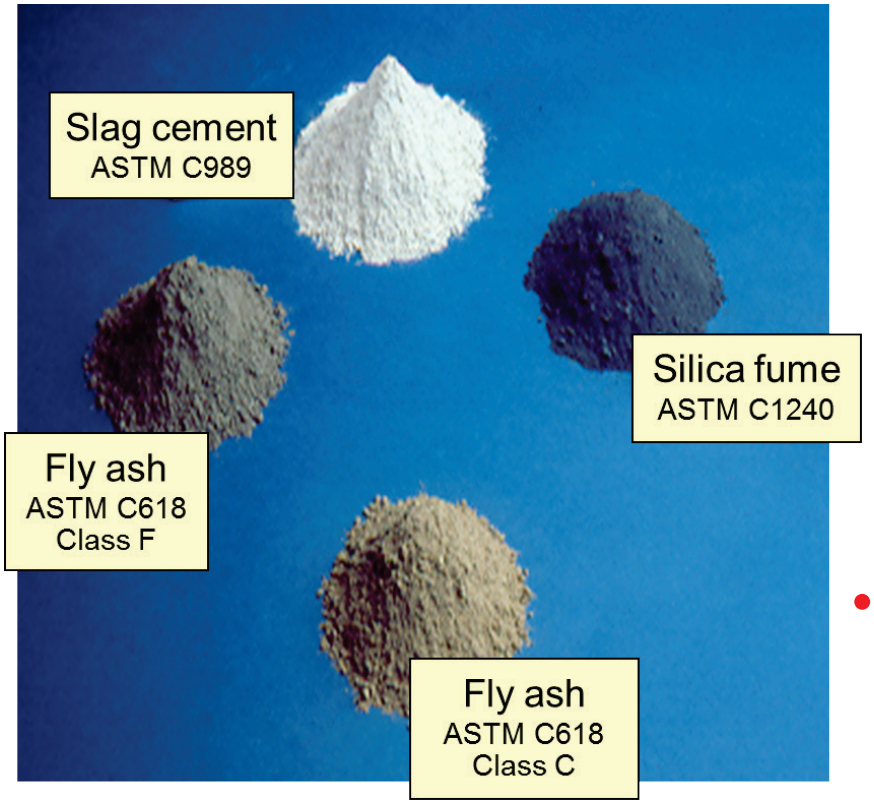
Update on PLC and the potential for enhanced SCM performance

NCC – Reno, NV
April 22, 2015

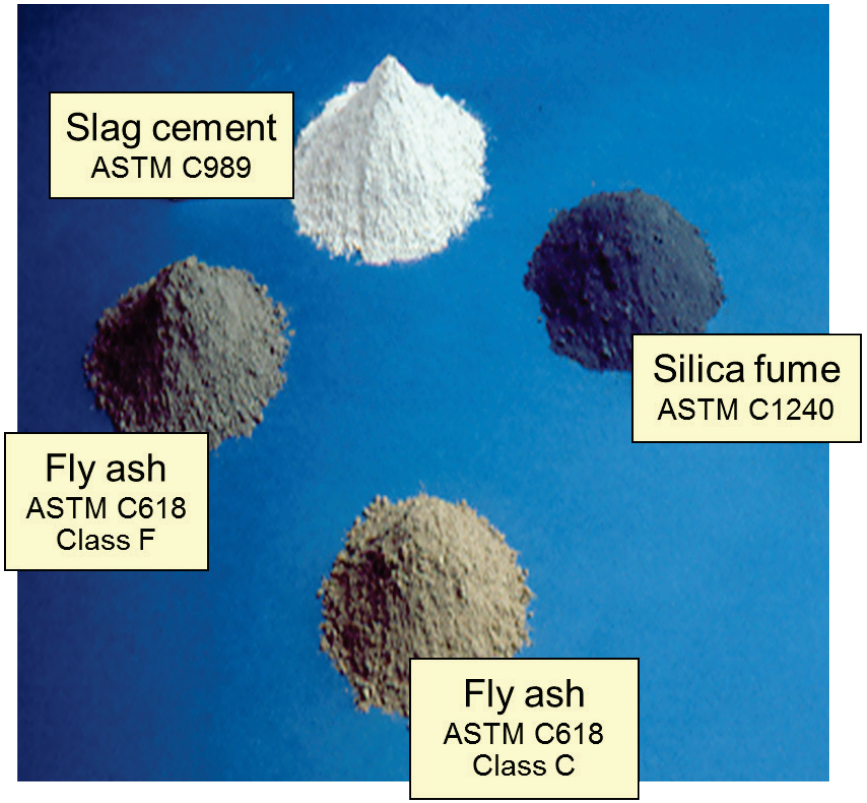
Tim Cost, PE, F.ACI
Holcim (US) Inc.

Use of supplementary cementitious materials (SCMs)



- Benefits
  - Recycled or byproduct materials used to replace some cement
  - Sustainability benefits – SCMs carry essentially no GHG emissions and embodied energy
  - Durability benefits and improvement of fresh concrete properties
  - Favorable economics, generally
- Challenges
  - Practical limitations on replacement rate due to early age influences (setting & early strength)

Use of supplementary cementitious materials (SCMs)



- ***Portland-limestone cement*** *(PLC) may enable extending SCM replacement rate and/or reducing performance side-effects via favorable hydration synergies between the fine limestone particles and SCM chemistry.*
  - PLC is more sustainable via lower cement clinker content
  - Sustainability can be extended by increasing SCM replacement rate and/or raising strength efficiency (reducing powder)

Background / review – PLC and SCM Interaction

- PLC contains 5% to 15% limestone
  - Since 2012: ASTM C595 and AASHTO M 240, Type IL
  - Available under ASTM C1157 in much of the US for 10+ years
  - Development driven by sustainability considerations
- PLC Performance ≈ OPC in common applications
- Enhanced basic concrete performance often found with PLC in combination with common SCMs
  - Improved strengths at all ages
  - Accelerated setting / mitigation of SCM-associated retardation
- Ongoing study (near completion) at Mississippi State University to explore and provide guidance on concrete performance enhancement via PLC-SCM “synergies”

Concrete Products, March Edition

Contains an article summarizing 5 papers from TRB 2015, 2 of which were about PLC

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Concrete Products, March Edition

Recapped PLC papers from TRB 2015 included:

- *Rupnow & Icenogle, (LTRC)*
- *Shannon, Howard, Cost, & Wilson (MSU)*

TECHNICAL TALK
2015 TRB MEETING

INTERGROUND LIMESTONE/CEMENT BLENDS WILL WORK IN LOUISIANA

Interground limestone/cement blends are appropriate for all uses in the Pelican State, say Tyson D. Rupnow, Ph.D, P.E., and Patrick J. Icenogle, P.E., Louisiana Transportation Research Center, Baton Rouge, in the paper, *Louisiana's Laboratory Experience with Type IL Portland Cement*.

Portland cement concrete (PCC) is the world's most versatile and most used construction material, note Rupnow and Icenogle, but it occupies a substantial carbon emissions "footprint." A new method of reducing the carbon footprint and increasing the sustainability of PCC, however, has emerged that incorporates a much larger portion of interground limestone (Type IL cement) into the finished cement.

ASTM and AASHTO have now changed specification language of C595 and M240, respectively, to allow up to 10 percent use of interground limestone, the authors report. The incorporation of the increased limestone content significantly reduces the carbon dioxide (CO_2) footprint of the resultant PCC while extending the life of cement quarries. The blend also permits cement companies to make powder "go farther," producing more cementitious material without having to expand production facilities—thus sidestepping associated capital expenditures and environmental permitting.

"The use of these cements is widespread in Europe and much of the research work can be found in state-of-the-art reports," observe Rupnow and Icenogle, adding other research finds portland/limestone cement and ordinary portland cement has similar mechanical performance, with restrained ring shrinkage behavior of the blend being similar as well.

Several states have conducted field trials or currently allow the use of PLC, including Utah, Oklahoma and Iowa. "Work is also ongoing at the University of Toronto and University of New Brunswick, looking at low temperature sulfate attack, potential interaction with deicers, and early age shrinkage cracking potential," Rupnow and Icenogle report. "Work by Holcim has also shown the potential for further synergistic action of ternary cementitious systems that contain Type IL cement."

Recently the Louisiana Department of Transportation and Development has implemented the use of ternary mixtures for both structural and paving concrete applications at the rate of 70 and 50 percent replacement of cement, respectively, they write, but a concern arose with the introduction of Type IL cement as to whether the new specifications would need revision.

Evaluation saw the researchers characterize the fresh and hardened concrete properties of binary and ternary combinations incorporating Type IL cement. Three binary and three ternary mixtures were prepared and tested for both fresh and hardened characteristics. Concrete samples were produced in laboratory conditions with a w/cm ratio of 0.45. Fresh concrete properties measured included: slump, unit weight, air content, and set time. Hardened concrete properties measured included: compressive strength, flexural strength, surface resistivity, freeze-thaw durability, and shrinkage.

