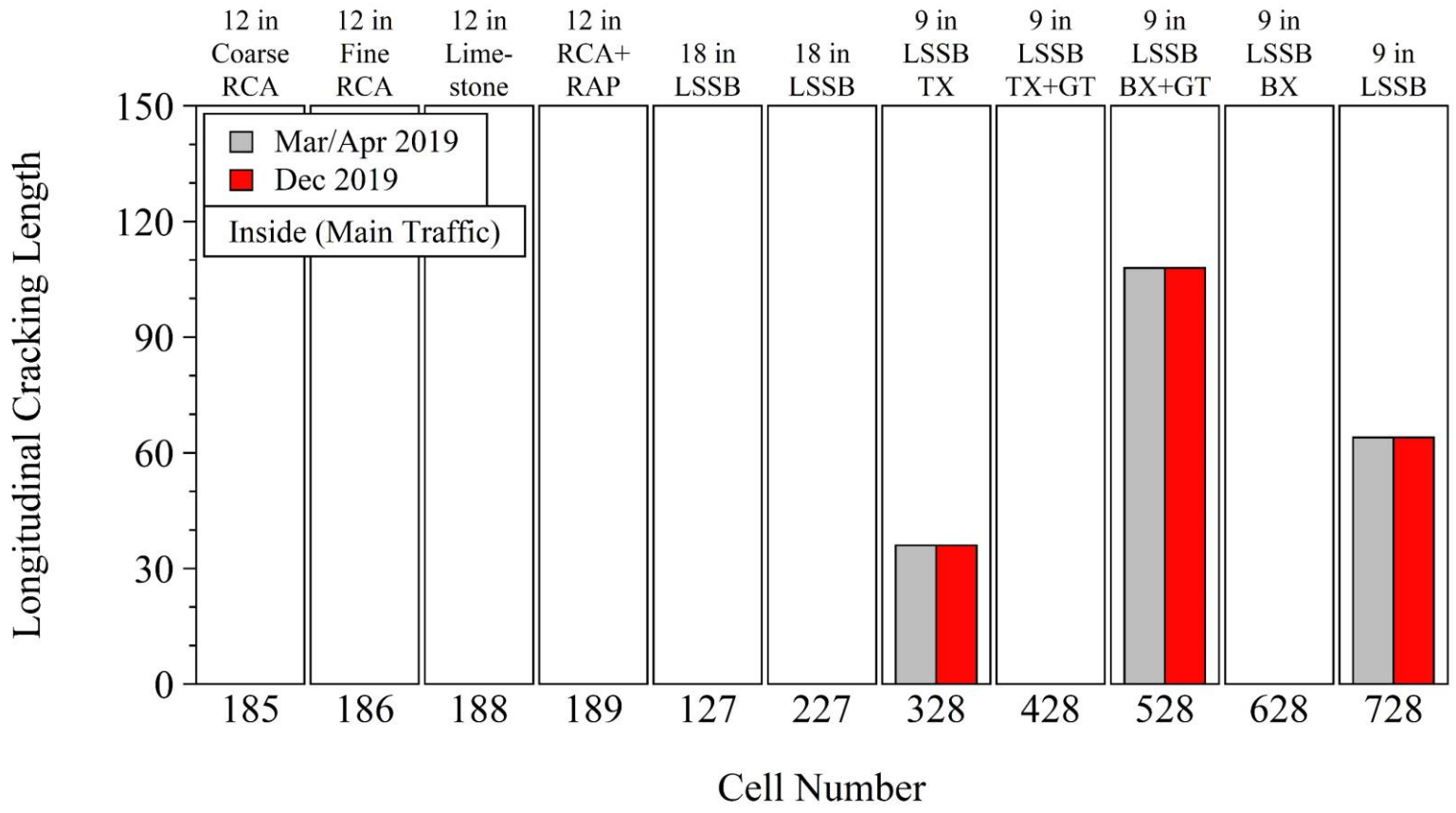






PAVEMENT DISTRESSES

- Longitudinal cracking
  - Low severity (a crack with a mean width ≤ 6 mm)



SUMMARY

- LSSB layers
  - Low VWC in base layers
  - Effective drainage
  - Installation of geocomposites?
- Frost penetration depths
  - 0°C isotherm – more representative
- Freezing and thawing periods
  - 2018-2019 winter was longer
  - Difference in periods – material-related
    - Thawing periods were higher for RCAs
- Max frost penetration depths
  - Difference in depths – material related
    - Higher for limestone and RCA-RAP

SUMMARY

- FWD – different lanes & wheel paths
  - Max deflection – inside E_{FWD} < outside E_{FWD}
  - E_{FWD} – inside E_{FWD} > outside E_{FWD}
- FWD – long-term performance
  - Coarse RCA & fine RCA > others
  - Limestone > RCA+RAP
  - 18 in LSSB > 9 in LSSB
- Elevation change in F-T
  - Only thaw subsidence
  - Coarse RCA, fine RCA > RCA+RAP, 18 in LSSB > limestone > 9 in LSSB

SUMMARY

- Rutting
  - Rutting ↑ over time
  - 9 in LSSB with geosynthetics > others
  - Limestone > coarse RCA, fine RCA, RCA+RAP, 18 in LSSB
- IRI
  - IRI ↑ over time (overall)
  - 18 in LSSB & 9 in LSSB > others
- Pavement distresses
  - Only transverse & longitudinal cracking (low severity)
  - No distress ➔ Coarse RCA, fine RCA, limestone, 18 in LSSB (cell 127), 9 in LSSB – TX+GT, 9 in LSSB – BX
  - Raveling (related to asphalt material)

Discussion & Recommendation

- Long-term performance
  - RCAs performance increase after freeze-thaw cycles
  - Cementation of RCA
  - Stress hardening & softening

- Effective thickness – LSSB
  - 9 inches thickness for LSSB may not be adequate
  - Geocomposite should be installed at the center of LSSB to increase lateral flow capacity

FUTURE STUDY

- **Task 7** – Pavement design criteria
  - Analyze field and laboratory testing
  - Characterize engineering properties of the materials
  - Explain how testing results effect pavement design inputs
  - Analyze seasonal frost depth and freeze-thaw
  - Explain long-term performance of the materials
  - Develop methods to estimate the stiffness and permeability
  - Make cost-benefit analyses
  - Recommend pavement design input values
  - Recommend construction specifications

Thank You!

QUESTIONS??

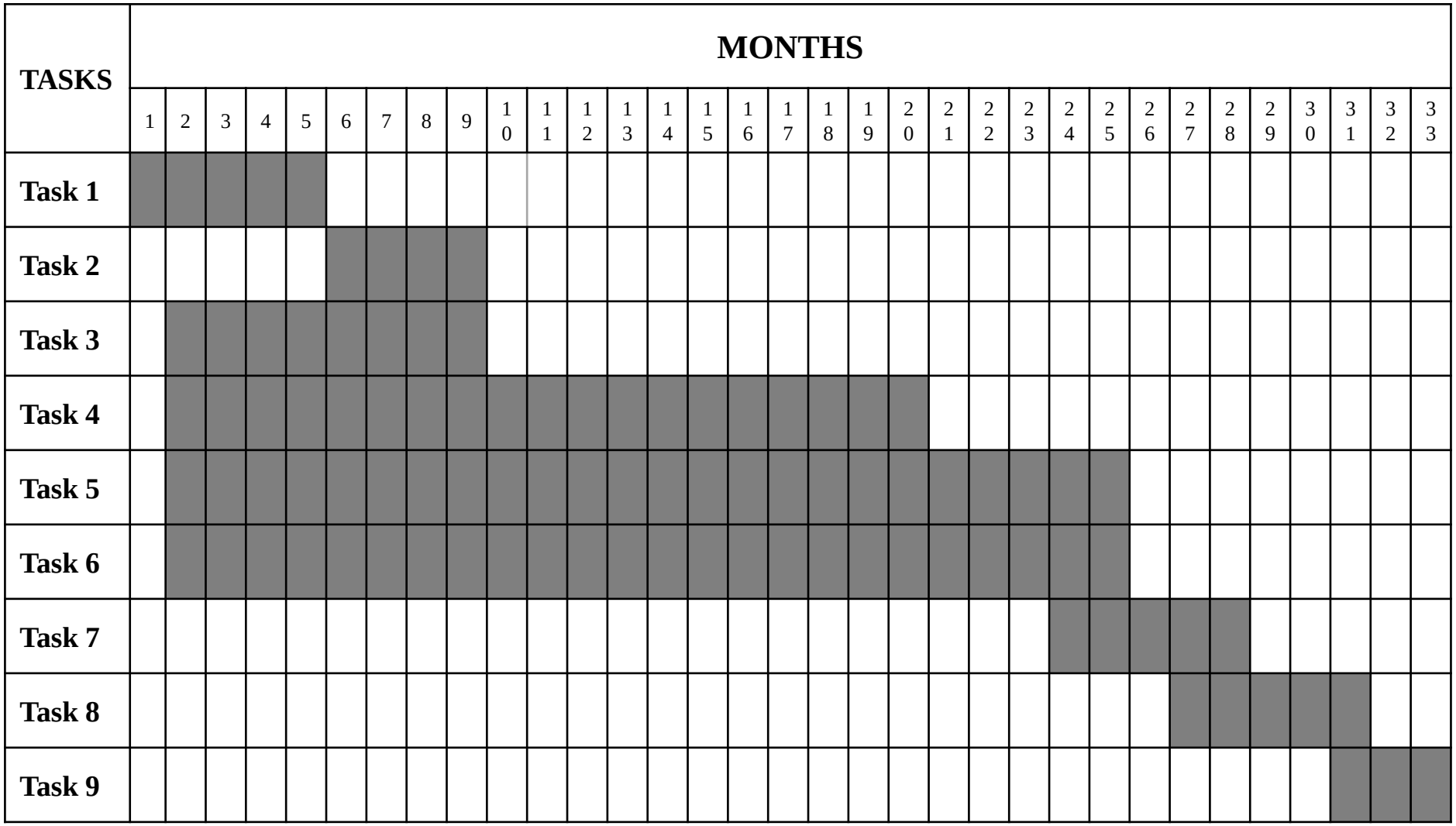
IOWA STATE UNIVERSITY

WISCONSIN
UNIVERSITY OF WISCONSIN-MADISON

MICHIGAN STATE
UNIVERSITY

Iowa State University | University of Wisconsin-Madison | Michigan State University

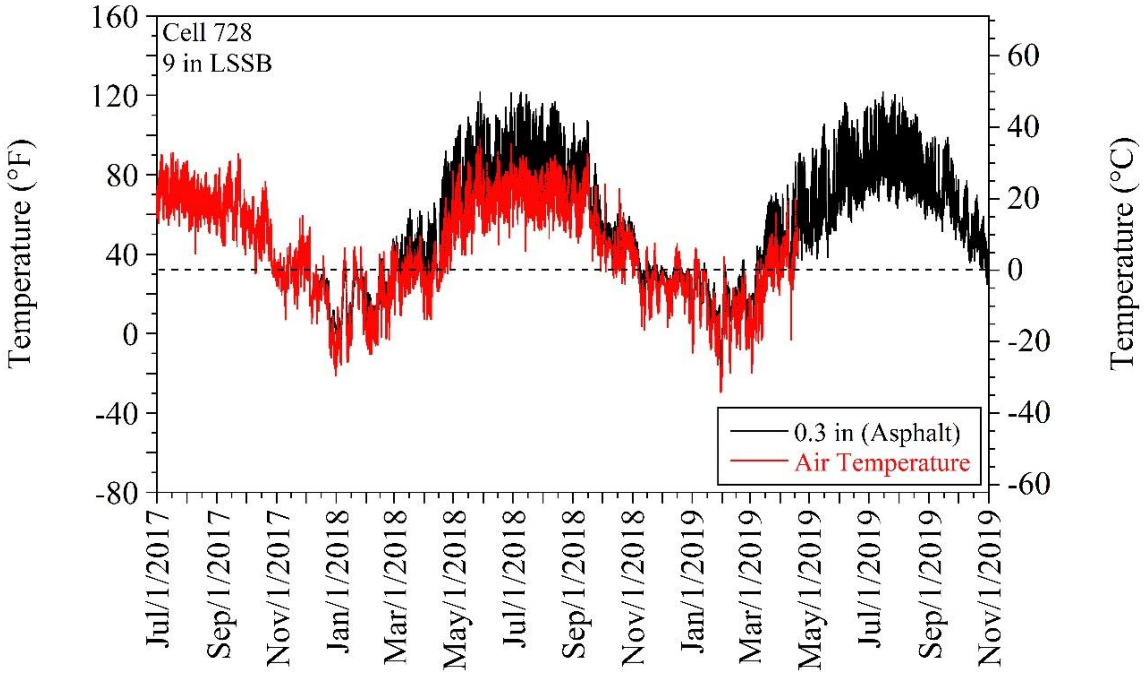
SCHEDULE


TASKS
MONTHS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33
Task 1
Task 2
Task 3
Task 4
Task 5
Task 6
Task 7
Task 8
Task 9

