Testing the w/cm of fresh concrete with the Phoenix

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Acknowledgements

Oklahoma Department of Transportation
Dolese

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Overview

Water to cement ratio (w/cm)
MnDOT experience
The Phoenix!
Future Implementation in Minnesota

What is the water to cement ratio?

What is the water to cement ratio?

$$w/cm = \frac{\text{mass water}}{\text{mass cementitious}}$$

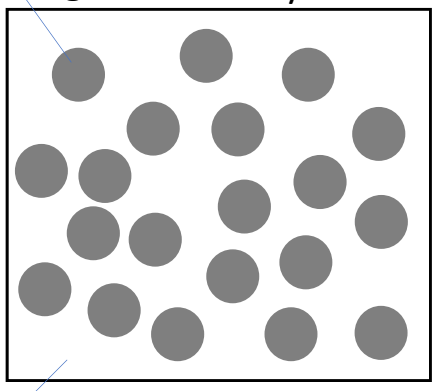
What is the water to cement ratio?

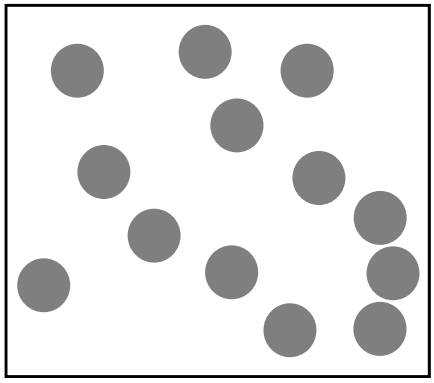
The w/cm is the most important parameter for determining the strength, durability, and consistency of concrete.

cement grain

w/cm = 0.40

w/cm = 0.50



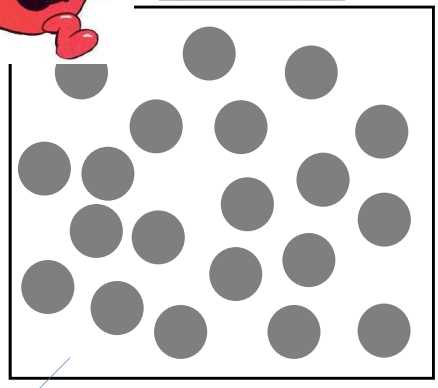


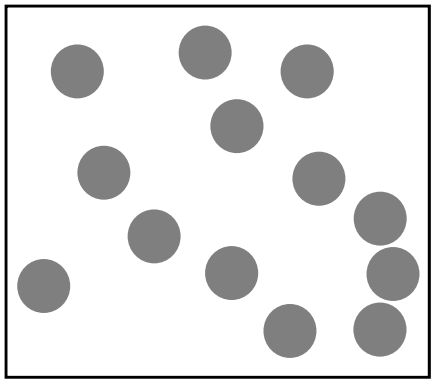
water

7

n = 0.40

/cm = 0.50





water

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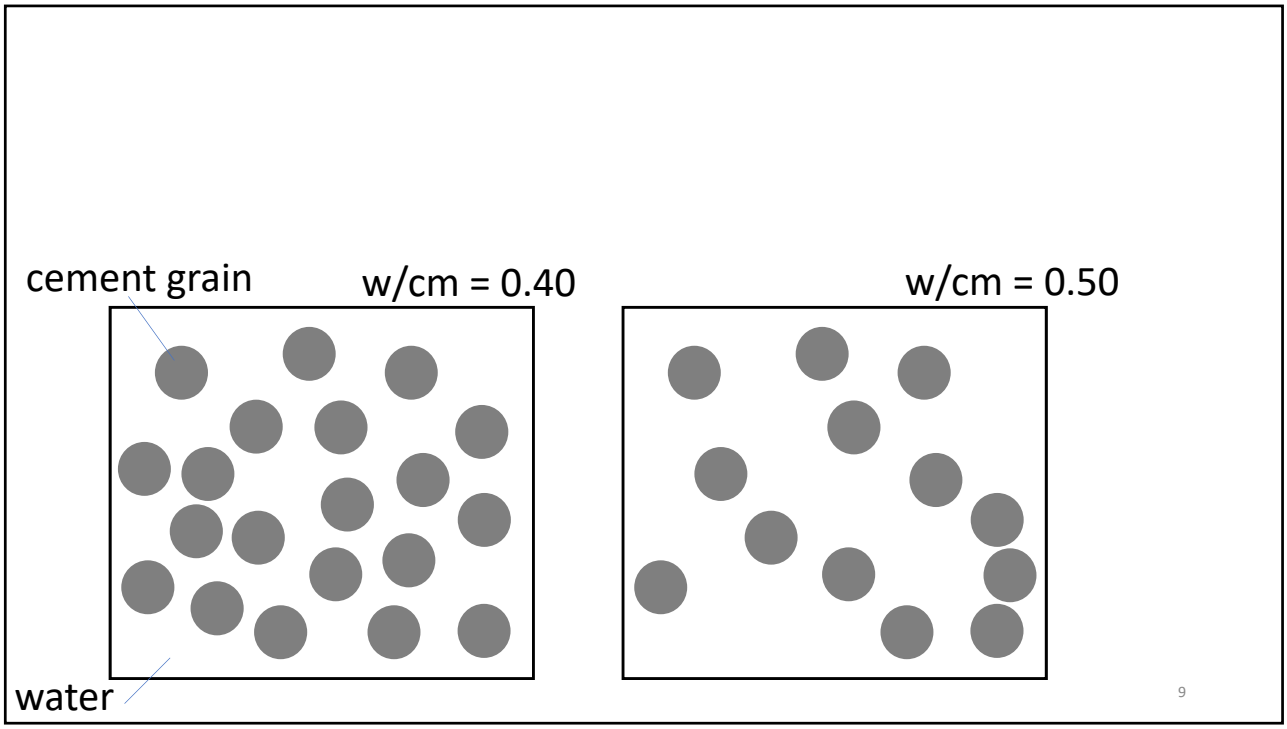
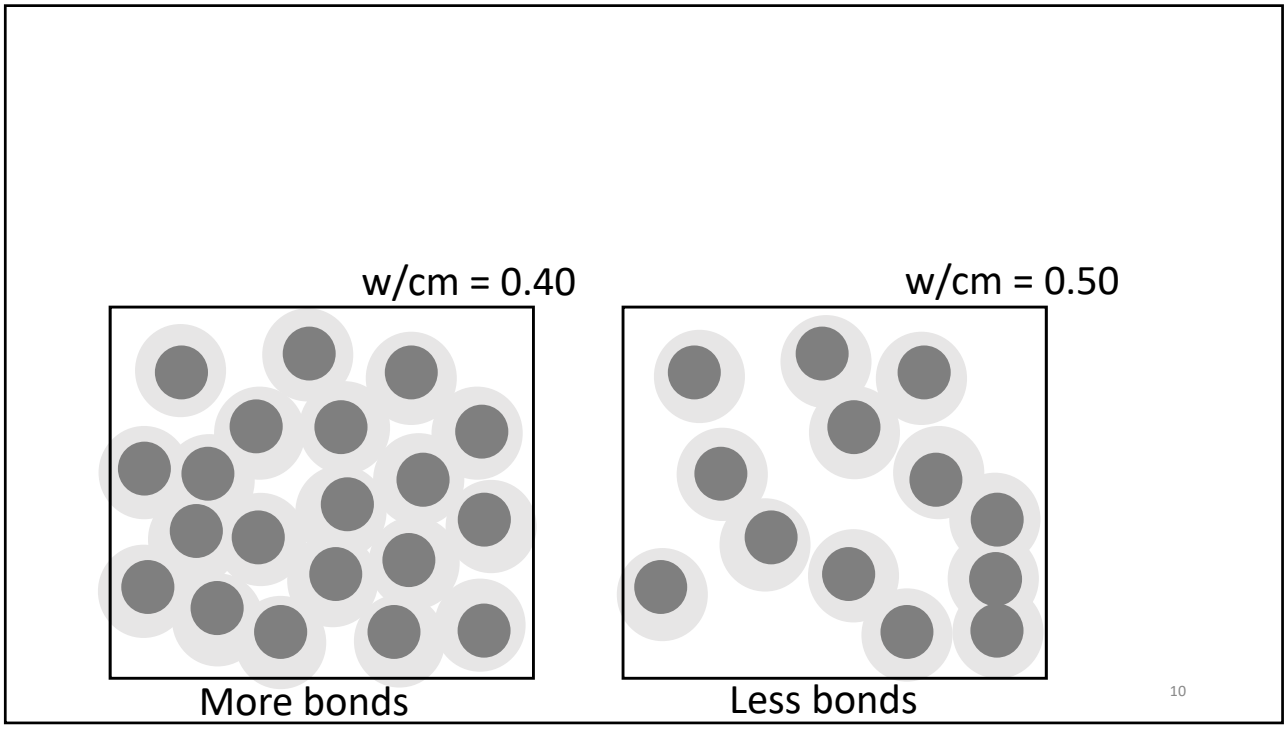

