Determining the Effectiveness of Curing Concrete

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Acknowledgements

Oklahoma Department of Transportation
Oklahoma Transportation Center
Minnesota Department of Transportation
Three keys to successful concrete

1. Initial cement grain spacing
2. Final cement grain spacing
3. Promote reaction
Three keys to successful concrete

1. Initial cement grain spacing – water to cement ratio
2. Final cement grain spacing - consolidation and finishing
3. Promote reaction - curing
Three keys to successful concrete

1. Initial cement grain spacing – water to cement ratio
2. Final cement grain spacing - consolidation and finishing
3. Promote reaction - curing
Let’s compare two mixtures with the same w/cm but different qualities of curing.
If you keep the concrete moist and warm then it will react.
Hydration product

Good curing

Water

w/cm = 0.40

Poor curing

Water

w/cm = 0.40
Good curing

Poor curing
Summary

As curing improves then the mixture will be stronger and have a lower permeability

“Good” Curing

“Not as Good” Curing
Your concrete will be compromised if it is not properly cured.

Curing helps the concrete reach its potential.
No curing

Curing
Uncured concrete

Cured concrete
Poorly cured concrete
Compromised surface

Poorly cured concrete

Sound interior
Formed surfaces

If my concrete is strong enough can I remove the forms?

How does our curing choices impact the life of the concrete?
Overview

Contractors have requested to remove wall forms at 12 h to accelerate construction.

The concrete has sufficient strength but when you remove the forms you stop curing the concrete. Does that reduce the durability?
How are we going to do this?

Phase I
Compare the effectiveness of curing with wood, steel, and rubber forms curing for 12, 24, and 72 h.

Phase II
Can you use other curing methods to extend the effective curing after removing steel forms at 12 h?
Testing

Typical wall concrete mixture

• 0.45 w/cm
• 20% Class C ash
• 6.5 sacks (611 lbs)
• Limestone and natural sand
• 5” slump
How do you test a wall?
What if we just test a piece of the wall.
What if we just test a piece of the wall.
Samples

- 4” concrete cubes were cast
- Phase I – compared steel, wood, or rubber forms
- We used steel forms for Phase II
- The other faces were surrounded by an impermeable membrane
After form removal
Testing

If the concrete is cured well then:
1. It will be hard for the concrete to lose moisture.
2. The concrete will be resistant to water uptake.
3. The concrete will be resistant to chloride penetration.

“Good” Curing

“Not as Good” Curing

We only ran this test in Phase I
## What did we do?

<table>
<thead>
<tr>
<th>Step</th>
<th>Test</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>drying</td>
<td>Mass change in 50% RH and 73°F for 28 days</td>
</tr>
<tr>
<td>2</td>
<td>water uptake</td>
<td>Mass change in lime water for 6 days</td>
</tr>
<tr>
<td>3</td>
<td>chloride penetration</td>
<td>Mass change in 5% NaCl for 35 days Chloride profile</td>
</tr>
</tbody>
</table>
Step 1 – Dry the sample

Measure mass change in 50% RH and 73°F for 28 days
Discussion

• The samples are losing water as they dry.
• The better the curing the less mass was lost.
• Wood forms seem to be the best followed by steel and rubber.
• The longer you cure the sample the less moisture is lost.

• This shows that extended curing in the forms helps resist water loss.
• This means that the concrete should be better at resisting outside chemical penetration.
Discussion

• While there was some differences between the different types of forms, the differences were not that large.

• For the Phase II testing we will use steel molds.
Curing in Phase II

• Cure samples within steel molds for 12 h
• Remove molds and then cure with:
  • Sealed curing for 1d, 3d, 7d
  • Wet curing for 3d, 7d
  • Curing compound PAMS and dissipative curing compound

We also looked at curing in steel molds for 24 h and 72 h
Molds 12 h
Molds 72 h
Molds 12 h + 3d plastic
Molds 12 h + dissipative cure
Molds 12 h + 1d plastic
Molds 12 h + PAMS cure
Molds 12 h + wet cure
Molds 12 h
Discussion

• The sample cured in steel molds for 12 h did the worst and the sample in the steel molds for 72 h did the best.

• The samples that were sealed with plastic for 3 d and 7 d and curing with the dissipative curing compound performed slightly less to samples cured in the steel molds for 72 h.