"The results of this study showed that the use of Type IL portland cement in Louisiana should be allowed for all applications including ternary mixtures up to 70 percent replacement," Rupnow and Icenogle affirm. "Compressive and flexural strength results were comparable. Type IL mixtures exhibited less shrinkage when compared to the control mixtures with Type I cement. Surface resistivity results were comparable and indicated that the surface resistivity meter use will be applicable for mixtures containing Type IL cement."

Zoom in

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TECHNICAL TALK
BY TOM KUENNEN

FLY ASH, LIMESTONE/CEMENT BLENDS BOOST COMPRESSIVE STRENGTHS

Research in Mississippi shows that portland cement/limestone blends (PLC) result in notable compressive strength improvements in mixtures with high Class C fly ash replacement versus conventional Type I portland cement, say Jay Shannon and Dr. Isaac L. Howard, P.E., Mississippi State University, and V. Tim Cost, P.E., F.ACI, and Wayne M. Wilson, P.E., Holcim (US) Inc., in their 2015 TRB paper, *Benefits of Portland-Limestone Cement for Concrete with Rounded Gravel Aggregates and Higher Fly Ash Replacement Rates*.

PLC interest has increased in recent years, especially with new specifications, which should further facilitate marketplace use and acceptance. "Various studies have been conducted to clarify PLC's perceived benefits and to optimize properties and use protocols for performance," the authors report. "Laboratory-based research studies [indicate] promising PLC behavior, and there has also been successful use of PLC with 50 percent SCM [supplementary cementitious material] replacement in structural concrete for a southeastern U.S. college football stadium expansion and renovation."

Concrete mixes made with rounded gravel aggregates and a single SCM (generally fly ash) are the most common case in Mississippi, they add. "While rounded gravel aggregates are not common to all markets, they are heavily used for concrete in Mississippi as well as numerous other regions of the U.S."

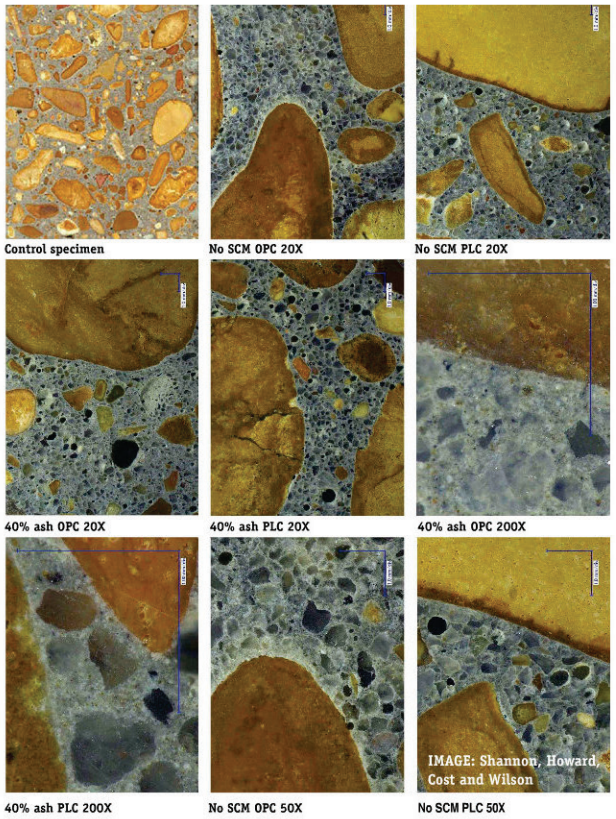
Rounded gravel aggregates sometimes pose certain concrete quality challenges that may tend to detract from strength, observe Shannon, Howard, Cost and Wilson. "Potential issues include entrained air void clustering and inherent difficulties with paste-aggregate bond," they write. "Some studies have documented more extreme strength loss when fly ash was used in concrete mixes with rounded gravel aggregates."

Yet data produced in previous studies by the authors have suggested that PLC may help to relieve or even reverse such strength loss trends, making a more complete study of performance associated with this set of materials of even greater interest. The authors conclude that PLC can be used to enhance the performance (e.g. strength performance) of concrete containing rounded gravel aggregates and increased Class C fly ash replacement of portland cement. "Implementation benefits would appear to be many, including increased sustainability by way of an economically competitive and well performing concrete mixture," they write.

PLC produced higher strengths than Type I cement, dubbed "ordinary portland cement" or OPC, in essentially all mixtures with fly ash replacement, and concrete at the 40 percent replacement level notably excelled, Shannon, Howard, Cost and Wilson find. "Strengths of concrete mixtures with slag cement were higher than those with fly ash overall, though OPC vs. PLC distinctions were less apparent," they add.

Fresh concrete properties of slump and air content were not statistically different between PLC and OPC mixtures. Time of setting was found to be lower in PLC mixtures by approximately 0.7 hour in concrete and setting indication lower by about 2.7 hours in concrete paste. Petrography revealed lighter, less uniform paste portions in OPC compared to PLC, possibly indicative of more complete cementitious hydration with PLC. The addition of fly ash appeared to lessen the differences between OPC and PLC paste appearance. OPC mixtures also appeared to have higher w/cm at the paste-aggregate interfacial transition zone.

The differences in performance trends of concrete and CP may suggest that the paste-aggregate bond is a component of some strength differences seen in mixtures with SCMs, which could be associated with particle size distribution effects influenced by significant fineness differences of the SCMs, as well as cement types (OPC vs. PLC).

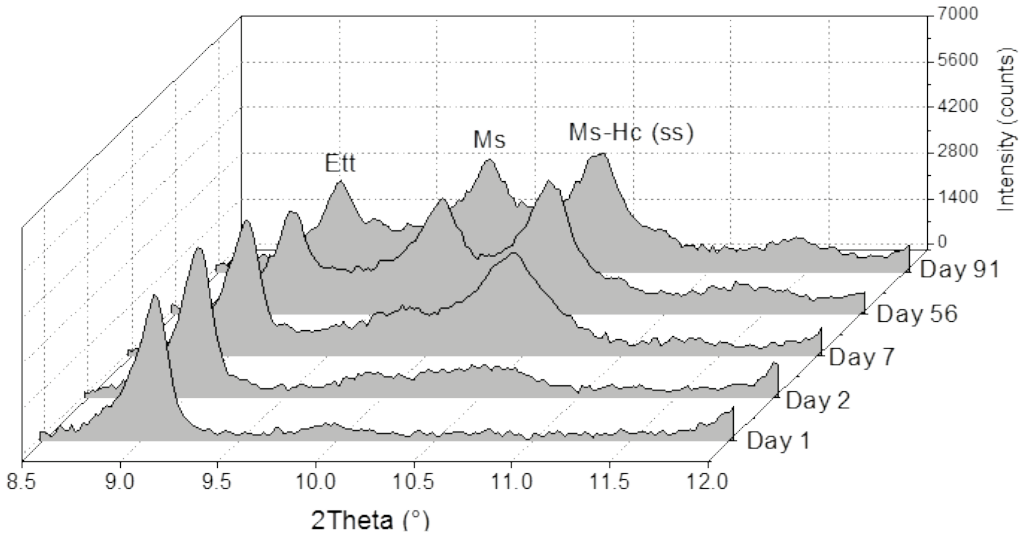


Concrete petrography was performed on four specimens (No SCM OPC [ordinary portland cement], No SCM PLC, 40 percent fly ash OPC, and 40 percent fly ash PLC), in the interest of exploring observed strength trends thought to be possibly related to paste-aggregate bond. In the fly ash mixtures, general paste texture appeared finer with a slight chalky like appearance relative to the SCM-free mixtures. The OPC with fly ash appeared slightly coarser overall relative to the PLC fly ash mixture. PHOTOMICROGRAPHS: Shannon, Howard, Cost, Wilson

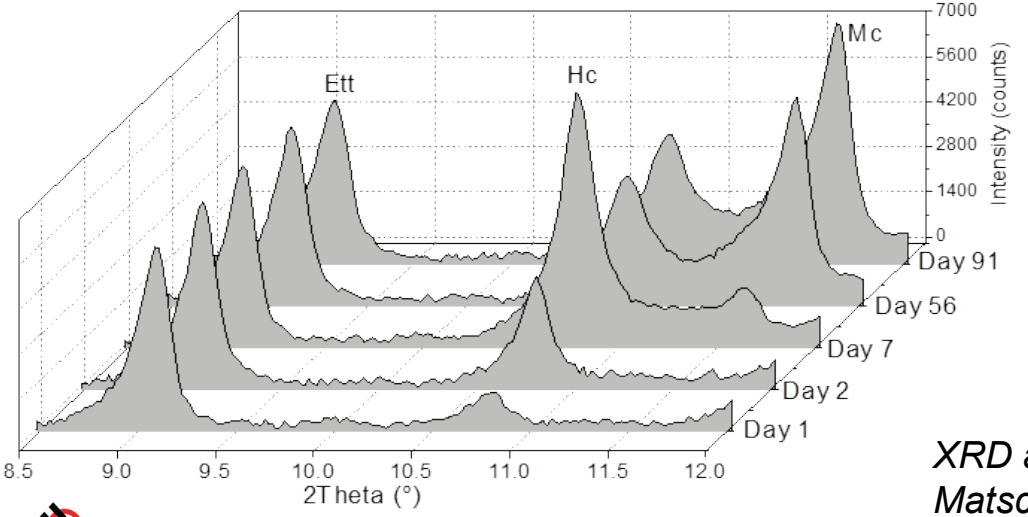
Conclusions (to date) of interest – MSU study