cement grain
w/cm = 0.40
w/cm = 0.50
water
9


w/cm = 0.40
w/cm = 0.50
More bonds
Less bonds
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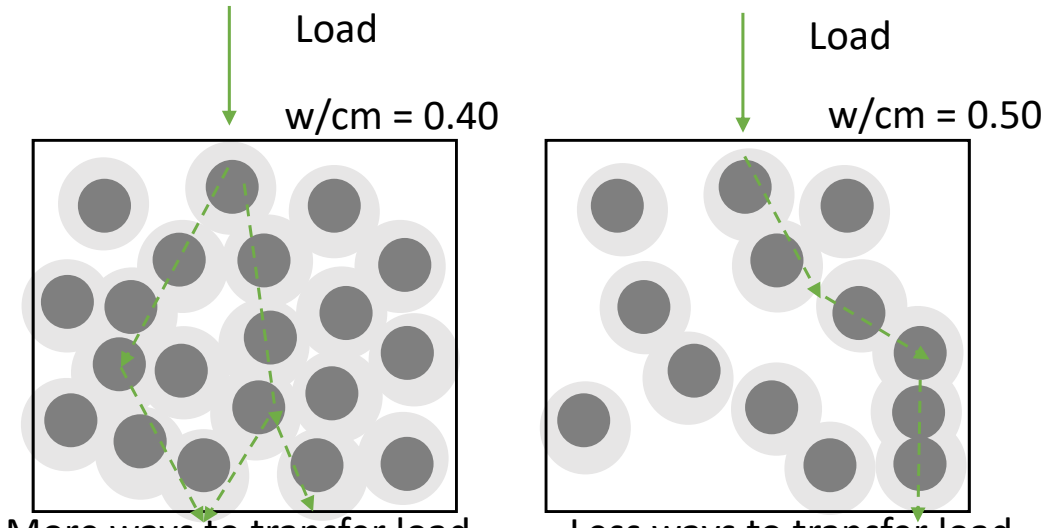
Strength



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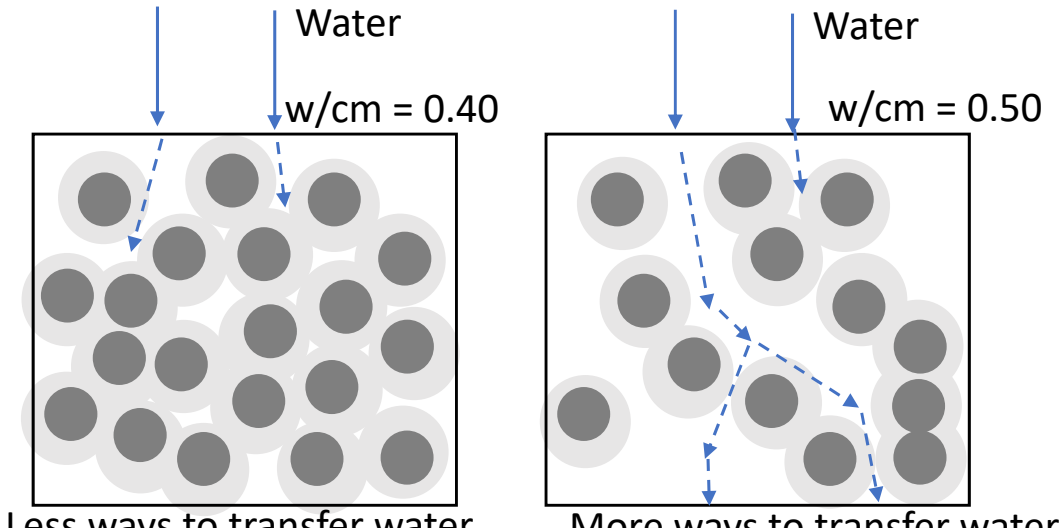
Permeability



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Premature Pavement Deterioration

- Minnesota Pavements from the 80's showed premature deterioration (mostly materials related)

Slide after Masten

How did MnDOT address pavement deterioration?

