Curling and Warping of Concrete Pavements

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Tyler Ley

Acknowledgements

- Oklahoma Department of Transportation
- Oklahoma Transportation Center
- Continued funding from FHWA through LTPP

Summary

- Background
- Curling/Warping
  - Lab Data
  - Field Data
  - What can you do about it?

- Are all curing compounds the same???

  (If there is time!)

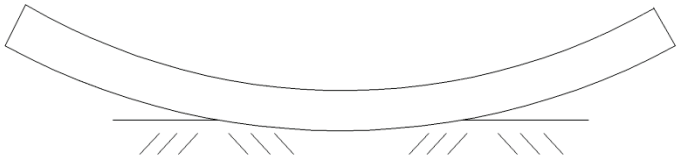
Background

- Concrete pavements are sensitive to volumetric changes
- These changes can impact the ride quality, support by the foundation, and stresses

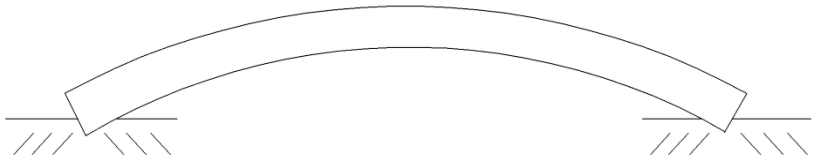
What is Curling/Warping?

- It is when the edges of a concrete pavement (or slab) deflect compared to the middle
- Instead of worrying about which is which let's agree that both are bad and should be avoided

positive curvature



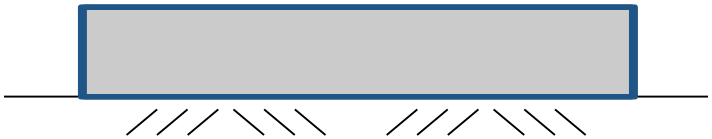
negative curvature



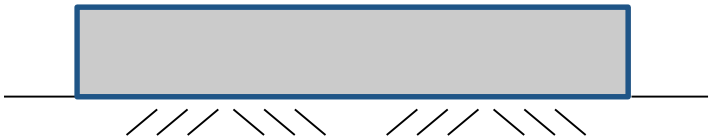
Why do pavements curl/warp?

- Curling/Warping occur when there is a differential volume change between the top and bottom of the slab
- These occur when there is a differential in either temperature or moisture
- This phenomenon is all about gradients…

moisture

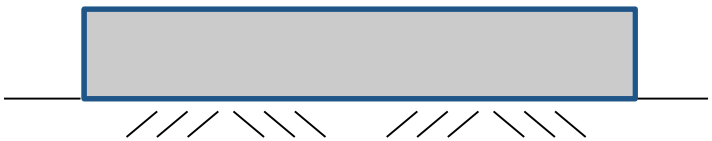


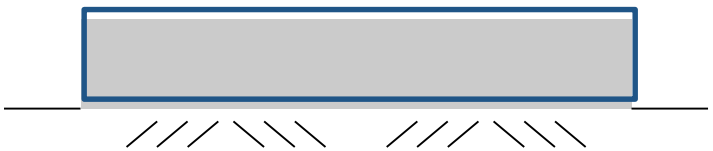
temperature



moisture

temperature





moisture

temperature

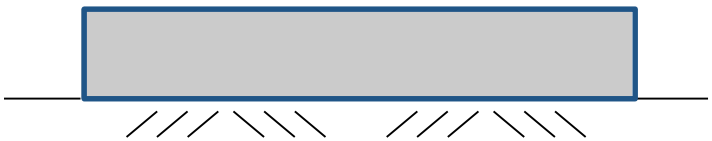
dry

wet

moisture

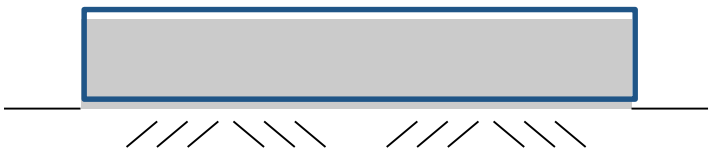
temperature

dry



~~wet~~

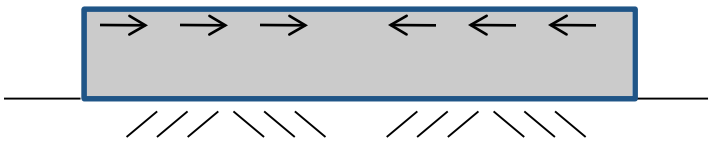
less dry



moisture

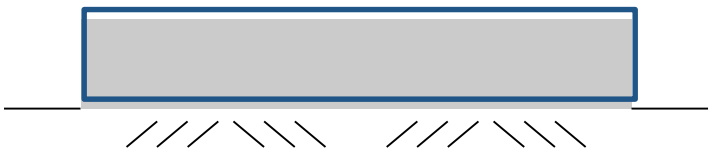
temperature

dry



~~wet~~

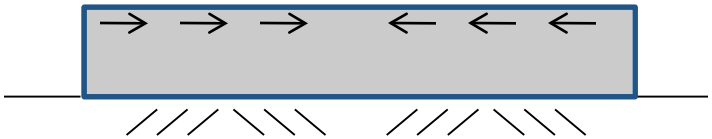
less dry

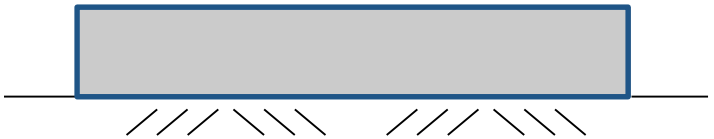


moisture

temperature

dry





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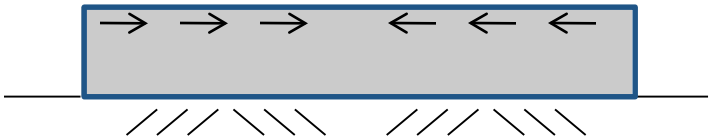
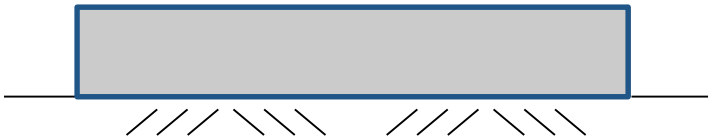
less dry

moisture

temperature

dry





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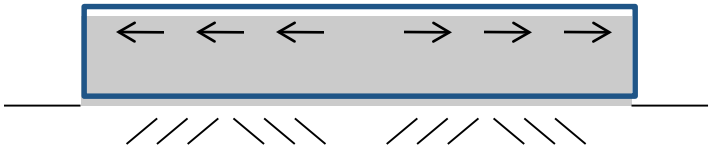
less dry

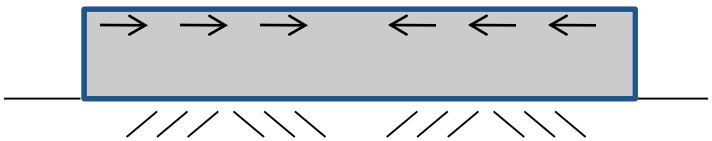
wet



less wet

moisture

dry



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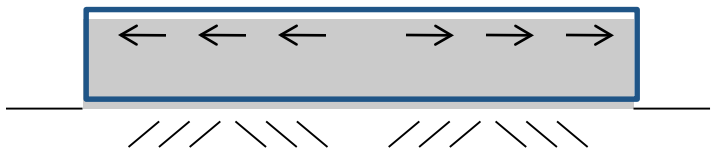
less dry

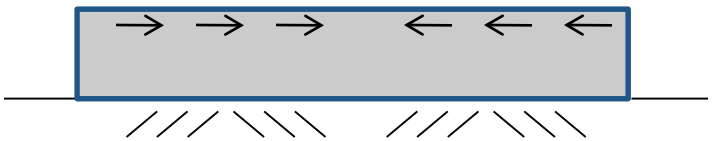
wet



less wet

temperature

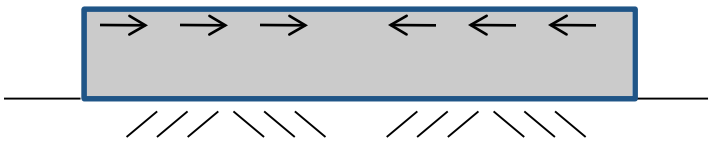
cold



less cold

moisture

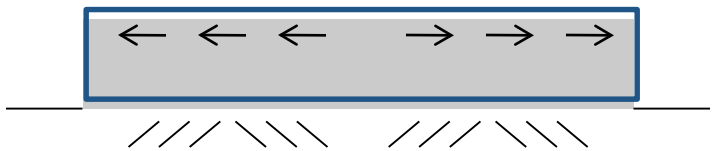
dry



~~wet~~

less dry

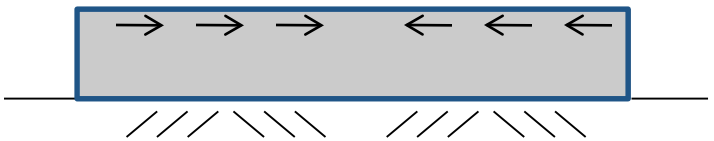
wet



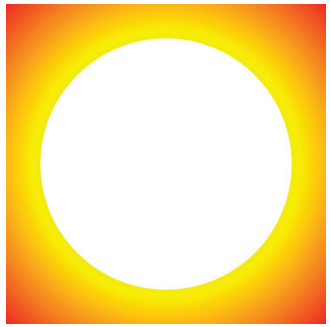
less wet

temperature

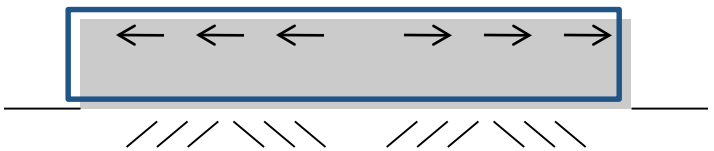
cold



less cold



hot



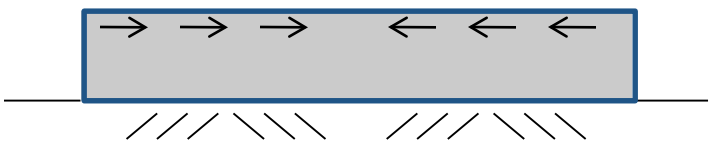
less hot

moisture

temperature

dry

cold



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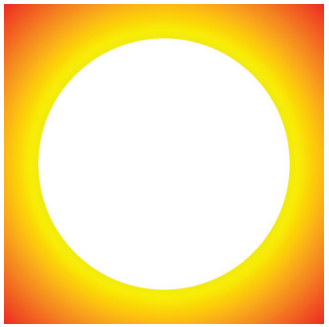
less dry

less cold

wet



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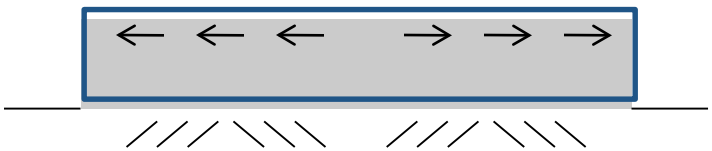

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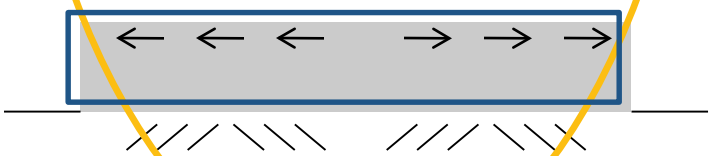


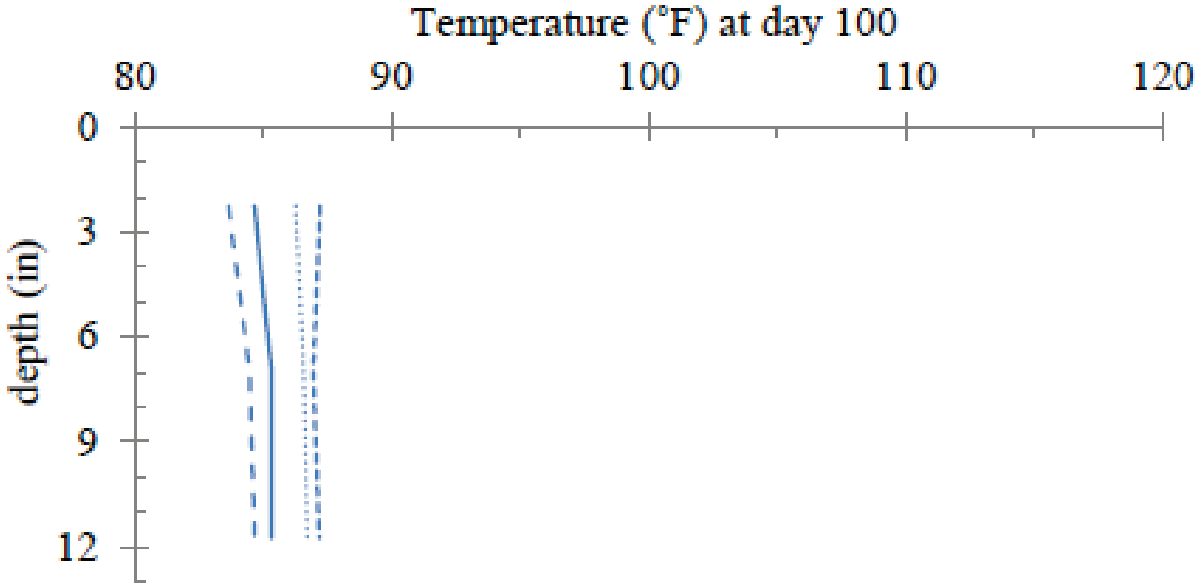
less hot

Volume change from temperature

- Aggregate accounts for about 60 to 75% of the concrete volume
  - Coefficient of Thermal Expansion (CTE) of aggregates dominates CTE of concrete
    - Pure limestone ~ 3 x 10^{-6} in/in/°F
    - Quartzite ~ 6.5 x 10^{-6} in/in/°F
- Cement volume
  - Cement paste CTE ~ 10.5 x 10^{-6} in/in/°F
- The CTE of concrete is dependent on the mixture

Volume change from temperature

- This is only a problem if there is significant temperature gradient from the top and bottom of a pavement

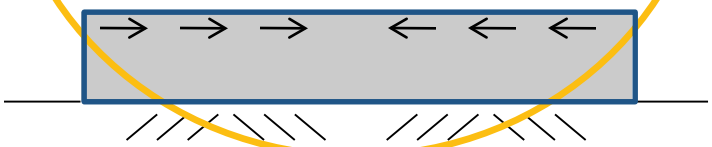


moisture

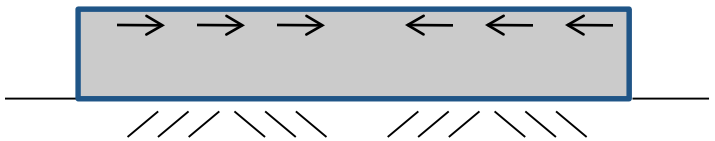
temperature

Important for curl/warp

dry



cold

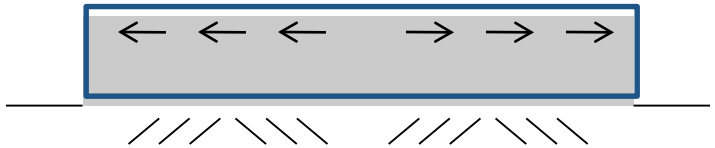


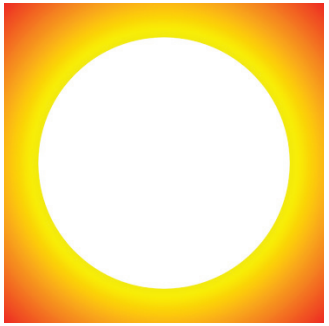
~~wet~~

less dry

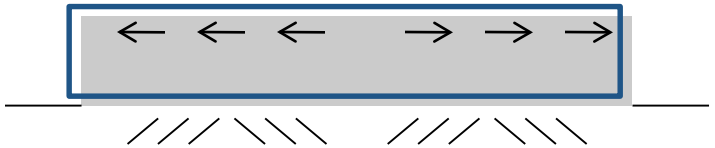
less cold

wet





hot

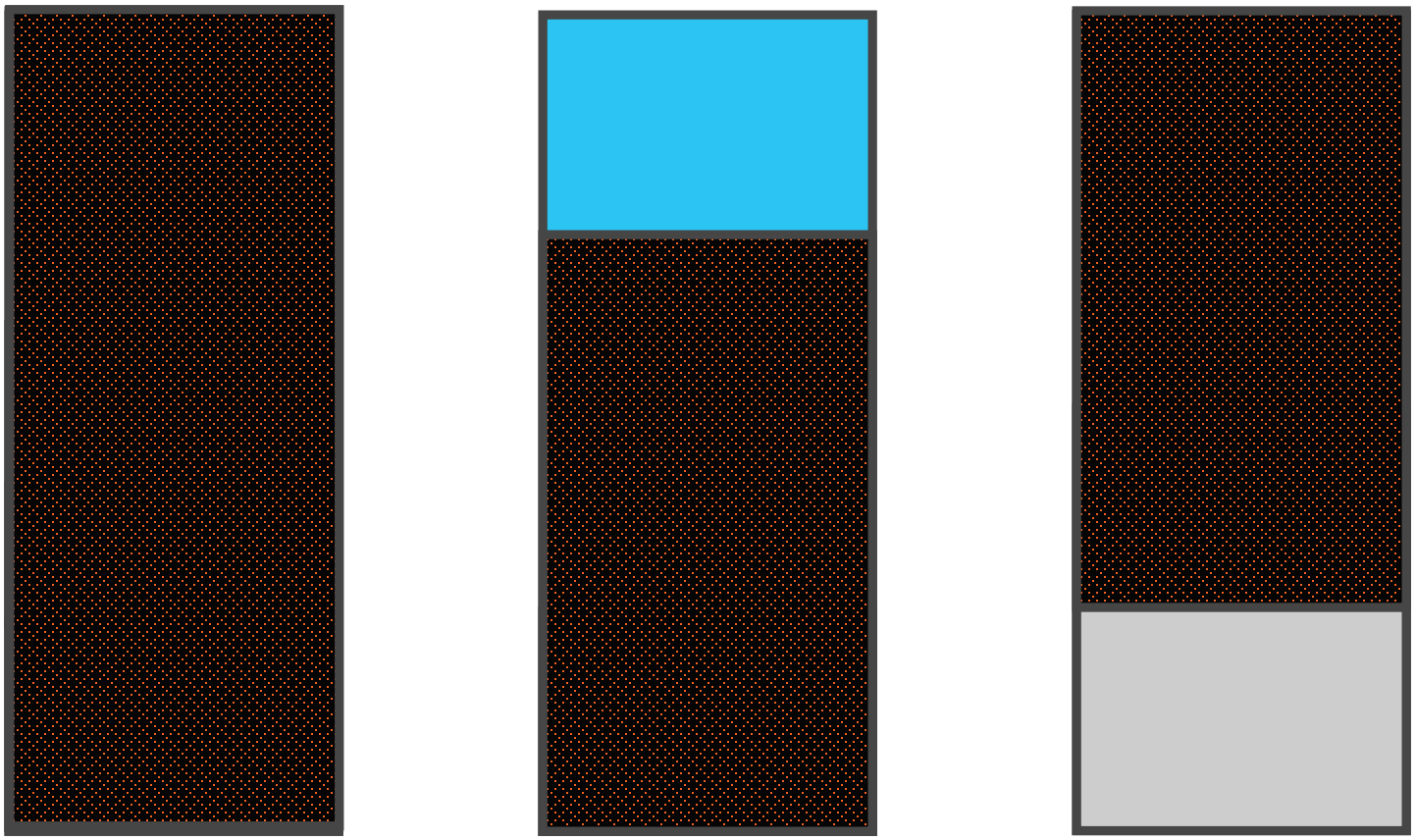


less wet

less hot

Volumetric Changes Due to Drying Shrinkage

- Loss of water over time due primarily to evaporation from exposed surface
  - Overall volume contracts
  - Greater paste content results in greater drying shrinkage
  - Air humidity is important
- Strains are primarily influenced by characteristics of capillary pores