- Potential strength benefits are most prevalent in combination with SCMs containing calcium aluminates and result from at least 2 different mechanisms:
  - Enhanced cement paste strength, from chemical interaction with aluminates and formation of carboaluminate crystals
  - Enhancement of paste-aggregate bond (especially significant using smooth gravel aggregates)
- Extent of benefits influenced by cement properties, including but not limited to fineness, as well as SCM type and chemistry
- Enhanced performance potential may also include setting (mitigation of SCM retardation), permeability, perhaps other properties

Analytical evaluation of limestone-aluminate interaction



60% OPC-2a and 40% Class C fly ash



60% PLC-2a and 40% Class C fly ash

XRD Diffractograms: evolving mineralogy differences, OPC and PLC mixtures with 40% Class C fly ash

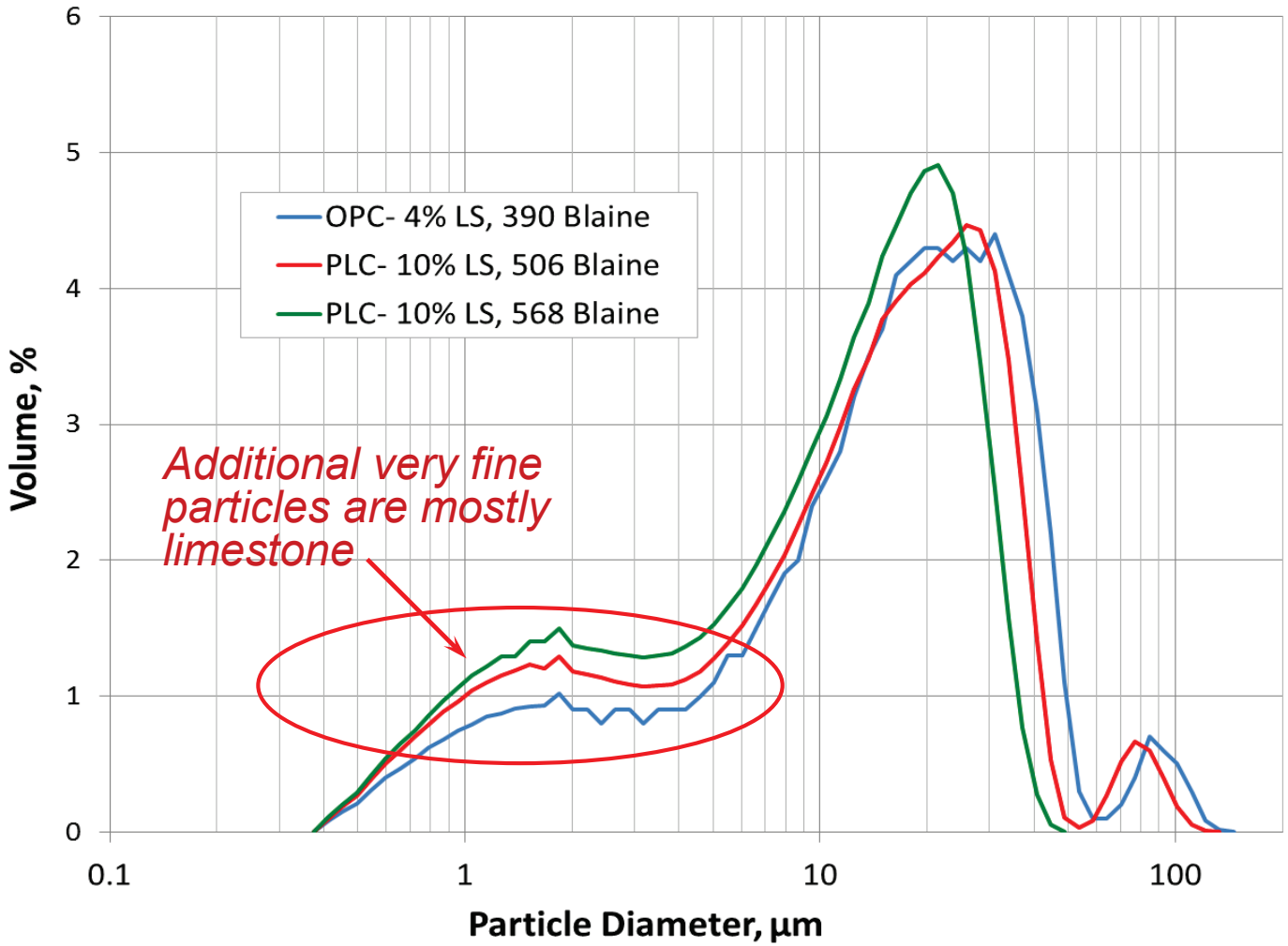
Legend:

- *Ett – Ettringite*
- *Ms – Monosulfoaluminate*
- *Hc – Hemicarboaluminate*
- *Mc – Monocarboaluminate*
- *Ms-Hc(ss) – Monosulfoaluminate-Hemicarboaluminate solid solution*

Synergistic strength benefits are, in large part, the result of documented $CaCO_3$ interaction w/ aluminates and formation of carboaluminate crystals

XRD analyses and Rietveld refinements by Thomas Matschei and Luis Baquerizo, Holcim Technology, Ltd.

Typical PSDs and fineness differentials (PLC vs. OPC)



MSU CMRC work began in 2012

- MSU Construction Materials Research Center
  - PLC research project supported by 4 cement companies, in-kind support from several MS ready-mixed concrete companies
- Over 200 concrete mixtures, hundreds of paste and mortar mixtures to date, analytical work by several partners
- Some of the topics investigated:
  - Optimum SCMs and total cementitious systems (2- and 3-way) for hydration benefits & improved basic concrete performance
  - Concrete with smooth gravel aggregates – performance enhancement via PLC use, esp. as influenced by SCMs
  - Extending the boundaries on SCM use in sustainable mixtures
  - Case history of a construction project, Davis-Wade Stadium, MSU, with 50% replacement mixtures & OPC vs. PLC comparisons
  - PLC chemical and physical properties for optimum SCM synergies

Acknowledgements – MSU research

Companies contributing cementitious components:

- Argos US
- Cemex, Inc.
- Headwaters, Inc.
- Holcim (US) Inc.
- Lehigh Cement Company
- Separation Technologies, LLC

Ready-mixed concrete supplier to DWS project:

- MMC Materials Inc.

MSU concrete mixtures, multiple cement sources

- OPCs and PLCs from 4 sources compared
  - Each of 8 cement samples used in 4 mixture groups, 2 different coarse aggregate types (limestone, gravel)
    - No SCMs (100/0/0)
    - 40% Class C fly ash (60/0/40C)
    - 40% Class F fly ash (60/0/40F)
    - 30% Slag cement + 20% Class C fly ash (50/30/20C)
- All non-AE, 320 kg/m^3 (540 lb/yd^3) total cementitious, 0.43 w/cm, with identical dosages of common admixtures

OPC, ASTM C150 Type I or II, or **PLC**, ASTM C595 Type IL								
Property	OPC-1	PLC-1	OPC-2a	PLC-2a	OPC-3	PLC-3	OPC-4	PLC-4
C_3S (%)	60.2	---	59.4	---	59.1	---	59.0	---
C_3A (%)	8.8	---	7.4	---	5.9	---	6.8	---
SO3 (%)	3.2	3.9	3.1	3.2	3.2	3.4	3.3	3.3
Na_2O eq. (%)	0.56	0.52	0.41	0.44	0.52	0.54	0.41	0.36
LOI (%)	2.4	4.7	1.2	4.2	1.5	7.0	2.6	7.3
Blaine (m^2/kg)	422	522	403	549	421	556	407	681
Limestone (%)*	2.6	8.8	0.1	8.5	0.3	14.0	4.1	15.7