SENSORS

Air vs Asphalt Temperature

- Dark-colored materials
  - Less reflection
  - Heat absorption
- Rougher texture
  - Higher surface area
  - More absorption
- Daylight temperature
  - Asphalt > air
- Nighttime temperature
  - Asphalt > air
  - Slow heat release



SENSORS

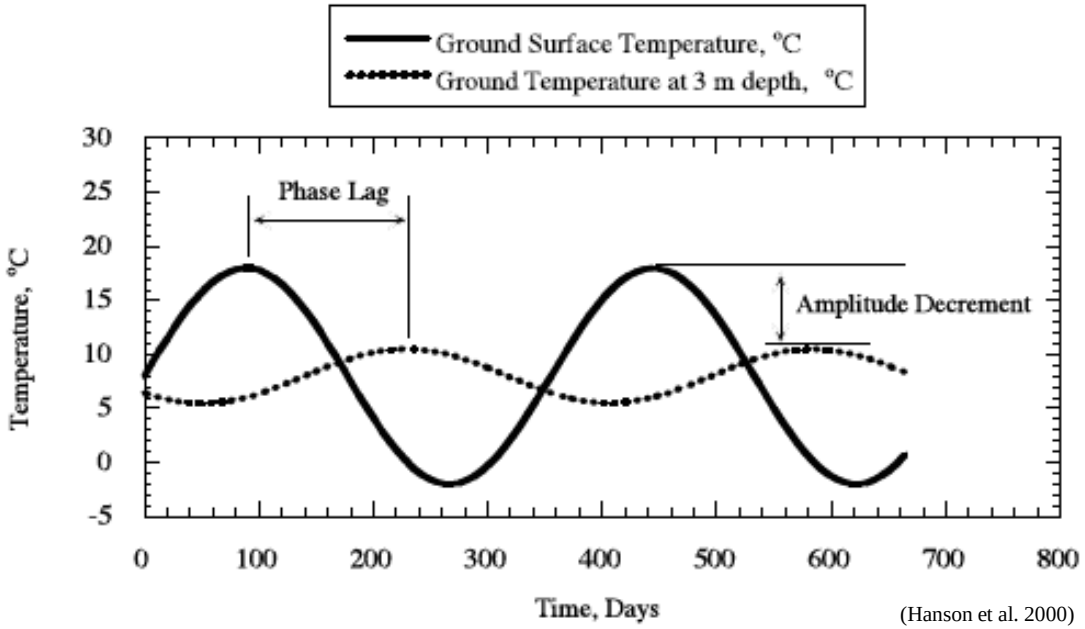
One-dimensional conduction heat transfer (Horton et al. 1983)

- At a specific depth (z) and time (t)

$$T(z,t) = \overline{T} + Ae^{-z\sqrt{\frac{\omega}{2\alpha}}} \sin\left(\omega t - z\sqrt{\frac{\omega}{2\alpha}} + C_4\right)$$

$\overline{T}$ = the average soil temperature
A = the surface amplitude of temperature
ω = the radial frequency $\left(\frac{2\pi}{p}\right)$
p = the period
α = the thermal diffusivity
C_4 = the phase constant

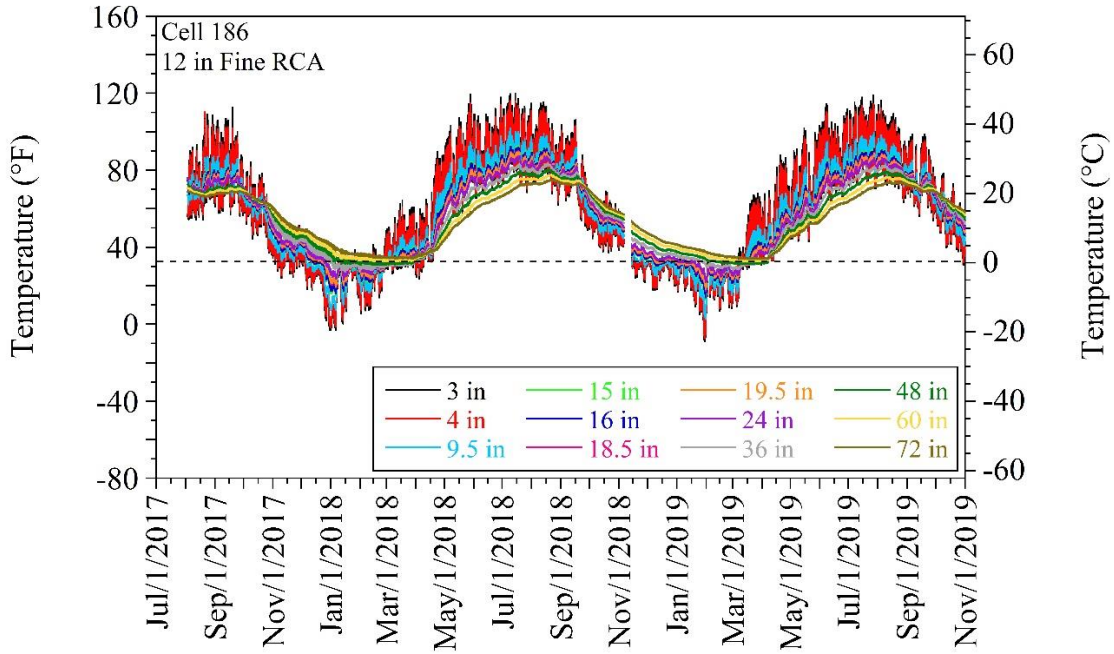
- Soil depth ↑
  - Amplitude (A) ↓
  - Phase lag

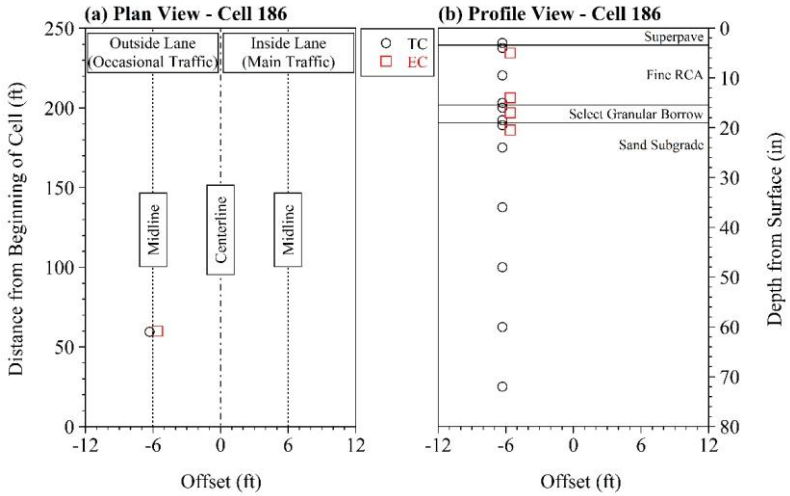


(Hanson et al. 2000)