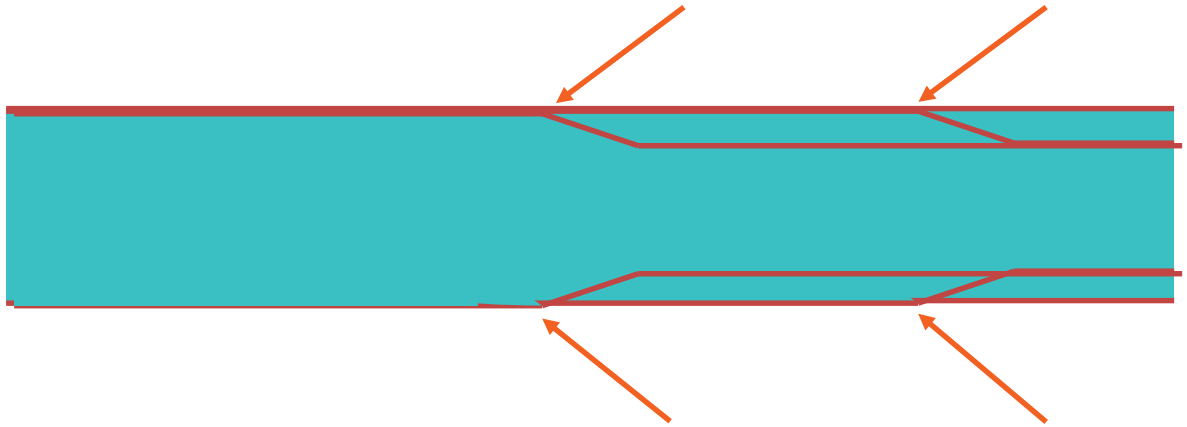


W/C = 0.40 **W/C = 0.75** **W/C = 0.25**

From Peter Taylor

Capillary Pores

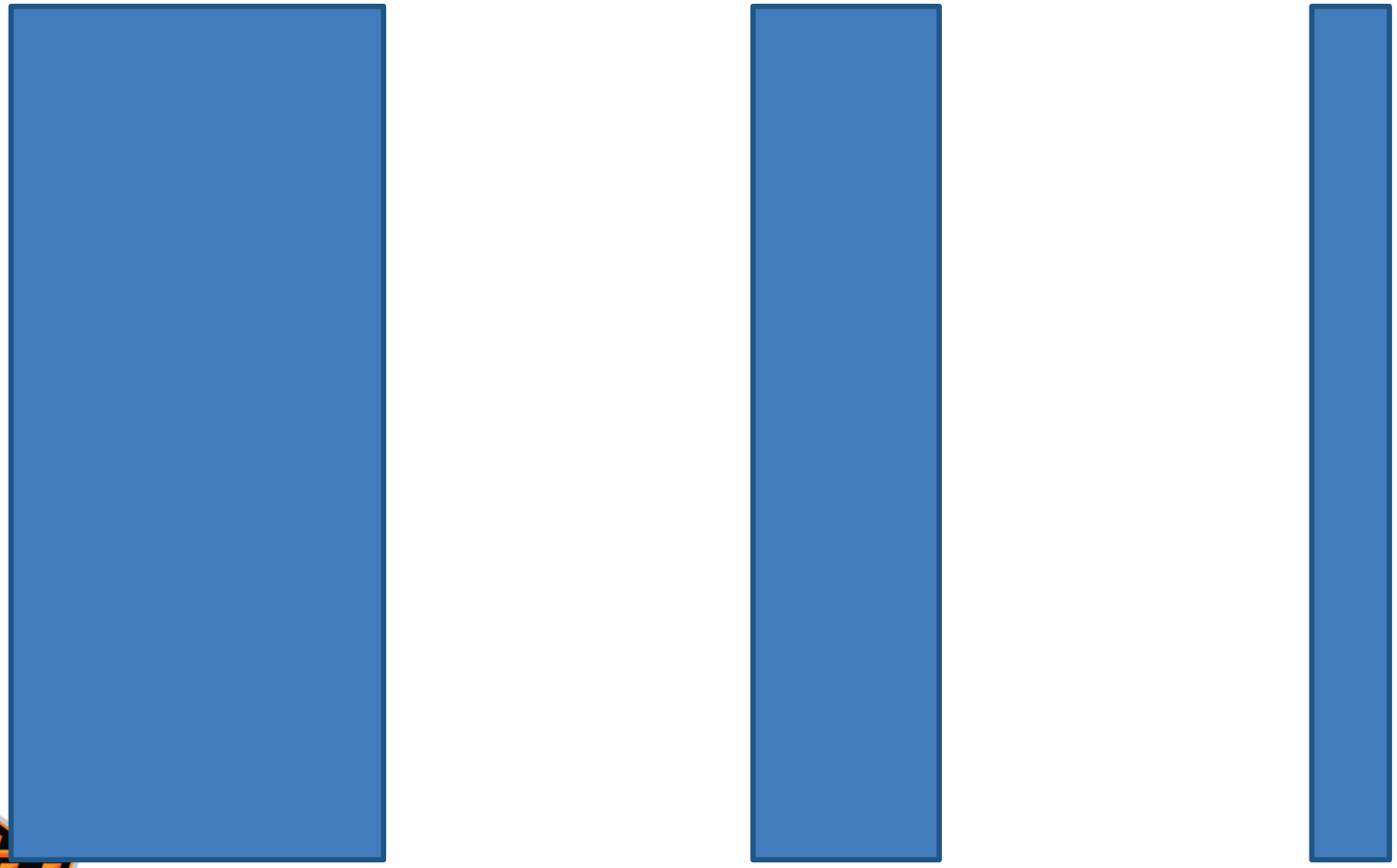
- Contribute to permeability and strength loss
- Vary in size from 0.01 µm to 5 µm
- Menisci pull against void walls at air/water interface



From Peter Taylor

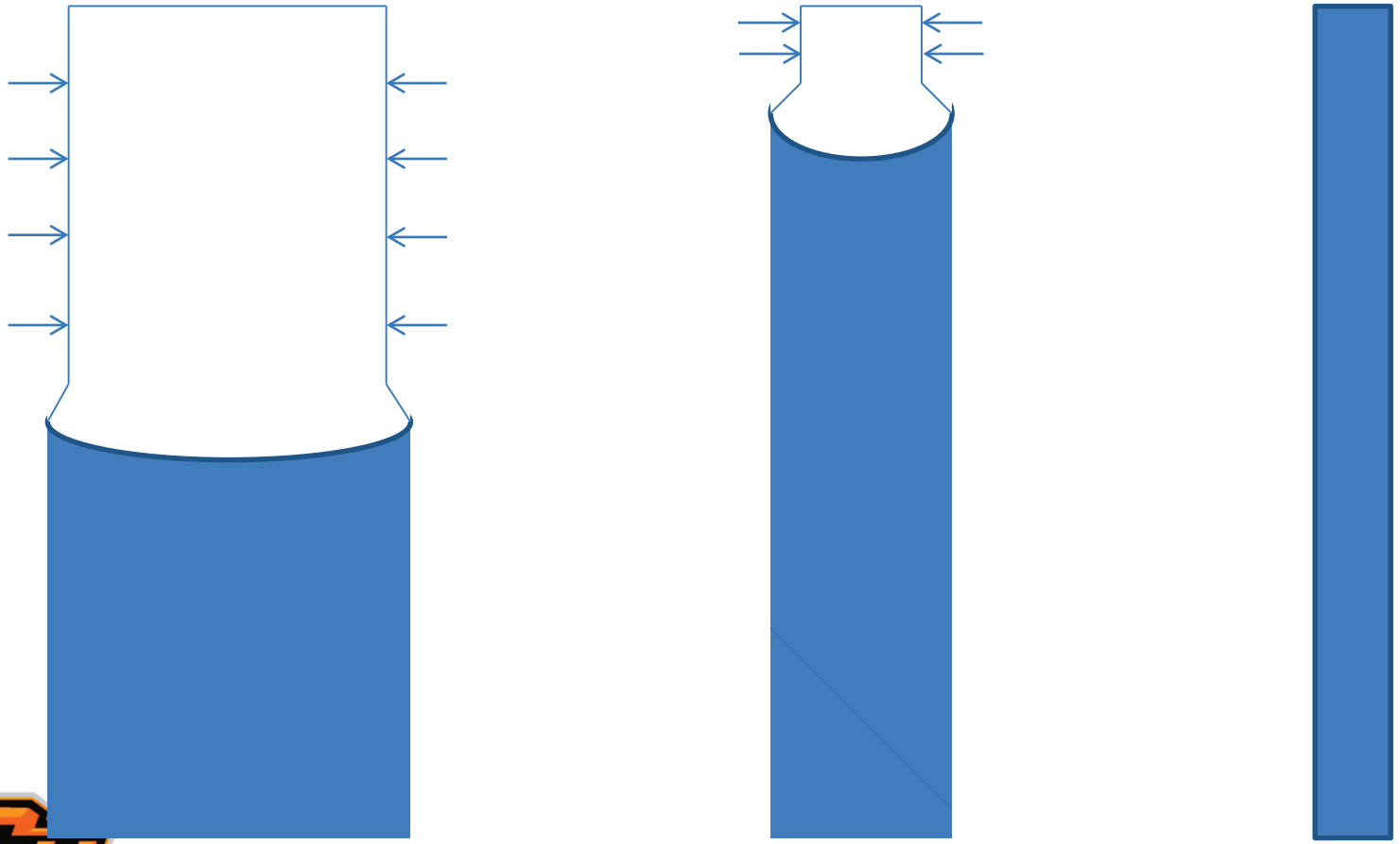
Capillary Pores, Drying Rate, and Magnitude of Shrinkage

100% rH

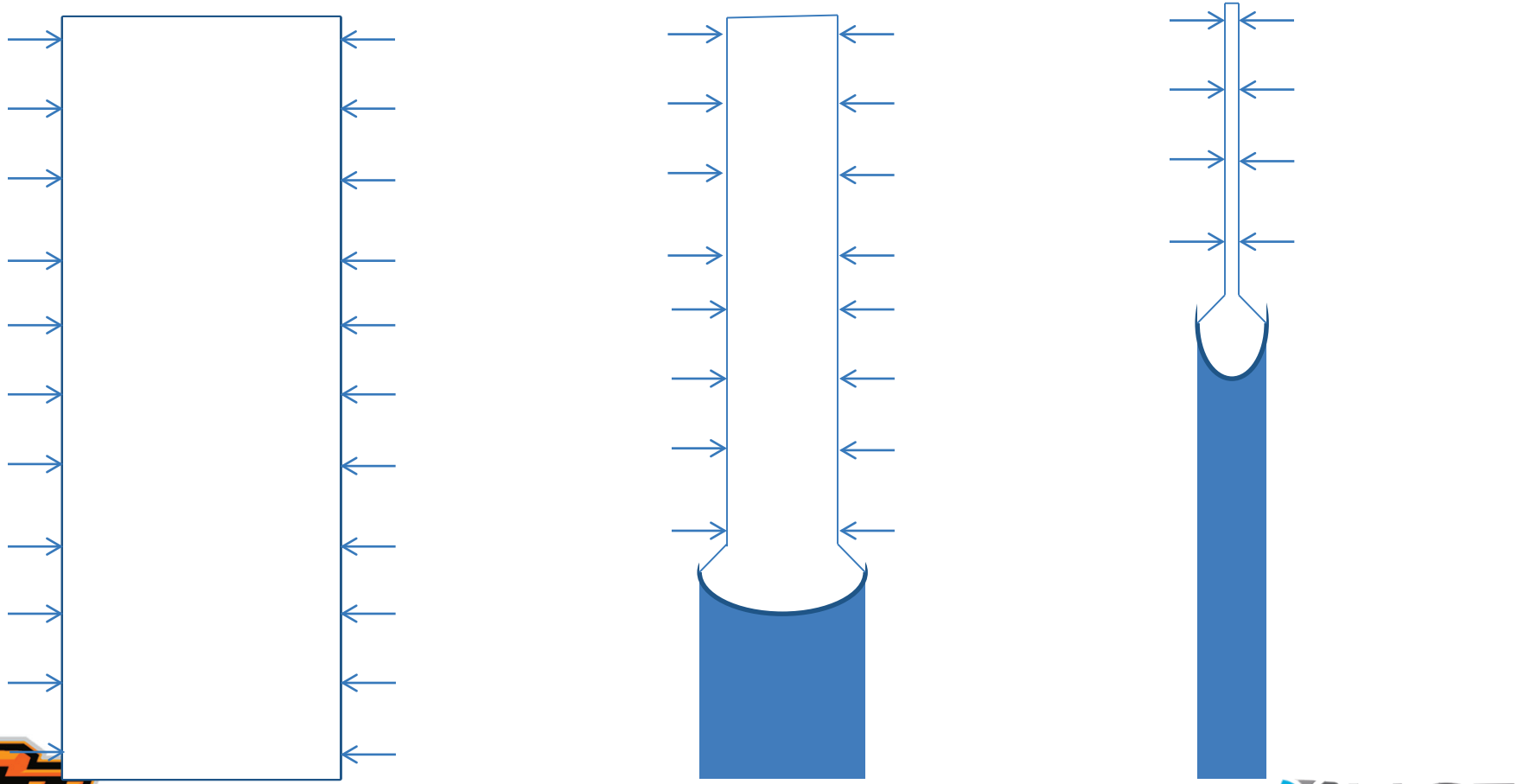


Capillary Pores, Drying Rate, and Magnitude of Shrinkage

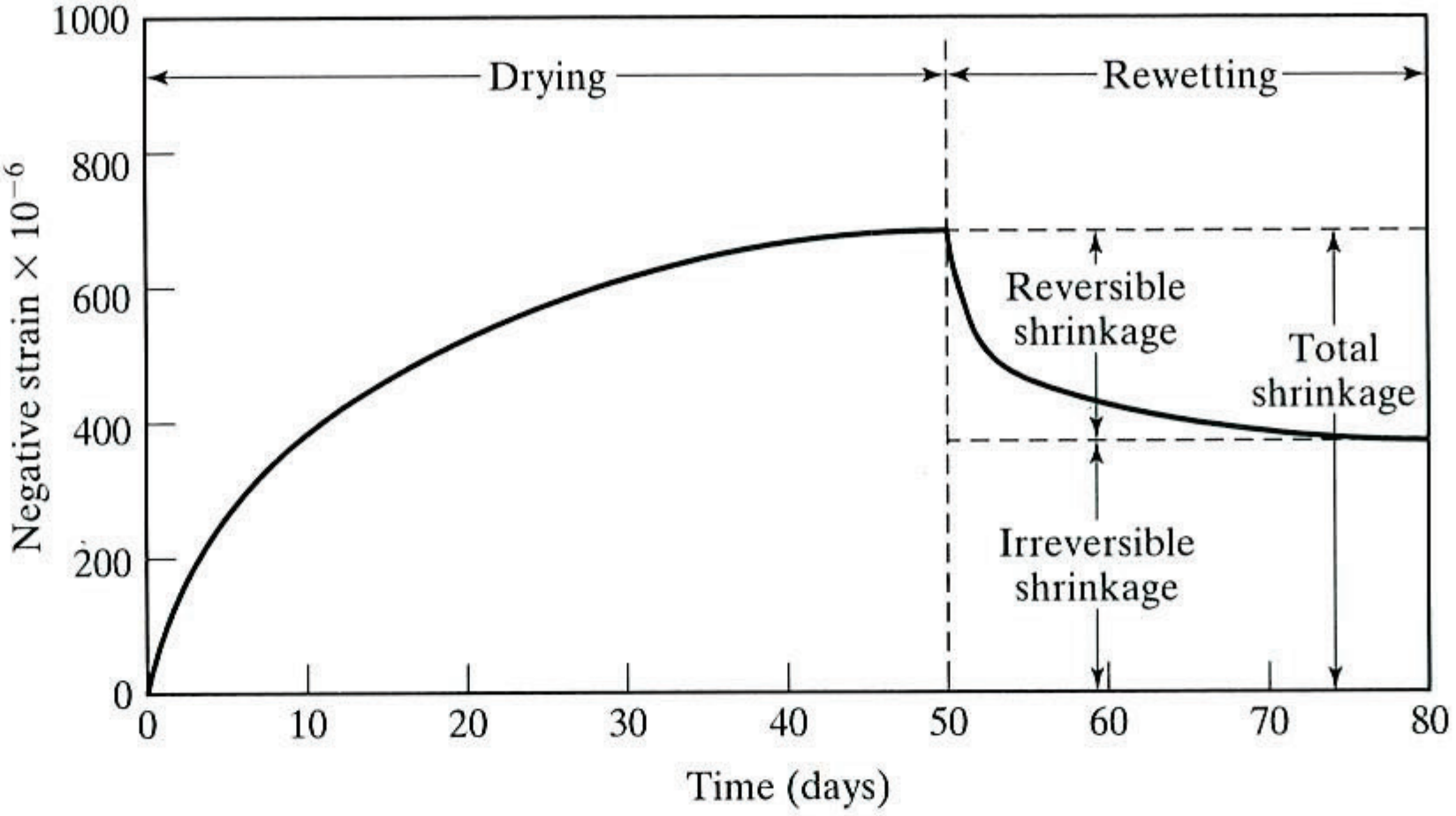
75% rH



Capillary Pores, Drying Rate, and Magnitude of Shrinkage

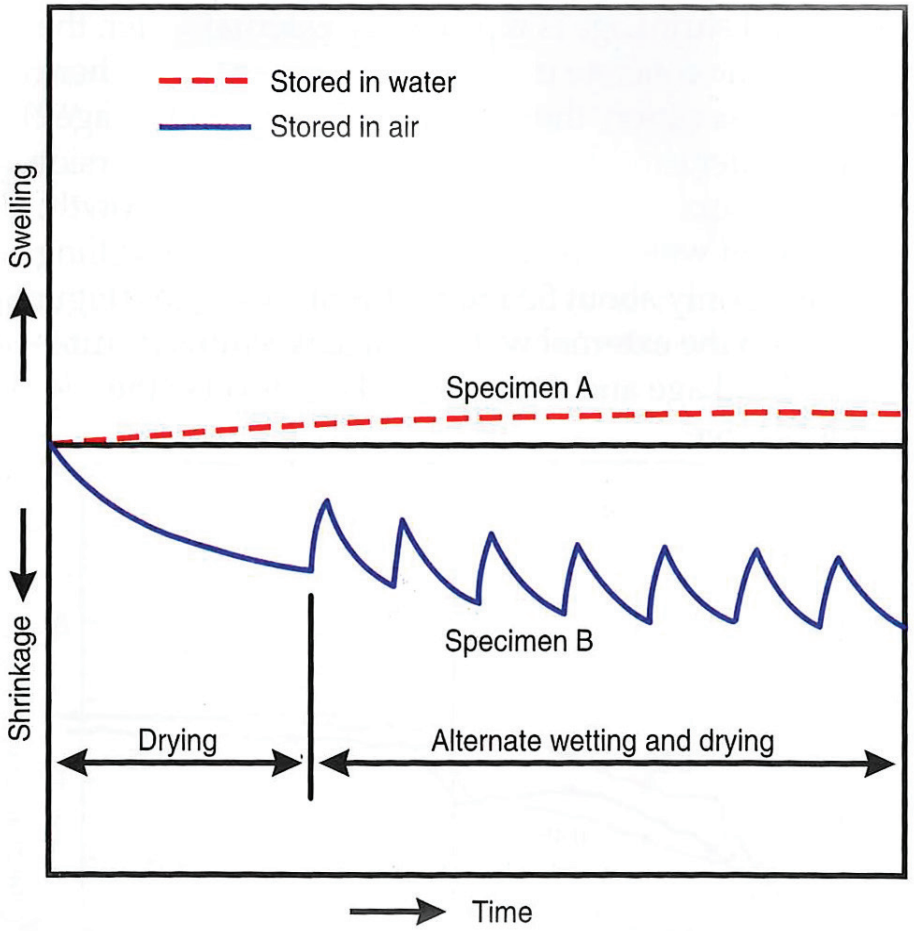


Reversible and Irreversible Shrinkage



From Mindess, Young, and Darwin 2003

Effects of Wetting and Alternate Wetting and Drying



From Kosmatka and Wilson 2011

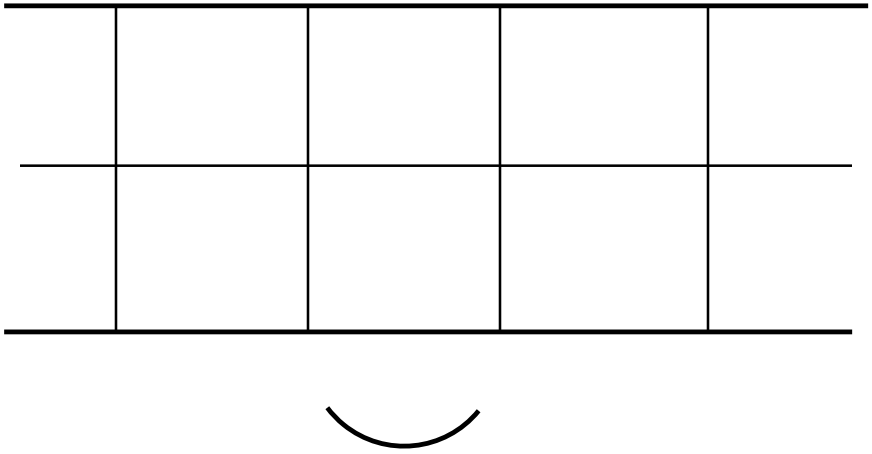
What does this mean?