* calculated

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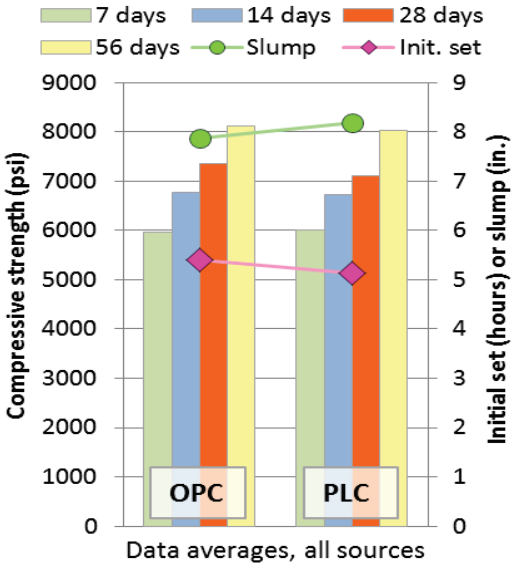
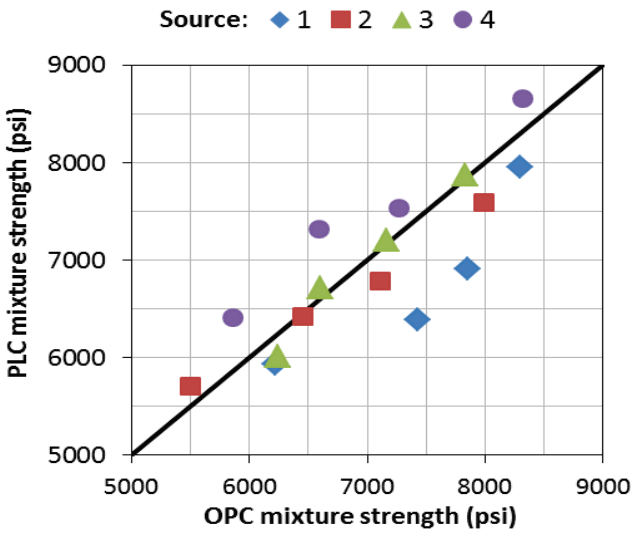
Concrete test results, averages for each mix category
Shown: mixtures with crushed limestone aggregates

Mixture group	OPC source	Compr. strength (psi)				Air (%)	Slump (in.)	In. Set (hours)	PLC source	Compr. strength (psi)				Air (%)	Slump (in.)	In. Set (hours)
		7 d	14 d	28 d	56 d					7 d	14 d	28 d	56 d			
No SCM	OPC-1	6215	7431	7849	8294	2.30	7.50	5.7	PLC-1	5930	6392	6906	7953	2.60	8.00	5.3
	OPC-2a	5501	6452	7112	7987	2.20	8.50	5.6	PLC-2a	5705	6424	6784	7592	2.10	8.25	4.6
	OPC-3	6242	6598	7160	7836	2.70	8.00	5.7	PLC-3	6018	6724	7203	7874	2.80	8.50	6.4
	OPC-4	5854	6594	7267	8316	2.70	7.50	4.6	PLC-4	6411	7322	7535	8660	2.70	8.00	4.2
	OPC Avg	**5953**	**6769**	**7347**	**8108**	**2.48**	**7.88**	**5.4**	**PLC Avg**	**6016**	**6716**	**7107**	**8020**	**2.55**	**8.19**	**5.1**
60/0/40C	OPC-1	3561	4234	5541	6975	2.20	8.00	7.2	PLC-1	4123	5323	6289	7392	2.30	8.25	7.6
	OPC-2a	3651	4484	5994	7475	2.30	7.50	6.8	PLC-2a	4815	6143	7317	9023	2.60	8.50	6.5
	OPC-3	---	---	---	---	---	---	---	PLC-3	---	---	---	---	---	---	---
	OPC-4	3452	4738	5853	7293	2.60	8.00	7.2	PLC-4	4285	5298	6636	7544	2.70	8.00	6.4
	OPC Avg	**3555**	**4485**	**5796**	**7248**	**2.37**	**7.83**	**7.1**	**PLC Avg**	**4408**	**5588**	**6747**	**7986**	**2.53**	**8.25**	**6.8**
60/0/40F	OPC-1	3293	4230	5250	6380	3.00	7.75	5.8	PLC-1	2962	3712	4837	5649	2.60	8.00	5.3
	OPC-2a	2927	3970	4926	6245	2.30	8.50	6.6	PLC-2a	3600	4637	5488	6775	2.30	9.00	5.7
	OPC-3	---	---	---	---	---	---	---	PLC-3	---	---	---	---	---	---	---
	OPC-4	2563	3742	4540	5248	3.00	8.00	5.8	PLC-4	2507	3504	4090	4680	2.70	7.75	4.9
	OPC Avg	**2928**	**3981**	**4905**	**5958**	**2.77**	**8.08**	**6.1**	**PLC Avg**	**3023**	**3951**	**4805**	**5701**	**2.53**	**8.25**	**5.3**
50/30/20C	OPC-1	3640	5184	7055	8677	2.70	7.50	6.5	PLC-1	4934	6263	8369	9266	2.30	9.00	6.6
	OPC-2a	2907	4235	6354	7678	2.50	8.00	6.2	PLC-2a	4212	6206	8064	9179	2.60	8.00	5.8
	OPC-3	3317	4872	5726	6625	2.10	7.50	7.8	PLC-3	3808	5190	6081	6708	2.50	8.25	6.3
	OPC-4	3424	6104	7773	9210	2.60	9.00	6.9	PLC-4	4044	6166	7535	8595	2.40	8.50	5.3
	OPC Avg	**3322**	**5099**	**6727**	**8048**	**2.48**	**8.00**	**6.9**	**PLC Avg**	**4250**	**5956**	**7512**	**8437**	**2.45**	**8.44**	**6.0**

OPC vs. PLC comparisons – category average trends and equivalency plots of individual results, limestone aggs

No SCM control (100/0/0)

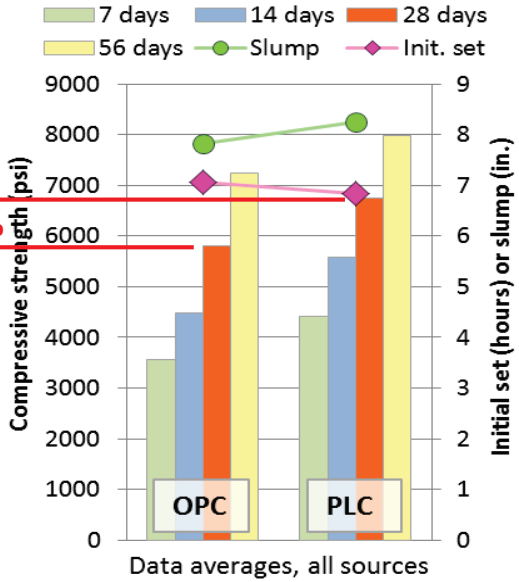


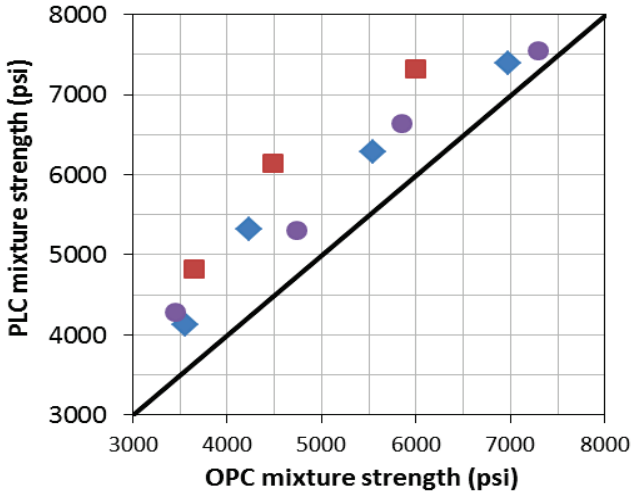


40% Class C ash (60/0/40C)

16%

(13% to 22% for individual sources)





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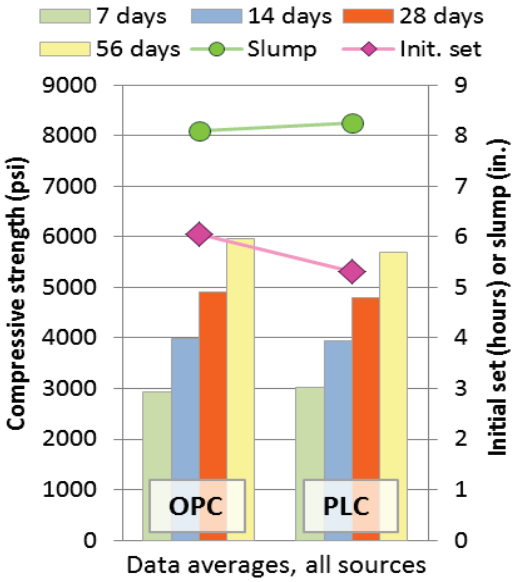
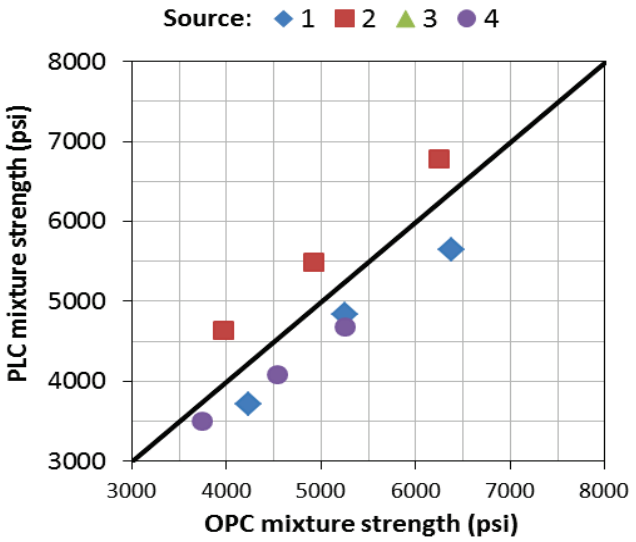
OPC vs. PLC comparisons – category average trends and equivalency plots of individual results, limestone aggs

