Impact of Curing Methods on Curling of Concrete Pavements

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How to make smooth pavements that don’t crack (at least for the first 100 days)

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Overview

➢ If we learn why things happen then we have a chance to fix them.
The tip of the iceberg...
Overview

- Background
- Are all curing compounds the same?
- How does different weather impact curling?
- How does drainage impact curling?
- How does mix design impact smoothness?
- Conclusions
What is Curling/Warping?

It is when the edges of a concrete 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
What is Curling/Warping?

Curling/Warping occurs 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, moisture, or both.
What is Curling/Warping?

Curling/Warping occurs 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, moisture, or both.

Beware of the gradient!!!
moisture

temperature
moisture                                      temperature

dry                                        dry

wet                                        wet

less dry                                   less dry
moisture
dry
less dry

temperature
dry
wet
less dry
After Weiss (2009)
Why is this important?

Most paving contracts base pay on only three hardened concrete properties:

- Strength
- Smoothness/Ride
- Slab cracking
Why is this important?

Most paving contracts base pay on only three hardened concrete properties:

- Strength
- Smoothness/Ride
- Slab cracking

Curling contributes to this!!!
Once the slab deflects, loadings or self weight can cause cracking.

Even if the slab does not crack then this dimension change will hurt your smoothness.
What impacts curling?

Curing
Weather
Drainage
Mixture design (minimum paste content)
Non uniform base
Temperature gradients

I will cover!!!
I will not cover!!!
How does curing impact curling??

Differential drying is one cause of curling.

Curing controls the drying rate of concrete.

Three types of curing compounds:

<table>
<thead>
<tr>
<th>Compound</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poly-Alpha-methyl-styrene (PAMS)</td>
<td>3x</td>
</tr>
<tr>
<td>Resin-Based</td>
<td>2x</td>
</tr>
<tr>
<td>Wax-Based</td>
<td>x</td>
</tr>
</tbody>
</table>
Are all curing compounds the same???

• They don’t cost the same and so you wouldn’t expect them to perform the same!

• But how much better is one then the other?
Paste beams

Wax on all sides but the surface

0.42 w/cm
Stored at 40% RH 73F
PVC mold

metronome

connected to the tank

nozzle

bolts to be adjusted at desired nozzle heights

marks to be passed on each metronome beat

moving forward
maximum deflection
Maximum curling height at the middle
Three different curing compounds were investigated:

- Poly-Alpha-methyl-styrene (PAMS)  3x
- Resin-Based                   2x
- Wax-Based                  x
100% of manufactured recommended coverage was used.
100% of manufactured recommended coverage was used
Wax single layer
Resin
PAMS
Wax double layer

maximum curling (mm)

application rate (kg/m²)

manufacturer's recommended coverage

20%

IJPE Hajibabaee and Ley, 2016
Wax single layer
Resin
Wax double layer
PAMS

No curing

IJPE Hajibabaee and Ley, 2016
Discussion

- The wax based curing compounds showed some improvement over not curing
- A double layer of curing compound (without increasing coverage) showed a 20% reduction in curling
- As the coverage increased all of the curing compounds showed improved performance
Discussion

• Higher cost curing compounds showed improved performance over lower cost products even at lower coverage rates!

• PAMS showed the best performance of all curing compounds
Why is this important?

• Curling is tied to moisture loss and curing compounds help with this.

• A “higher” priced curing compound will have improved performance and could help your obtain smoother pavements with less cracking.

• A double layer coat of curing compound is a good practice.
Concrete Lab Testing

• We made a concrete specimen that mimicked a strip from a concrete pavement.
Modified version of a concrete beam used by Springenschmid et al. (2001) and Hansen et al. (2007)
Fixed

8'

8"

6"

Free

Wood dowels
Beam depth (in)

RH %

60 65 70 75 80 85 90 95 100

PAMS

no curing

20 days
Tip Deflection

Curling Height (in)

Days exposed to drying

- No curing
- Wax double layer
- PAMS
METHODOLOGY (Concrete Elements)

Modified version of a concrete beam used by Springenschmid et al. (2001) and Hansen et al. (2007)

