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The Economics, Performance, and Sustainability of Internally Cured Concrete, Part 1

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Tengfei Fu is a Ph.D. candidate at Oregon State University, Corvallis, OR who is investigating drying shrinkage limits and internal curing techniques of high performance concrete for Oregon DOT. He completed his M.S. in February 2011 with a focus on early-age properties of high performance Portland cement concrete and calcium aluminate cement concrete. He is a recipient of Portland Association Education Foundation Fellowship ($20K in 1 year) in 2011

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Prediction of Drying Shrinkage For Internally Cured High-Performance Concrete

Tengfei Fu
Ph.D. Candidate
Tyler Deboodt
Faculty Research Assistant
Jason H. Ideker, Ph.D.
Assistant Professor and Kearney Faculty Scholar

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Project Goals

- Investigate the effectiveness of the incorporation of pre-wetted FLWA and SRA in terms of reducing drying shrinkage and external curing duration;
- Identify a drying shrinkage threshold criteria for HPC bridge deck to ensure high cracking-resistance concrete
- Develop a simple testing procedure which can be easily used by contractors or materials suppliers to evaluate the cracking-resistant performance

Source: Oregon DOT

Methods

- **Evaluate** the accuracy of different shrinkage prediction models for FLWA and/or SRA incorporated HPC.
  - It is critical to choose a proper model to predict shrinkage for concrete using local materials.
- Predict long-term shrinkage based on ACI 209 model.
  - It allows the **prediction of long-term shrinkage** strain using short-term experimental measurements.

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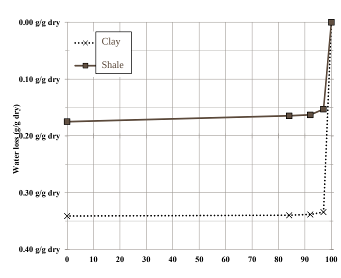
December 17, 2012

Materials – FLWA



	Shale	Clay
Absorption (%)	17.5	34.1
Desorption (%)	16	34

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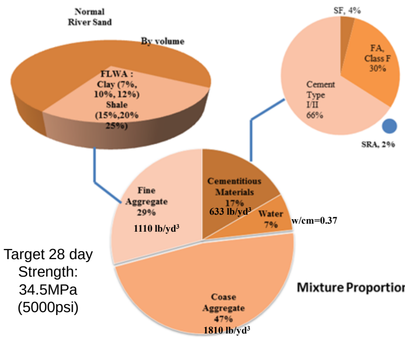
Materials – HPC Mixture Design



1-Control
1-SRA
2A (Clay 7%)
2B (Clay10%)
2C (Clay 12%)
3A (Shale 15%)
3B (Shale 20%)
3C (Shale 25%)
3D (Shale 100%)
3C-SRA (Shale 25%+SRA)

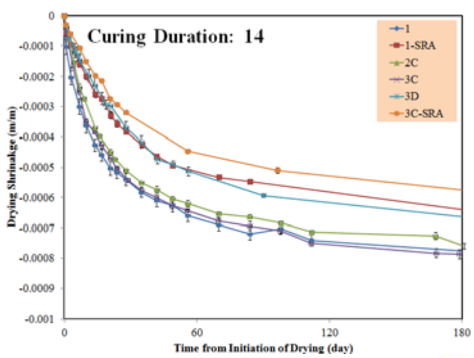
Target 28 day Strength: 34.5MPa (5000psi)

Experimental – ASTM C157

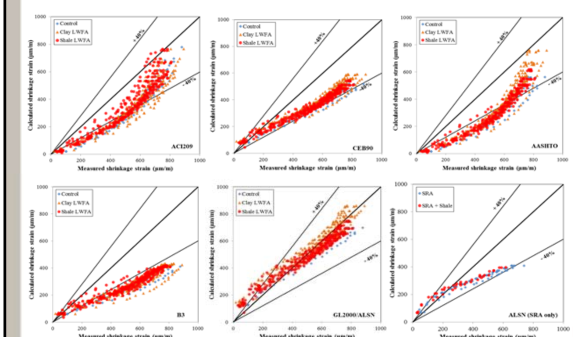
ASTM C157
Free Drying Shrinkage Test

- Sample stored in an environmental chamber with 73±3° F and 50% RH;
- Drying initiated at 1, 3, 7, 10, 14 days;
- Length change over time was monitored.