- As concrete dries there is some of that volume change that you will never recover
- Rain can reduce moisture gradients but they don’t stop curling/warping
- Since the pavement dries out faster on the surface this causes the edges of the pavement to deflect upwards

Concrete Lab Testing

- We made a concrete specimen that mimicked a strip from a concrete pavement

JPCP



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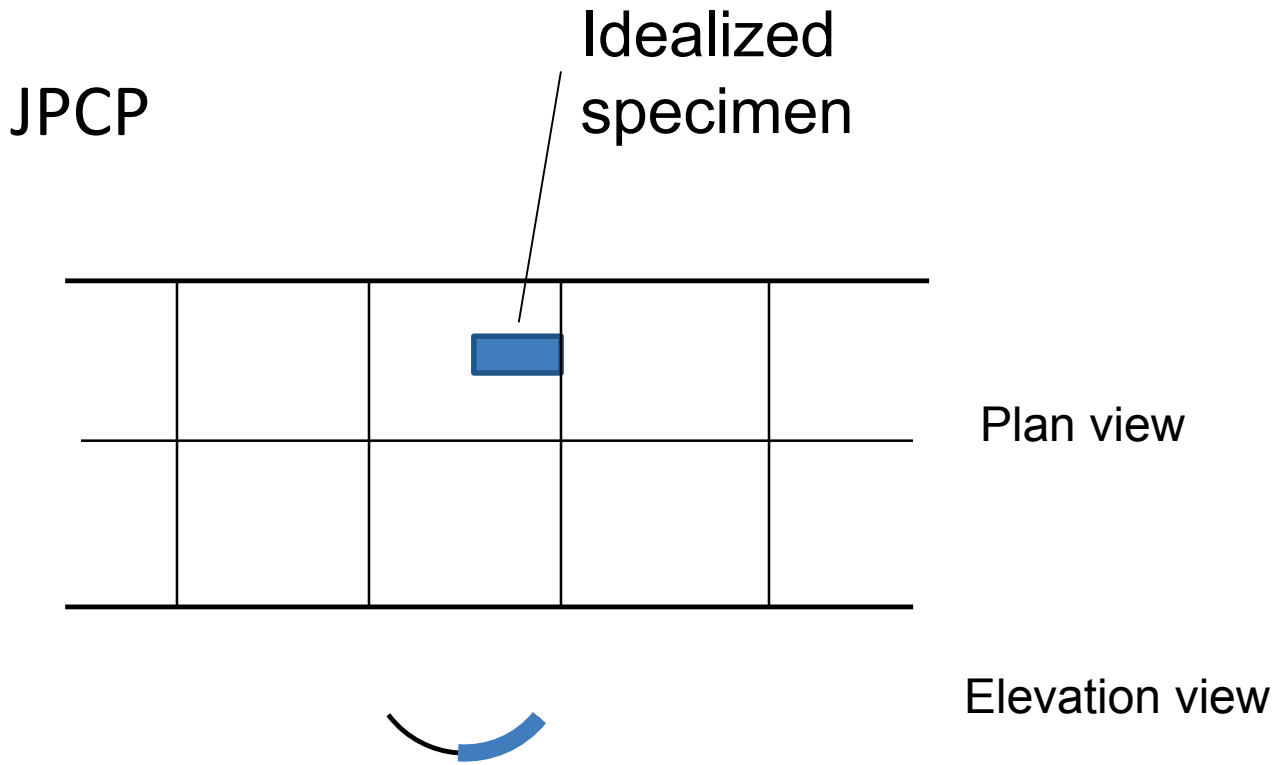
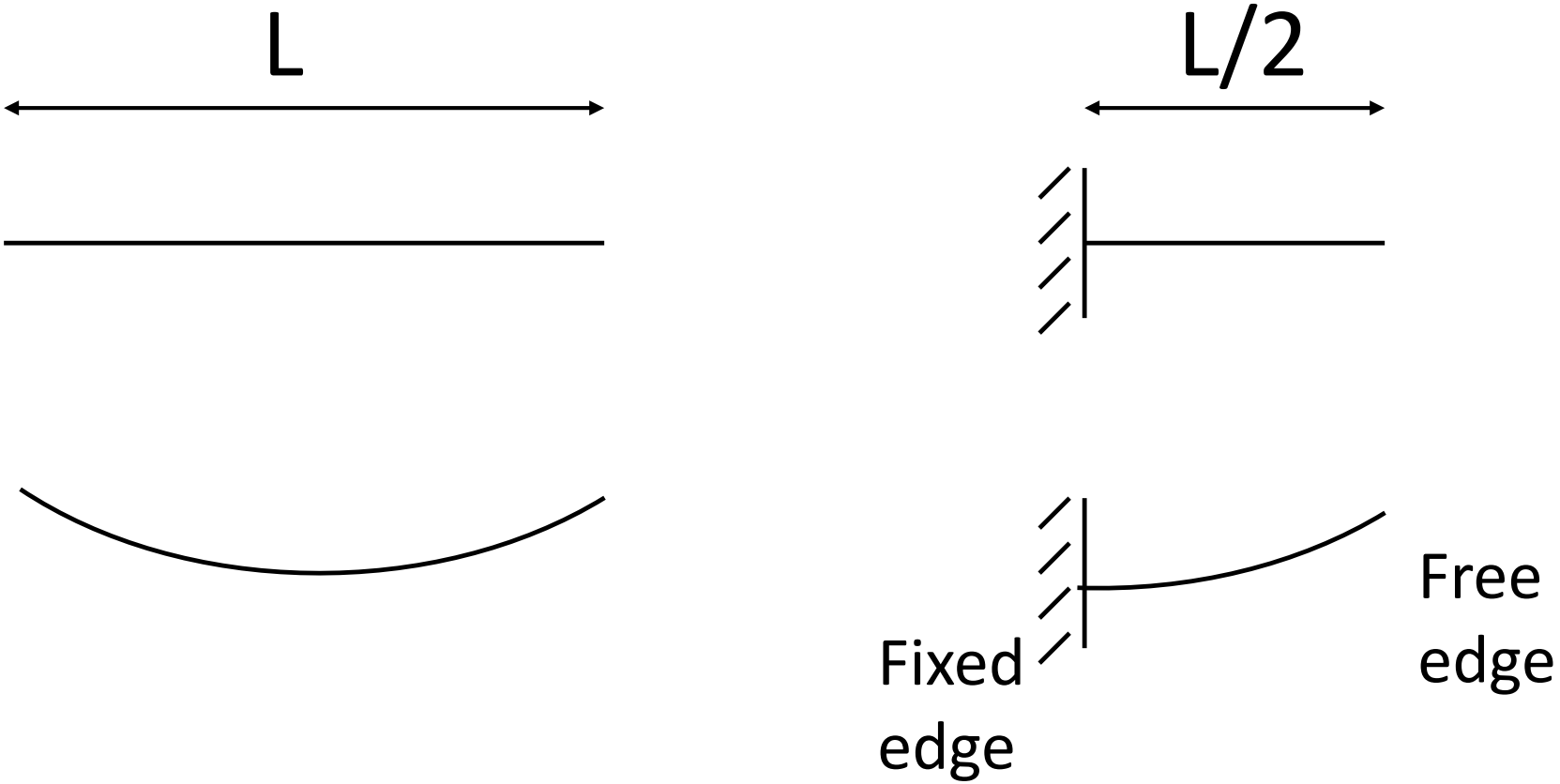
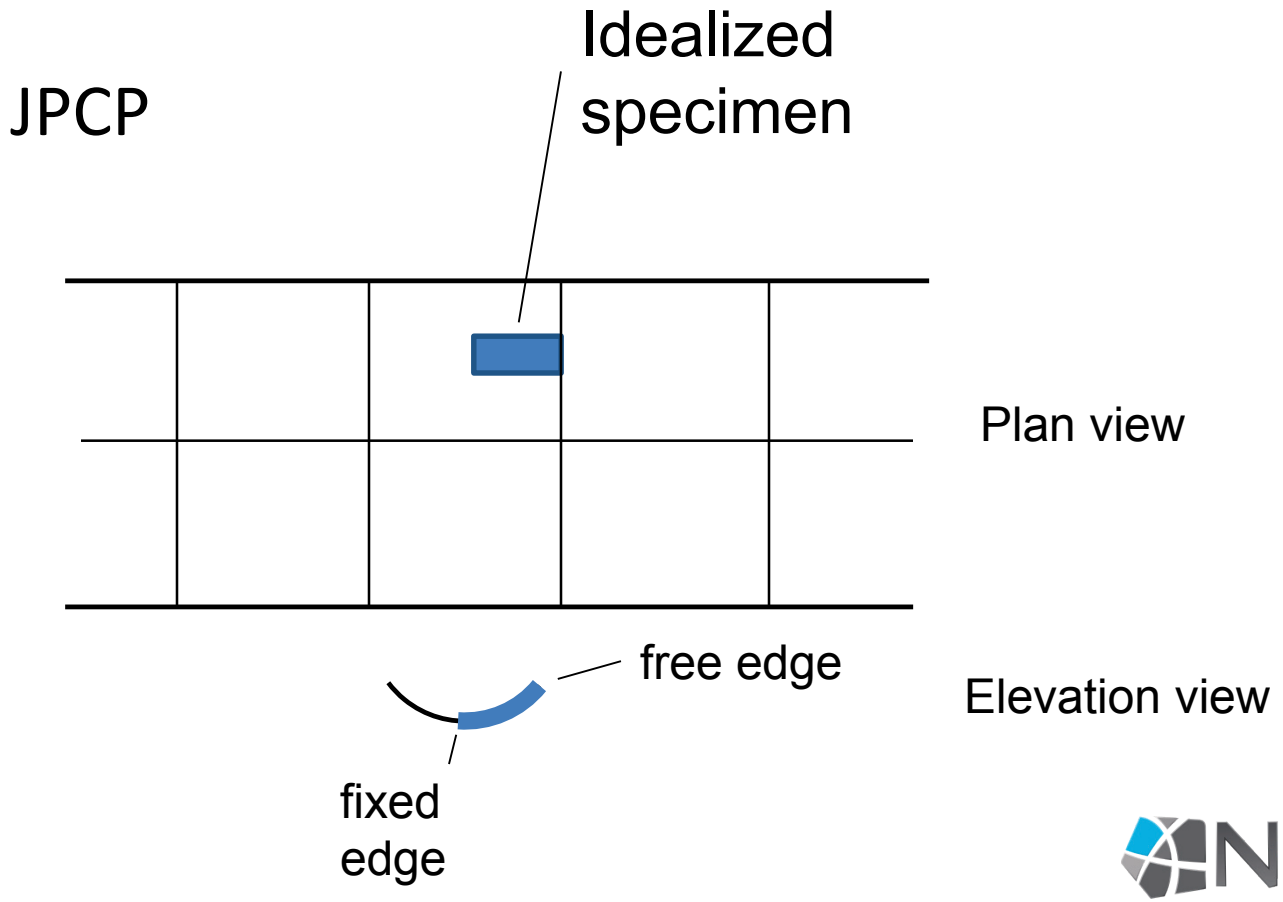



L
L/2
Fixed edge
Free edge

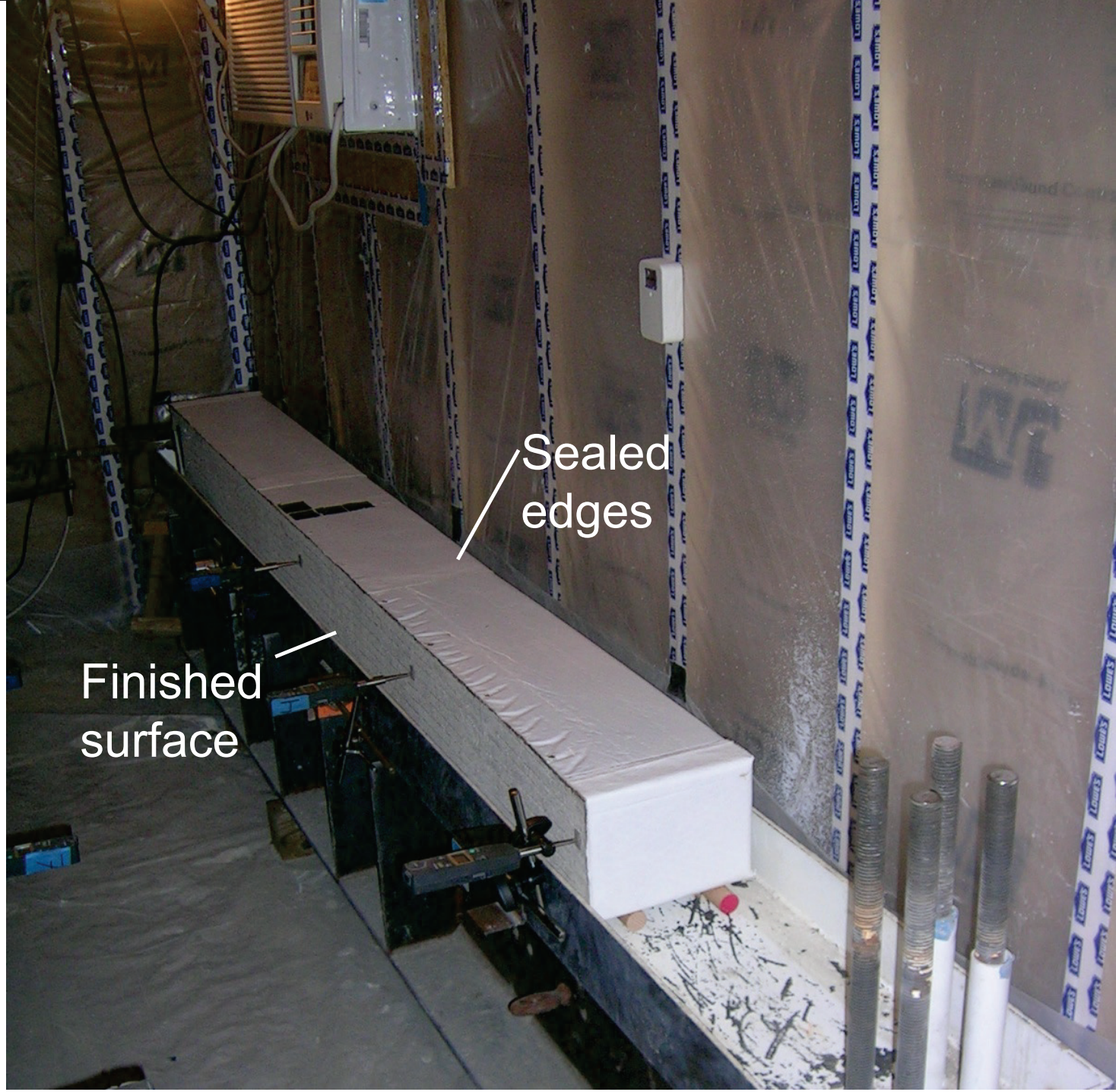
Concrete Lab Testing

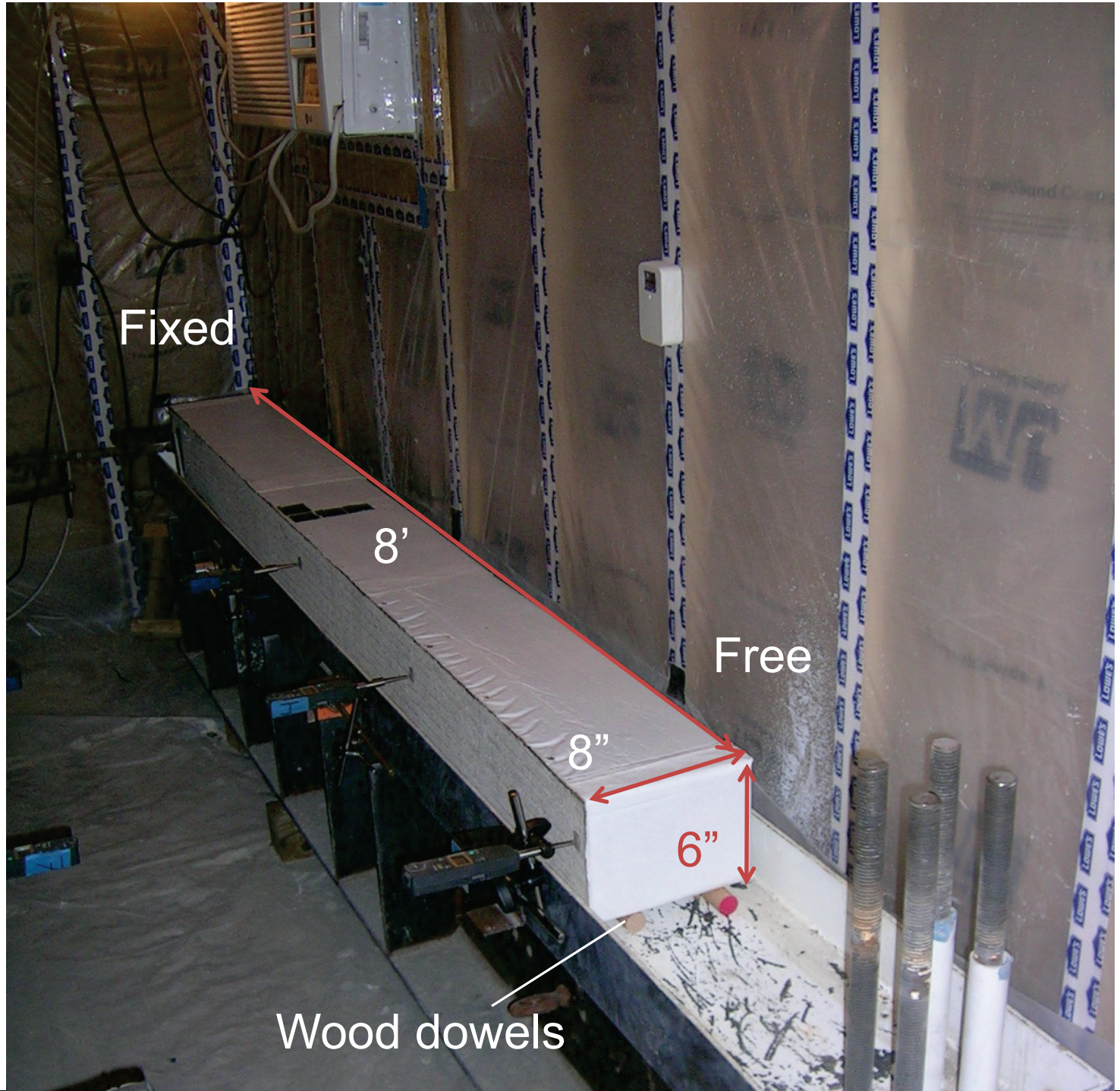
- We made a concrete specimen that mimicked a strip from a concrete pavement