- Diameter: 1.8 cm
- Depth: 1.8 cm
- Moisture barrier
- RH sensor
- Demec points
- RH sensors covered with tape
- Tined & exposed surface
- Fixed with C-clamp
- Length: 2.28 m
- 1.14 m
- 15.2 cm
- 20.3 cm
- Deflection gage
- 0.42 w/cm
- 23 °C and 40% RH
- 0, 7, 14 day wet cure
Modified version of a concrete beam used by Springenschmid et al. (2001) and Hansen et al. (2007)
METHODOLOGY (Concrete Elements)

Modified version of a concrete beam used by Springenschmid et al. (2001) and Hansen et al. (2007)

0.42 w/cm
23 °C and 40% RH
0, 7, 14 day wet cure
Calculation of max curling deflection

Euler-Bernoulli equation

\[
\delta_{\text{max}}(t) = \frac{3l^2}{2L^3} \int_{0}^{L} \varepsilon(y, t) y \, dy
\]

Small concrete beam
beam length = 7.5 ft

Deflection (in) vs. Days Exposed to Drying (40% RH)
OK, now what?

- These little beams can give us comparable data to the big beams
- Now we can start to answer some of the really hard questions.
How does different weather impact curling?

• We made more beams and stored them outside in Stillwater, OK.
5 year RH and precipitation history in Oklahoma
Mass loss of the samples in the field

Mass gain

Days after exposure

-0.100
-0.050
0.000
0.050
0.100
0.150
0.200

0 50 100 150 200 250 300 350 400 450 500 550 600 650

1-day wet
3-day wet
7-day wet

water-wax, S 100%
water-wax, S 150%
water-wax, D 100%
resin, S 100%
PAMS, S 100%

No curing
Curing compounds
Wet curing
Sealed

No curing
Strain at a top of the concrete after being exposed

Curing compounds
No curing
Wet curing

Days exposed to drying
Observations

• The average RH in Oklahoma is about 65% and it rains often.

• The samples are gaining mass from rain but are showing shrinkage at the top surface.

• This is likely caused by irreversible shrinkage.

![Graph showing shrinkage strain over time with drying and rewetting phases, illustrating reversible and irreversible shrinkage.](image)
Strain at a top of the concrete over first 100 days

- 1-day wet
- 3-day wet
- 7-day wet
- water-wax, S 100%
- water-wax, S 150%
- water-wax, D 100%
- resin, S 100%
- PAMS, S 100%
- No curing

Shrinkage (→) — swelling (+)

Days exposed to drying

PAMS
Wax
Wet curing
No curing
Observations

- The no curing and wax based curing compounds showed very similar performance.
- The wet curing performs well early but then at 100 days behaves similar to the no curing.
- PAMS had the lowest shrinkage over the first 100 days.
Strain at a top of the concrete after being exposed

- 1-day wet: water-wax, S 100%
- 3-day wet: water-wax, S 150%
- 7-day wet: water-wax, D 100%
- resin, S 100%
- PAMS, S 100%
- No curing

days exposed to drying

- Curing compounds
- No curing
- Wet curing
Observations

- After 200 days the no cure and curing compounds start to decrease shrinkage!
- The wet cured samples show increased shrinkage with time.
How much does RH impact the results?
beam length = 7.5 ft

Standard tests

RH in Oklahoma

40% RH

70% RH

66%

deflection (in)
days exposed to drying

66%

Oklahoma
Curling from drying is more significant

Curling from drying not as significant
Observations

- Environments with higher average RH substantially reduces shrinkage.

- This means that drying based curling should be more important in some regions and less important in others.
What else impacts curling?
Pavements with poor drainage
Some key parameters

(Hansen et al. 2007)
drying shrinkage + water intake at bottom

> 400% increase

drying shrinkage alone

Warping (mm)

Drying time (days)
What else impacts roughness?
**Fine Sand**
Summation of #30 - #200
24% - 34%

**Coarse Sand**
Summation of #8 - #30
Above 15%

---

The Tarantula Curve!
Minnesota Pavement Mixtures from 1996 - 2011

% within the Tarantula limits

20 point change

What does this mean?

- If you are building a pavement in a low RH environment (< 50% average RH) curing with a high quality curing compound is recommended.

- If you in a higher RH environment (> 60% average RH) curing has a lot less impact on curling.
What does this mean?