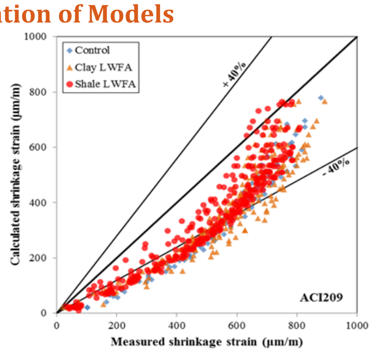
Measured Drying Shrinkage (14 day cure)



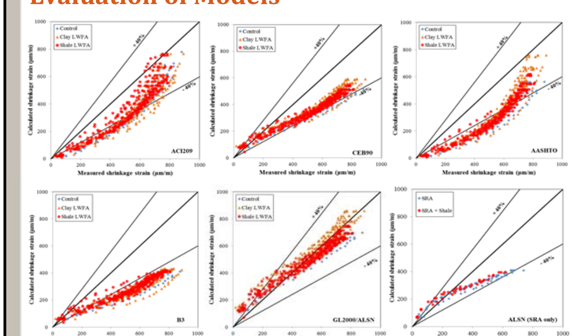
Evaluation of Models



Evaluation of Models



Evaluation of Models



Drying Shrinkage

Features of Drying Shrinkage development curve:
- Monotonic increasing;
- Increasing rate slows down in time;
- Should have a theoretical ultimate value. (converge to an asymptote).

Thus, a good prediction model should:
- Good description of the time function;
- Converge to an asymptote;
- Easy to use.

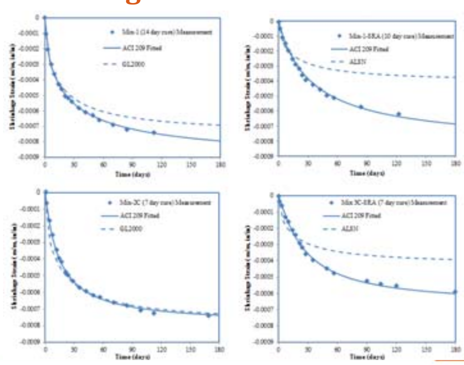
ACI-209 Model

$$\varepsilon_{sh}(t,t_c) = \frac{(t-t_c)^{\alpha}}{f+(t-t_c)^{\alpha}} \cdot \varepsilon_{shu}$$

$$\varepsilon_{shu} = 780\gamma_{sh} \times 10^{-6} mm/mm\ (in/in)$$

$\varepsilon_{sh}(t, t_c)$ = shrinkage strain at concrete age t since the start of drying at age t_c, mm/mm (in/in);
ε_{shu} = ultimate shrinkage strain, mm/mm (in/in);
α, f = constants defining the shape of time-dependent curve;
γ_{sh} = the cumulative product of the applicable correction factors including initial moist curing duration, ambient relative humidity, size of the drying specimen in terms of the volume-surface ratio, and fresh concrete properties/

Curve Fitting



Sensitivity Study

Mixture	Number of days from initiation of drying (14 day curing, μm/m)										Difference between selected cut-off date and 180 day
	28	35	42	49	56	70	84	98	120	180	
1	1090	1050	1000	**950**	970	980	990	950	930	910	4.4%
1A	910	980	910	**890**	870	860	-	-	840	860	3.5%
2B	760	730	730	**720**	710	720	740	740	750	780	-7.7%
2C	730	750	740	**750**	750	770	760	770	770	780	-3.8%
3A	880	820	810	**800**	780	780	780	780	780	820	-2.4%
3B	920	900	860	**850**	840	840	840	840	850	860	-1.2%
3C	870	880	840	**840**	830	830	830	830	870	880	-4.5%
3D	910	980	910	**890**	870	860	-	-	-	860	3.5%
1-SRA	NC	2850	1680	1300	-	860	**780**	780	790	790	-1.3%
3C-SRA	NC	-	-	-	820	-	**670**	670	640	660	1.5%

Proposed Procedure

- Perform ASTM C157 test
- After 28 days of drying, perform curve fitting to all data at hand using ACI full equation, determine the three parameters *(ε_{sh} α, and f)*;
- Keep tracking the shrinkage development till the fitted ε_{sh} is stable at certain drying period (cut-off time), take the last fitted ε_{sh} as the ultimate shrinkage value;
- Cut-off time in this research:
  - 50 day for HPC;
  - 50 day for HPC with FLWA;
  - 90 day for HPC with SRA.