- In 1995, MnDOT moved away from strength to a w/cm ratio specification for acceptance
- 3 Principal factors that guide the current spec:
  - Mix durability
    - Optimized Gradations
    - Controlling the w/c ratio
    - Incentives/disincentives
    - ASR mitigation requirements
  - Pavement Smoothness
  - Improved Curing Materials and Practices

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Concrete Strength

- Historically
  - Strength achieved in 7 days
  - HE mixes achieved strength in 3 days
- W/C specs
  - Achieve strength in ≈ 3 days
  - HE mixes can be designed to easily achieve opening times in 24 hours.
- Strength is not a specification but a side effect of low w/c is:
  - Pre w/c spec core strength average ≈ 4500 psi
  - Post w/c spec core strength average > 6000 psi

MnDOT Water/Cement (w/c) Ratio Spec

- Place concrete with a w/c ratio not to exceed 0.40 when using cement only or fly ash
- Place concrete with a w/c ratio not to exceed 0.42 when using slag or ternary
- Immediate adjustments should be made when the w/c exceeds 0.40 or 0.42
- No w/c ratio incentive payments on high-early mixes (>615 # cementitious)
- Concrete delivered in ready-mix trucks are not eligible for w/c ratio incentives
- Full time QC and QA personnel at plant

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Advantages of w/c ratio

- Immediate results
- Eliminate testing variables related to strength
- Assured quality & performance
- Increased strengths

Determination of w/c ratio incentive

- Based on the Contractor's batch ticket as verified by Agency testing
- Agency does moisture testing
  - 1 per 1000 yd^3 or completed every 4 hours, whichever results in the higher sampling rate
  - Take initial samples for aggregate moisture testing within the first 250 yd^3
- Agency takes aggregate samples for testing from belt
- Agency takes concrete samples from truck at plant (approximately 4-10 loads after obtaining aggregate moisture samples)
- The Agency uses the actual water and cementitious contents from an average of 10 batch tickets
- Agency testing to verify water content is performed according to AASHTO TP23-93 "Standard Test Method for Water Content of Freshly Mixed Concrete Using Microwave Oven Drying"
  - Coincides with aggregate moisture testing

Possible Sources of Error in Water Content

- Batch Ticket vs. Microwave Oven Test
- Water Meter Calibration (2461.3.D.1.c)
- Testing Errors
  - Sampling and Testing Procedures
  - Equipment
- ***Used as a verification tool ~ not for acceptance***

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WATER/CEMENTITIOUS RATIO INCENTIVES

W/C Ratio Payment Incentive/Disincentives Per Cubic Yard		
QI Value	$/Cubic Yard (Pre-2011)	$/Cubic Yard (2011-Present)
0.35 or less	4.00	-
0.36	3.00	-
0.37	2.00	3.00
0.38	1.25	1.75
0.39	0.50	0.50
0.40	0.00	0.00
0.41	-0.50	-0.50
0.42	-1.25	-1.75
0.43	-2.00	-3.00
0.44	-3.00	As determined by the Concrete Engineer
0.45+	As determined by the Concrete Engineer	-

"Blessing the Slab"

- Do not add water to the surface of the concrete to aid in finishing without the approval of the Engineer. The Engineer will give approval to replace evaporated surface water directly behind the paver caused by a halt in forward progress from short-term breakdown in Equipment or supply of concrete.

- The Contractor can request approval to add water to the surface when cutting bumps or filling dips in the plastic concrete each time additional water is needed. If the Contractor adds water to the pavement surface without approval by the Engineer, the Department will not pay incentives for water/cement or pavement smoothness on sections where water is added. The Engineer may also reject the pavement in accordance with 1512, "Unacceptable and Unauthorized Work."

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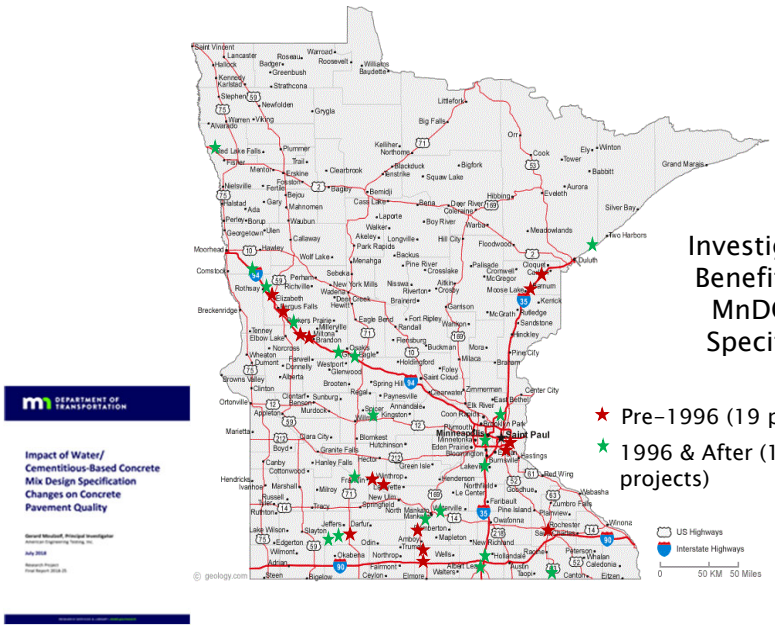
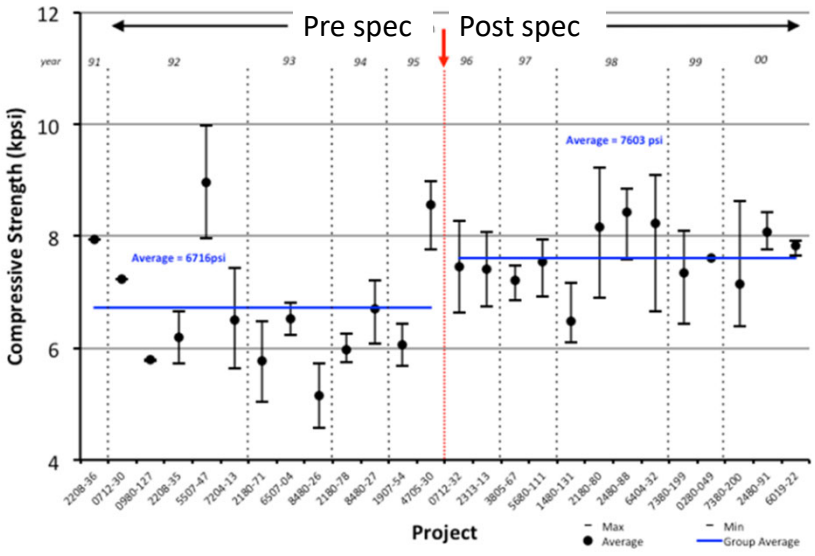