- Poor drainage can significantly increase curling.
- As the number of aggregate gradations within the Tarantula Curve increased the IRI decreased.
- Be as consistent as you can with your mixture design, curing, and finishing practices.
When should roughness be measured?

• Within the first 30 – 100 days
• At several different temperatures
• The longer you wait the more the weather will influence the curling
  > 60% RH the curling should decrease
  < 50% RH the curling will increase
There are still big needs…

- The current MEPDG design for curling is woefully inaccurate
- Ride specifications are being used but do we really know what we are measuring?
- This work could be extended to learn much more…
Next steps…

- We have a model that does a pretty good job of predicting curling performance for the environments that we have investigated.
- We need more field data
- If you are interested in helping then please contact me.
Conclusions

• Higher priced curing compounds show improved performance over lower priced ones.

• Weather has a significant impact on curling.

• Pavements that do not drain show increased curling.

• The average roughness decreased in Minnesota as more gradations met the Tarantula Curve bounds.
Questions?

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Concrete Beam Data

- The results from the concrete beams are similar to the paste!
- The wet cured samples lost moisture at a slower rate.
- The strain gradient was larger in the wet cured samples and so this in turn would cause greater curling.
What does this mean?

- Wet curing can:
  - Reduce mass transport
  - Increase strength
  - Increase stiffness
  - Increase resistance to surface abrasion
  - Increase the capillary forces near the surface on drying
- This means it will take longer for the concrete to dry but once it does then it will lead to greater surface shrinkage.
- This greater surface shrinkage will lead to a greater strain gradient in the concrete and so a greater amount of curling
- This phenomenon is magnified at lower RH
What does this really mean?

- Wet curing slabs will cause increased deflections from differential drying.
- This phenomenon is more severe in lower RH
- If you want to wet cure these slabs for other reasons then you can add reinforcing steel, increase thickness, and/or reduce the paste content of your mixture.
CONCLUSION

• Increasing the wet curing length increases the degree of saturation of the paste and concrete.
• This increased level of saturation will lead to increased strains on subsequent drying.
• Wet curing will also reduce mass transport.
• This will in turn lead to larger differential drying in the sample.
• All of this causes greater curling in wet cured paste and concrete samples.
• Our experiments showed good agreement with 1D drying shrinkage models from Grasley.
The diagram illustrates the relationship between Max Curling Height (in inches) and Days for different conditions of curing:

- **No curing**: The curve shows a steady decrease in Max Curling Height over time.
- **1 day sealed**: The height increases significantly in the first day and then decreases gradually over time.
- **1 day wet**: Similar to the 1 day sealed condition, with a slight increase in height in the first day.
- **3 days sealed**: The height increases more slowly and reaches a higher peak compared to the other conditions.
- **3 days wet**: The height increases rapidly in the first day and then decreases more gradually than the 3 days sealed condition.

The data points with error bars indicate the variability in the measurements for each condition.
BACKGROUND

- When concrete dries it shrinks from the following:
  1. Capillary pressure
  2. Disjoining pressure,
  3. Interfaces pressure.
- The Kelvin-Laplace equation is used to at least partially define this phenomenon (Adamson and Gast 1997):

\[
p_c = -\frac{2\gamma}{r} = \frac{2\gamma \cos(\theta)}{a} = -\frac{\rho_lRT}{M_v} \ln(RH) = -\frac{RT}{V_m} \ln(RH)
\]

- Change in the radius of the curvature of the meniscus \( r \), and the relative humidity \( RH \) can change the capillary pore pressure \( p_c \).
BACKGROUND

• This means that the relative humidity of the surrounding environment and the size of the pores have an impact on the magnitude and the rate that your concrete will shrink.

• When you cure your concrete in different ways then you change the rate that it dries and the size of the pores.

• The equation suggests that the smaller the pores, the larger the capillary pressure.
This says that the better your curing is. The worse your curling should be.

This is not expected. Let’s see what happens.

The literature has varied opinions on the impact of wet curing on curling:

- Perenchio (1997): higher drying shrinkage with more curing.
- Suprenant (2002): little effect on curling with longer curing!
METHODOLOGY (Paste Elements)

- Concrete shrinks because of the paste.
- We are going to first focus on the paste and then talk about concrete.
- Our test was modeled after work by Berke et al. (2004).
- Water to cement ratio was 0.42.
- Samples were either not cured, or in wet burlap for 1, 3, 7, and 14 days.