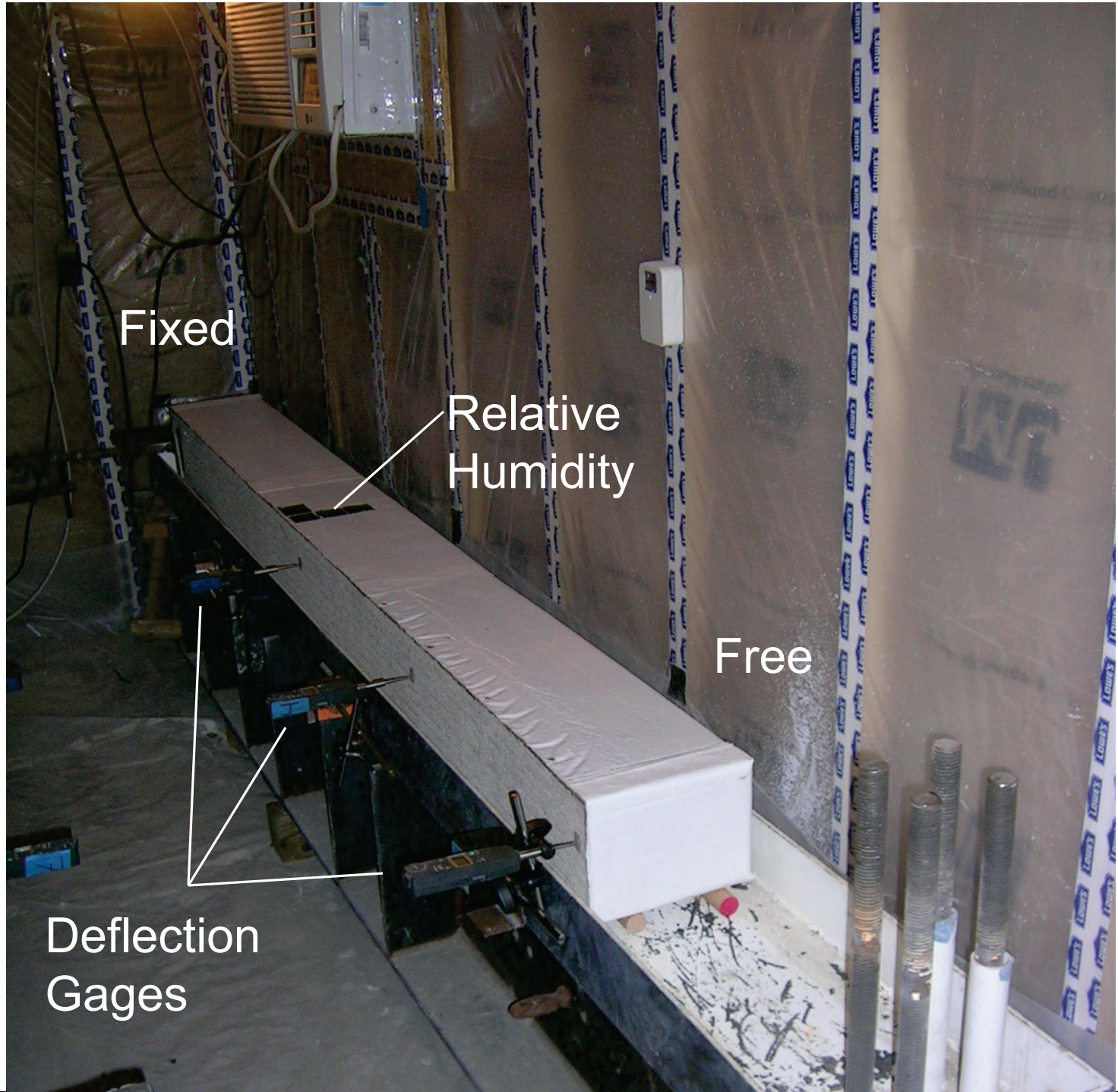


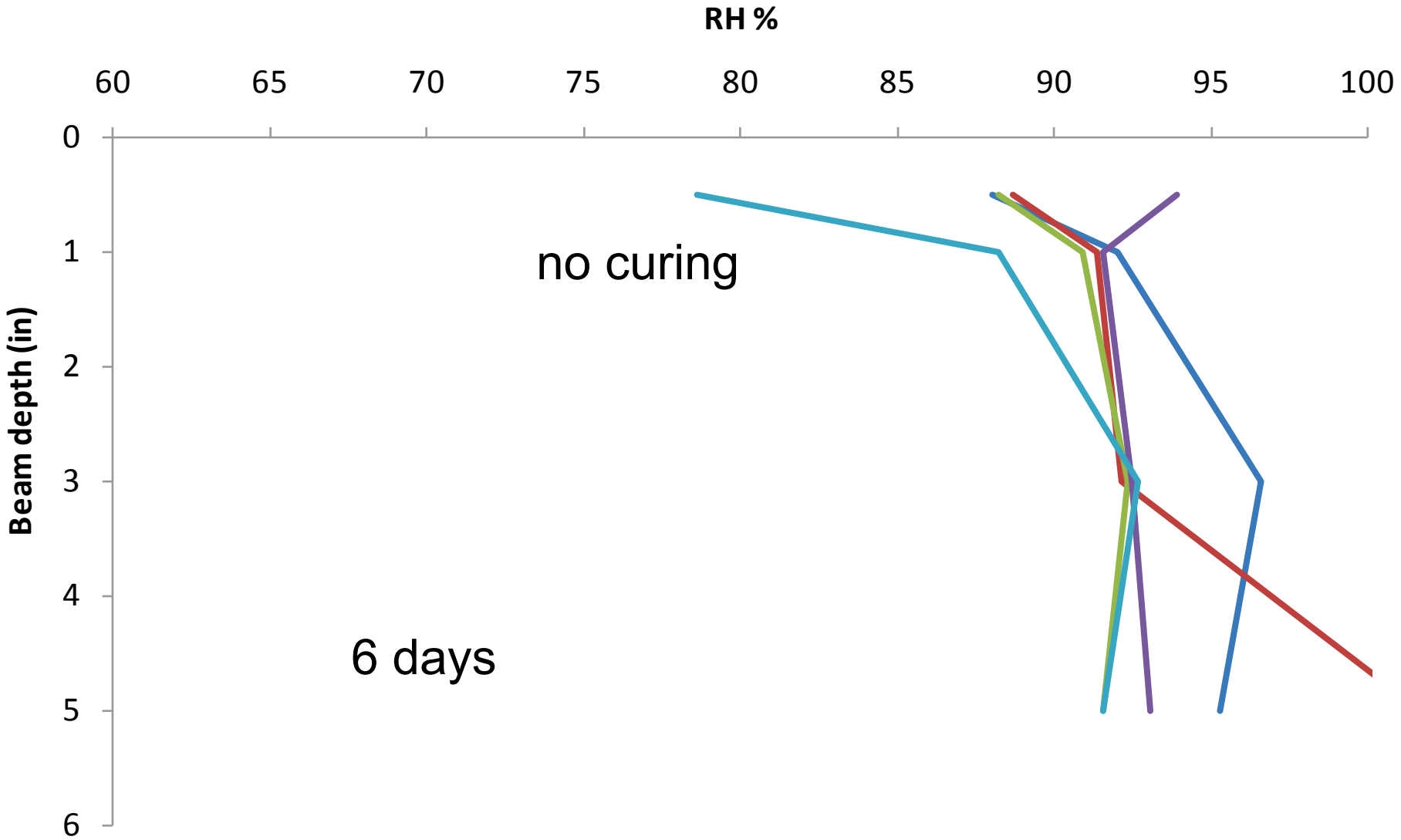
Concrete Beam

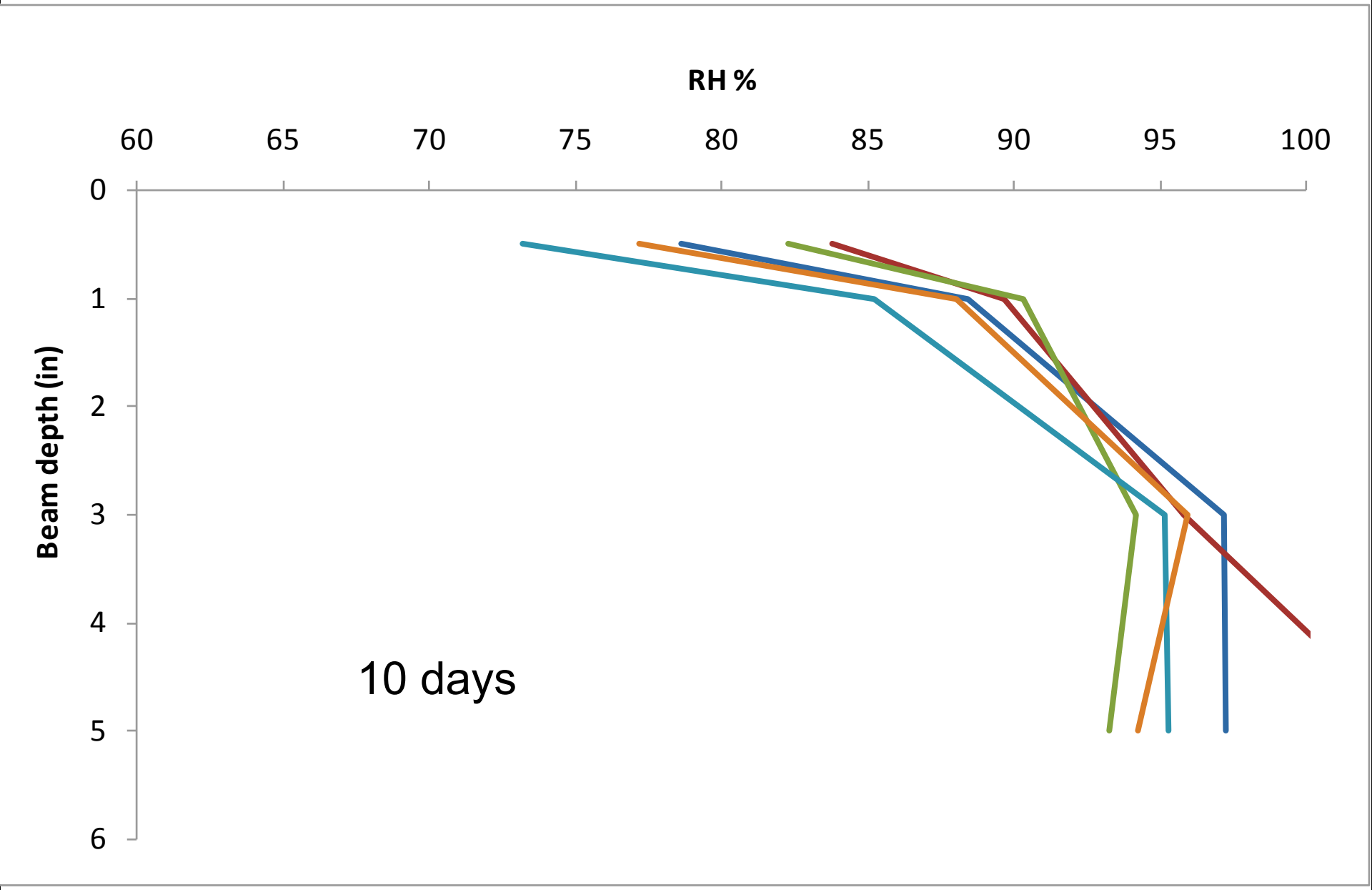
- 20% fly ash
- 564 lbs total cementitious
- 0.42 w/cm
- Specimens were stored at 73°F and *40%* RH
- The specimen is coated on all edges but the finished surface
- Specimen is flipped on the side after casting.