• The wet curing samples did not perform well. This is probably because the burlap did not hold the moisture on the surface of the concrete.
Chloride Profiles

• Next we cut the samples and investigated the surface with a XRF microscope
μXRF technique description

Khanzadeh Moradillo, Sudbrink and Ley, 2016
Black regions are aggregates.

Curing:
- **Low**: Paste: Cl < 300 ppm
- **Medium**: Paste: 0.3K < Cl < 2K ppm
- **High**: Paste: 2K < Cl < 6K ppm
- **Very High**: Paste: Cl > 6K ppm

Curing:
- **None**: Paste: Cl < 300 ppm
- **Low**: Paste: 0.3K < Cl < 2K ppm
- **Medium**: Paste: 2K < Cl < 6K ppm
- **High**: Paste: Cl > 6K ppm
We can digitally cut the sample into layers and find out how much is on each layer.
Data from grinding and titration of powder.

mXRF Data

Chloride concentration (ppm)

Depth (mm)
Likely caused by a crack
<table>
<thead>
<tr>
<th></th>
<th>Service life in years for 2&quot; cover of epoxy coated steel bar</th>
<th>% reduction in service life compared to 24 h curing in the steel molds</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 h steel molds - 2</td>
<td>42</td>
<td>~</td>
</tr>
<tr>
<td>12 h steel molds + 2245 CC</td>
<td>35</td>
<td>17</td>
</tr>
<tr>
<td>12 h steel molds + sealed cure 3 d</td>
<td>34</td>
<td>19</td>
</tr>
<tr>
<td>12 h steel molds + 1100 CC</td>
<td>32</td>
<td>24</td>
</tr>
<tr>
<td>12 h steel molds + 3 d wet cure -1</td>
<td>30</td>
<td>29</td>
</tr>
<tr>
<td>12 h steel molds + 3 d wet cure -2</td>
<td>28</td>
<td>33</td>
</tr>
<tr>
<td>12 h steel molds - 2</td>
<td>27</td>
<td>36</td>
</tr>
<tr>
<td>12 h steel molds - 1</td>
<td>27</td>
<td>36</td>
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* These values indicate surface cracking.  
** These values indicate a low level of surface penetration.
Discussion

• Based on service life models in Minneapolis with epoxy coated rebar with 2” cover -

• You can increase your service life by 36% if you leave the forms in place for 24 h instead of 12 h.
Discussion

• If forms are removed at 12 h then it is suggested to use dissipative curing compound, PAMs curing compound, or require plastic to be placed for 3 days.

• The service life is reduced by about 20% for these concretes that use a combination of steel molds for 12 h plus some other method compared to leaving the forms in place for 24 h.
Discussion

• The wet curing samples did not perform well. This is likely because the burlap can not hold the moisture on the surface of the concrete on a vertical surface.
What does this mean?

Curing time in the forms does impact the durability of the concrete. If concrete durability is important, then you should leave the forms in place for as long as practical.

If you remove the forms early, then you can continue to cure with a curing compound.
How about a bridge deck?
What is the cost of curing?

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<th>Percentage of Oklahoma bridge cost/sf **</th>
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<tr>
<td>Burlap wet cure</td>
<td>0.42</td>
<td>0.47%</td>
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<tr>
<td>Premium curing compound</td>
<td>0.17</td>
<td>0.19%</td>
</tr>
<tr>
<td>Common curing compound</td>
<td>0.06</td>
<td>0.07%</td>
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* from an Oklahoma contractor

** Using $89/sf from 2013 NHS
Testing

We developed a testing protocol to evaluate how curing impacts the concrete microstructure.

- 0.40 w/cm
- 20% Class C ash
- 6.5 sacks (611 lbs)
- Limestone and natural sand
- 5” slump
How did we cure them?

• No curing
• Wet curing for 1, 3, 7, 10, 14 days with wet burlap covered in plastic
• Lithium silicate curing compound
• Poly Alpha Methyl Styrene (PAMS) curing compound

• Curing compounds were applied in two layers with a total coverage of 200 sf/gal
Testing

If the concrete is well cured then:

1. It will be hard for the concrete to lose moisture.
2. The concrete will be resistant to water uptake.
3. The concrete will be resistant to chloride penetration.

Remember the straws!!!
Good curing

Poor curing
What did we do?