FINAL REPORT: http://www.dot.state.mn.us/research/reports/2018/201825.pdf Slide after Masten

W/C Spec Impact on Strength (C39)



28 day

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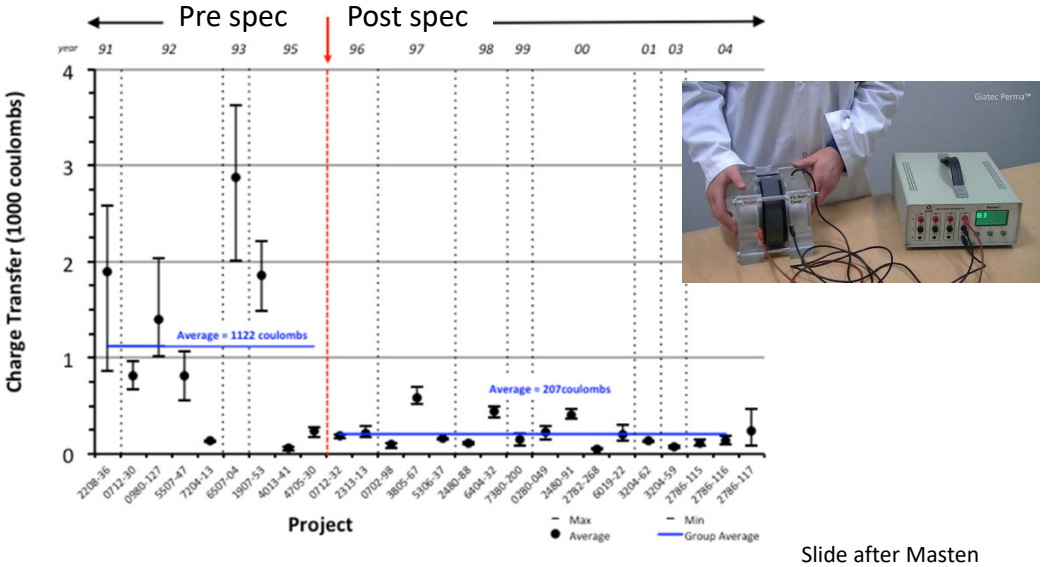
W/C Spec Impact on RCPT (Permeability) (C1202)



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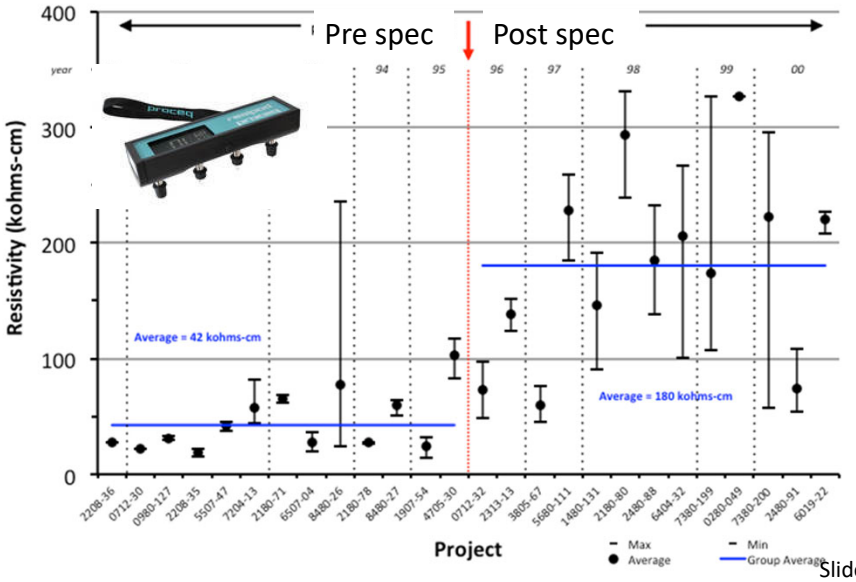
W/C Spec Impact on Resistivity (T358)



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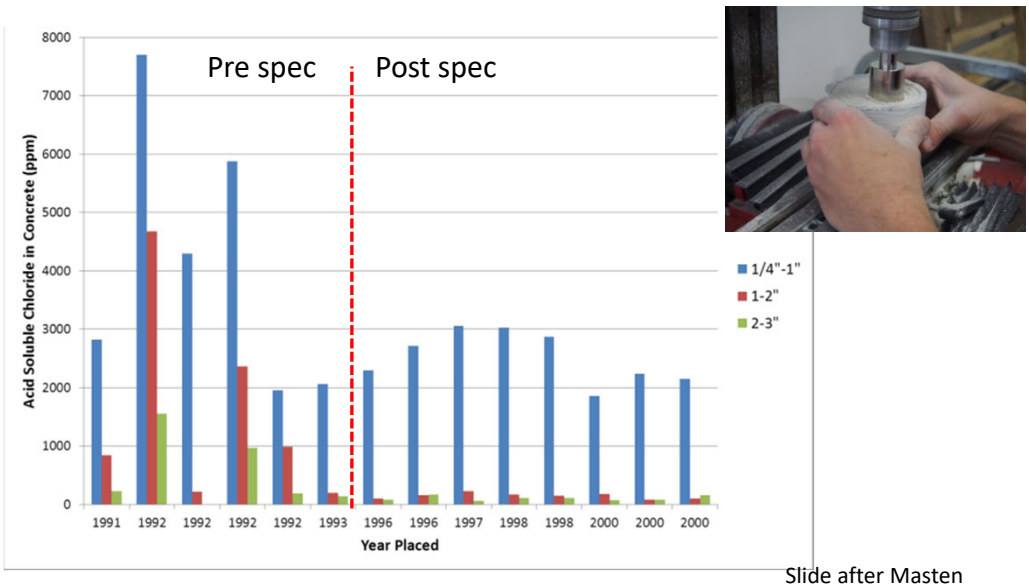
W/C Spec Impact on Chloride Penetration



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Discussion

By adding a specification on w/cm MnDOT improved strength and lowered permeability

Concrete with lower permeability holds less water and reduces deicer ingress.