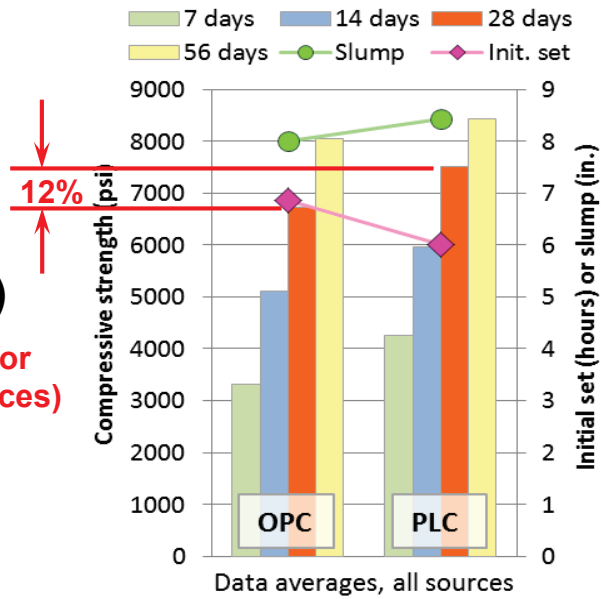
40% Class F ash (60/0/40F)

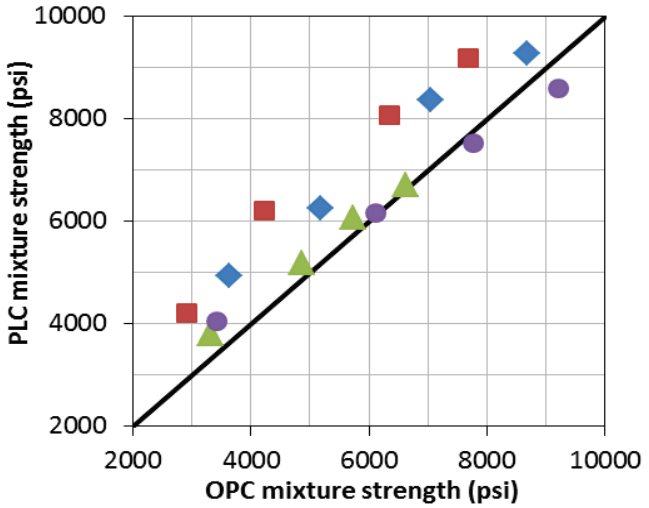




2-SCM mixture, 30% slag + 20% C ash (50/30/20C)

(-3% to 27% for individual sources)

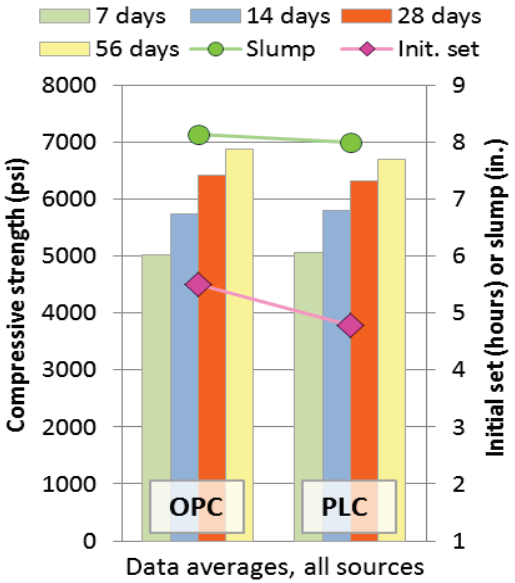


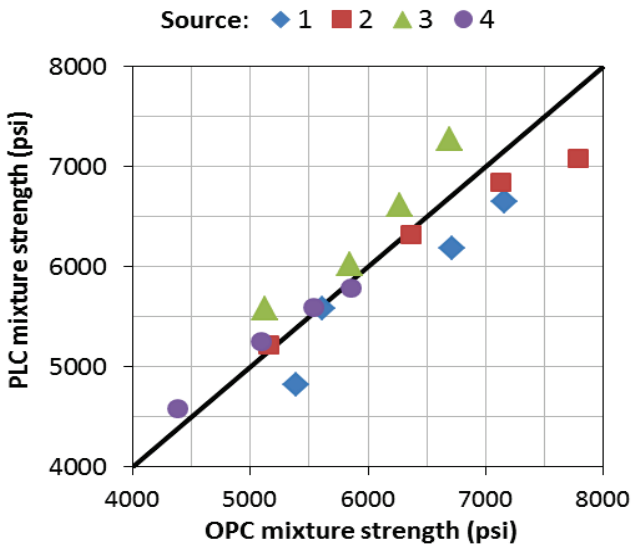


OPC vs. PLC comparisons – category average trends and equivalency plots of individual results, gravel aggs

Comparison: gravel aggs

No SCM control (100/0/0)

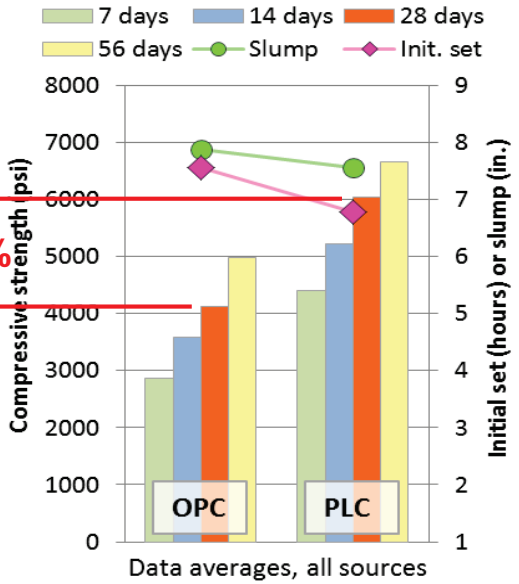


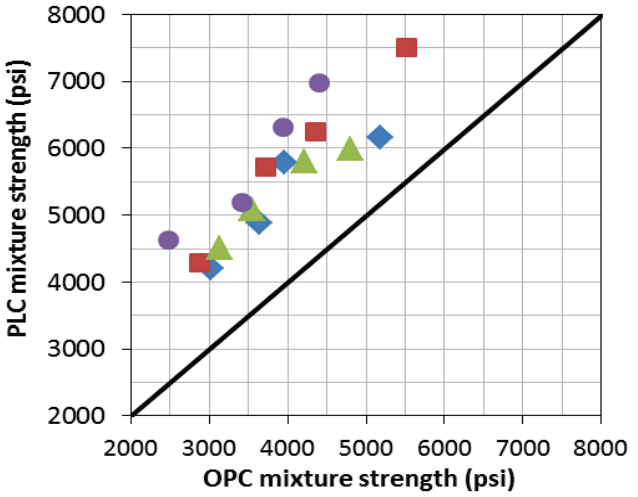


40% Class C ash (60/0/40C)

46%

(38% to 60% for individual sources)