SENSORS

Temperature Profiles

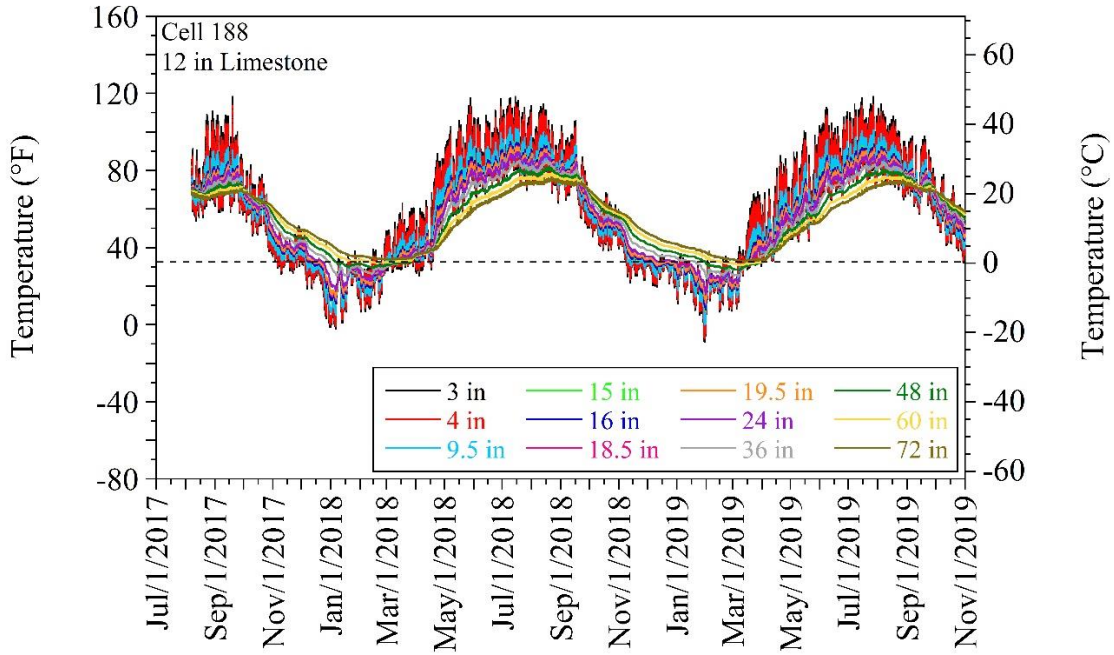


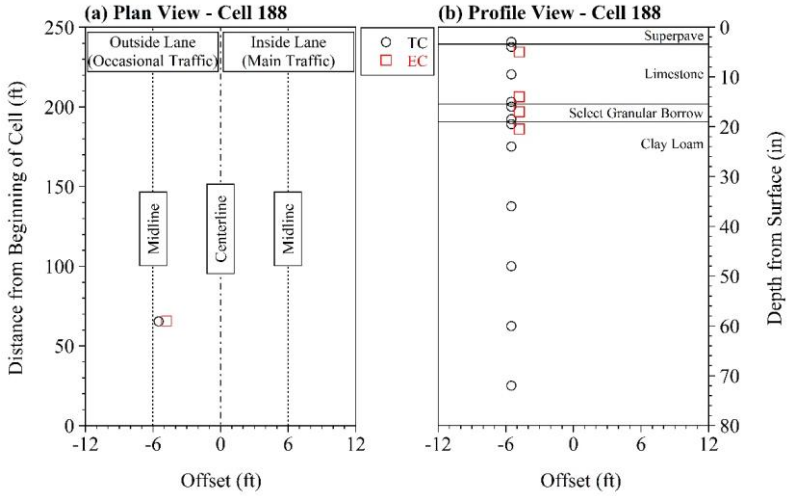


TC = Thermocouple
EC = Moisture probe

SENSORS

Temperature Profiles





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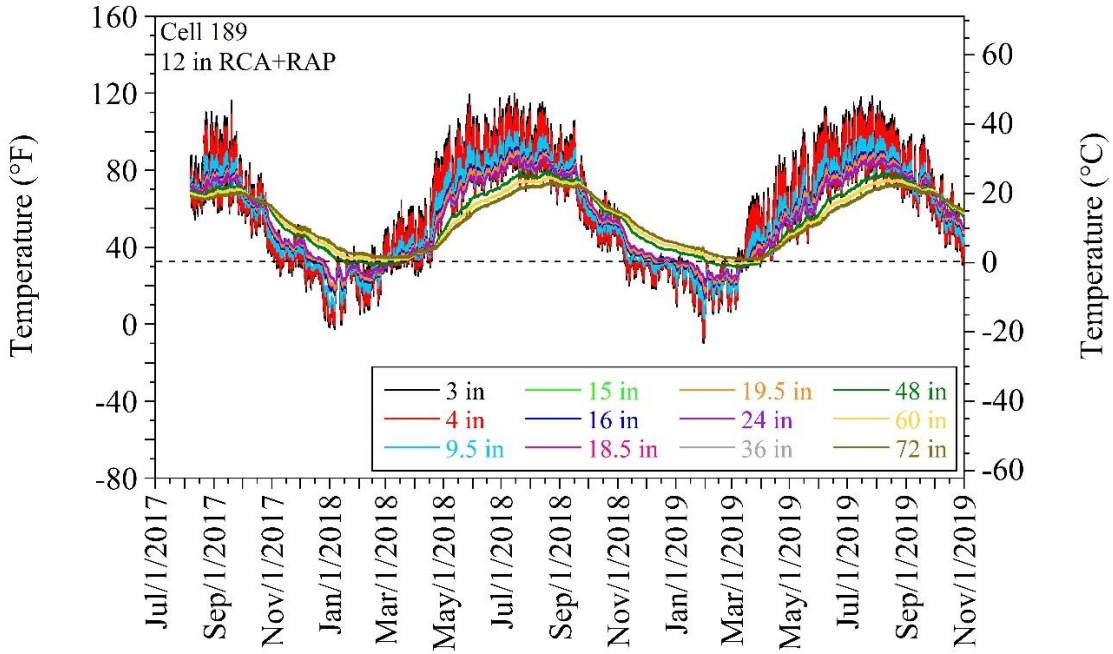
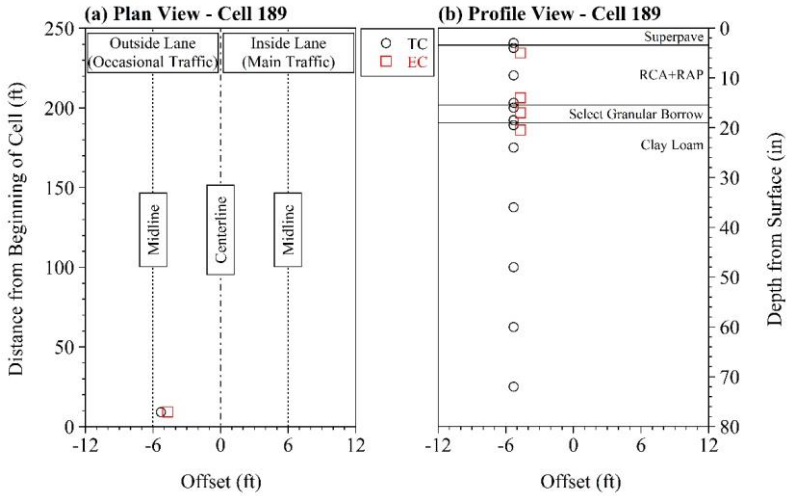
SENSORS

Temperature Profiles





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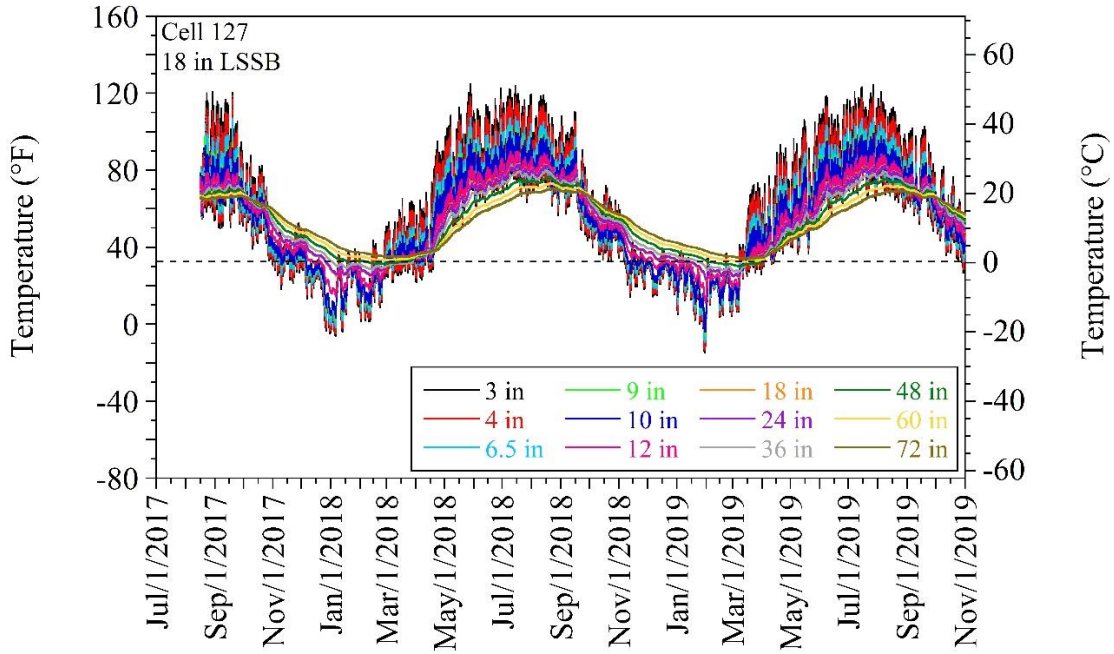
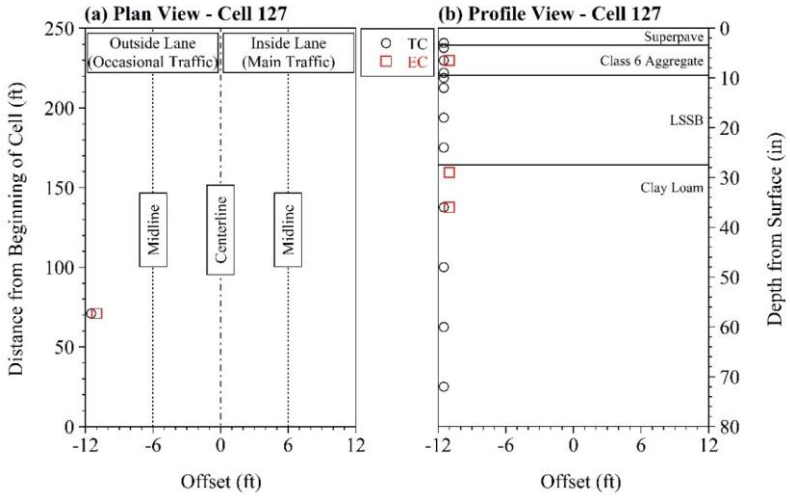
SENSORS

Temperature Profiles





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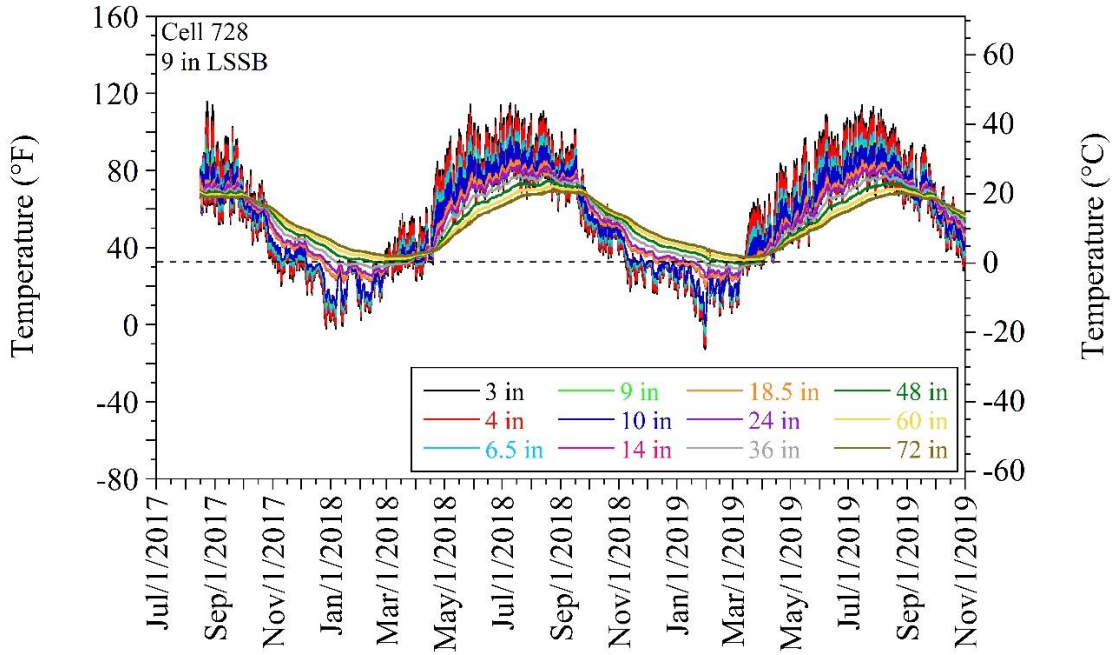
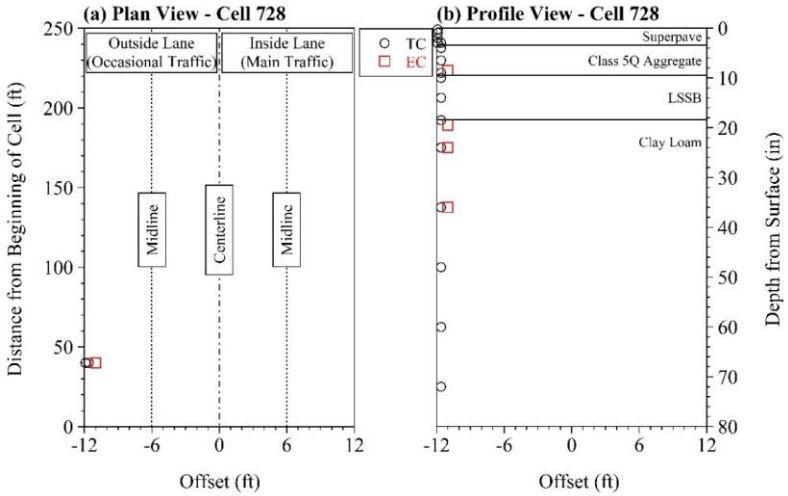
SENSORS