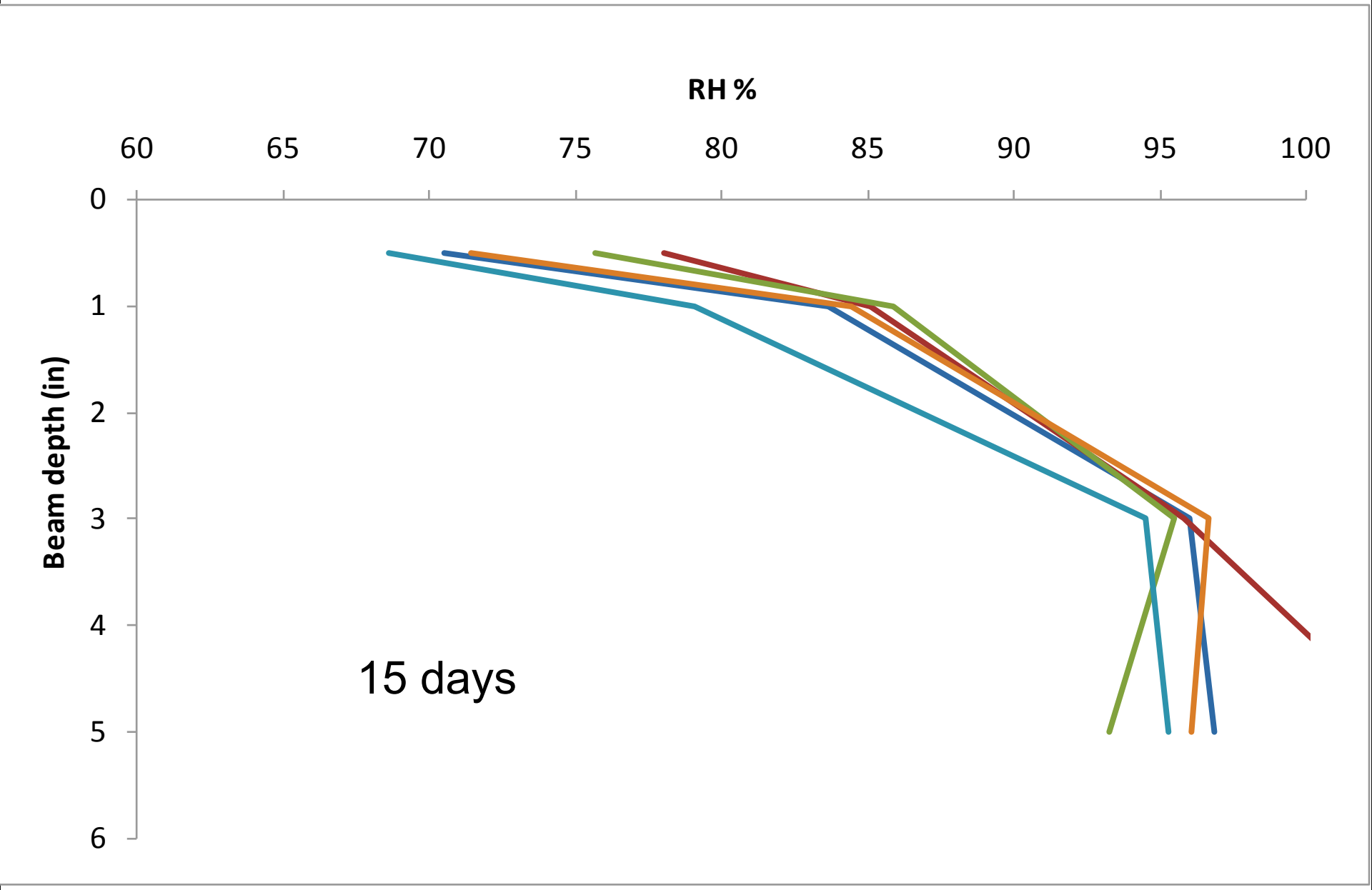

Sealed
edges
Finished
surface

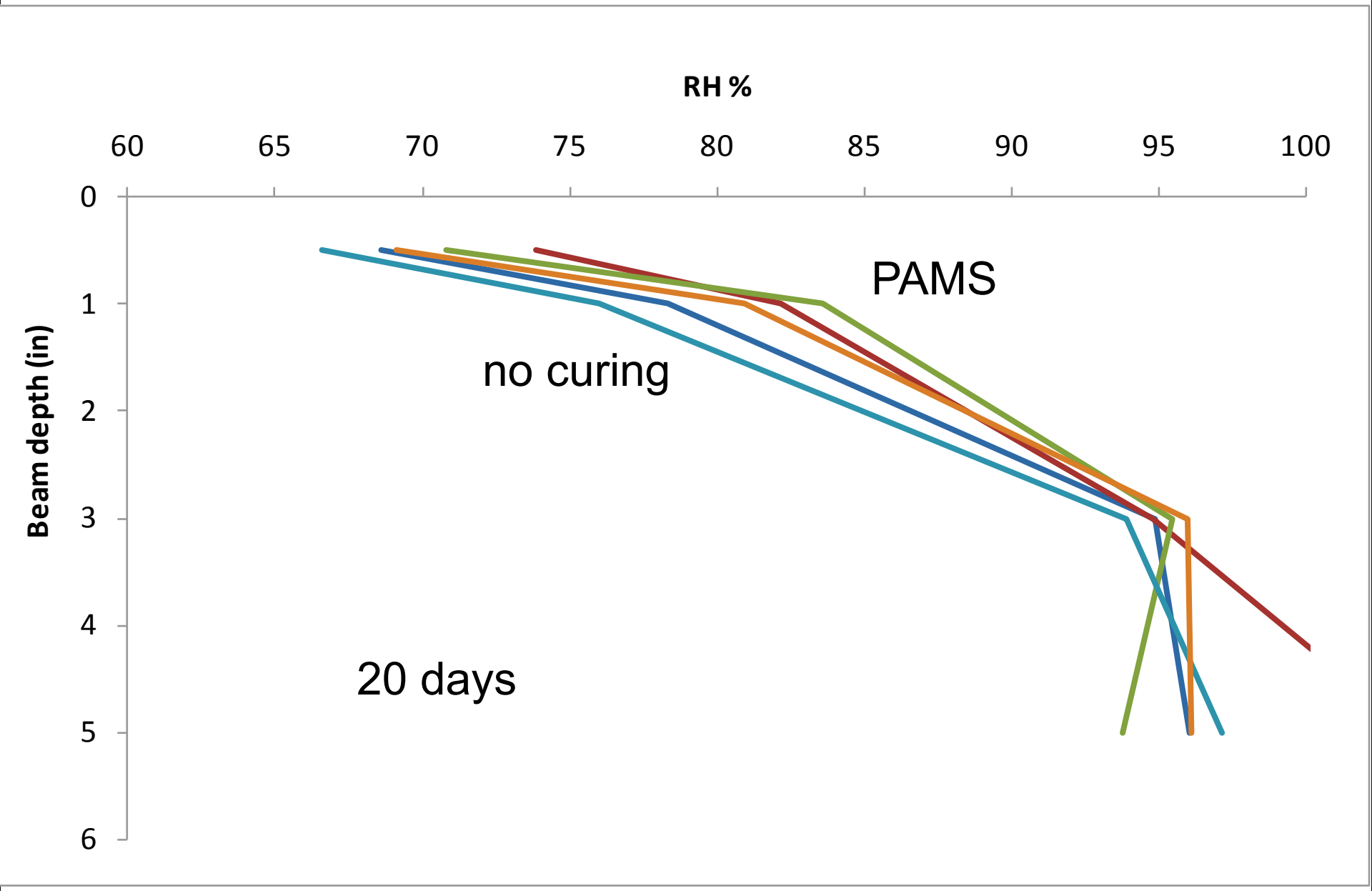

Fixed
8’
Free
8”
6”
Wood dowels

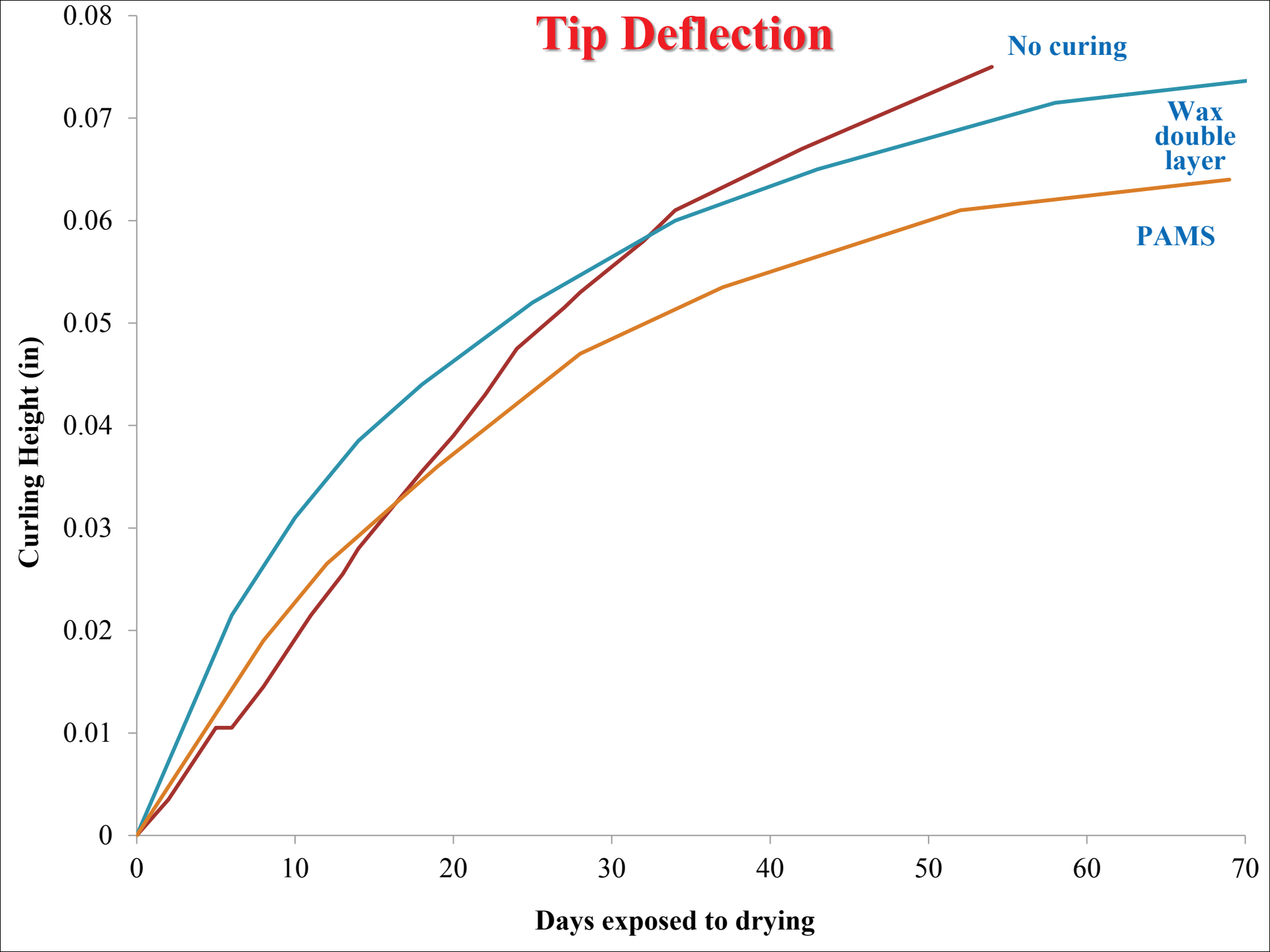

Fixed
Relative
Humidity
Free
Deflection
Gages

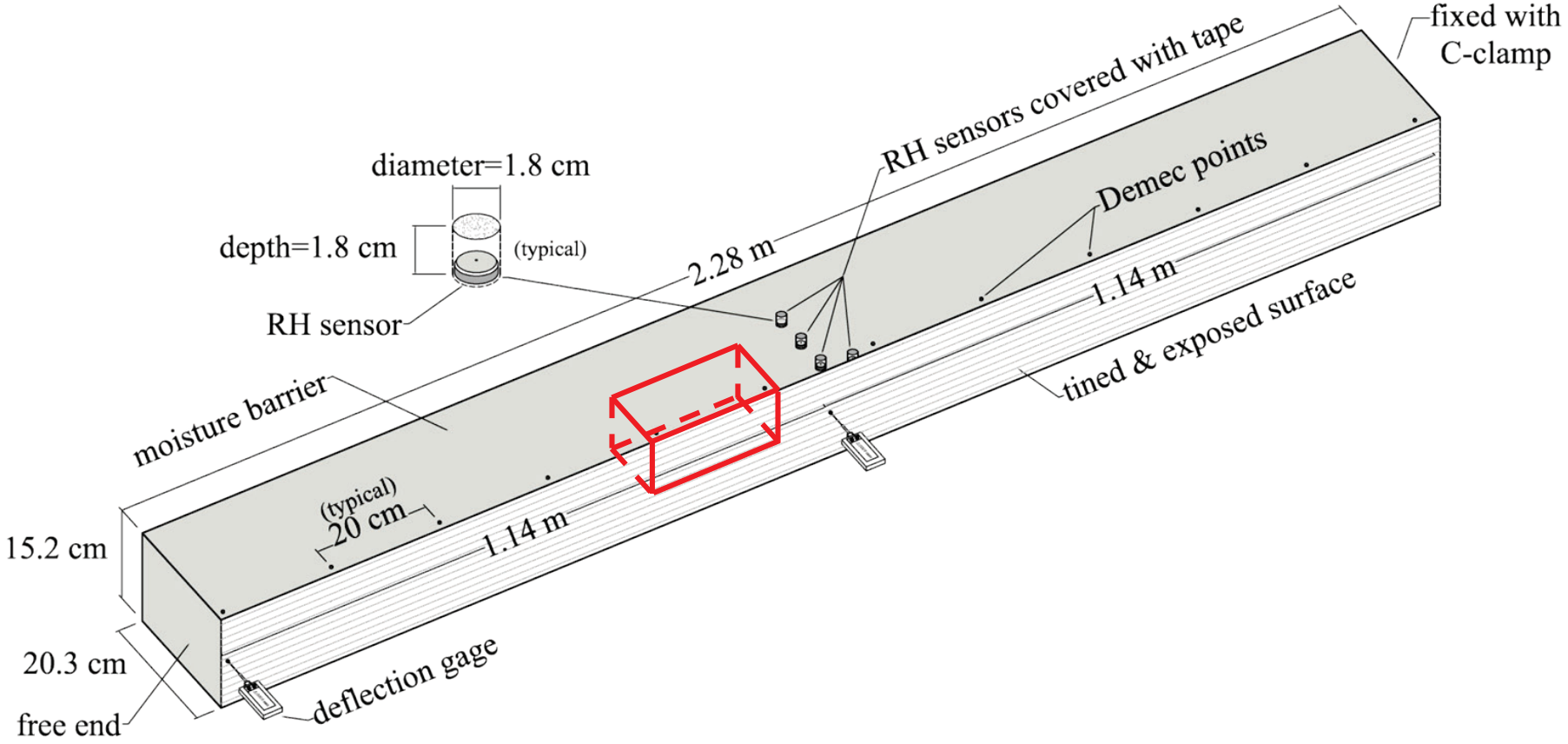

RH %
60
65
70
75
80
85
90
95
100
0
1
2
3
4
5
6
Beam depth (in)
no curing
6 days

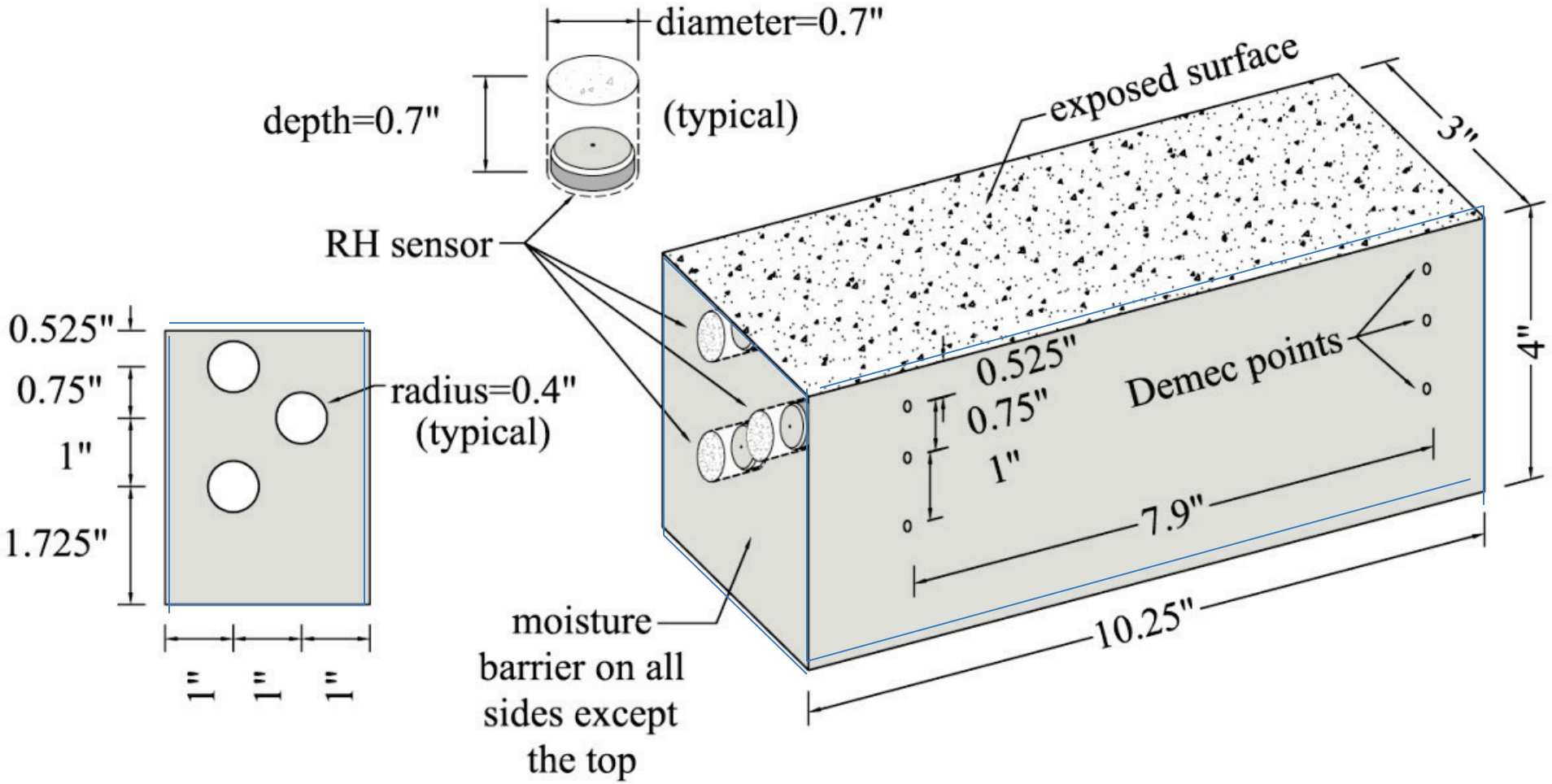

RH %
60
65
70
75
80
85
90
95
100
0
1
2
3
4
5
6
Beam depth (in)
10 days


RH %
60
65
70
75
80
85
90
95
100
0
1
2
3
4
5
6
Beam depth (in)
15 days


RH %
60
65
70
75
80
85
90
95
100
0
1
2
3
4
5
6
Beam depth (in)
PAMS
no curing
20 days

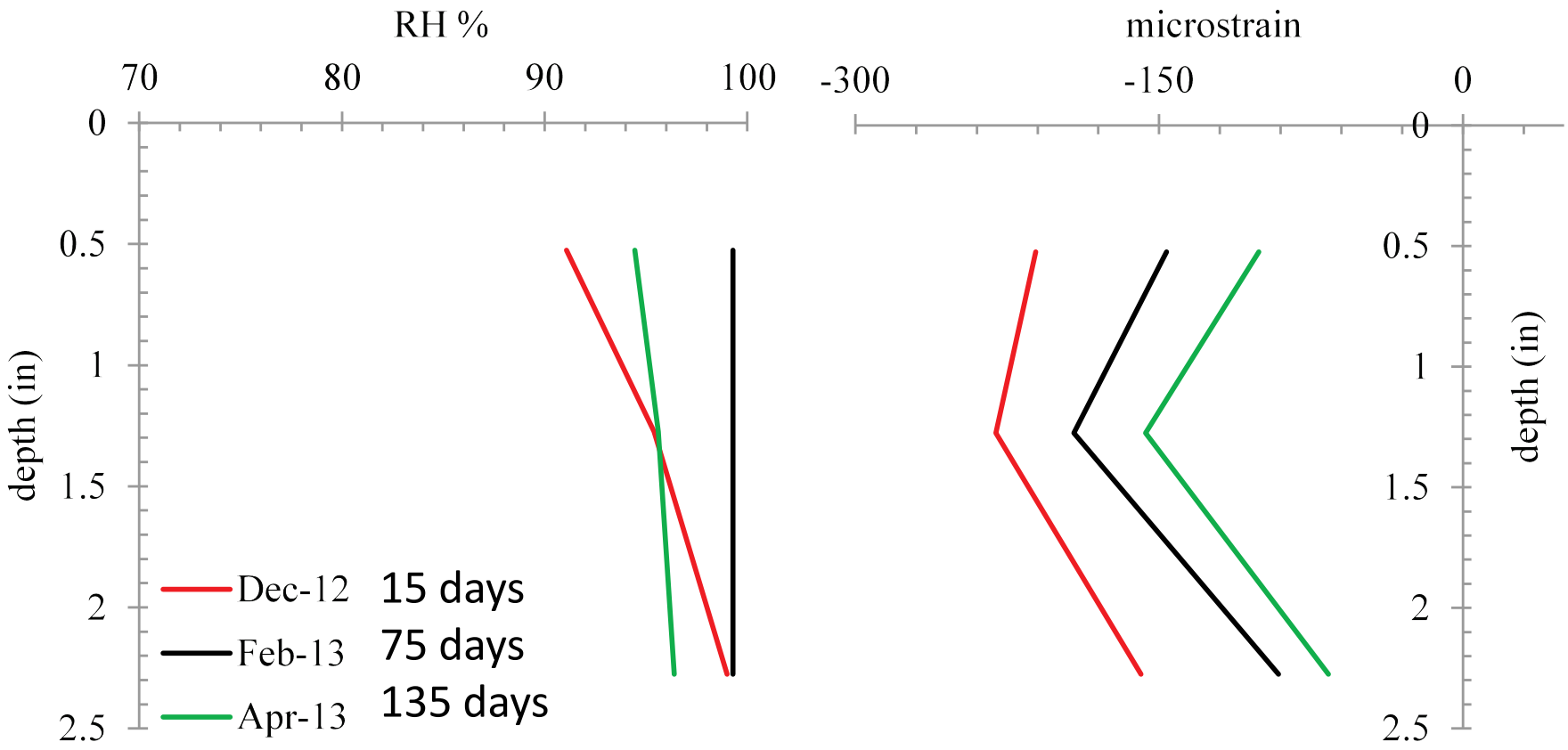

Tip Deflection
No curing
Wax double layer
PAMS
Curling Height (in)
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
10
20
30
40
50
60
70
Days exposed to drying


diameter=1.8 cm
depth=1.8 cm
(typical)
RH sensor
RH sensors covered with tape
fixed with
C-clamp
Demec points
2.28 m
1.14 m
moisture barrier
tined & exposed surface
(typical)
20 cm
1.14 m
15.2 cm
20.3 cm
free end
deflection gage


diameter=0.7"
depth=0.7"
(typical)
RH sensor
exposed surface
3"
4"
0.525"
0.75"
1"
1.725"
radius=0.4"
(typical)
1"
1"
1"
0.525"
0.75"
1"
Demec points
7.9"
10.25"
moisture
barrier on all
sides except
the top

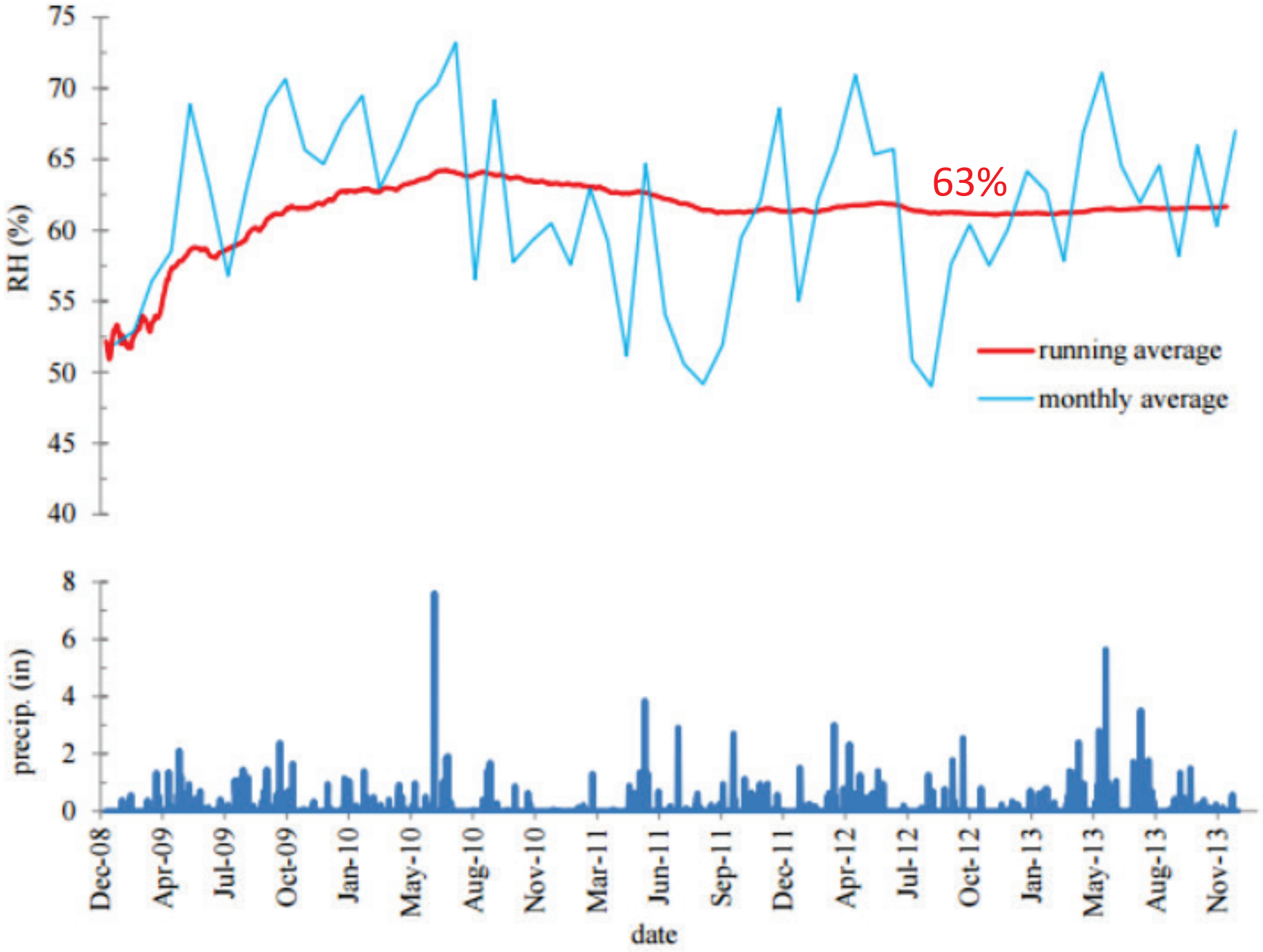
Field Data

- We made more beams and stored them outside in Stillwater, OK.