This improves freeze thaw resistance, joint deterioration, and reduces curling and warping

What does this mean?

Measuring the moisture content of the aggregates and looking at the water added to the mix has been a useful tool but it does not tell you what is in the concrete.

A fast test that measures the water in the concrete would be more accurate and it would be simpler for MnDOT to implement.

Contractors would not need to change any of their processes.

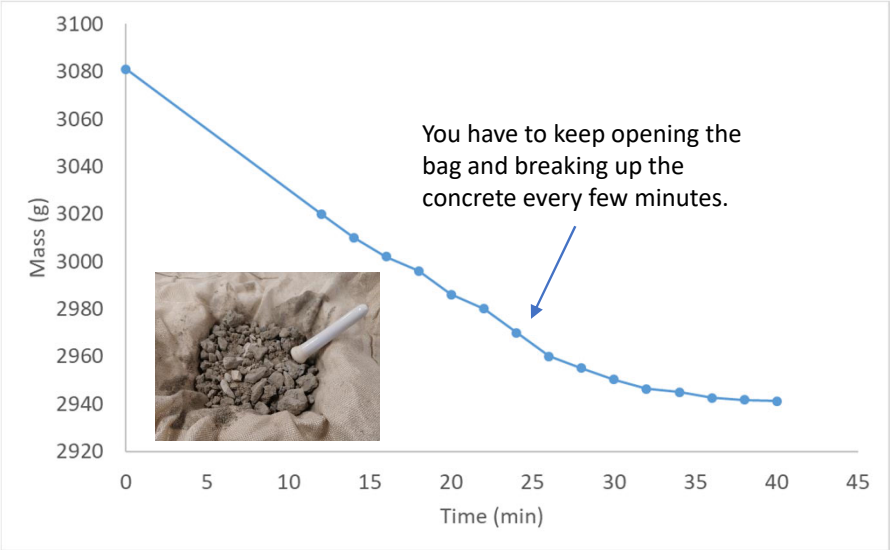
Microwave Oven – AASHTO T 318

- Collect 1500 g of concrete
- Weigh sample
- Remove water with heat
- Weigh sample
- Compare to cement content in the mix and determine w/cm

- Sounds simple, right?

Challenges with microwave oven test

- ≈40 min in length
- Labor intensive
- Results are variable (+/- 0.05 w/cm)



Challenges with microwave oven test

- Results are variable +/- 0.05 w/cm

Amount required in the test

1500 g
≈1/3 of 4x8 cylinder

4x8 cylinder

Discussion

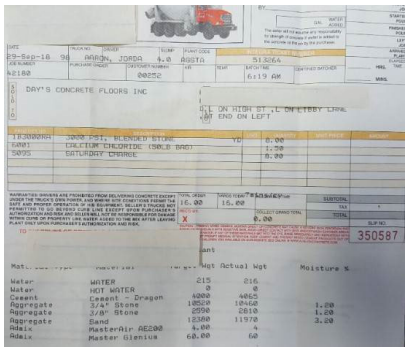
- The industry would benefit from a test that can measure the water content in fresh concrete.
- There are challenges with the microwave oven test.

We call this test “The Phoenix”!!!

Steps

- Record batch ticket and aggregate properties
- Make and weigh 6”x 4” cylinder (1640 cm^3)
- Dump cylinder into pan and weigh
- Start test
- Come back 15 min
- Weigh pan

Items needed…



Batch and agg info

Cylinder and a scale

Pan

Awesome kiln!!!

1500 °F (max temp)

Dry concrete

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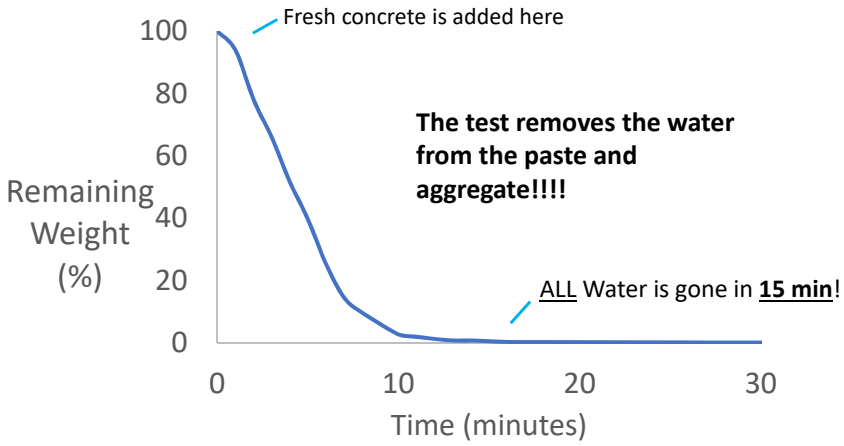
Change in weight over time



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The Phoenix removes all the water!!!

- If we know the absorption capacity of the aggregate then we can remove this from the total water content and get the w/cm
- During mixing the moisture content of the aggregate will become SSD

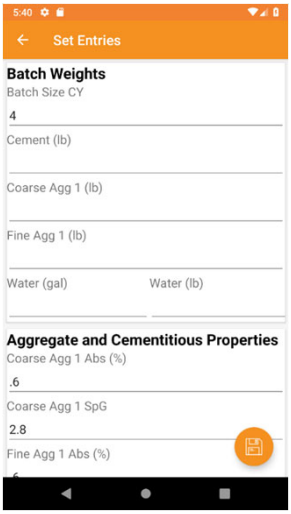
How do you get w/cm?

- The change in mass before and after cooking = amount of water in the cylinder
- Calculate how much water will be in aggregate after reaching SSD and remove that from the total water

How do you get w/cm?

- Use the batch ticket information to find the amount of binder within the cylinder
- Make a correction based on the measured cylinder unit weight versus the theoretical unit weight to correct for air
- You can also measure the air content if you want

There is an app for that!!!



How can we test it?