Temperature Profiles





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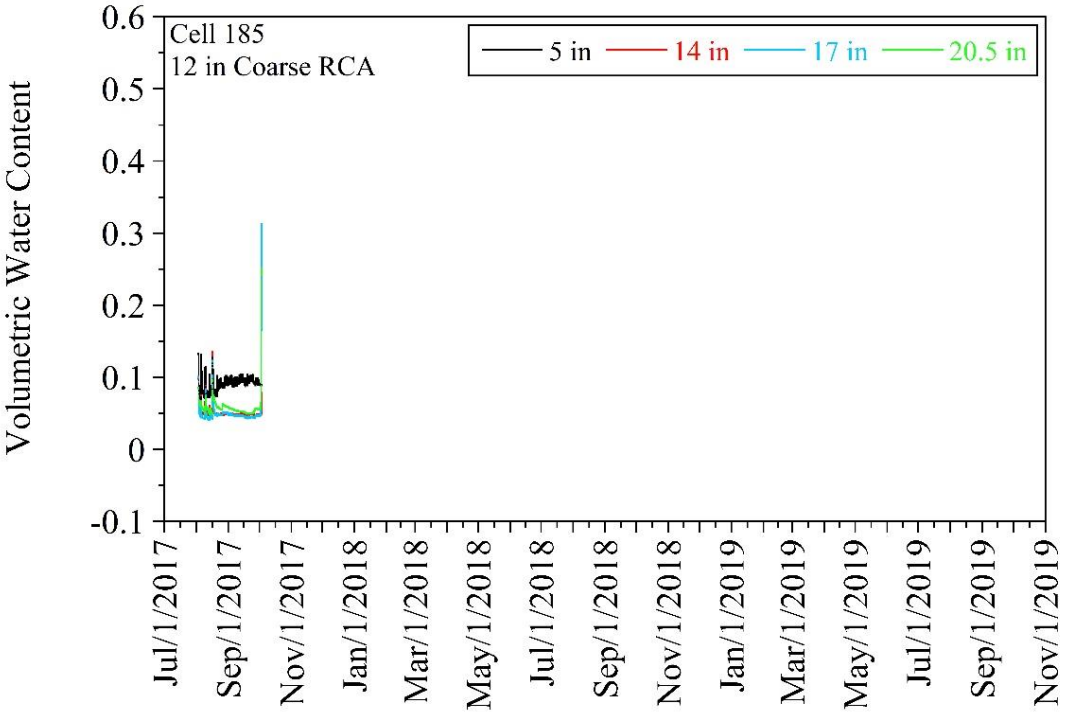
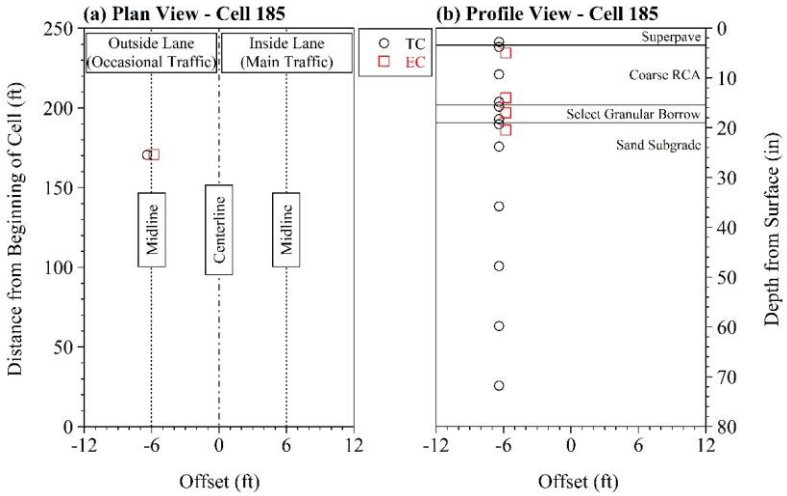
SENSORS

Temperature Profiles





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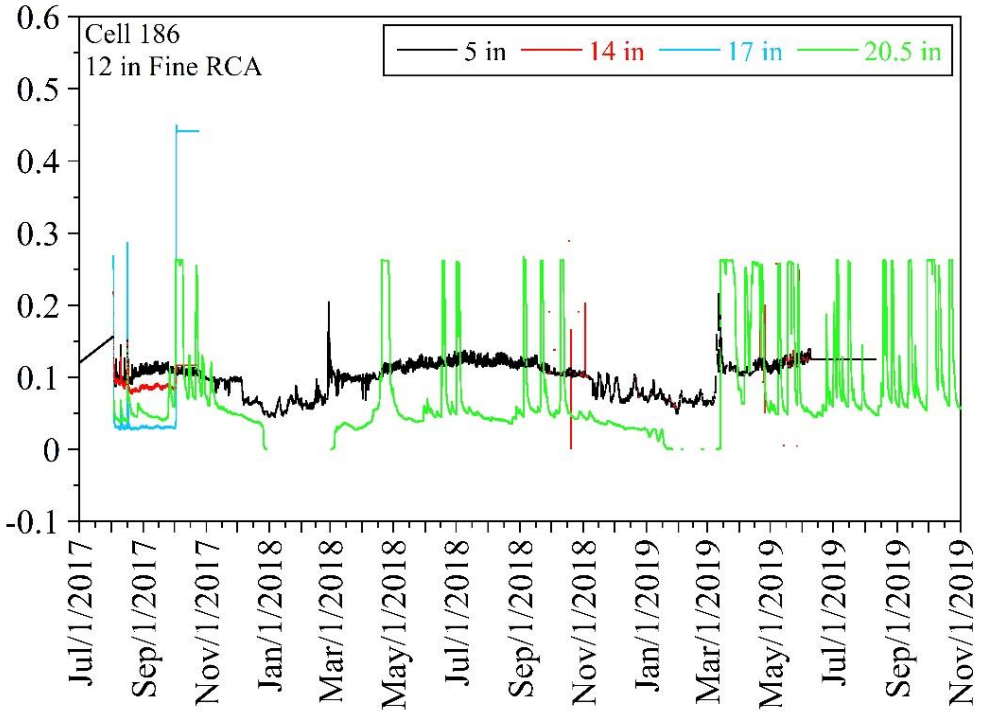
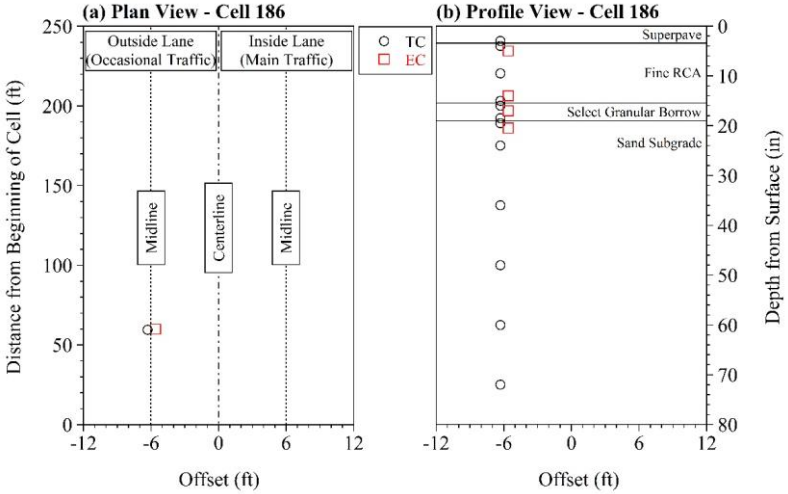
SENSORS

Temperature Profiles





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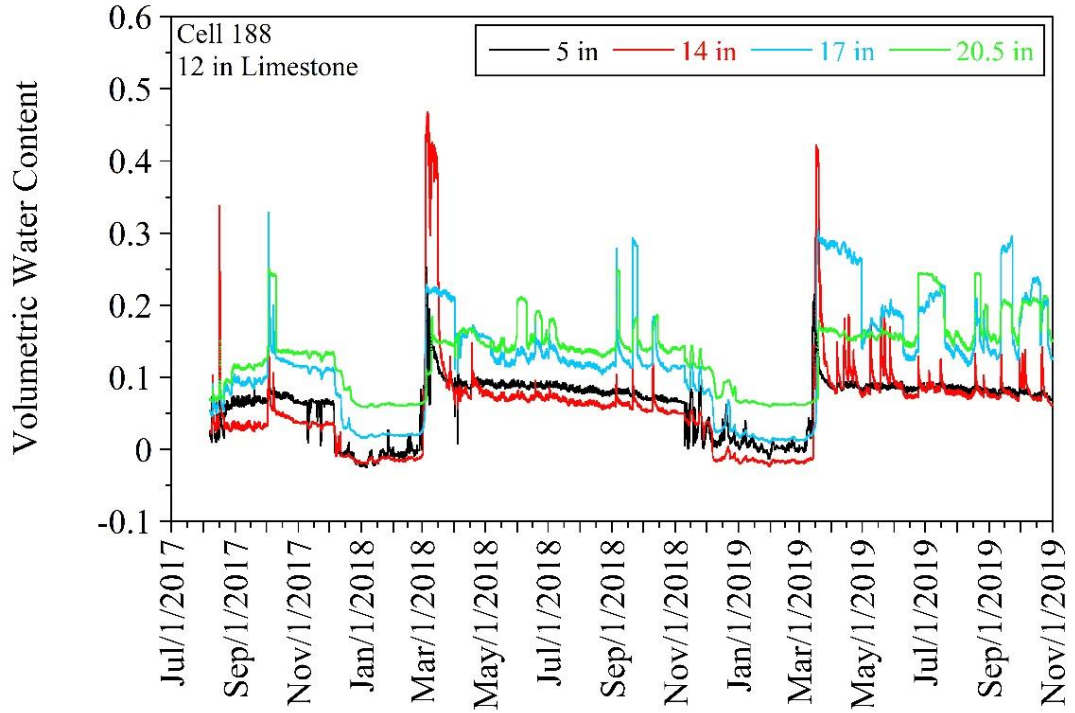
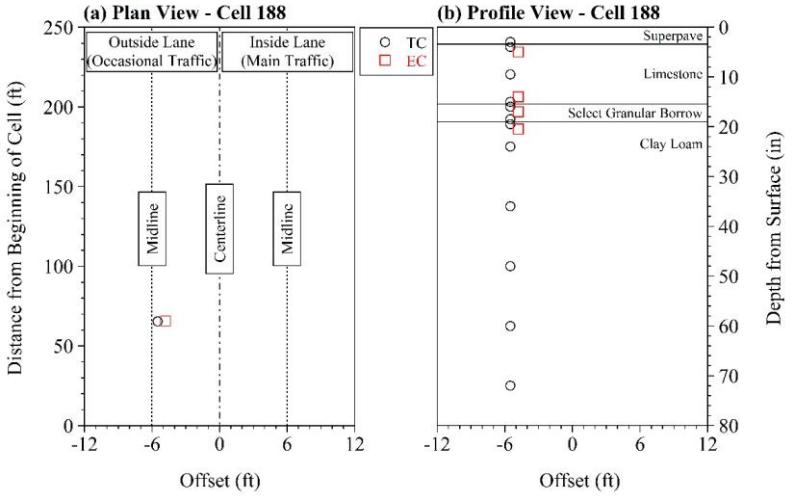
SENSORS