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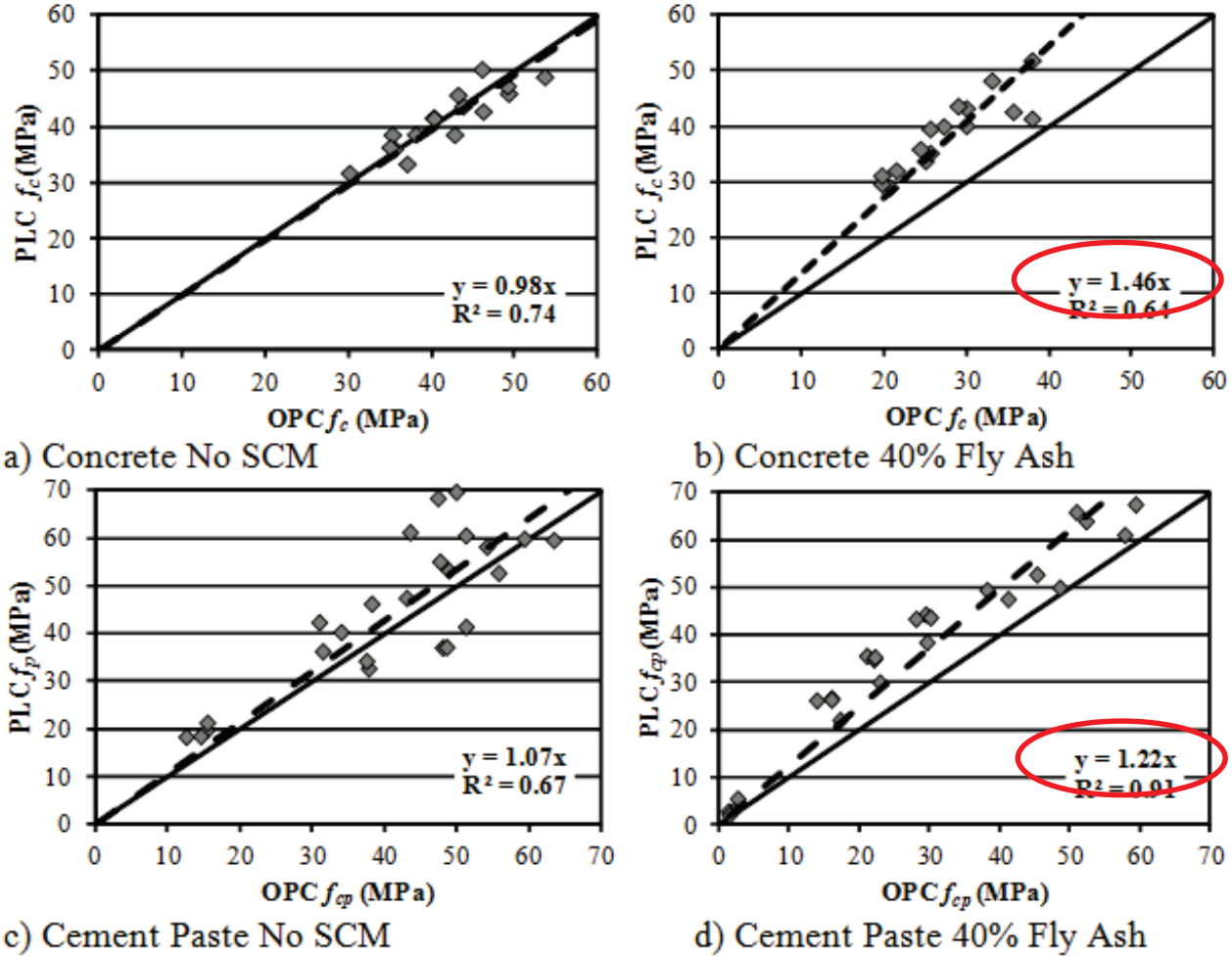
Paper presented at TRB 2015:

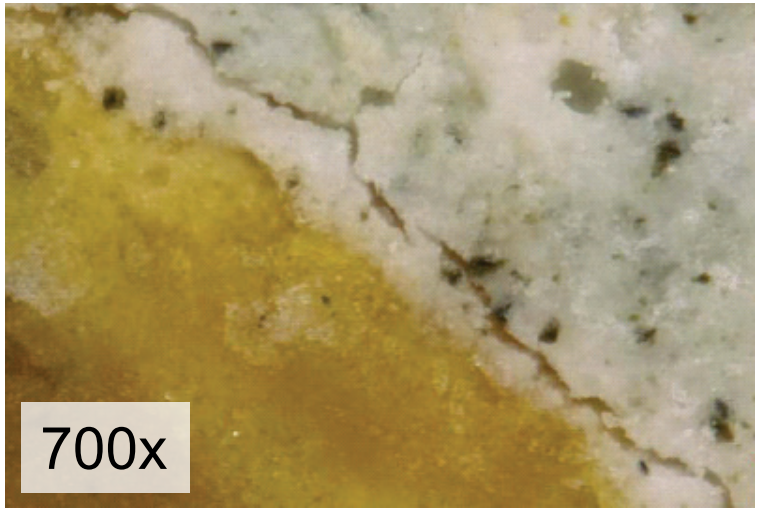
BENEFITS OF PORTLAND-LIMESTONE CEMENT FOR CONCRETE WITH ROUNDED GRAVEL AGGREGATES AND HIGHER FLY ASH REPLACEMENT RATES

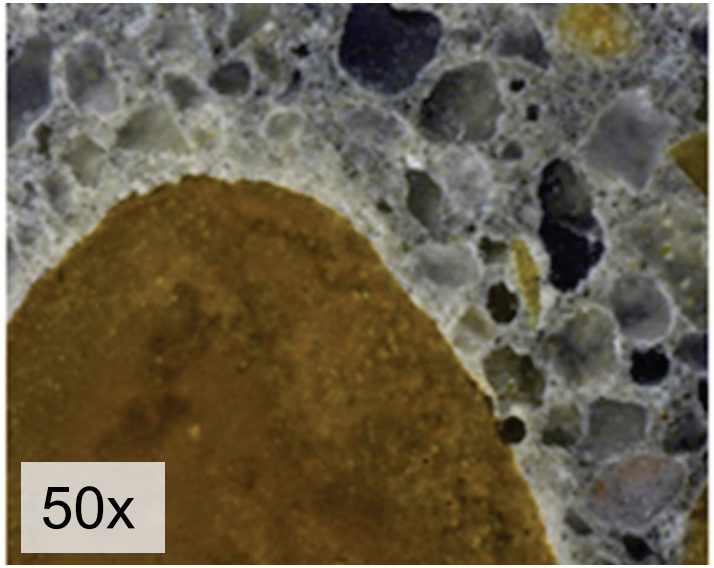


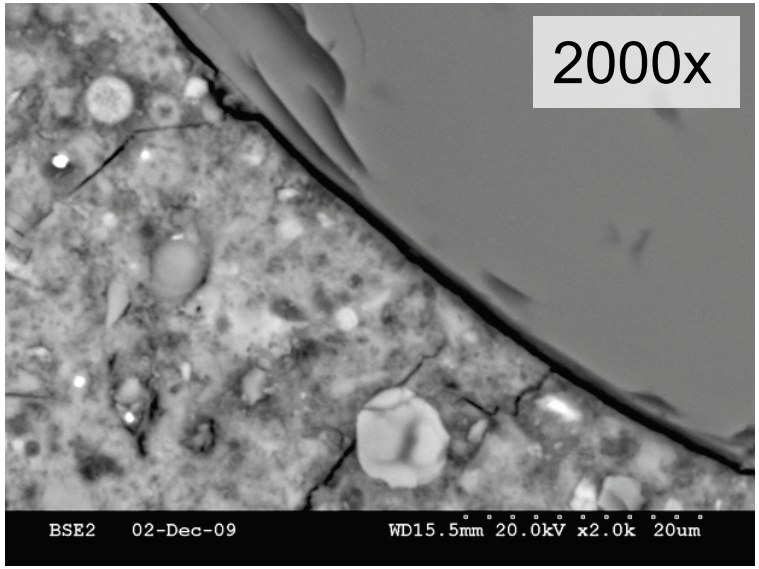
Equivalency plots comparing PLC with OPC in gravel aggregate concrete with "No SCM" and with 40% Class C fly ash replacement

Petrography micrographs of paste near agg surfaces

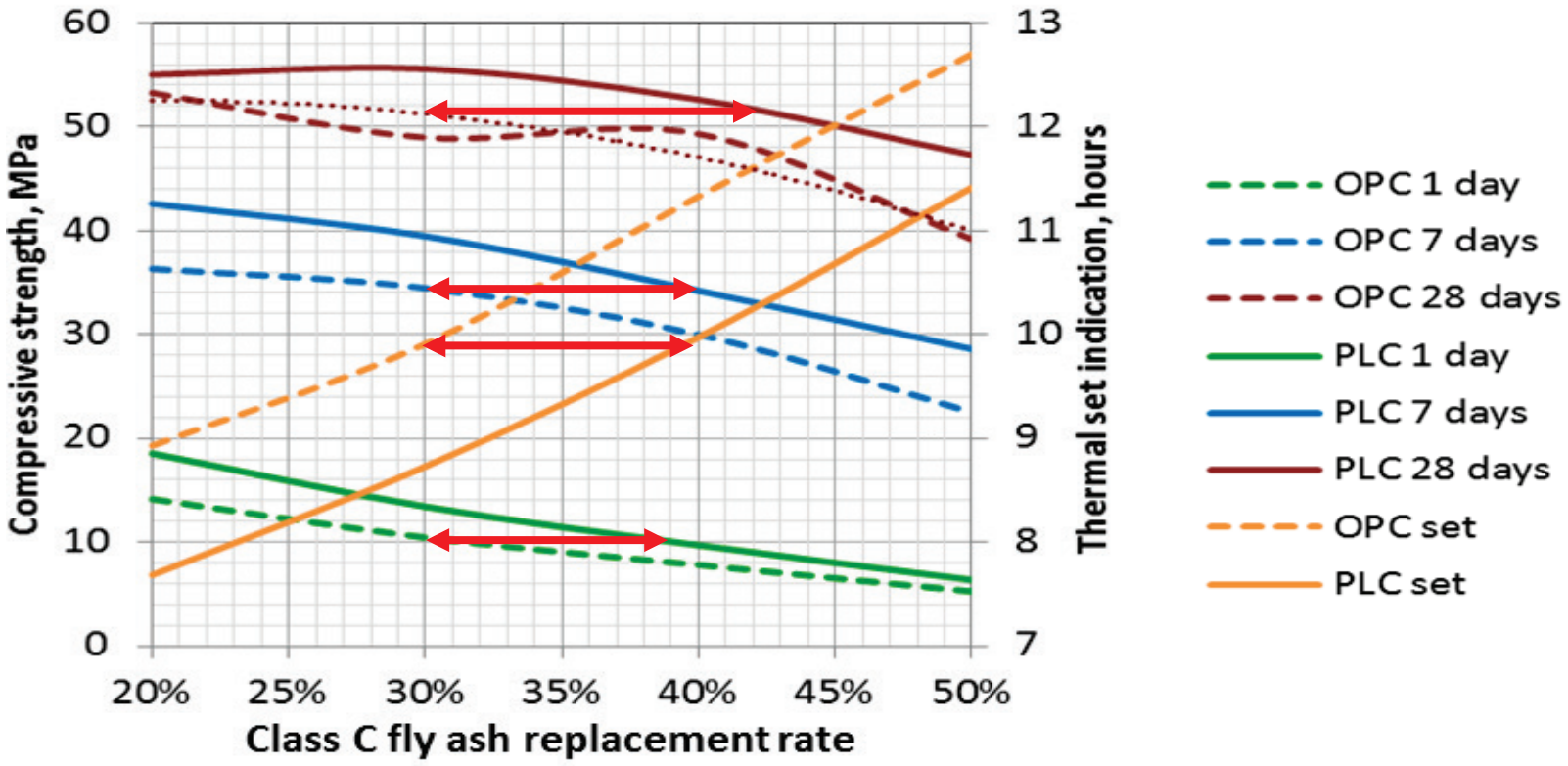
- Micrographs show changes in paste character near the ITZ in smooth gravel agg mixes
  - Higher w/cm
  - Some microcracks
  - Frequent failure zone near aggregate surface