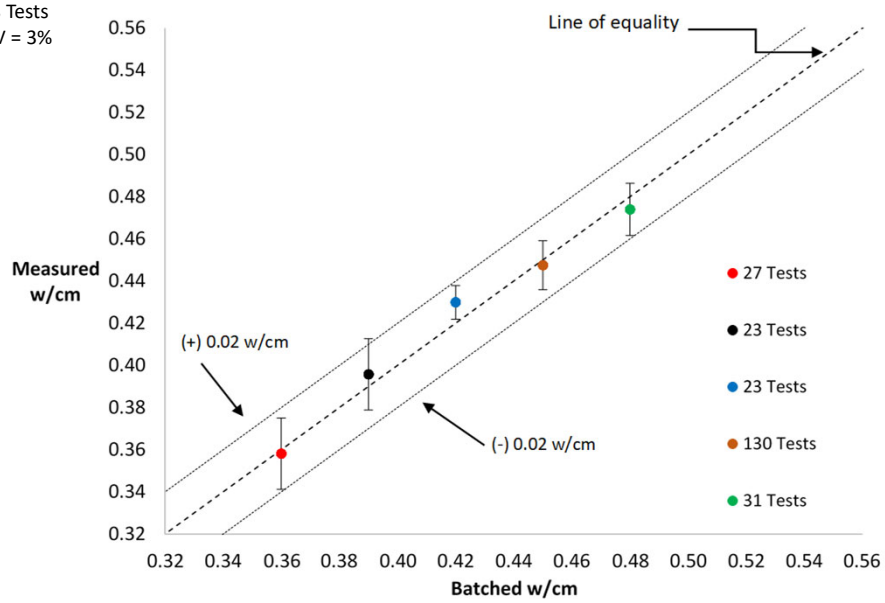
- Make mixtures in the lab where we carefully control the moisture contents and batch weights.
- We should know the w/cm very accurately.
- Measure the w/cm with the Phoenix and compare.

Mix Information

- 9 Sources of Coarse Aggregate
  - Granites and Limestones
- 3 Sources of Fine Aggregate
  - Natural sands and Manufactured sand
- Specific Gravities: 2.42-2.75
- Absorptions (%): 0.46-4.69
- Five different w/cm
- Different paste contents

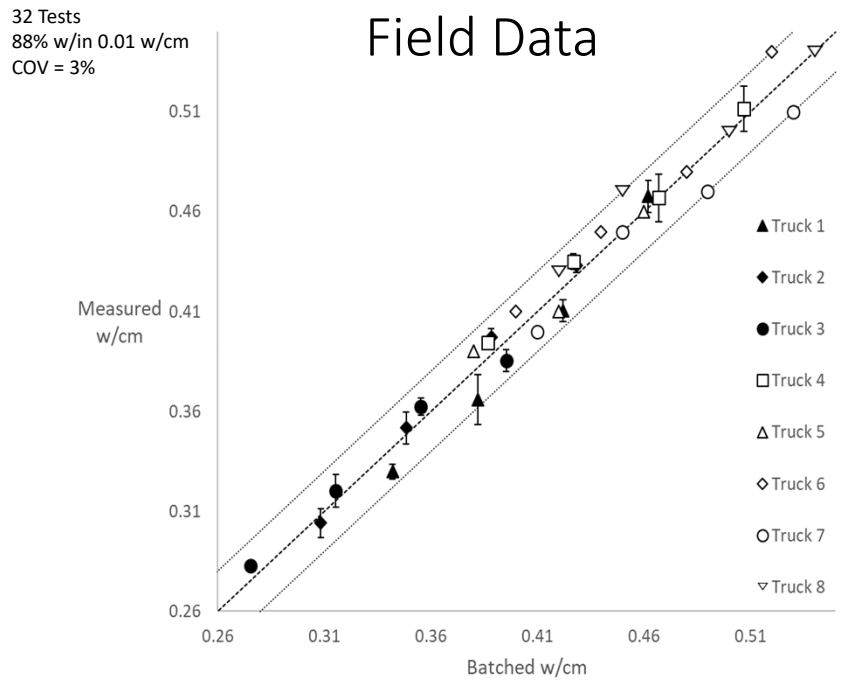
Lab Data

9 Coarse Agg
3 Fine Agg
5 Different w/cm
228 Tests
COV = 3%



Field testing

- Run the Phoenix off a generator.
- We measured the moisture content of the coarse and fine aggregate with the Phoenix in 5 min.
- We also helped them check their trucks for water.



Discussion

- The Phoenix can consistently measure the w/cm within 0.01 in 15 mins with fresh concrete in the field.
- The Phoenix can measure the moisture content of an aggregate in 5 min.

MnDOT W/C Ratio Testing

	average w/cm	standard dev	Time	Does it test concrete?
Mixing water + agg moisture	0.39	0.021	30 min	No
Phoenix	0.41	0.030	15 min	Yes
Microwave	0.41	0.033	45 min	Yes

This is from 144 tests from two different mixtures.

- The Phoenix and Microwave consistently measure a 0.02 higher w/cm than just measuring the aggregate moisture and water gauge.
- The Phoenix is faster, is more automated, and has a lower variability than the microwave test.

MnDOT W/C Ratio Testing (Summer 2022)

	average w/cm	standard dev
Project 1		
Mixing water + agg moisture	0.36	0.013
Phoenix	0.39	0.030
Project 2		
Mixing water + agg moisture	0.38	0.013
Phoenix	0.40	0.001

Phoenix is typically 0.02 to 0.03 higher on average then the typical methods of calculating the water content based on the mixing water + agg moisture.

Discussion

The Phoenix is more consistent, automated, and faster than the microwave oven test.

For the four projects, the values from the Phoenix typically measures 0.02 to 0.03 w/cm higher than using the mixing water + aggregate moisture.

If MnDOT implements the Phoenix they should revise the w/cm ranges that they use for incentives.

Phoenix – MnDOT Paving Implementation Plan

- 2022 - 2023 goals
  - Replace the microwave testing with the Phoenix to collect more data
  - Created MnDOT test standard
- 2024 goals
  - Pilot projects
  - Agency will test using the Phoenix
  - Contractor to do the moisture testing
  - Acceptance based on actual w/c ratio measured using the Phoenix
- Long term goals
  - Full implementation
  - Contractor will purchase and have a Phoenix in the testing trailer
  - Agency will test using the Phoenix
  - Contractor to do the moisture testing
  - Acceptance based on actual w/c ratio measured using the Phoenix

Additional MnDOT Phoenix Plans

- Research use for verification at the job site:
  - High Performance Concrete Bridge Deck
  - Low slump concrete overlay bridge deck mixes

Summary

- Test results show that **all** methods are statistically similar to the batched w/cm and to each other!
- The Phoenix and microwave test are done on concrete
- The Phoenix takes less time, less labor
- The Phoenix has a lower variability than the microwave
- The new version of the Phoenix speeds this up even more
- The new prototype was used in 2020 and 2021 paving projects
- Likely implementation in 2025

Why are you paying for strength?