Temperature Profiles

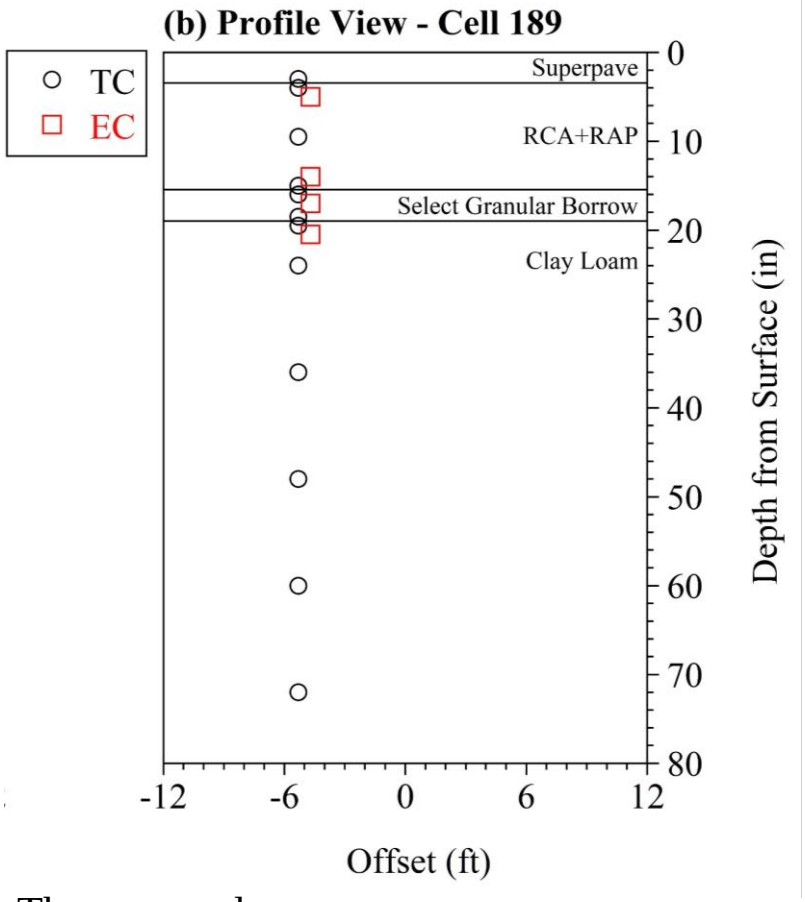


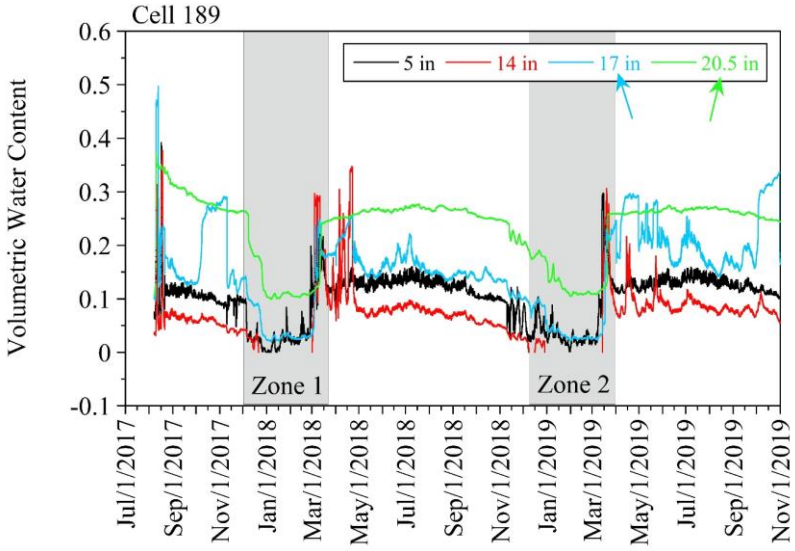


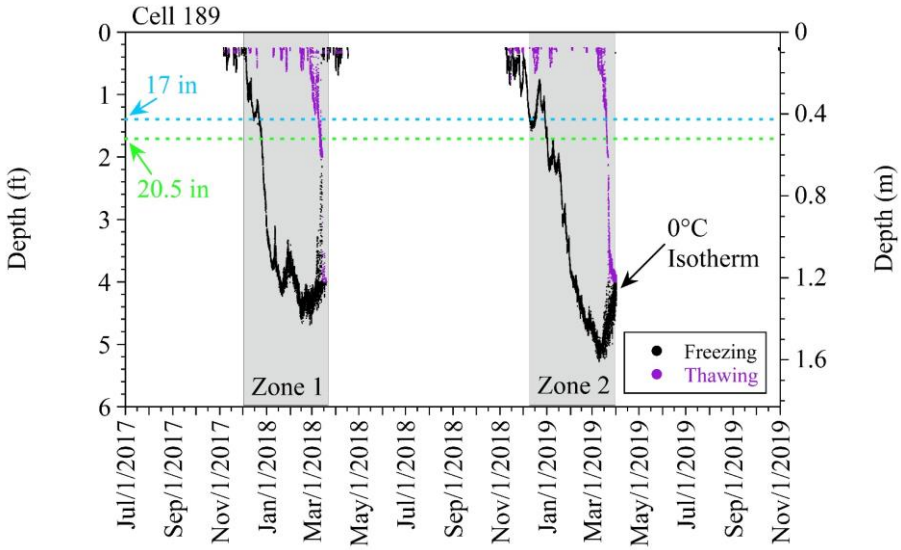
TC = Thermocouple
EC = Moisture probe

FROST PENETRATION DEPTH

Cell 189 – 0°C Isotherm



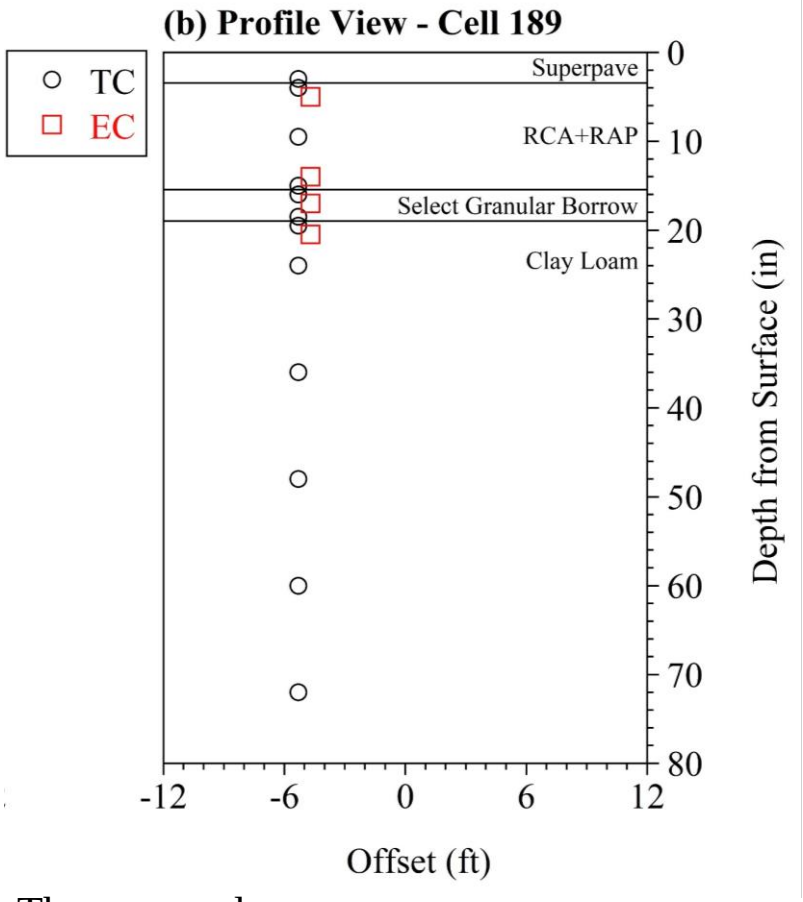


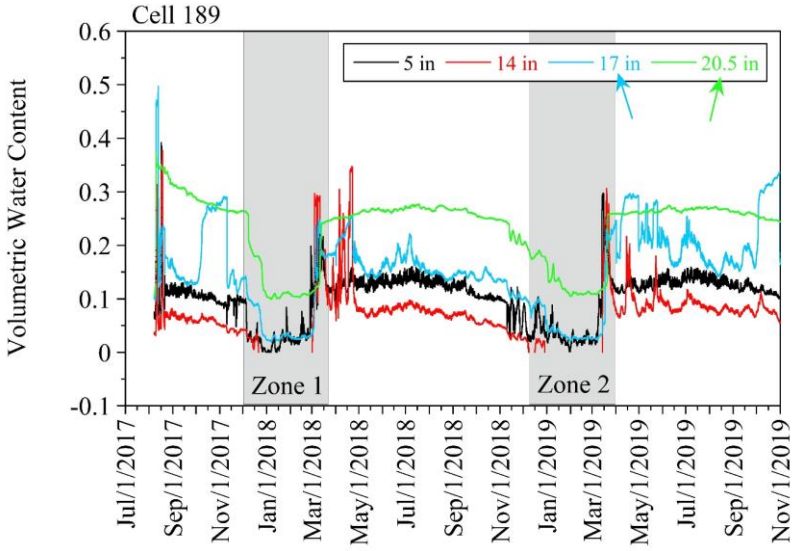


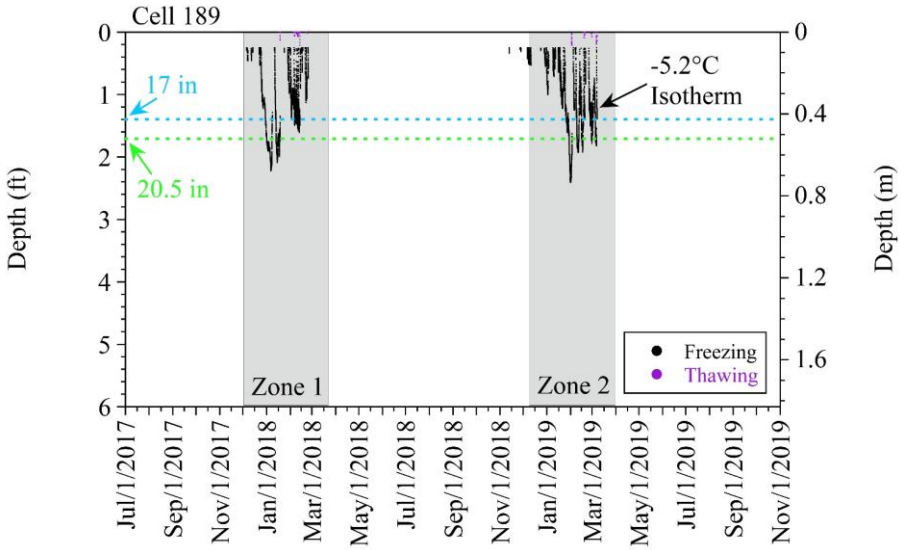
TC = Thermocouple
EC = Moisture probe

FROST PENETRATION DEPTH