All sides are coated with wax except the top.
maximum deflection
Impact of Wet Curing on Mass Loss

The graph shows the impact of different wet curing durations on mass loss over time. The x-axis represents the number of days exposed to drying, while the y-axis represents mass loss (%). The legend indicates the following curing durations:

- No additional curing
- 1 day wet
- 3 days wet
- 7 days wet
- 14 days wet

The graph demonstrates that longer wet curing periods result in lower mass loss when exposed to drying.
Impact of Wet Curing on Curling

max curling height (mm)

No additional curing

1 day wet
Impact of Wet Curing on Curling

- No additional curing
- 1 day wet
- 3 days wet

Days exposed to drying vs. max curling height (mm)
Impact of Wet Curing on Curling

- No additional curing
- 1 day wet
- 3 days wet
- 7 days wet
Impact of Wet Curing on Curling

max curling height (mm)

days exposed to drying

- No additional curing
- 1 day wet
- 3 days wet
- 7 days wet
- 14 days wet
Impact of Wet Curing on Curling

• The maximum amount of curling and the time needed to reach the maximum amount of curling increased as the length of wet curing increased.

• Additional curing sustains hydration and decreases the porosity of cement paste.

• This decrease in pore size:
  1. causes an increase in pressures upon drying.
  2. makes it more difficult for a specimen to lose moisture from drying.
METHODOLOGY (Paste Cylinders)

Samples were wet cured for 0, 1, 3, 7, and 14 days in saturated wet burlap.

3 pieces were made for each depth
METHODOLOGY (Paste Cylinders)

- Samples were measured in an oven, submerged, and stored above 85%, 72%, 50%, and 40% RH at 23 °C.
85%RH

- no curing
- 1-day wet curing
- 3-day wet curing
- 7-day wet curing
- 14-day wet curing
What does this mean?

• As you wet cure, the degree of saturation increases for a fixed relative humidity.
• This means that the longer you wet cure, the more of the pores in the sample will be filled with water and these pores will be smaller.
• This is a double whammy!
• The pores being small and having fluid in them will cause increased capillary pressures.
Prediction Using Drying Diffusion Model

- An analytical solution for 1D quasi-linear drying diffusion problem has been formulated by Grasley (2010)
- Results from the weight loss of the cement paste beams, and cylinders were used as inputs for the models.
- The model calculated free strain and deflection of the samples.
COMPARISON

max deflection (in)

no curing (experiment)

no curing (model)

days exposed to drying

0 5 10 15 20
max deflection (in)

model
- no curing
- 1-day wet curing

experiment
- no curing
- 1-day wet curing

days exposed to drying
predicted

- no curing
- 1-day wet curing
- 3-day wet curing
- 7-day wet curing

experiment

- no curing
- 1-day wet curing
- 3-day wet curing
- 7-day wet curing

max deflection (in)

days exposed to drying
COMPARISON

• The comparison between the maximum deflection of the paste elements that were calculated by the model and measured in the experiment:
Curling is a topic of serious debate. Many people have opinions why things occur based on their experiences.

The focus of this talk is provide data based on lab and field measurements.
Comparison between the maximum curling deflection of paste beams at 40% and 70% RH

- no additional curing @ 70% RH
- 1-day wet curing @ 70% RH
- 3-day wet curing @ 70% RH
- 7-day wet curing @ 70% RH
- 14-day wet curing @ 70% RH
- no additional curing @ 40% RH
- 1-day wet curing @ 40% RH
- 3-day wet curing @ 40% RH
- 7-day wet curing @ 40% RH
- 14-day wet curing @ 40% RH

max curling (mm) vs. days exposed to drying
What if we compared curing compounds at a constant cost???
The circled markers have the same cost.

cost X: small marker
cost 1.3X: medium
cost 1.6X: big

Wax single layer
Wax double layer
Resin
PAMS

max curling (mm) at given costs

application rate (kg/m²)
Observations

- At comparable costs the “high” cost curing compounds have better performance.

- The data suggests that we could use less than the manufacturer recommended dosage and achieve satisfactory performance.