- Why are we making important decisions based on how strength samples are collected, stored, and tested?
- What if payment was based on w/cm and air?
- Strength could be used as information only.
- Strength is already deemphasized by Minnesota and Iowa DOT.

Who is using the Phoenix?

FHWA – Mobile Concrete Lab
Utah DOT
New York DOT
Kansas DOT
Minnesota DOT x 2
Oklahoma DOT x 3
4 Contractors
1 Ready Mix
UNC Charlotte

Where can I find out more?

www.concretephoenix.com

www.globalgilson.com

Conclusion

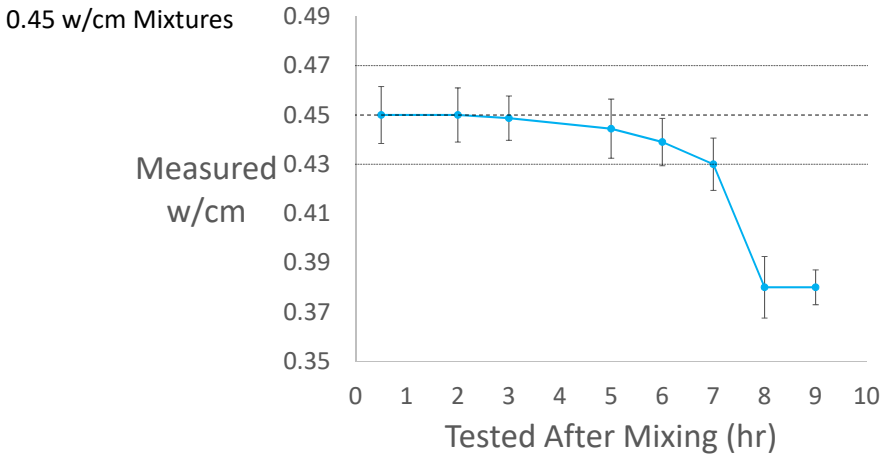
- The Phoenix is a field test that can be used to determine the w/cm of fresh concrete in 15 min to +/- 0.01 w/cm accuracy.
- The Phoenix can also measure the moisture content of the aggregates in 5 min.
- If we know our w/cm then this is an important step to provide the strength and durability that we need.


> 94K subscribers
> 9.5M views
Structural
Cracking in
Reinforced
www.youtube.com/tylerley


Questions???
Tyler.ley@okstate.edu
www.concretephoenix.com

Aggregate Type	Size	SpG	Abs (%)	State
Granite 1	Coarse	2.75	0.46	OK
Granite 2	Coarse	2.75	0.51	GA
Granite 3	Coarse	2.59	1.06	MN
Granite 4	Coarse	2.66	0.66	MN
Limestone 1	Coarse	2.42	4.69	IA
Limestone 2	Coarse	2.67	0.70	OK
Limestone 3	Coarse	2.67	0.64	OK
River Rock 1	Coarse	2.67	1.52	MN
River Rock 2	Coarse	2.68	0.81	MN
Natural Sand 1	Fine	2.62	0.64	OK
Natural Sand 2	Fine	2.61	0.20	OK
Man Sand	Fine	2.76	1.05	OK

What about water bound in the hydration products?



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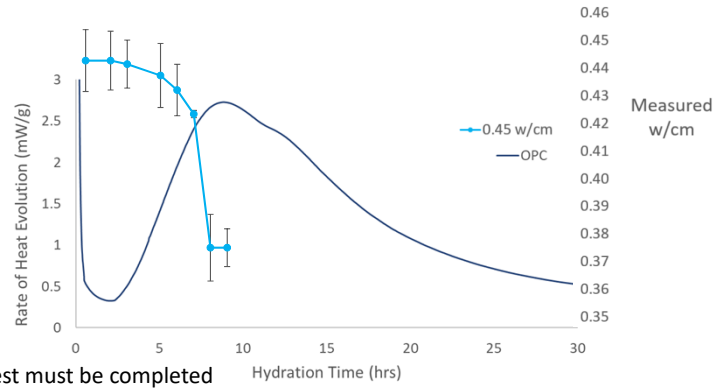
What about water bound in the hydration products?



Test must be completed before initial set. This is ≈4h for typical mixtures.

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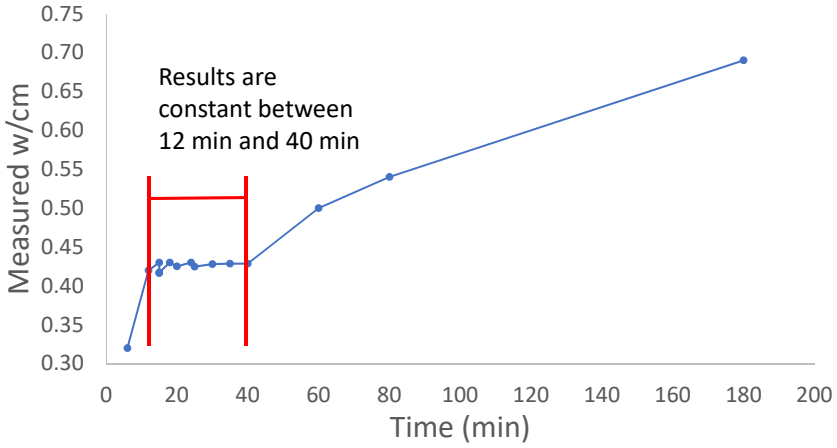
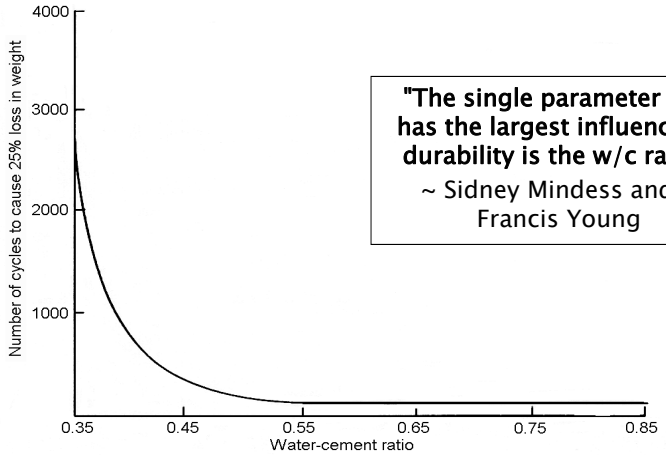


Relationship Between Water-Cement Ratio and Freeze-Thaw Resistance



"The single parameter that has the largest influence on durability is the w/c ratio."
~ Sidney Mindess and J. Francis Young

"Chemical Admixtures for Concrete" 2nd Edition by M.R. Rixom and N.P. Mailvaganam

Why is the water content off?