Cell 189 – -5.2°C Isotherm



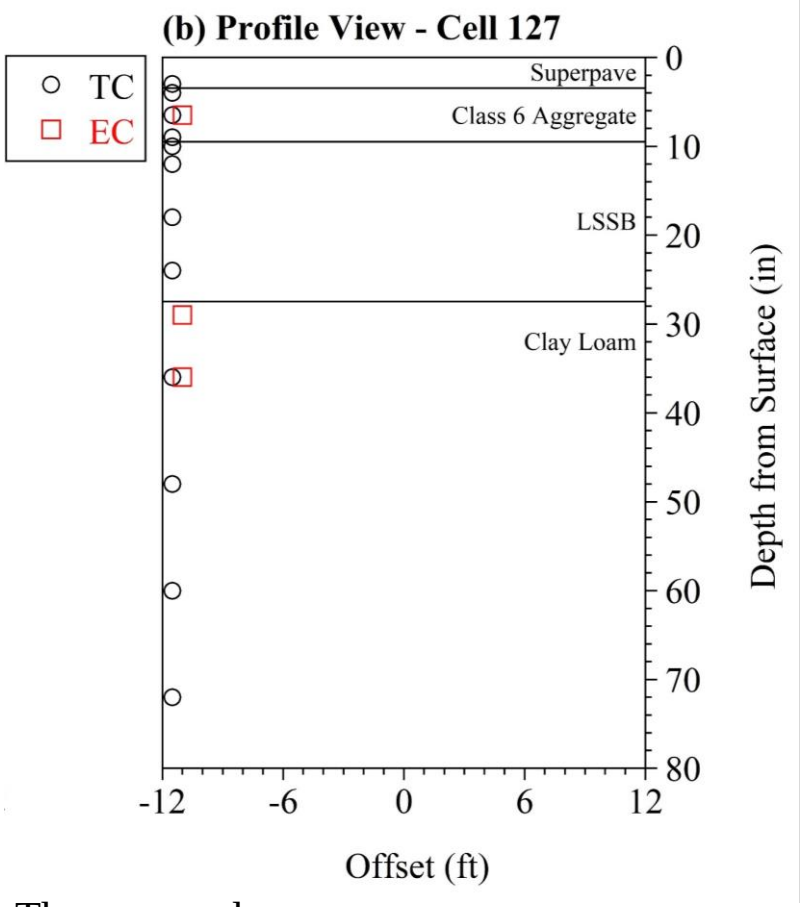


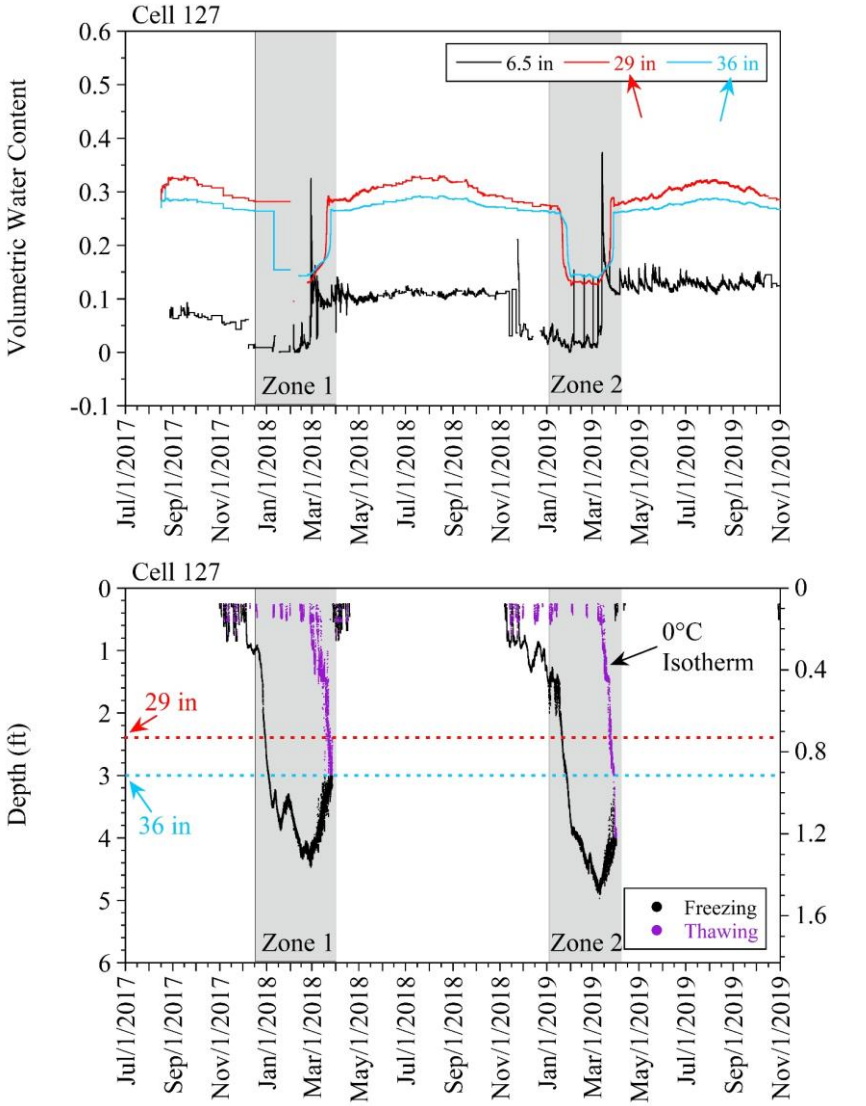


TC = Thermocouple
EC = Moisture probe

FROST PENETRATION DEPTH

Cell 127 – 0°C Isotherm

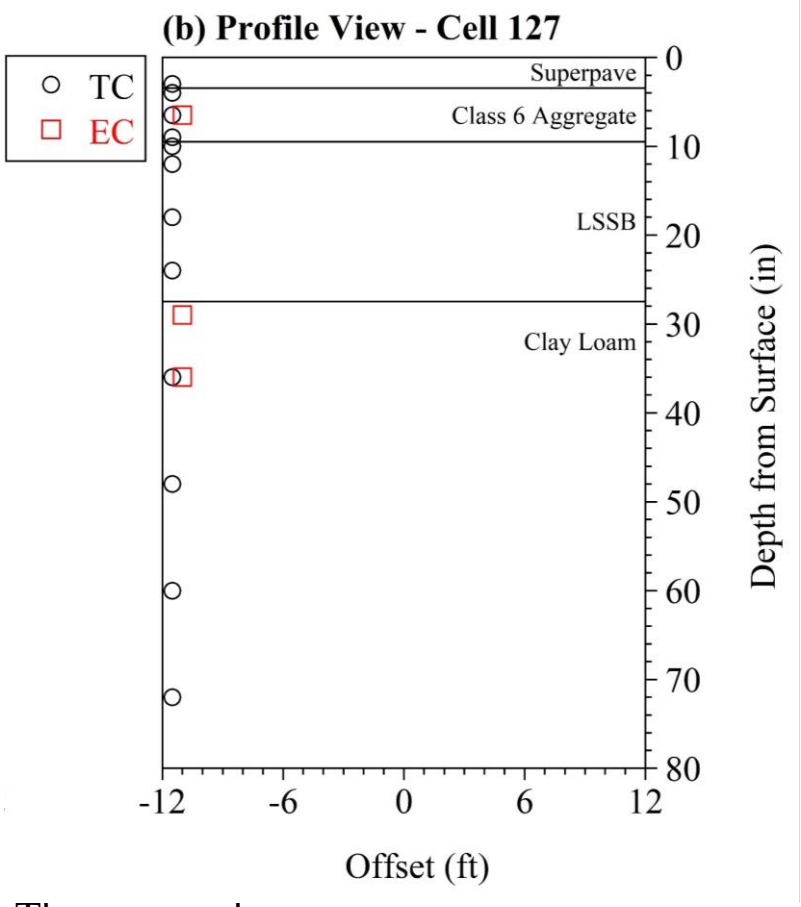


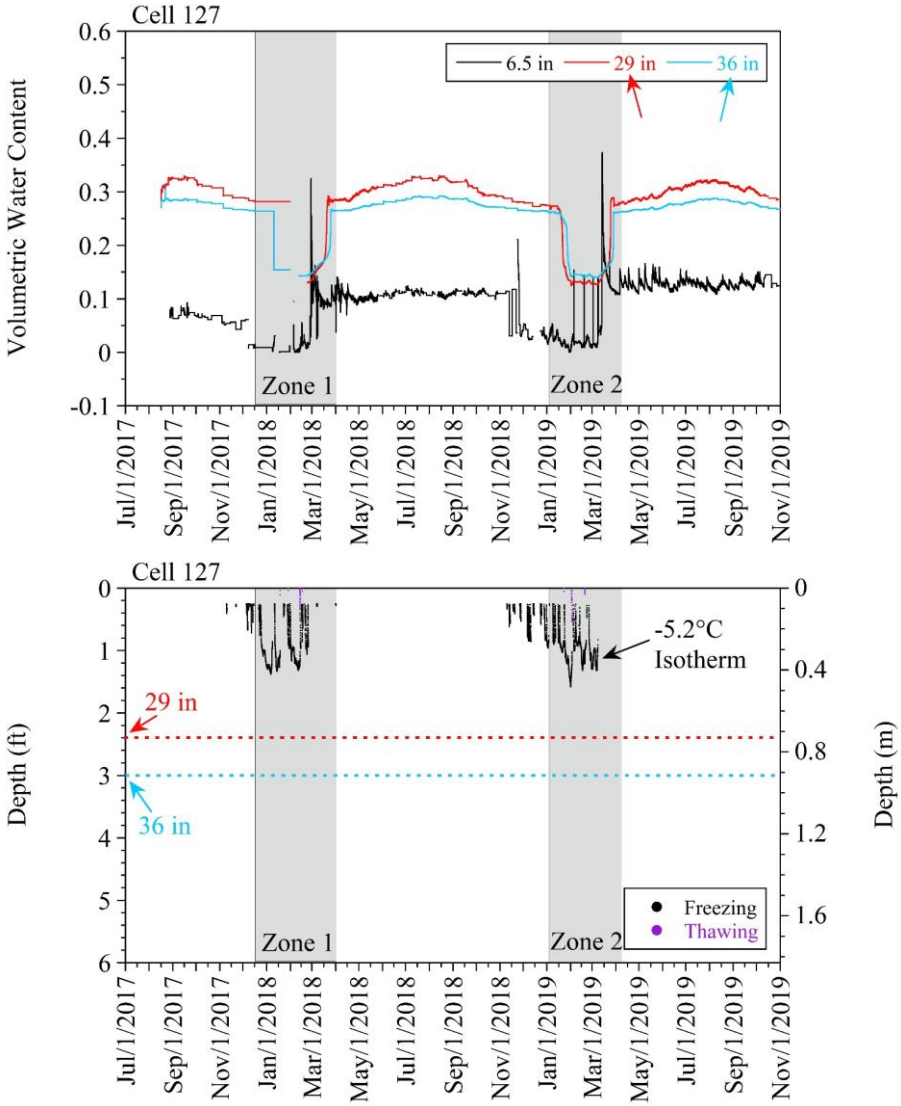


TC = Thermocouple
EC = Moisture probe

FROST PENETRATION DEPTH

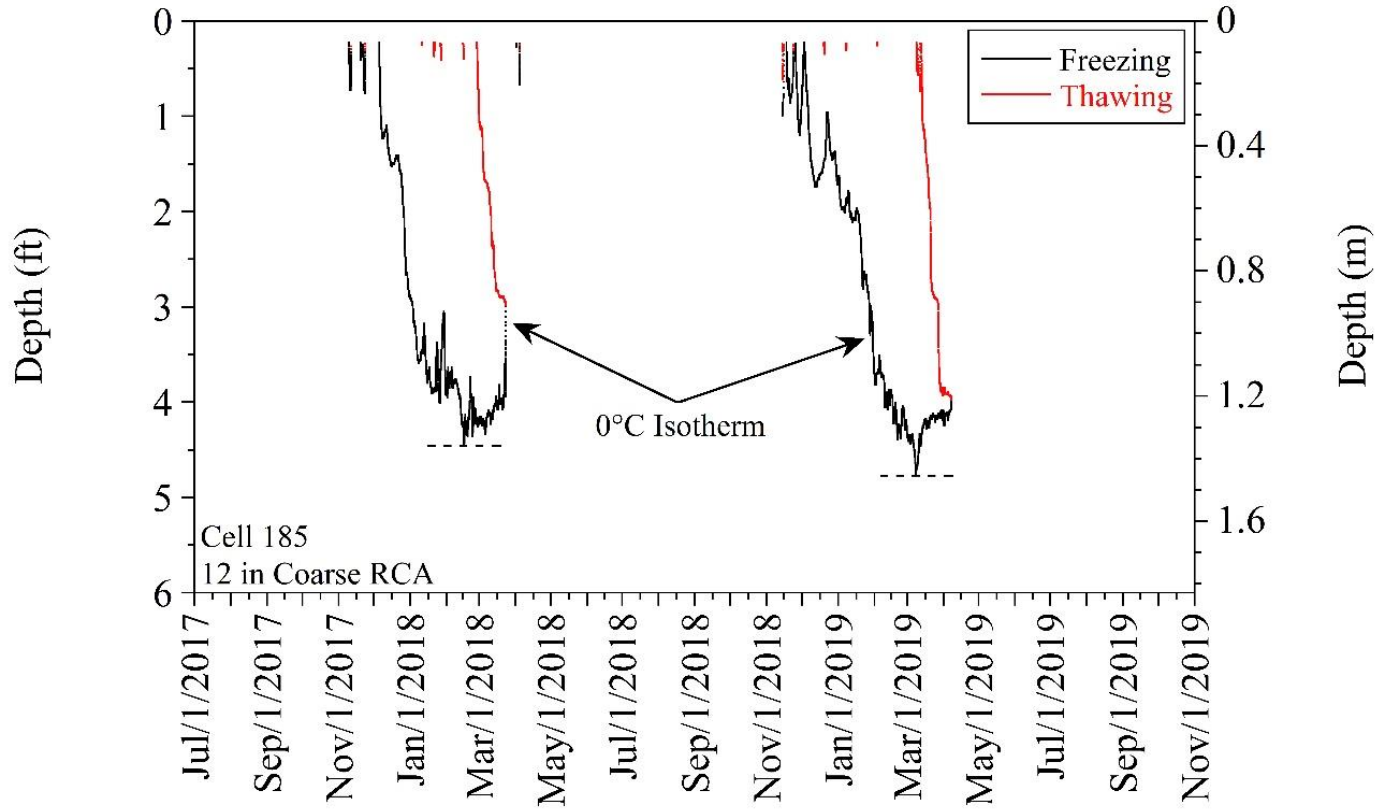
Cell 127 – -5.2°C Isotherm