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Step 1 – Dry the sample

Measure mass change in 40% RH and 73°F for 22 days
1. Mass change in 40% RH and 73°F for 22 days
Discussion

• The samples are losing water as they dry.
• The better the curing the less mass was lost.
• Lithium silicate reduced mass loss by 12% and the PAMS by 38% when compared to not curing.
• After 7 days of wet curing there was a low mass loss.
• There was little difference between 7, 10, and 14 days of wet curing for these conditions and materials.
Step 2 – Place concrete in lime water

Measure mass change in lime water for 5 days
2. Mass change in lime water for 5 days
2. Mass change in lime water for 5 days

3 day wet cure has a 68% reduction in water penetration compared to no curing
Step 3 – Place concrete in NaCl solution

Measure mass change in NaCl solution for 35 days
3. Mass change in 5% NaCl for 35 days
3. Mass change in 5% NaCl for 35 days

3 day wet cure has a 70% reduction in Cl compared to no curing
Discussion

• Concrete with a dense microstructure will gain less mass when wetting
• The trends are similar for initial water uptake and long term chloride penetration
• Lithium silicates performed similarly to no curing
• PAMS reduced fluid uptake by 25% when compared to no curing
• Wet curing for 3 days reduced fluid uptake by ~ 70%
• Very little difference between the fluid penetration for 3, 7, 10, and 14 days of wet curing
Chloride Profiles

• Next we cut the samples and investigated the surface with a XRF microscope
4. Chloride profile
4. Chloride profile

Wet curing for 3 days has a 60% reduction in Cl concentration.
Discussion

• The chloride penetration data had similar trends as the fluid uptake.
• No cure and lithium silicate performed similarly
• Wet curing performed better than the curing compounds
• There was about a 60% reduction in the chloride ingress for the 3 day wet cured sample compared to the sample that was not cured.
• *This suggests you get approximately double the lifespan for chloride ingress from wet curing your concrete compared to not curing.*
What is the cost of curing?

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** Using $89/sf from 2013 NHS

For ~ .5% of your cost you are doubling the lifespan of your concrete against outside chemicals.
Discussion

• The mass change from drying, moisture absorption, and chloride diffusion showed similar trends
• Lithium silicate and no curing had similar performance
• PAMS showed improved performance but not as good as wet cure
• Curing for 7 days had slightly better performance than 3 days.
• You can approximately double the lifespan of your bridge deck against chloride ingress with wet curing for 3 days over not curing
Conclusions

• Curing is an important part of the construction process that is often overlooked.

• Just because the concrete is strong does not mean it has stopped reacting.

• Not all curing methods are created equal and they should be chosen based on the long term needs of the concrete.
Questions?
www.tylerley.com
www.youtube.com/tylerley

WHAT IS FIBER
REINFORCED
CONCRETE?

TYLER LEY, PE, PHD
Thank You!
This concludes the Continuing Education Program.
Any Questions?

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Concrete.tyler

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405-744-5257
Do you think curing compounds and wet curing provide the same quality of curing?

If not then how different are they?
Curing for Durability

Does curing really impact durability?

Is curing worth the cost?
Let’s compare different curing methods...

- Wet curing
- Curing compounds
- No curing
Why is wet curing challenging?

1. Wet curing requires significant labor
2. If placed too early wet burlap can scar the surface and reduce cover
3. We don’t do a good job of keeping the burlap wet
4. Challenging to inspect
5. Expensive
For more videos go to:

www.tylerley.com/WOCcure
Plastic shrinkage cracking nomograph

More concern for cracking

Less concern for cracking
Ion penetration

\[ C_{(x,t)} = C_s \left(1 - \text{erf} \left( \frac{x}{2\sqrt{D_c t}} \right) \right) \]

Cs – Surface Concentration

Dc – Effective Diffusion Coefficient
Why do we do this?
Strength

Load

$w/cm = 0.40$

More ways to transfer load

Load

$w/cm = 0.50$

Less ways to transfer load
Strength

Load

w/cm = 0.40

More ways to transfer load

Load

w/cm = 0.50

Less ways to transfer load
Permeability

Water

w/cm = 0.40

Less ways to transfer water

Water

w/cm = 0.50

More ways to transfer water
Permeability

Water

Less ways to transfer water

Water

More ways to transfer water

w/cm = 0.40

w/cm = 0.50
Summary

The lower w/cm mixture did a better job at transferring load and keeping water out than the higher w/cm mixture.
Summary

The lower w/cm mixture did a better job at transferring load and keeping water out than the higher w/cm mixture.

**Remember!** w/cm is only the first step.
Curing promotes hydration!

We want to hold moisture and heat within the concrete

We want to protect and strengthen the surface