Conclusions

- SRA effectively reduced drying shrinkage, and synergy with FLWA worked best;
- To achieve less drying shrinkage in the long term, a higher FLWA replacement ratio is needed;
- It is possible to predict long term shrinkage, using ACI 209 model, based on short term (50~90 days) shrinkage measurement (ASTM C157).

Future Work

- Collect more data to verify the proposed procedure;
- Understand the physical mechanism of drying shrinkage;
- Understand the mathematical feature behind the ACI 209 model to stop the test at the minimum age and predict reasonably accurate long-term drying shrinkage;
- Incorporate this model in the drying shrinkage limits criterions;
- ASTM C1581 (Ring) Test.

Acknowledgement

Research Sponsor

Materials Donation

Questions?

Chemical Shrinkage – Bentz Equation

Determine appropriate replacement level of FLWA

Previous research by Bentz and associates provides starting point to determine replacement level

$$M_{LWFA} = \frac{C_f * CS * \alpha_{\max}}{S * \phi_{LWFA}}$$

Desorption Test of FLWA

Desorption of FLWA

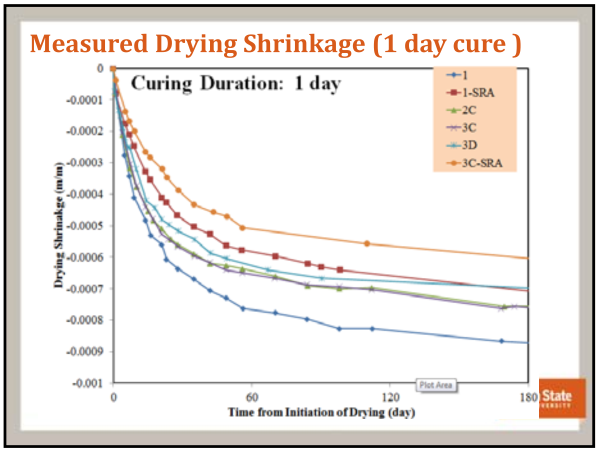
Measures the amount of water released from LWFA to a known RH

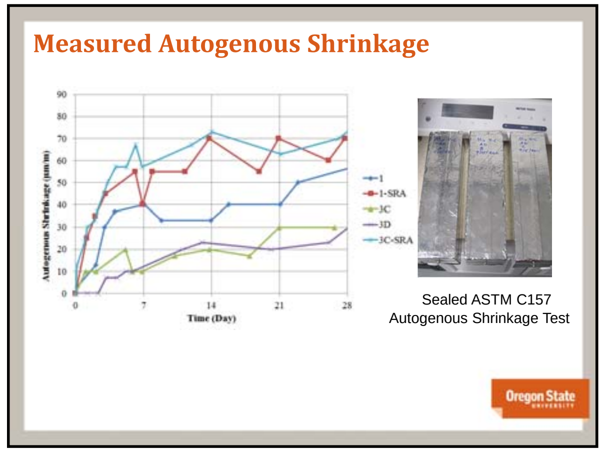
Different saturated salt solutions provide specific RH value at a given temperature

Start at SSD, allow to release water to an oven dry condition

Mechanical Properties

Mixture	1	1-SRA	2A	2B	2C	3A	3B	3C	3D	3C-SRA
Compressive Strength (Mpa)	36.8	33.2	23.8	28.6	38.1	41.4	31.7	36.6	46.8	35.0
Modulus of Elasticity (Gpa)	37.3	31.5	28.2	28.7	28.8	32.7	24.5	27.2	-	-


Measured Drying Shrinkage (1 day cure)
Curing Duration: 1 day
1
1-SRA
2C
3C
3D
3C-SRA
Drying Shrinkage (m/m)
0
-0.0001
-0.0002
-0.0003
-0.0004
-0.0005
-0.0006
-0.0007
-0.0008
-0.0009
-0.001
0
60
120
180
Time from Initiation of Drying (day)
State


Measured Autogenous Shrinkage
Autogenous Shrinkage (µm/m)
90
80
70
60
50
40
30
20
10
0
0
7
14
21
28
Time (Day)
1
1-SRA
3C
3D
3C-SRA
Sealed ASTM C157
Autogenous Shrinkage Test
Oregon State