RH %
70
80
90
100
0
0.5
1
1.5
2
2.5
depth (in)
Dec-12
Feb-13
Apr-13
15 days
75 days
135 days
microstrain
-300
-150
0
0
0.5
1
1.5
2
2.5
depth (in)

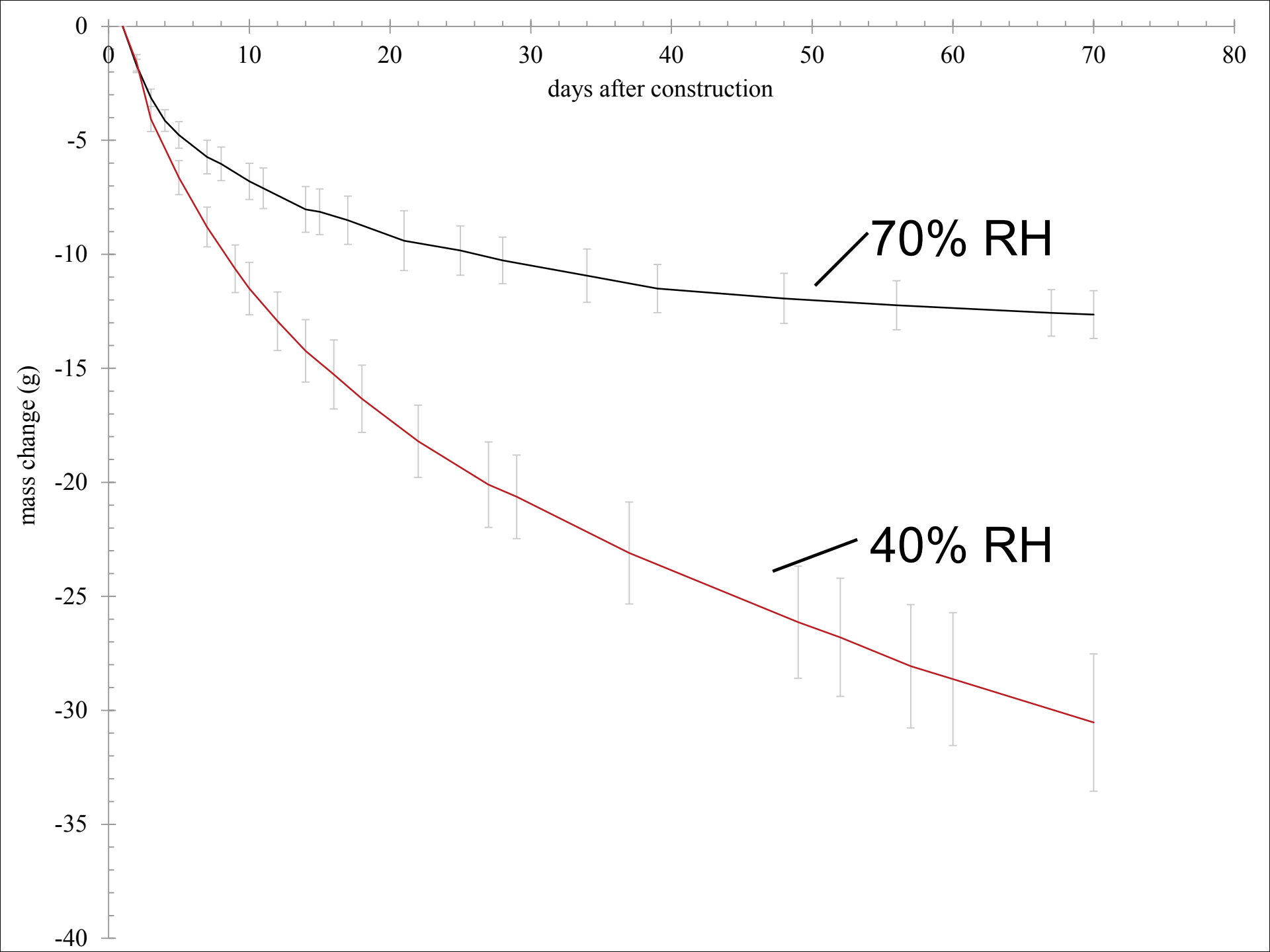
Observations

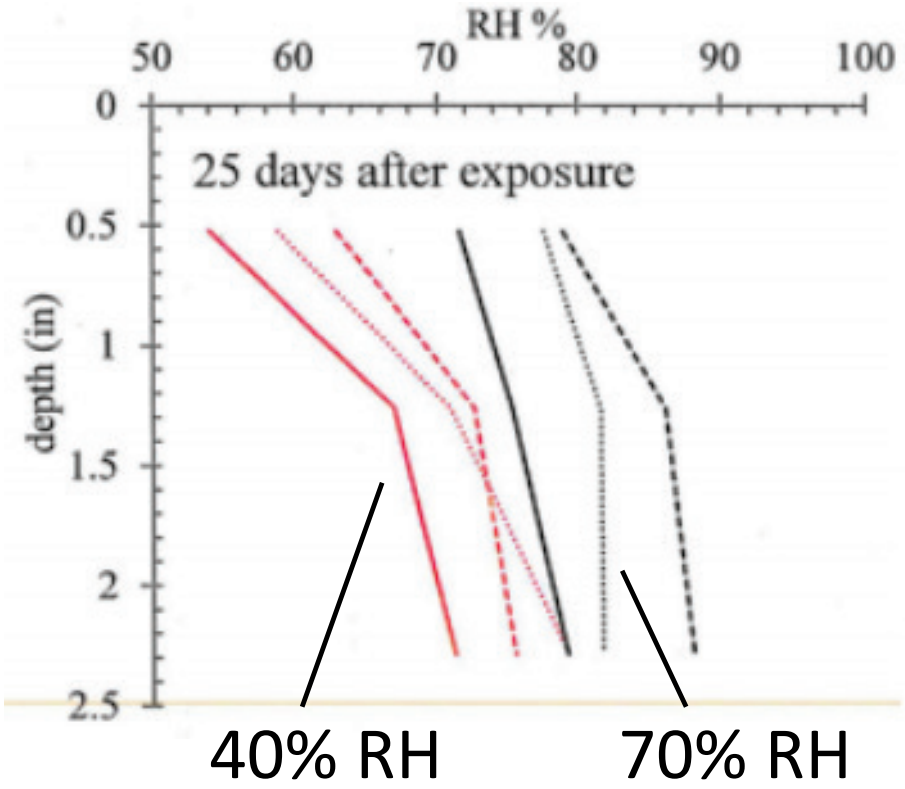
- The field concrete beams did not show large gradients in RH or strain
- Because these gradients are small, we would expect very little curling/warping from drying
- Why did this happen???

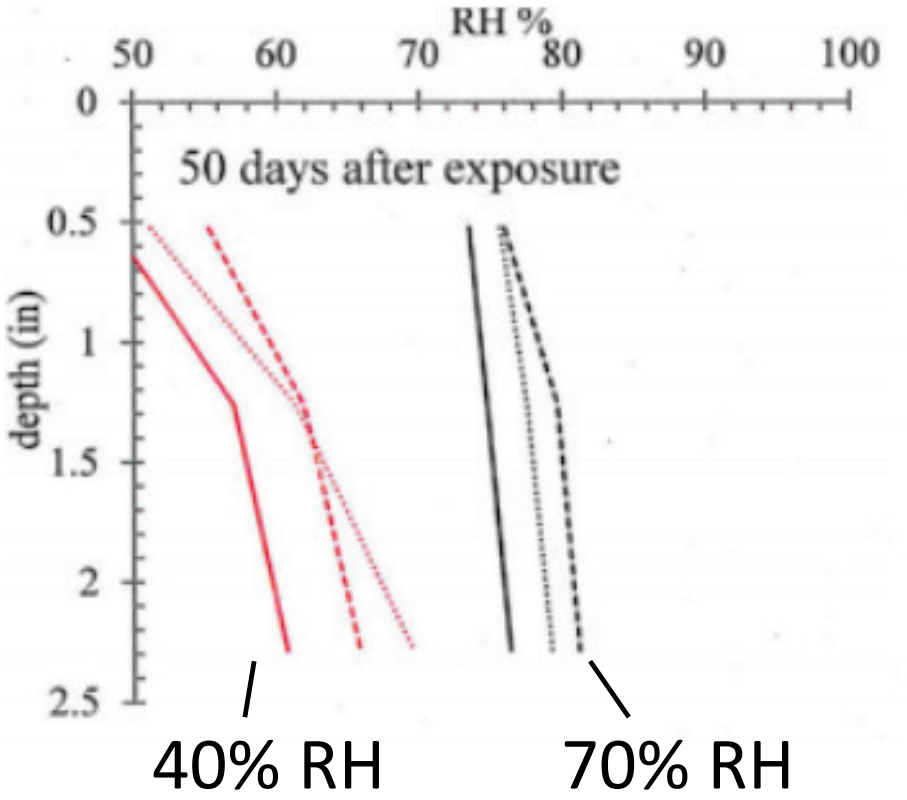

RH (%)
75
70
65
60
55
50
45
40
63%
running average
monthly average
precip. (in)
8
6
4
2
0
Dec-08
Apr-09
Jul-09
Oct-09
Jan-10
May-10
Aug-10
Nov-10
Mar-11
Jun-11
Sep-11
Dec-11
Apr-12
Jul-12
Oct-12
Jan-13
May-13
Aug-13
Nov-13
date

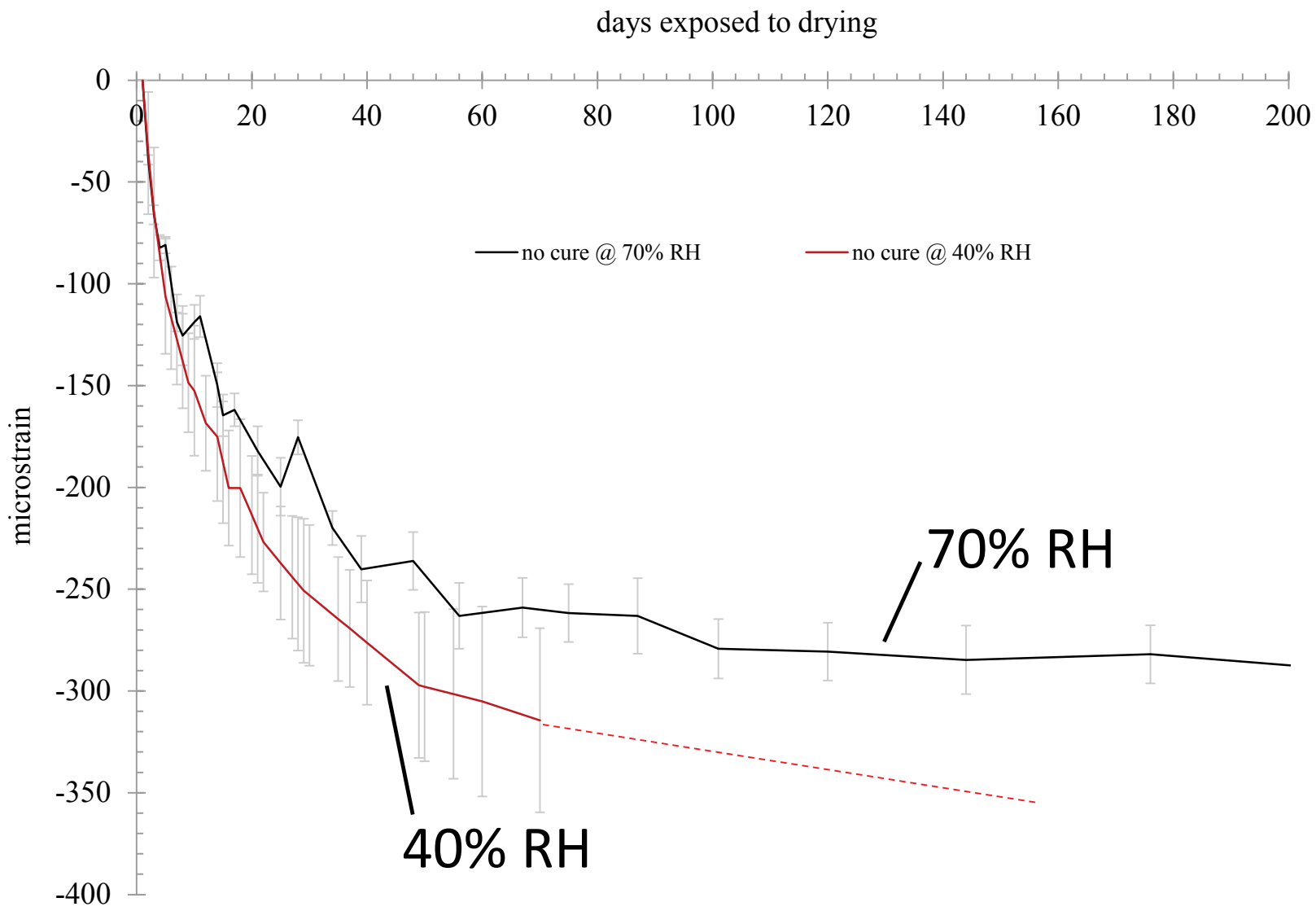
Observations

- The average RH in Stillwater, OK is 63% and it rains!!!
- All our previous lab tests were at 40% RH and no rain!!
- Because of the higher RH the surface doesn't dry as rapidly
- The rain will also help reduce the gradients
- We went back to the lab and tested the small beams at 40% and 70% RH


0
0
10
20
30
40
50
60
70
80
days after construction
-5
-10
-15
-20
-25
-30
-35
-40
mass change (g)
70% RH
40% RH


RH %
50
60
70
80
90
100
0
0.5
1
1.5
2
2.5
depth (in)
25 days after exposure
40% RH
70% RH

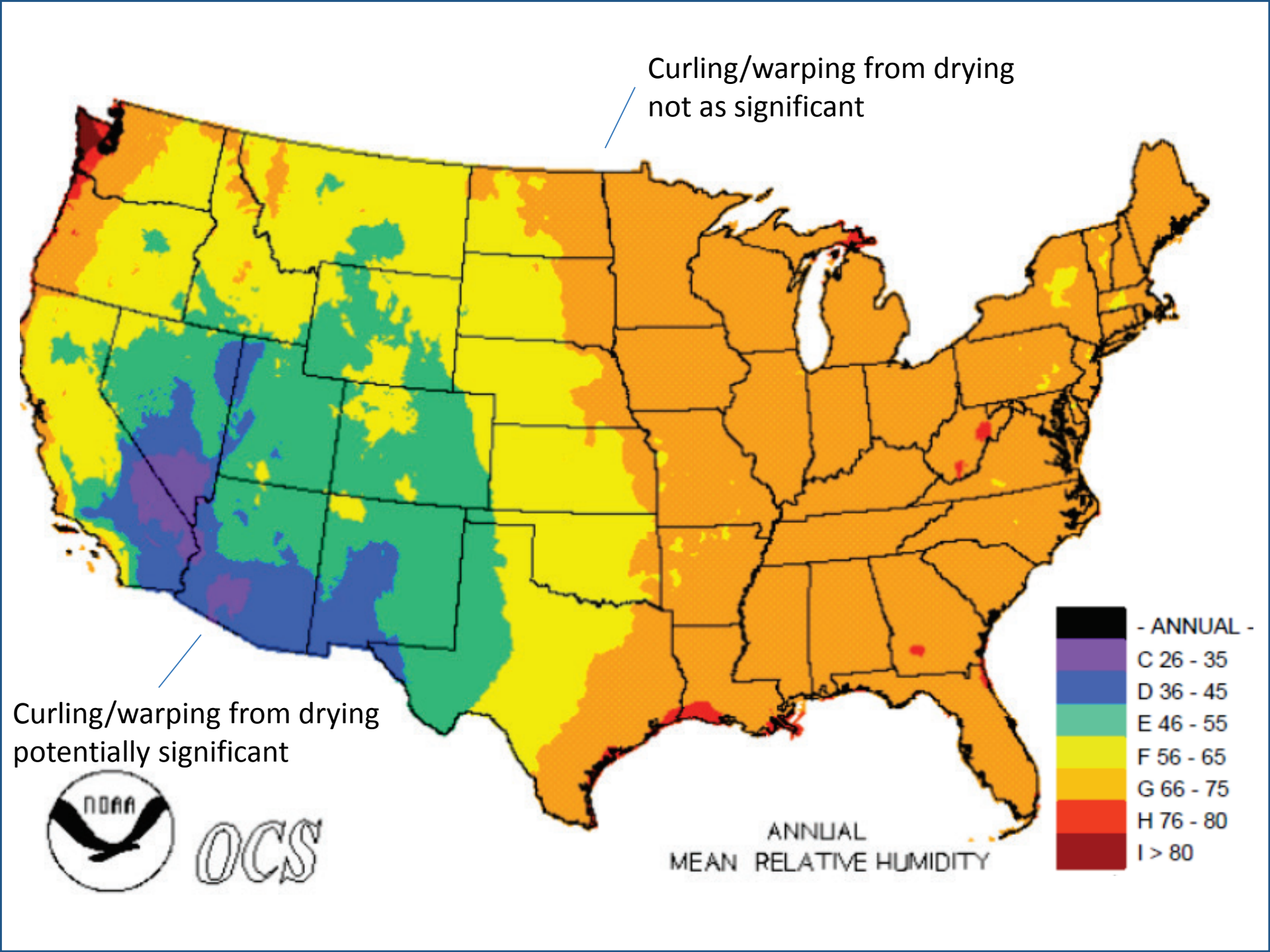

RH %
50
60
70
80
90
100
0
0.5
1
1.5
2
2.5
depth (in)
50 days after exposure
40% RH
70% RH



Shrinkage in concrete beams at depth 0.525"

Observations

- When your external RH is around 65% and above there is not a large moisture gradient in the lab or field concrete and curling/warping from drying is not as significant
- Lower RH (~40% RH) gives the potential for larger moisture gradients and cause curling/warping to become a problem


Curling/warping from drying not as significant
Curling/warping from drying potentially significant
- ANNUAL -
C 26 - 35
D 36 - 45
E 46 - 55
F 56 - 65
G 66 - 75
H 76 - 80
I > 80
ANNUAL
MEAN RELATIVE HUMIDITY
NOAA
OCS

Is there any evidence of this in the field???

How Has Slab Curvature Been Studied in the Field?

- Documented by Chang et al. (2010) in FHWA Tech Brief (FHWA-HIF-1-010)
- Applied to LTPP SPS-2 Site in Arizona by Karamihas and Senn (2012) (FHWA-HRT-12-068)
- Basis for new FHWA LTPP Data Analysis Program that is just getting started
  - Contractor is NCE
  - Looking at SPS-2 and GPS-3 sites

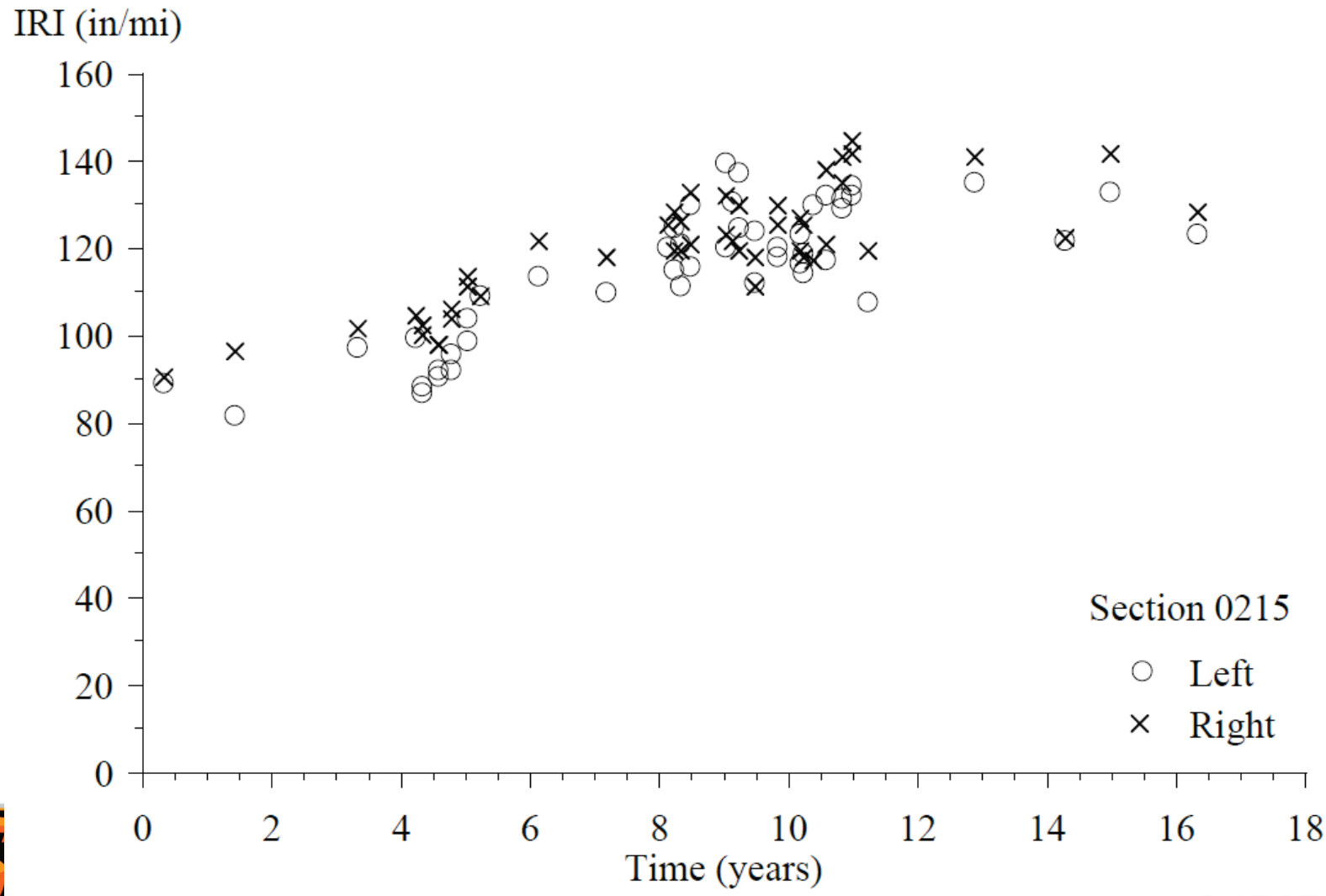
Evaluation of **Arizona** SPS-2 Section 0215

Property	0213	0215
Lane Width (ft)	14	12
PCC Thickness (in)	8	11
DGAB Thickness (in)	6	6
PCC Flexural Strength (psi)	550	
Max. Agg. Size	¾-inch	
Total Cement (20% FA)	500 lbs	
w/cm	0.47	