- Incorrect aggregate moisture content
- Batch plant tolerance
- Wrong amount is added
- **Renegade Water!**

Have you ever rejected concrete for high slump?

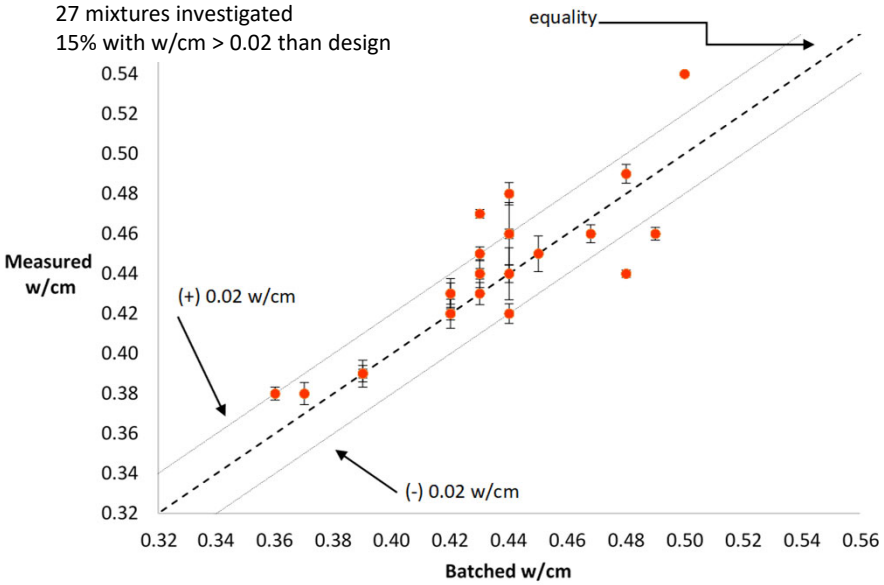
- Max slump spec = 7” for a pier
- Concrete was rejected but w/cm was measured on site to be within specified range

Truck Number	Specified Slump (in)	Slump (in)	Specified w/cm	Average Measured w/cm
Truck 6	7.00	9.00	0.25-0.48	0.47
Truck 7	7.00	8.00	0.25-0.48	0.42

Why does this happen?

- The water reducer dosage was too high but the w/cm was correct.
- The concrete was rejected because they were just measuring the slump.

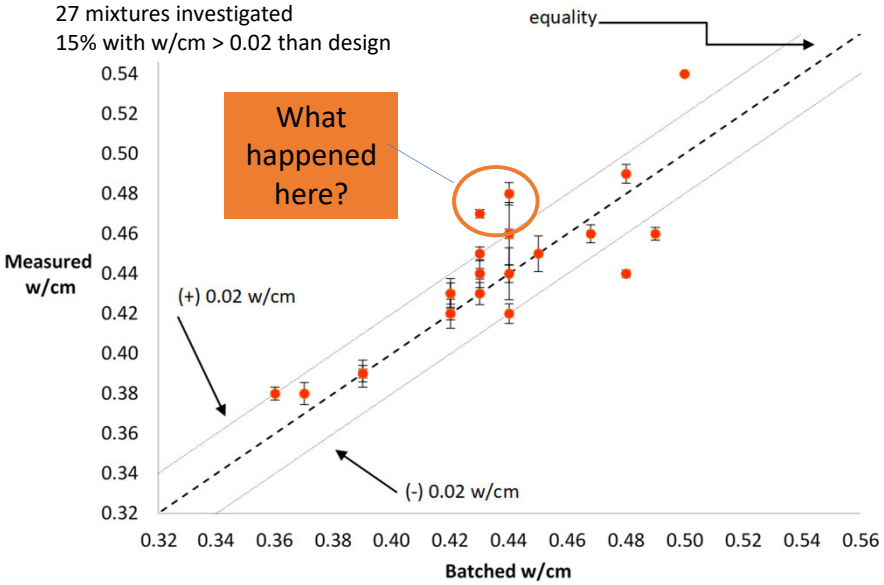
Field Data



Discussion

- The Phoenix data looks promising
- 15% of mixtures had a w/cm > 0.02 than what was reported on the batch ticket.
- All testing was done at the batch plant.
- The producers knew we were coming.

Field Data



W/C Ratio and Cementitious Content History

Year	Max. w/c ratio	Minimum Cement	Minimum Cementitious	Maximum Cementitious	% Fly Ash Allowed	% Slag Allowed	%Ternary Allowed
Pre-1996	0.46	450	530	850	15	35	N/A
1996	0.42	450	530	600	25	35	N/A
2000	0.40	450/420	530	600	25/30**	35	N/A
2002	0.40	400/385**	530	600	30**	35	N/A
2015	0.40/0.42	400/385	530	615	33	35	N/A
2018 - present	0.40/0.42	385	530	615	33	35	40
Total Alkalis (Na2Oe) in Cement (Pre-2020)						0.6%	
Total Alkalis (Na2Oe) in Concrete based upon cement content						3.0 lbs/yd3	

Implementation of w/c ratio

Year	Maximum w/c ratio	Minimum w/c ratio for incentive	Target Air Content (+/- 1.5%)	Admixtures Allowed
Pre-1996	0.46	NA	5.5%	None Allowed
1996	0.40	0.35	6.5%	Type A Water Reducers
2000	0.40	0.35	7.0%	Type A and Type A Mid Range Water Reducers
2010	0.40	0.35	7.0%	Viscosity Modifying Admixtures (VMA) and Hydration Stabilizers
2011	0.40	0.37	7.0%	
2015	0.40/0.42	0.37/0.39	7.0% (+2/-1%)	