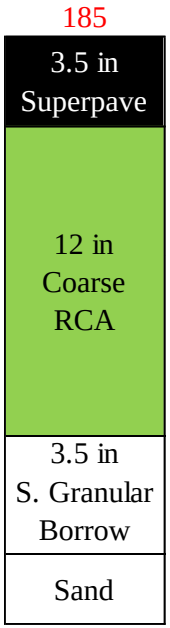




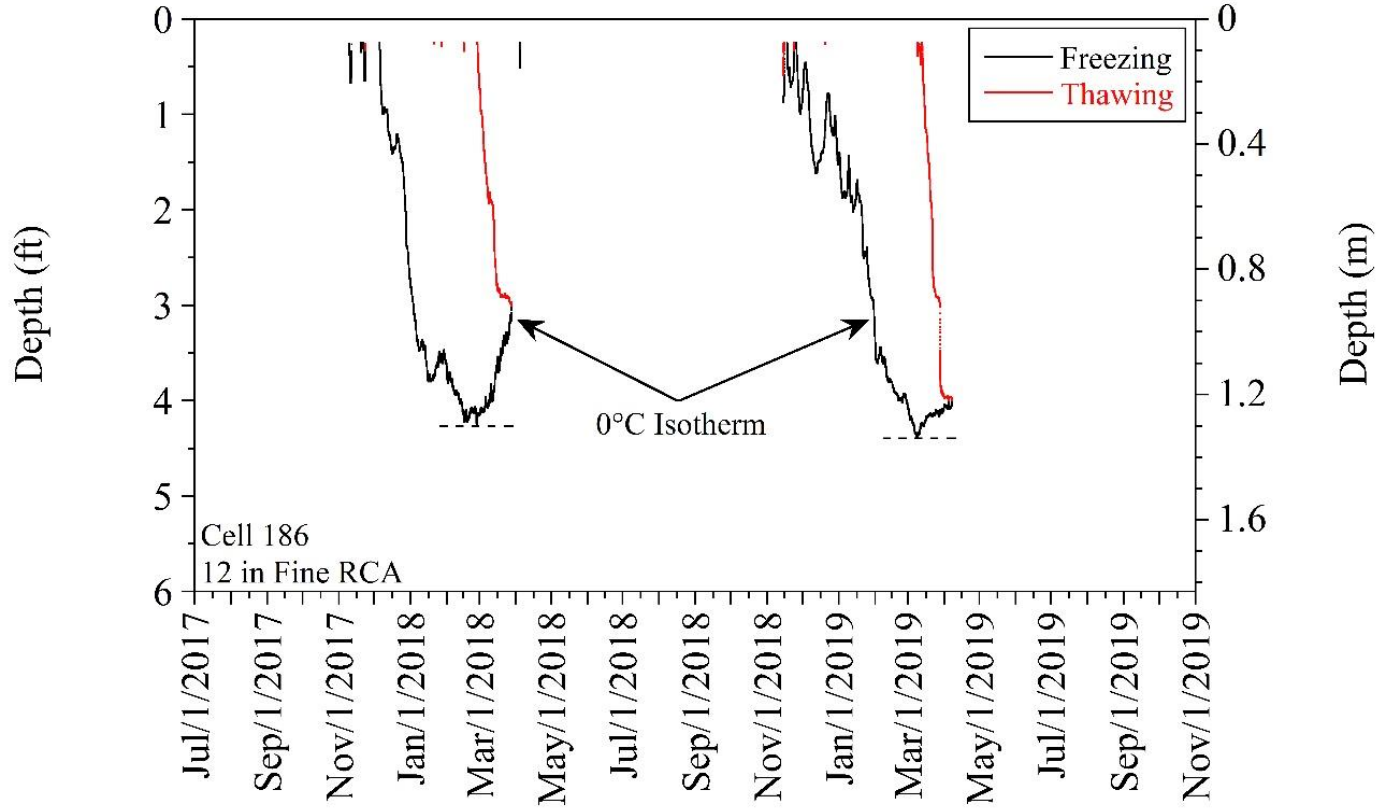
TC = Thermocouple
EC = Moisture probe

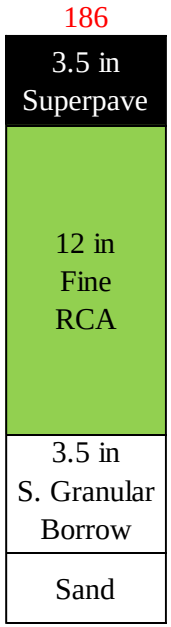
FROST PENETRATION DEPTH



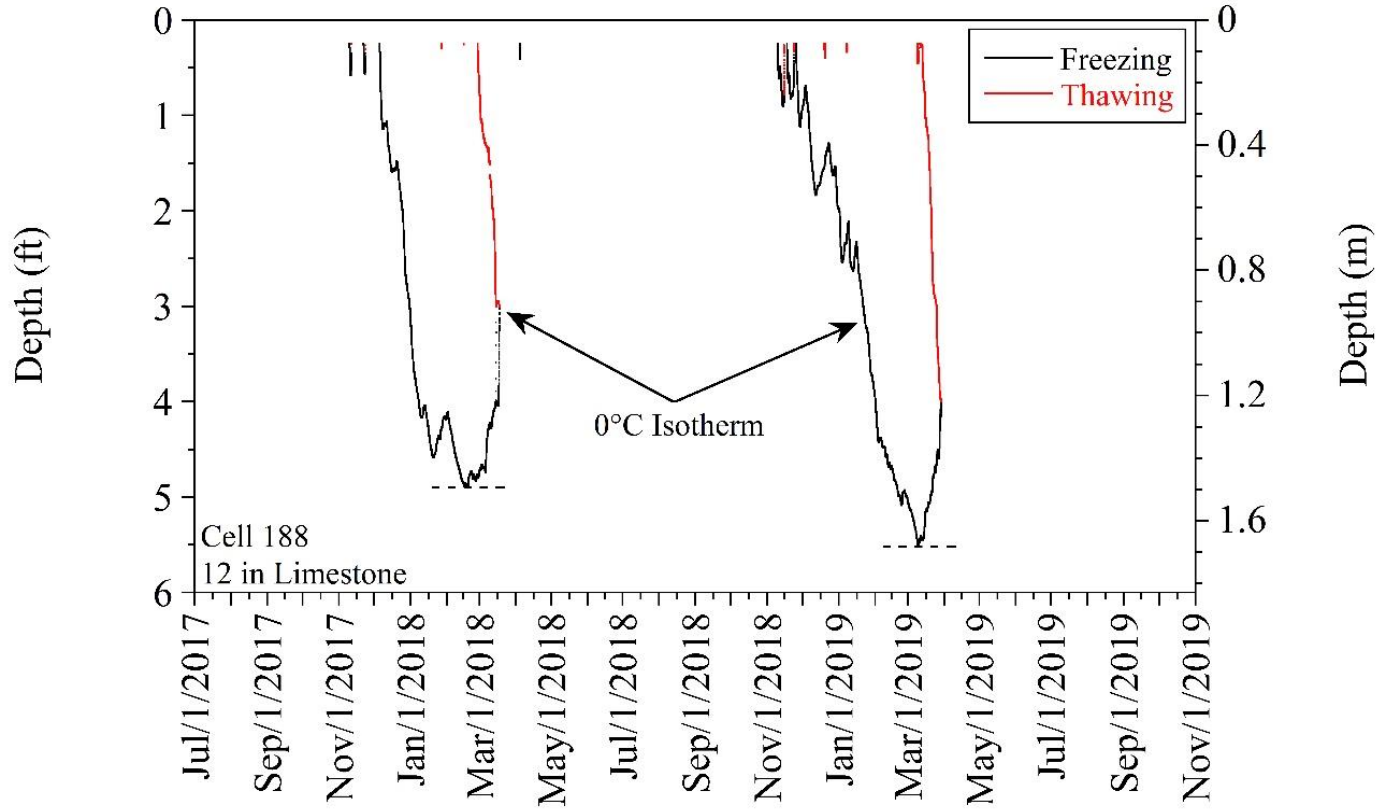


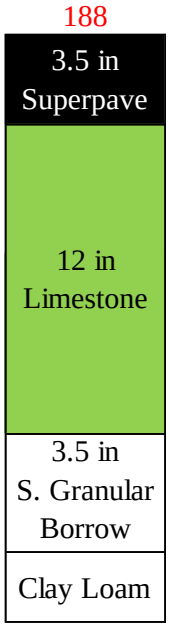
FROST PENETRATION DEPTH





FROST PENETRATION DEPTH





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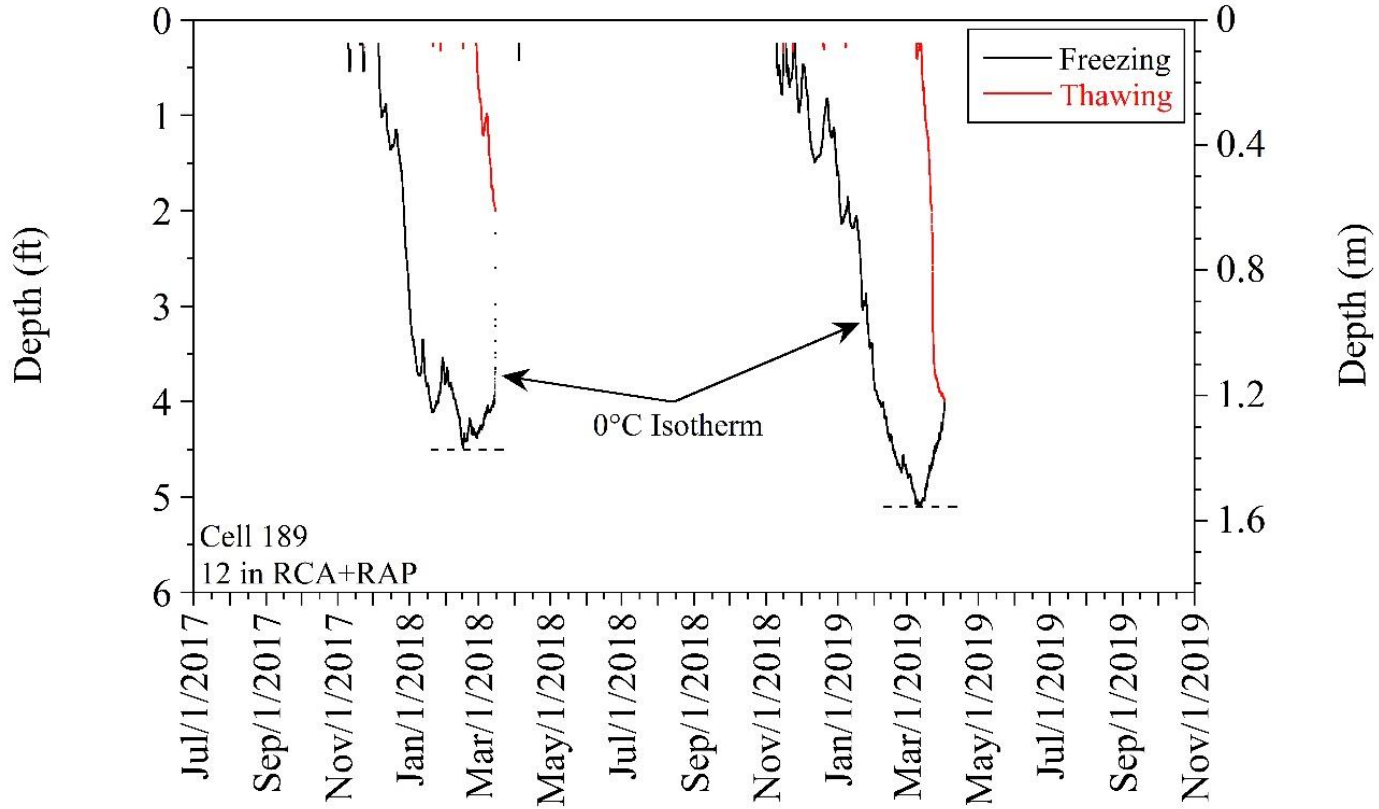