Is higher SCM replacement of cement possible with PLC? Paste trends alone: % replacement vs. strength, setting

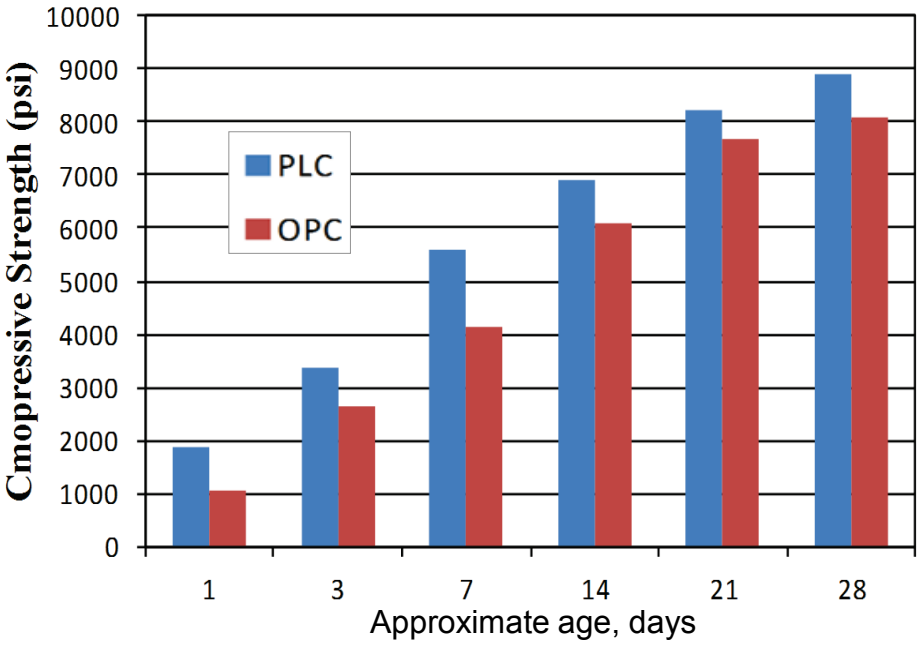


Mississippi DOT has adopted new specifications allowing Type IL and increasing fly ash replacement limit from 25% to 35% only when Type IL is used.

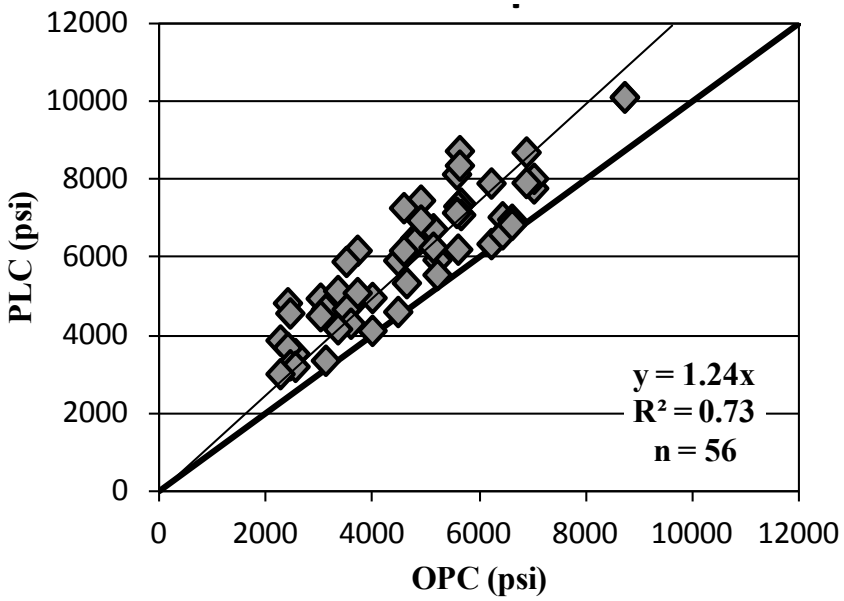
Expansion of Davis Wade Stadium, Mississippi State University

- $75M expansion & renovation
- Design focus on sustainable attributes of materials
- Most concrete using 50% replacement (30% slag + 20% Class C fly ash), some with OPC, some with PLC
- Study part of MSU research

MSU Davis-Wade Stadium project concrete data, 50/30/20C mixtures



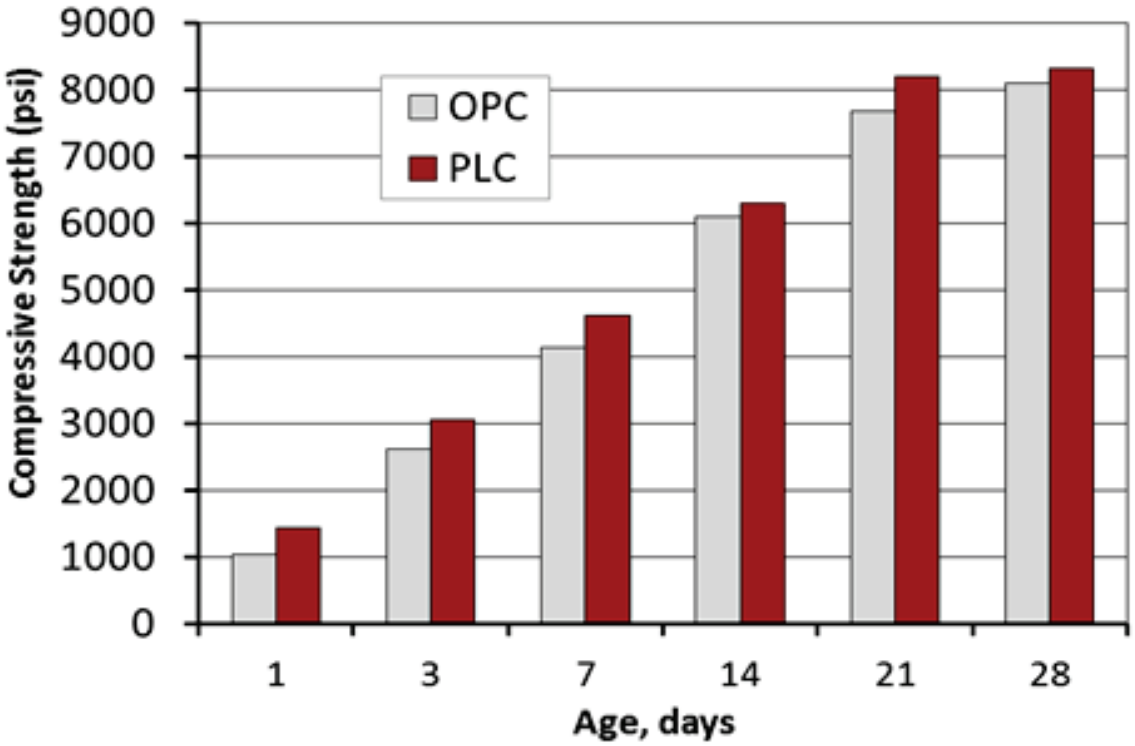
Strengths at ages up to 28 days, initial PLC use vs. previous OPC use in the same mix design



PLC vs. OPC equivalency, each data point = a PLC mixture strength vs. a corresponding OPC mixture strength, 3 cylinders averaged for each