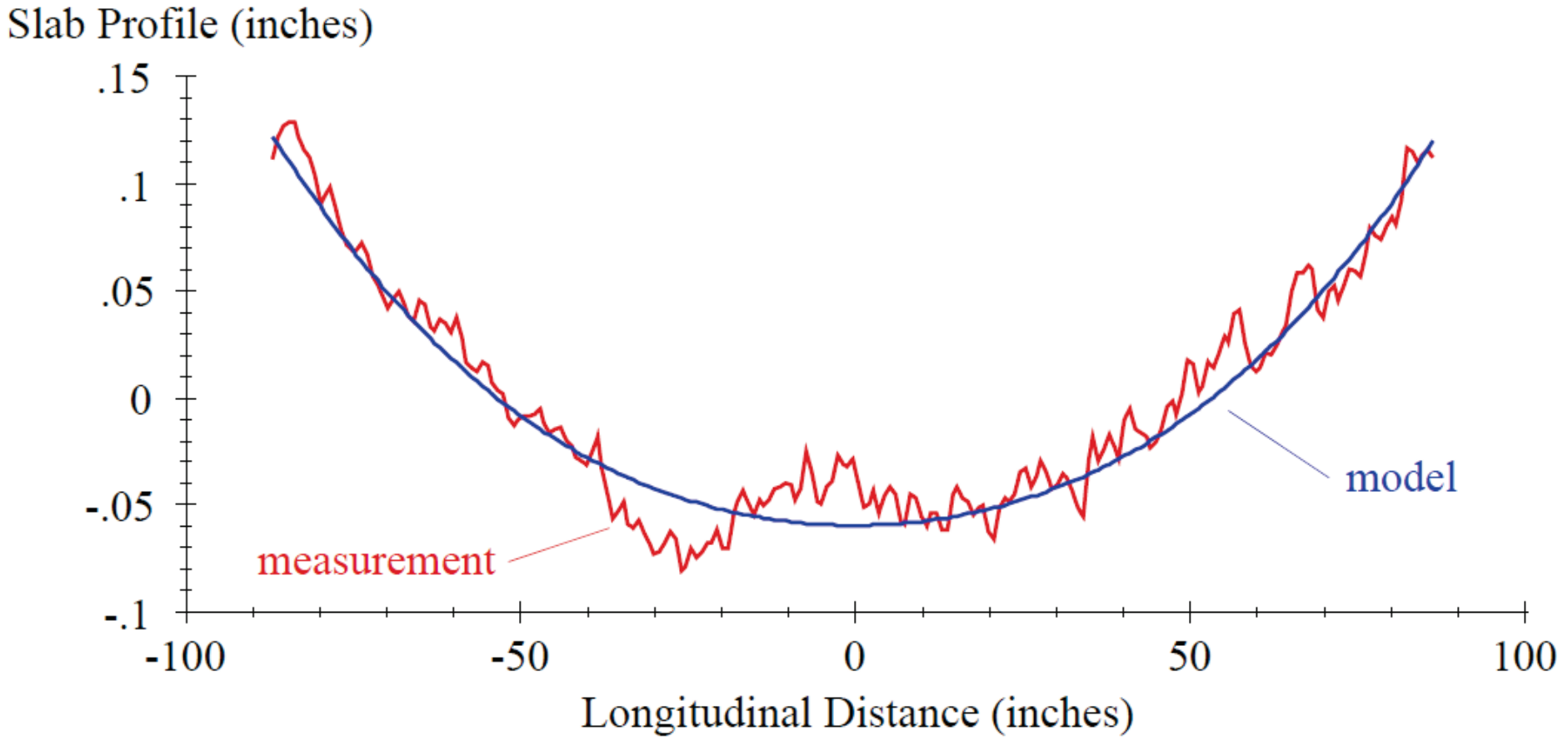
Evaluation of Arizona SPS-2 Section 0215

- Jointed Concrete Pavement
- Lane width: 12 ft
- PCC thickness: 11 inches
- DGAB Thickness: 6 inches
- PCC MOR: 550 psi
- Maximum aggregate size: 0.75 inch
- Total Cementitious (20% FA): 500 lbs
- w/cm: 0.47
- Average RH = 40%

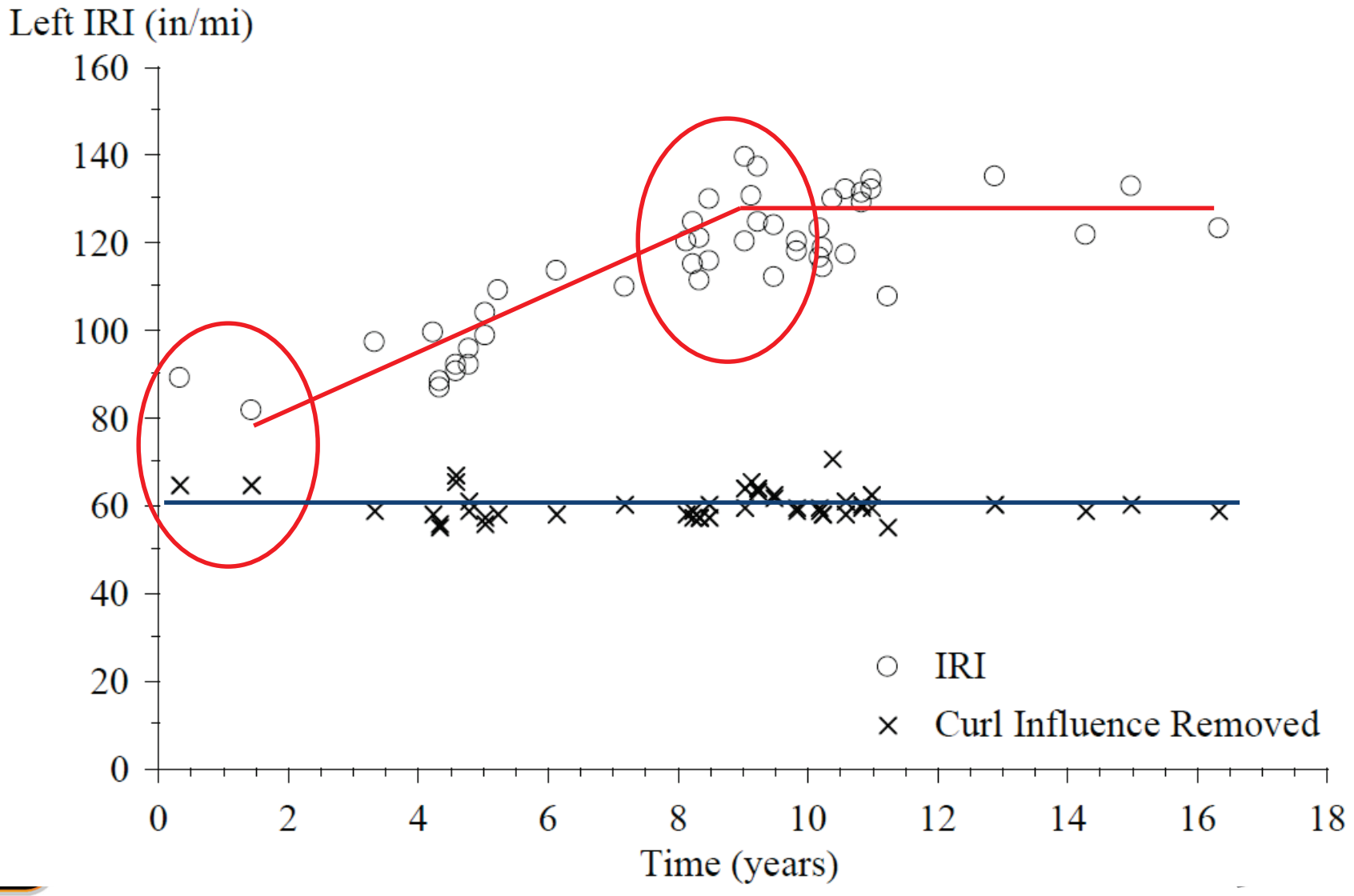
IRI Progression for Section 040215



Slab Curvature (Section 040215)



IRI Progression (Section 040215)



Observations

- IRI steadily increased from first measurement until 10 years with no observed distress
- Increase in IRI clearly linked to development of upward slab curvature
  - Effect of curvature roughly 50 in/mile
  - Approximately 20% due to temperature effects
  - Remaining due to moisture induced warping
- Diurnal impacts, although less significant, still very important
  - Ramifications for acceptance and as a performance indicator

Discussion

- The Arizona pavement data and presented lab data seem to agree.
- The IRI of the pavement will be at the lowest point right after casting.
- As the pavement dries then the IRI will increase because of the edge deflection of the slabs

Discussion

- The deflections will reach a maximum and then stop
- The length it takes to reach this maximum will depend on the volume of paste, w/cm of the concrete, and how well it was cured
- If you grind the slabs before they stop deflecting then you might have to grind again

What Can We Do About This?

- Reduced paste content
  - less shrinkage, less deflection
- Reduce joint spacing
- Diamond grind
- Shrinkage reducing admixtures
  - Adds 20% to the cost of concrete
  - Doesn't work well with air entrainment
  - Doesn't work as well in higher RH

What Can We Do About This?

- Internal curing
  - It may delay the shrinkage but likely won't stop it from happening. Long term experiments are needed
- By using high quality curing then you can delay when it occurs
- In low RH environments don't use extended wet cure on pavements! (Talk to Tyler)

Conclusions

- Gradients in temperature and moisture are important parameters for edge deflection in concrete pavements
- Drying shrinkage is an important driving force for edge deflections of concrete pavements in lab and field testing
- Environments with lower average RH seem to cause larger gradients and in turn larger edge deflections

Conclusions

- These deflections seem to increase until a point and then stop.
- The temperature gradients seem to only account for ~20% of the edge deflection in these low average RH environments

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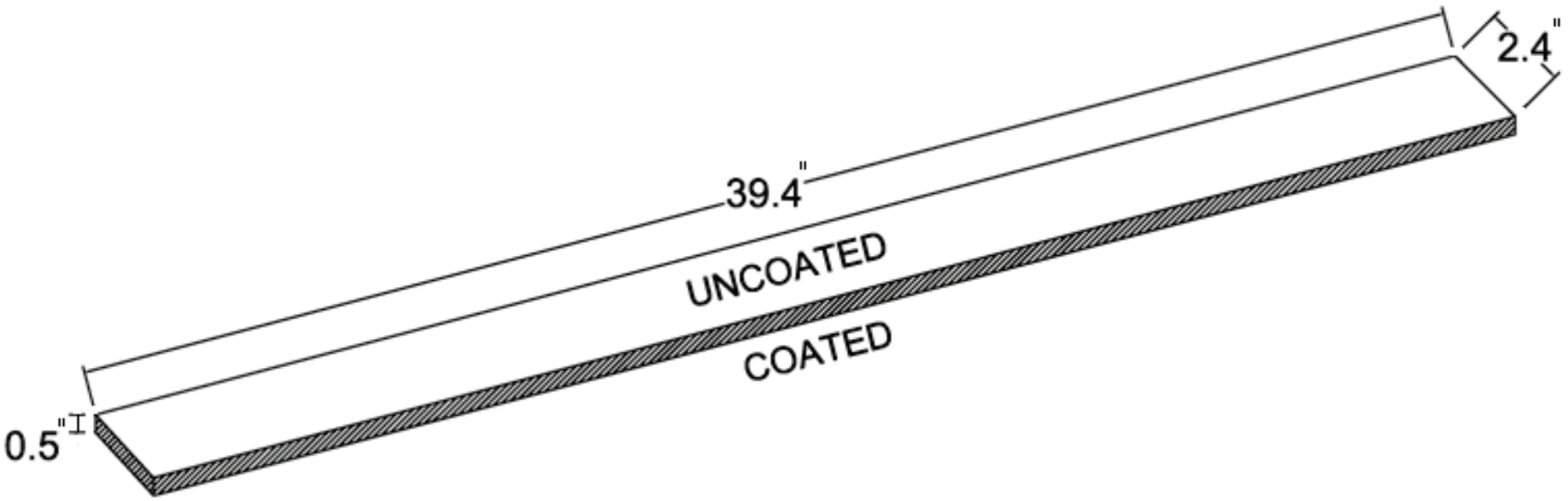
Are all curing compounds the same???

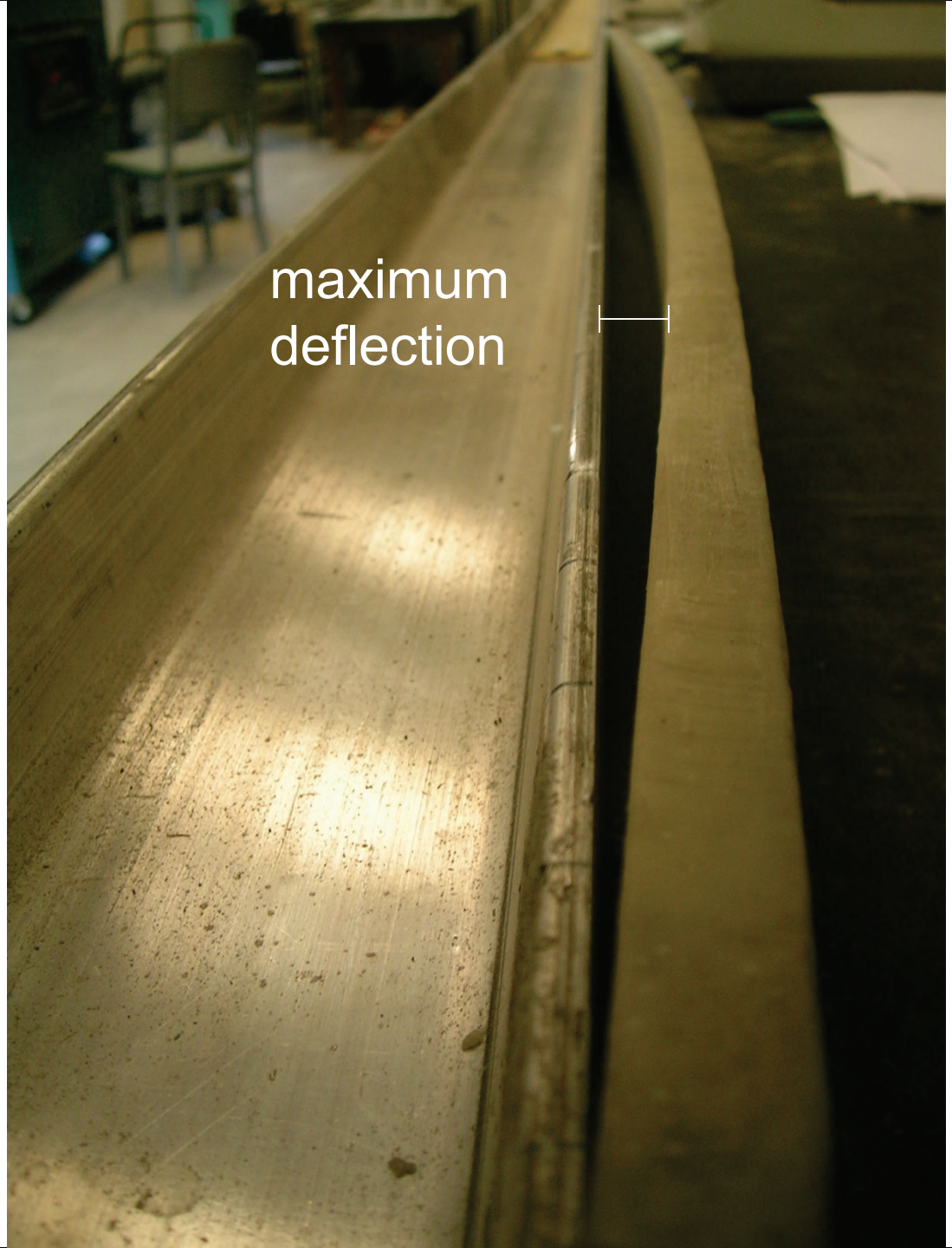
- They don’t cost the same so you wouldn’t expect them to perform the same!
- But how much better is one then the other?
- Why does it matter…

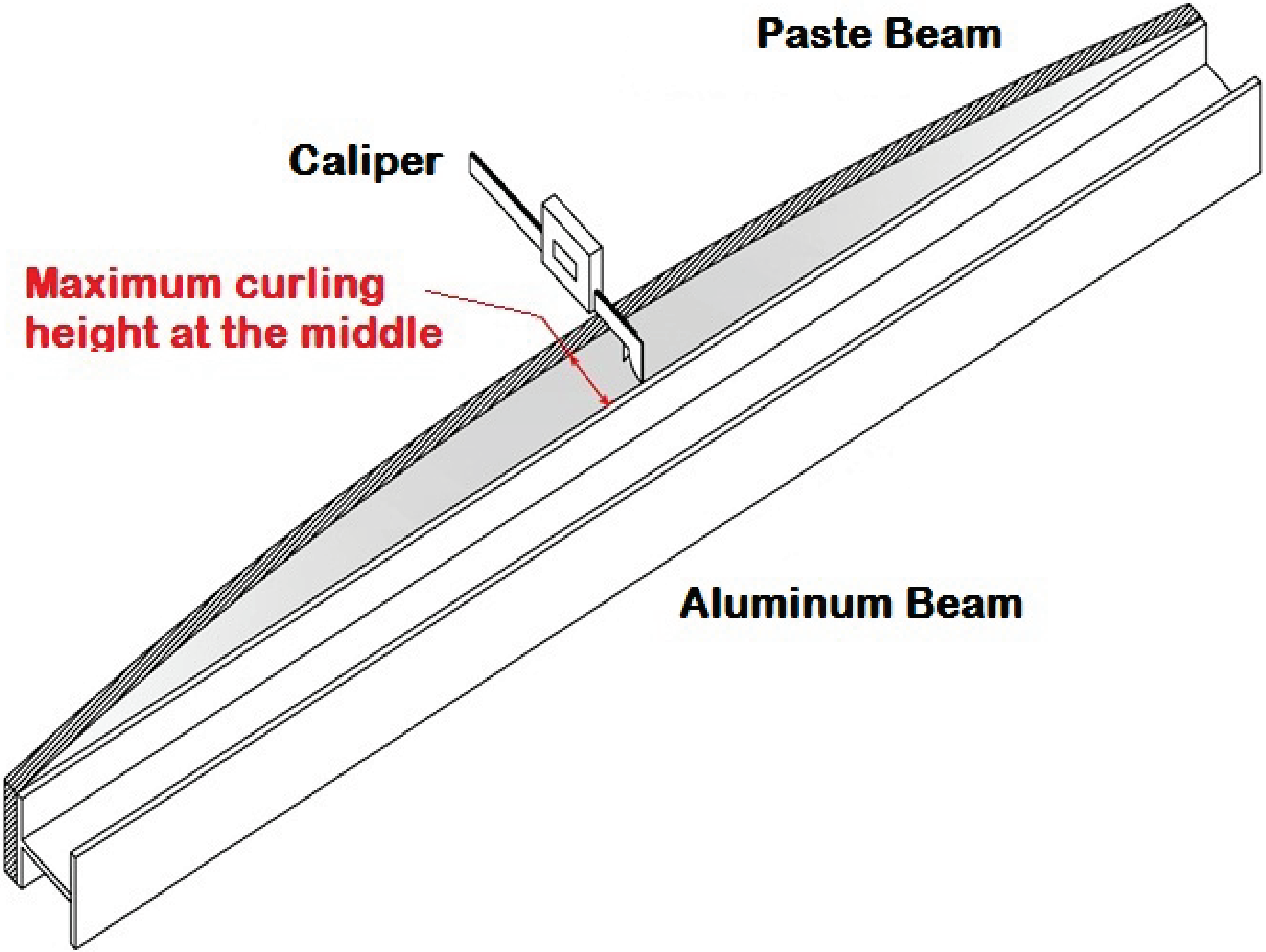
Paste beams

- A simple test was used where long and thin paste beams were made with 0.42 w/cm.
- Curing compound was placed on the beams after casting
- After demolding the beams were coated with wax on all sides but the surface and then placed in a drying chamber at 40% RH and 73F


2.4"
39.4"
UNCOATED
COATED
0.5"