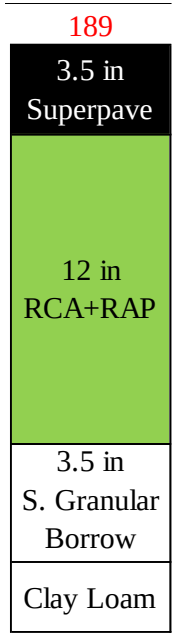

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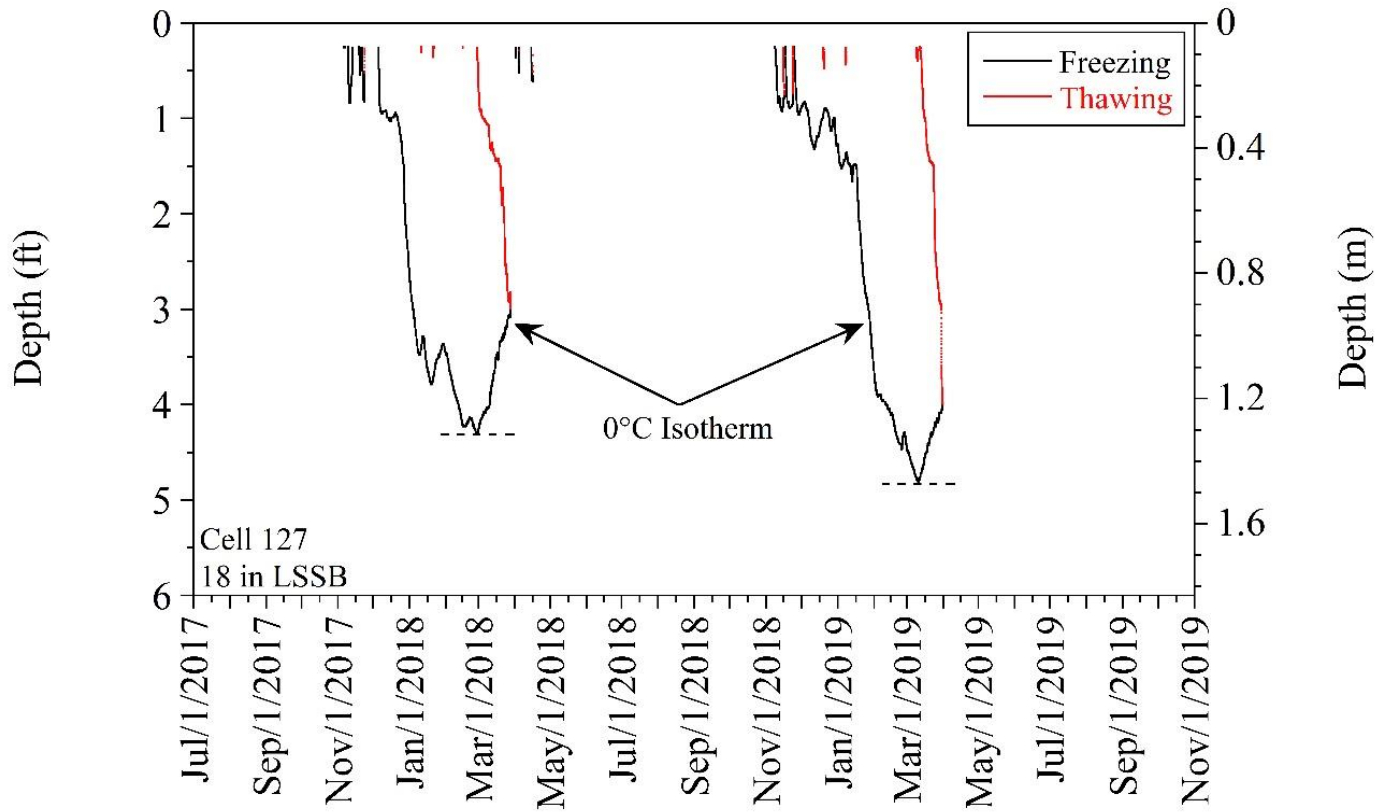

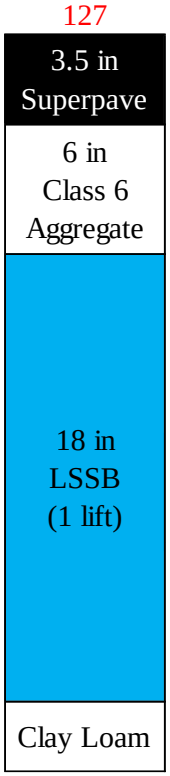

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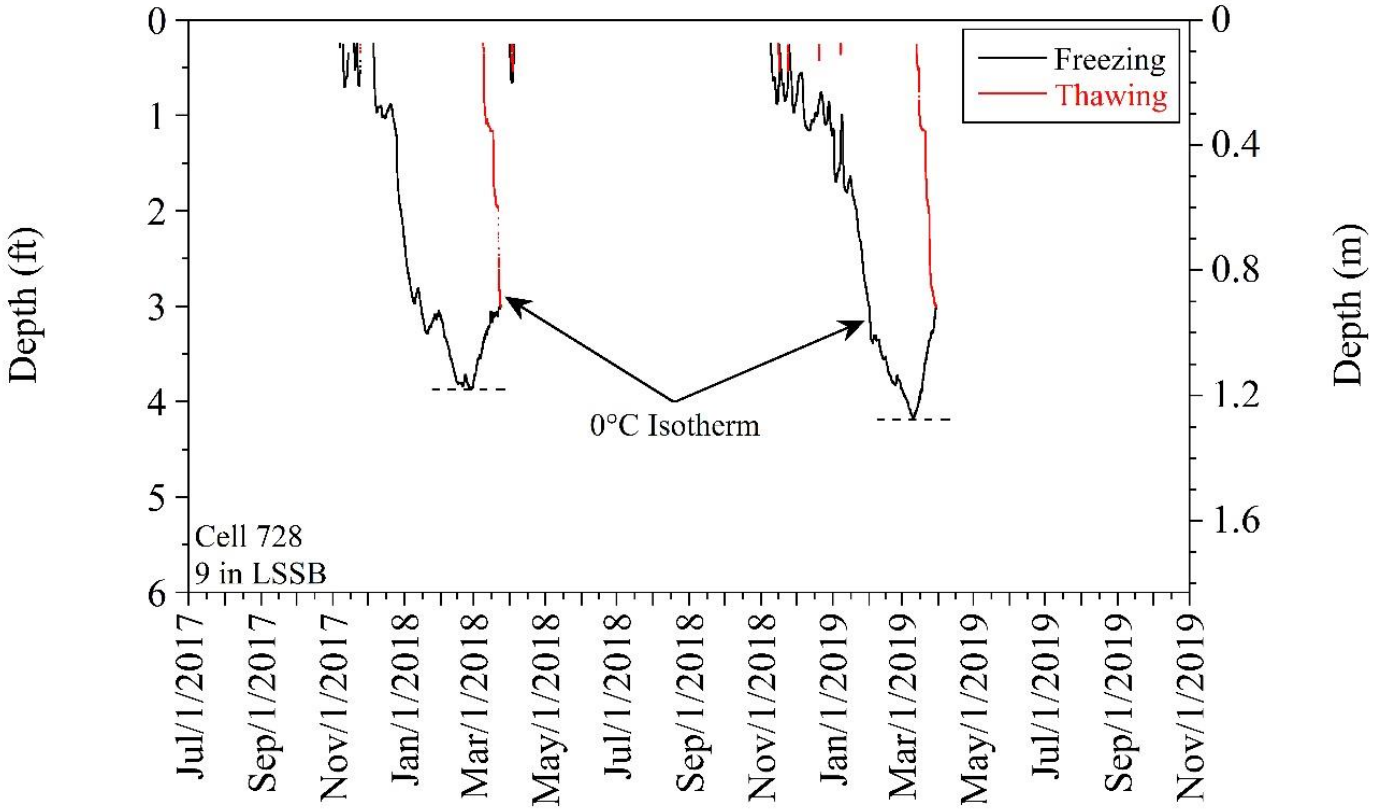
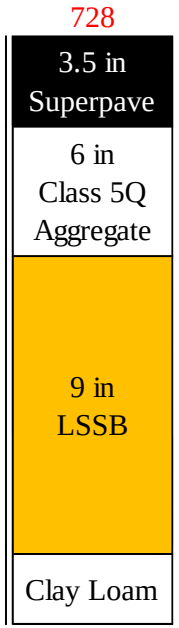
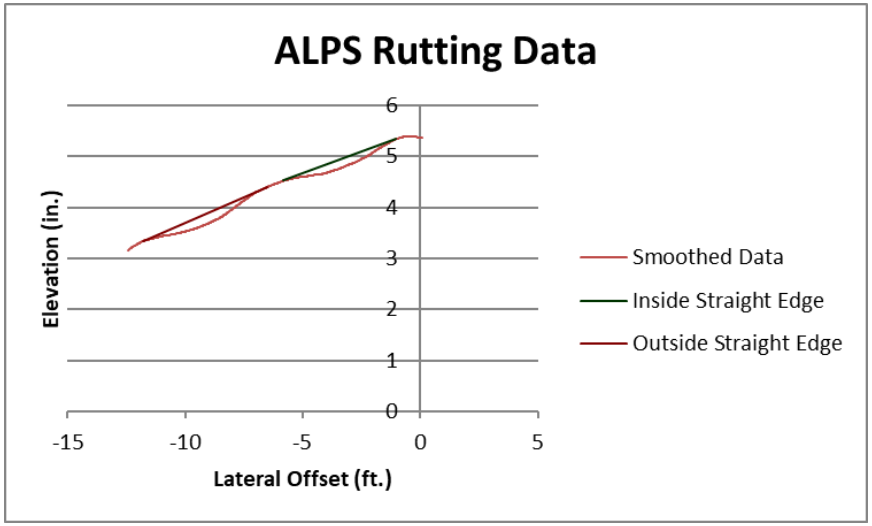
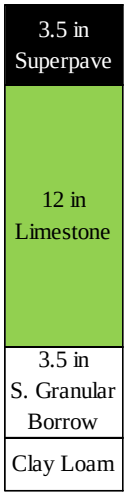


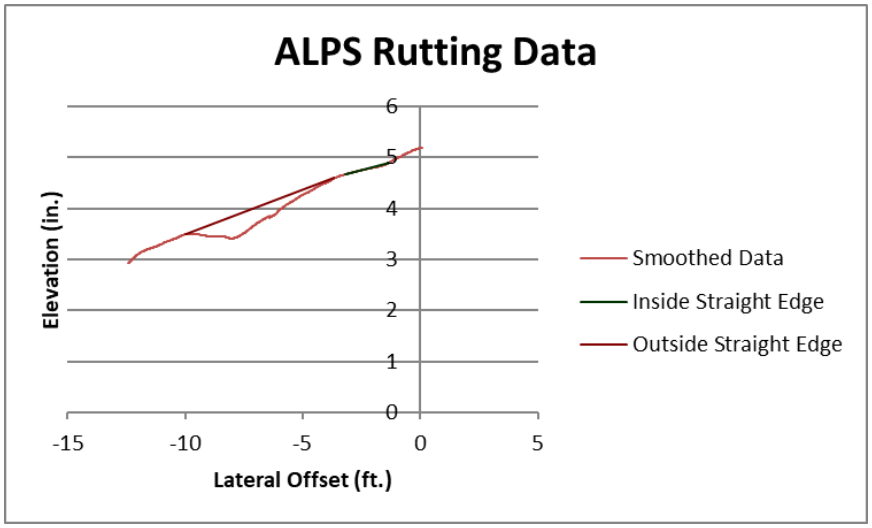


RUTTING

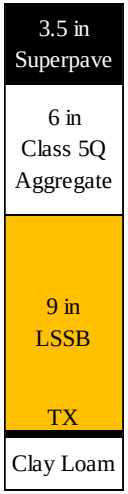


188





328



PAVEMENT DISTRESSES

- Raveling