Trend comparison, field-sampled concrete of similar proportions

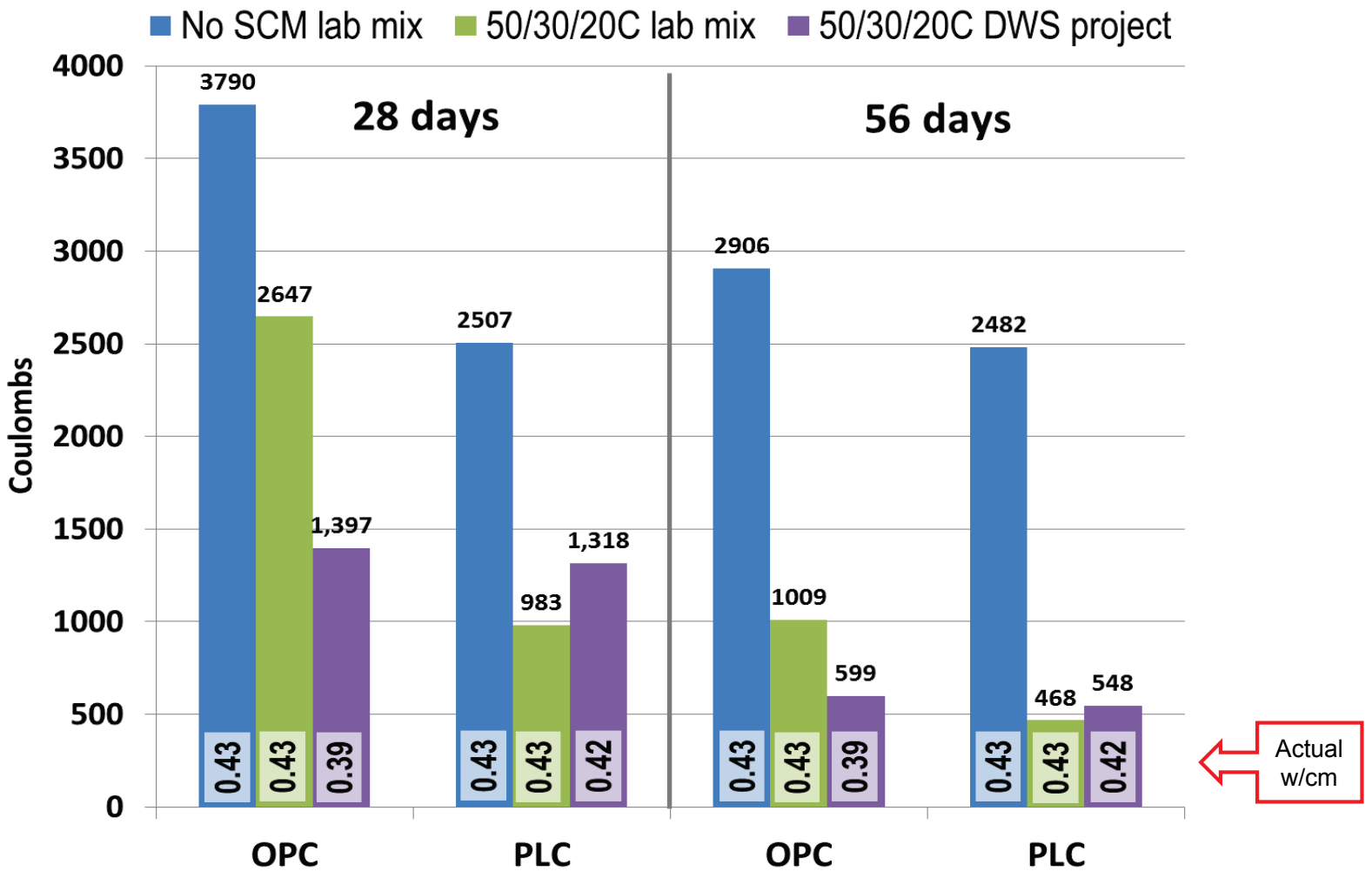
MSU Davis-Wade Stadium project concrete data, 50/30/20C mixtures



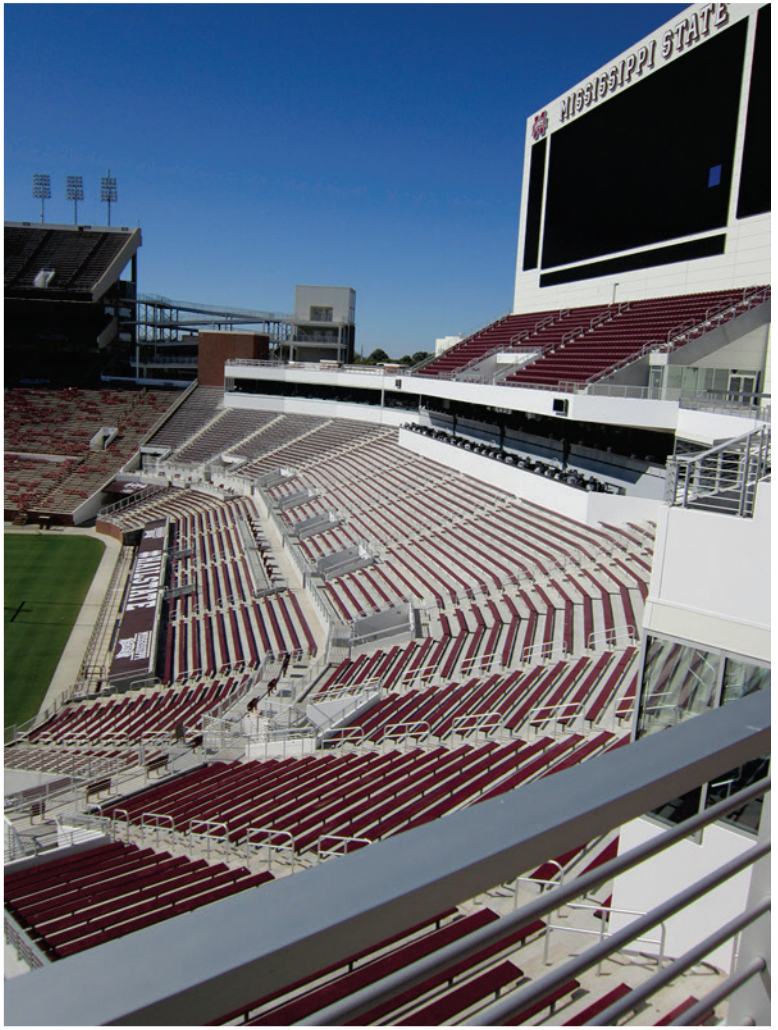
Averages of multiple project samples, OPC vs. PLC, after PLC mixtures were adjusted to lower total cementitious content by 29 pcy (on avg.) and higher w/cm by +/- 0.015

ASTM C1202 (RCP) result averages

Note: w/cm for all lab mixtures = 0.43, for DWS OPC = 0.39, for DWS PLC = 0.42.



Completed DWS views



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Completed DWS views

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Papers and manuscripts to date – research results

- Cost, V. T., and Bohme, P., "Synergies of Portland-Limestone Cements and Their Potential for Concrete Performance Enhancement," 2012 International Concrete Sustainability Conference, Seattle, WA, May 7-10, 2012, 14 pp.
- Cost, V. T., Howard, I. L., and Shannon, J., "Improving Concrete Sustainability and Performance with Use of Portland-Limestone Cement Synergies," *Transportation Research Record: Journal of the Transportation Research Board, No. 2342*, Washington, D.C., 2013, pp 26-34.
- Cost, V. T., Matschei, T., Shannon, J., and Howard, I. L., "Extending the Use of Fly Ash and Slag Cement in Concrete Through the Use of Portland-Limestone Cement," 2014 International Concrete Sustainability Conference, Boston, MA, May 12-14, 2014, 15 pp.
- Shannon, J., Howard, I. L., Cost, V. T., and Wilson, W., "Benefits of Portland-Limestone Cement for Concrete with Rounded Gravel Aggregates and Higher Fly Ash Replacement Rates," presented at the Transportation Research Board 94th Annual Meeting (paper no. 15-4049).
- Howard, I. L., Shannon, J., Cost, V. T., and Stovall, M., "Davis Wade Stadium Expansion and Renovation: Performance of Concrete Produced with Portland-Limestone Cement," accepted for publication, ASCE Journal of Materials in Civil Engineering, manuscript number MTENG-3228.

Summary and conclusions

- Without SCM's, Type IL performance = OPC performance
- In combination with C ash, PLC concrete strengths exceeded OPC strengths regardless of source; modest F ash strength benefits are possible with some sources
- Times of set were shorter with PLC's for all mixtures, but especially with F ash or with 2-SCM systems (slag + C ash)
- Higher SCM replacement of cement may be possible at similar performance levels, especially with C ash or slag + ash combinations, with some setting benefits possible
- Chemical mechanisms responsible for trends include robust formation of carboaluminates, with associated trends of stabilization of ettringite, improved water binding capacity, and decreased porosity

Mississippi State University
CMRC
Construction Materials Research Center
An Industry, Agency & University Partnership

Questions?

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