Wax
coated
surface
finished
surface

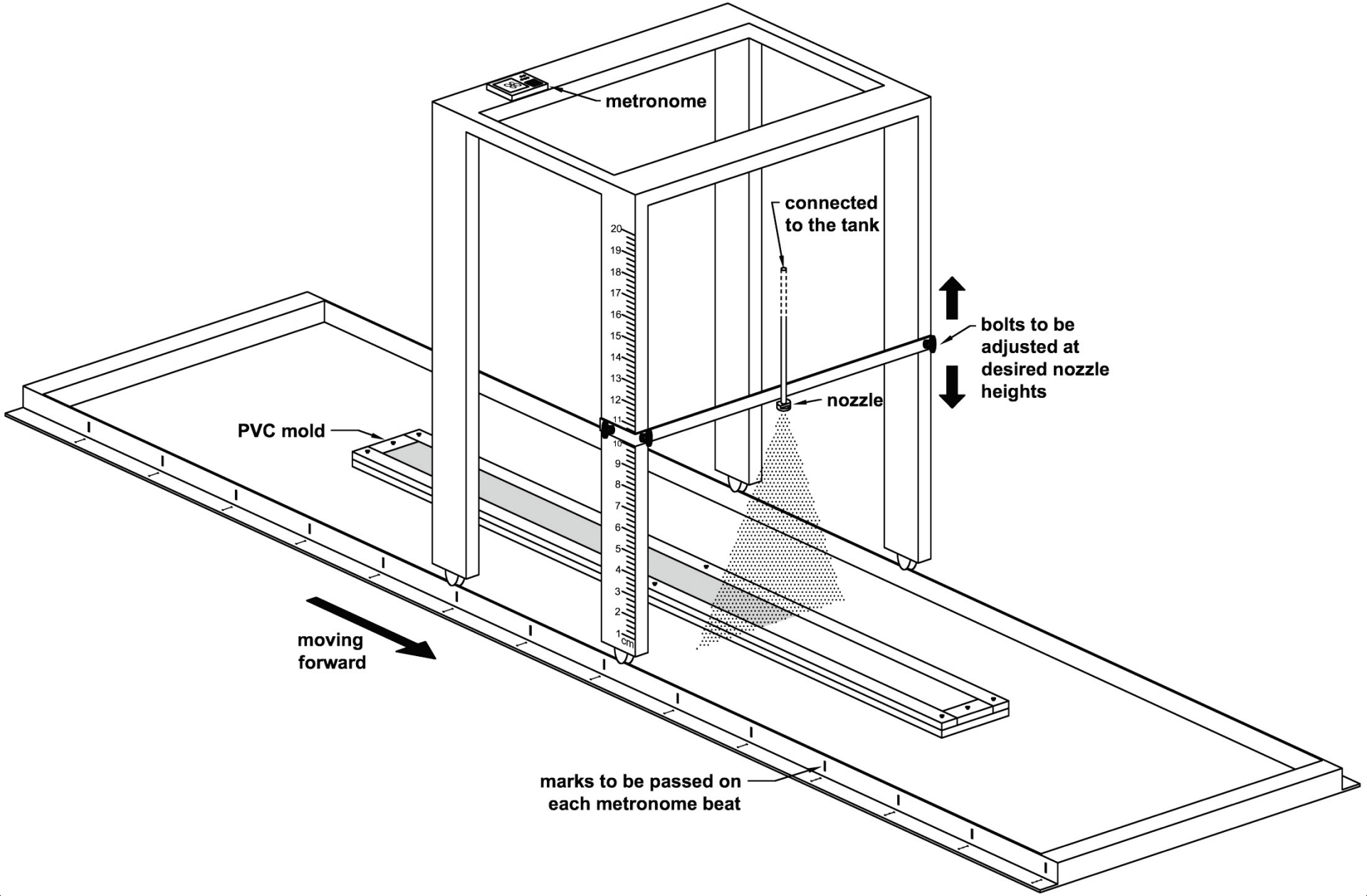

maximum
deflection

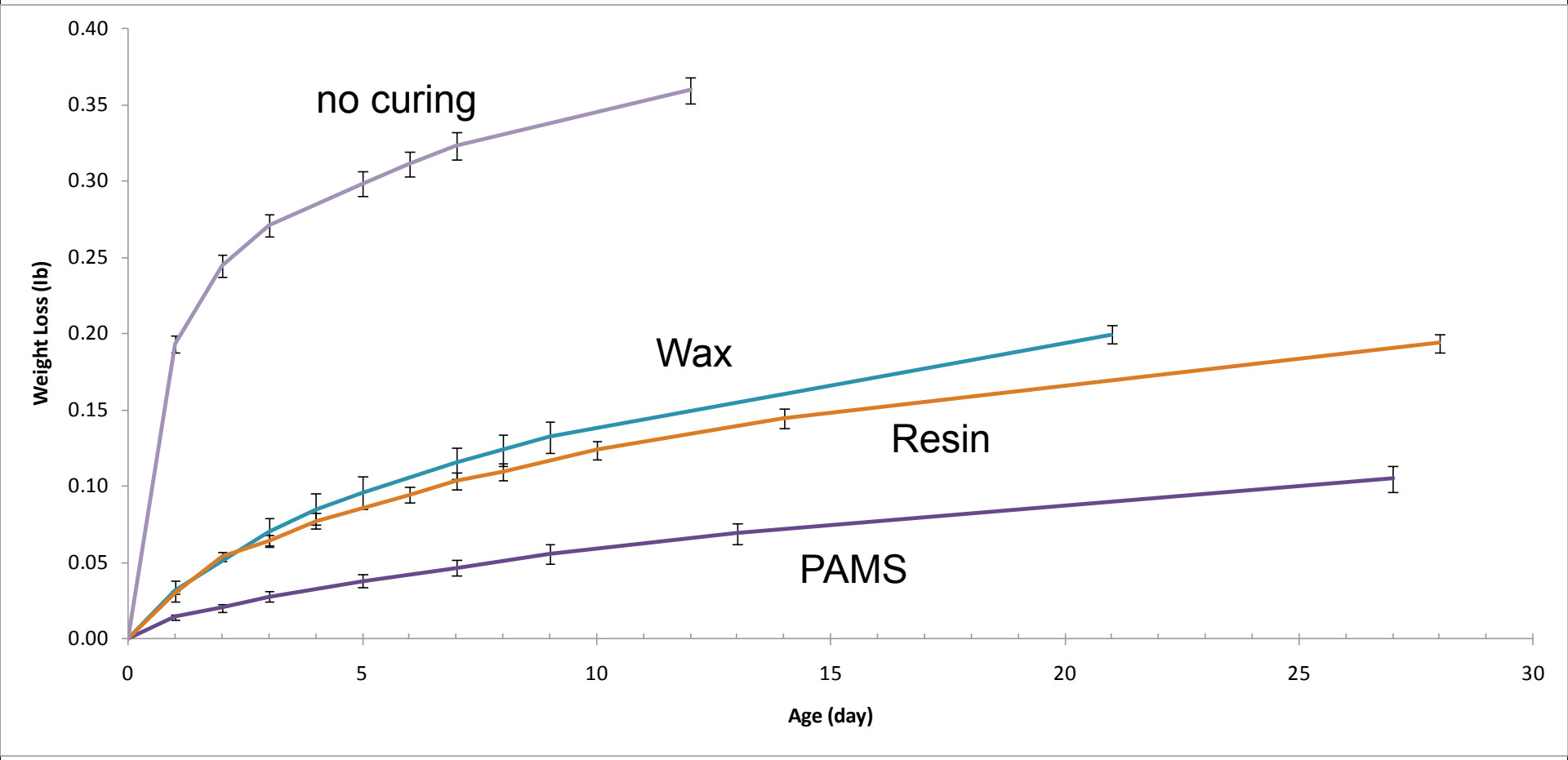

Paste Beam
Caliper
Maximum curling
height at the middle
Aluminum Beam

Curing Compounds

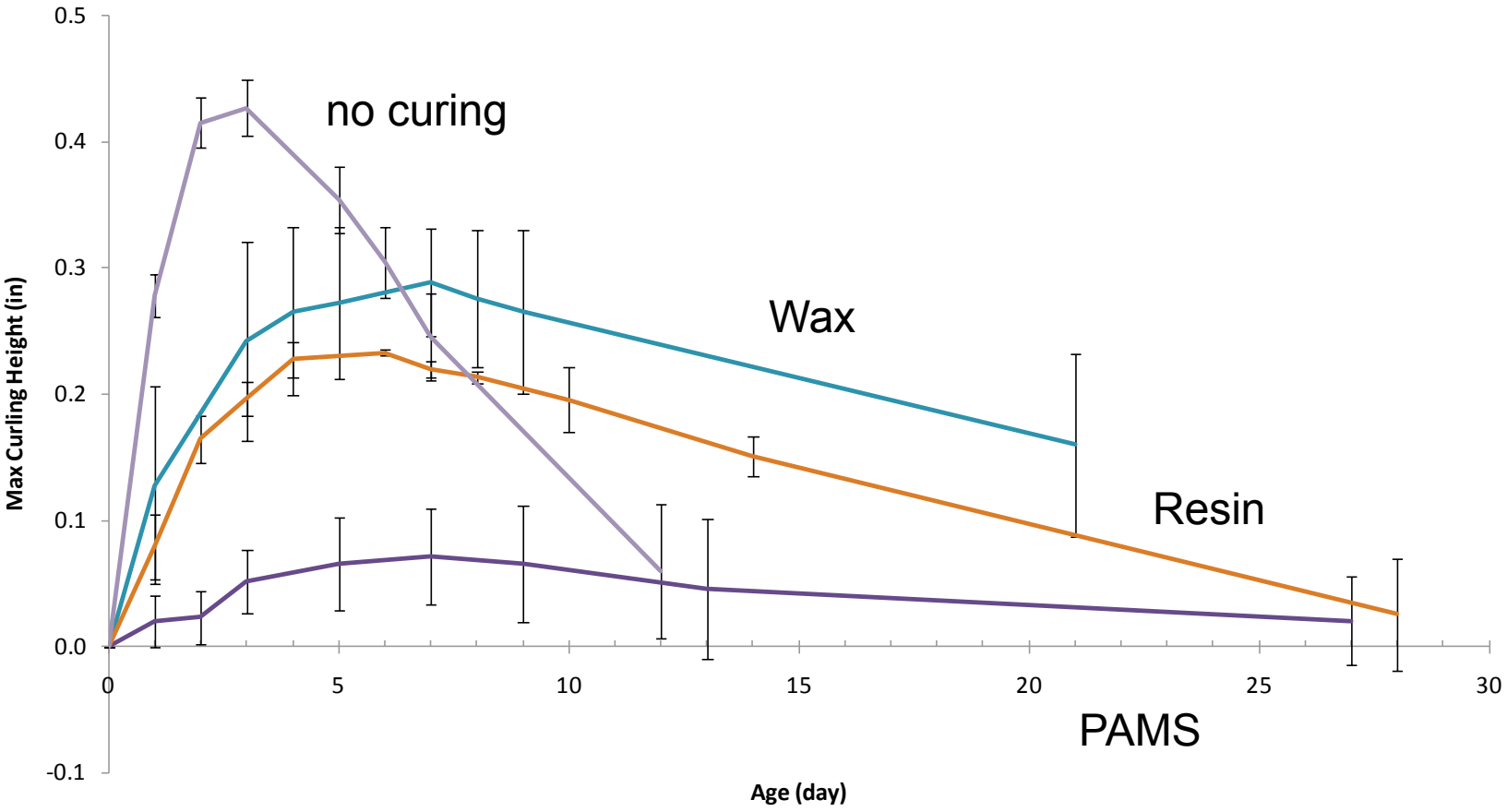
Three different curing compounds were investigated:

	Cost
– Poly-Alpha-methyl-styrene (PAMS)	3x
– Resin-Based	2x
– Wax-Based	x

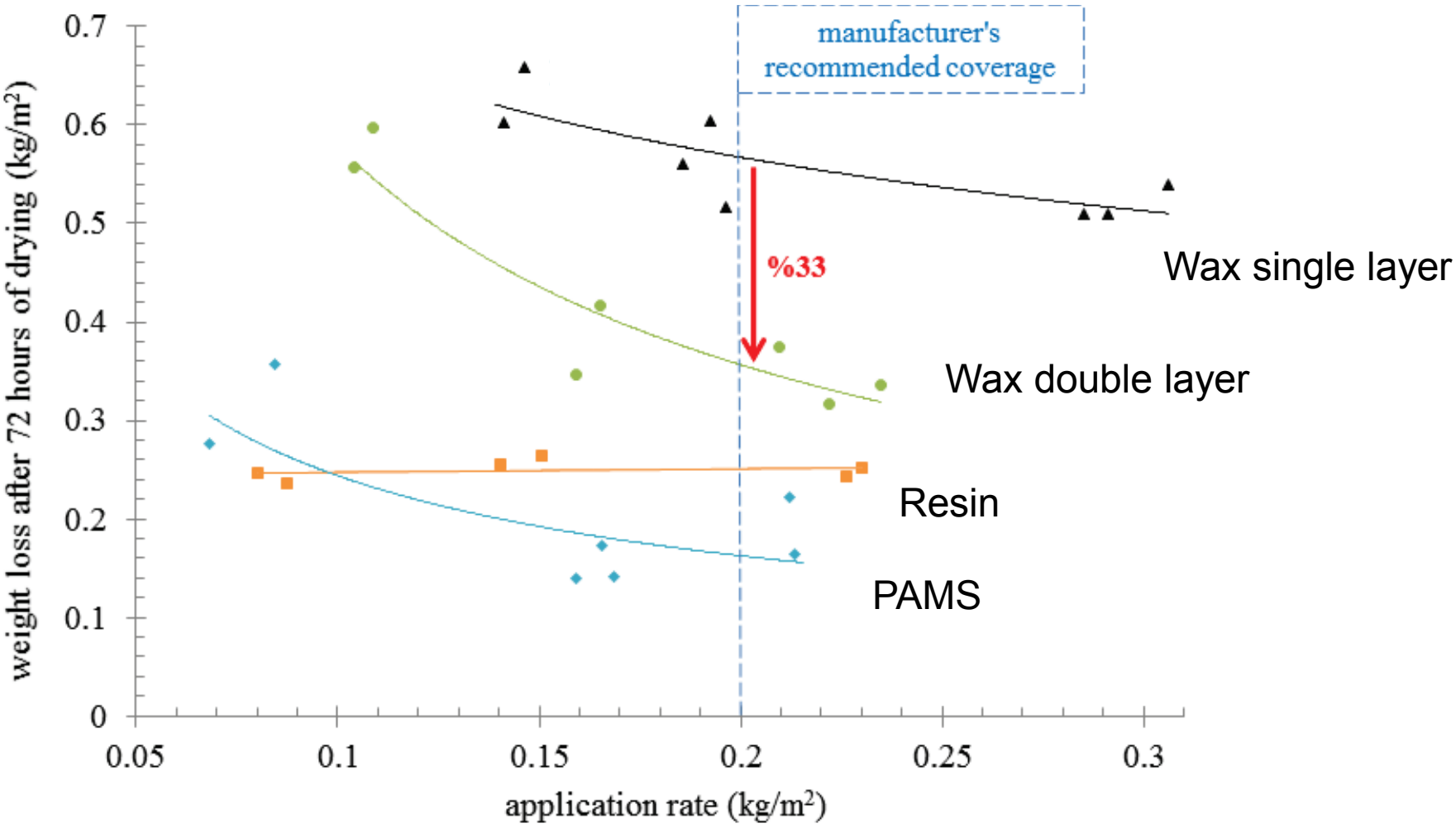

metronome
connected
to the tank
bolts to be
adjusted at
desired nozzle
heights
nozzle
PVC mold
moving
forward
marks to be passed on
each metronome beat

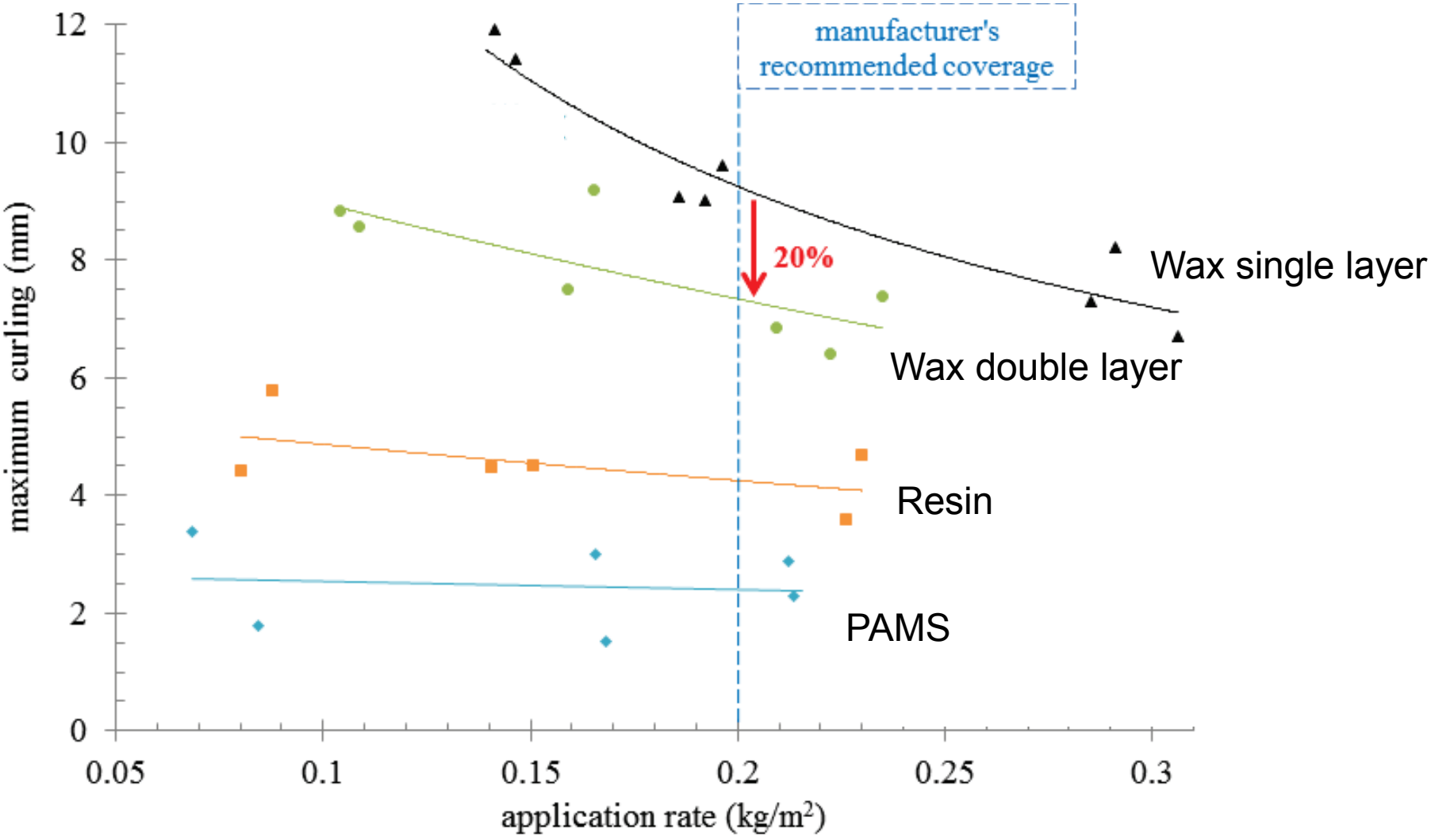


100% of manufactured recommended dosage was used



100% of manufactured recommended dosage was used


manufacturer's
recommended coverage
%33
Wax single layer
Wax double layer
Resin
PAMS
weight loss after 72 hours of drying (kg/m²)
application rate (kg/m²)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.05
0.1
0.15
0.2
0.25
0.3


manufacturer's
recommended coverage
20%
Wax single layer
Wax double layer
Resin
PAMS
maximum curling (mm)
application rate (kg/m²)
0
2
4
6
8
10
12
0.05
0.1
0.15
0.2
0.25
0.3

Observations

- If you compare moisture loss from PAMS to other at the recommended dosage

	moisture loss	cost diff
Resin/PAMS	1.4	33%
Double layer wax/PAMS	2	66%*
Single layer wax/PAMS	3	66%

* Double layer may cost more for extra application

Observations

- Double layers performed better than a single layer of curing compound
- As the coverage rate was increased all of the curing compounds showed an improvement in performance up to a point
- PAMS showed the best performance of all curing compounds

Summary

- There are benefits from using the higher quality curing compounds.
- “An ounce of prevention is worth a pound of **cure**”

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Thermal or Drying Shrinkage?

- Thermal
  - 140 to 350 millionths (40°F)
  - Starts with cooling
- Drying
  - 400 to 800 millionths
  - Starts with drying, continues for a long time