The PLC/Type IL Cement Conundrum

(Migrating Concrete Production based on the new cements)

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Recent field experiences – summary of ASCC survey

ASCC Type IL Cement Survey Summary (2023)

Have you had any strength issues with Type IL cement?		
YES	NO	Amount Lower
16	13	1. 5 to 10% lower; made strength at 56 days. 2. About 10% lower. 3. Up to 500 psi lower. 4. Roughly 10 to 15% lower. 5. Up to 25% lower. 6. Up to 500 psi lower. 7. 500 to 1,000 psi lower. 8. 10 to 15% lower. 9. Increased cement content by ½ sack. 10. About 200 to 400 psi at 28 days. 11. Low 3 day by 10 to 15% 12. Low 3 day by 7% 13. Low 7 day by 10%

Have you had any fresh concrete set issues?			
YES	NO	Retarded	Accelerated
16	14	1. 1 to 2 hours. 2. Longer, made worse by cold weather. 3. Longer by 45 to 60 minutes. 4. Up to 2 hours. 5. 30 minutes. 6. Longer by 20 to 30% 7. Longer by 60 to 90 minutes	1. 10 to 15% faster. 2. Faster by 25%. 3. Faster. 4. Faster by 30 to 60 minutes when pumping.

Have you had any issues with increased water demand?		
YES	NO	Comments
13	14	1. Much higher water demand; shrinkage cracking and workability issues. 2. Drinks up water, makes it really hard to flow. Spend more time working it and less time finishing it. Creates more man hours per job. 3. About 2 to 10% increase in water. 4. Requires more water, makes strength less. 5. More shrinkage cracking due to water demand. 6. Batch plant confirms more water or water reducer used.

Other Issues with Type IL Cement		
1.	Finishability	11
2.	Cold Weather Work	10
3.	Shrinkage	6
4.	Workability	4
5.	Proper Curing	4
6.	Cost Premiums	4
7.	Abrasion	2
8.	Availability	2
9.	Pumpability	1

Responses from 36 ASCC members – all size contractors, with 22 companies reporting annual sales volumes of $50M+

Why Portland-limestone cement (PLC)?

- Environmentally friendly product, lower CO_2 emission
- Worldwide recognized and well perceived product
- Cement characteristics are beneficial for various applications & processes
- Higher Blaine cement with similar sieve residue with potential higher initial strength development and similar setting time

Portland-Limestone Cement in NA

- While supplementary cementing materials can be used to reduce the clinker content of concrete, another proven solution is to inter-grind the cement clinker with raw limestone. They also can be used separately and in combination (but in US cannot count as cement).
- Since 1983, CSA has allowed up to 5% limestone in normal Portland cement.
- The CSA initiative is to introduce a class of Portland-limestone cements with up to 15% interground limestone.
- This will have a direct effect on reducing point-source CO_2 emissions at cement plants.

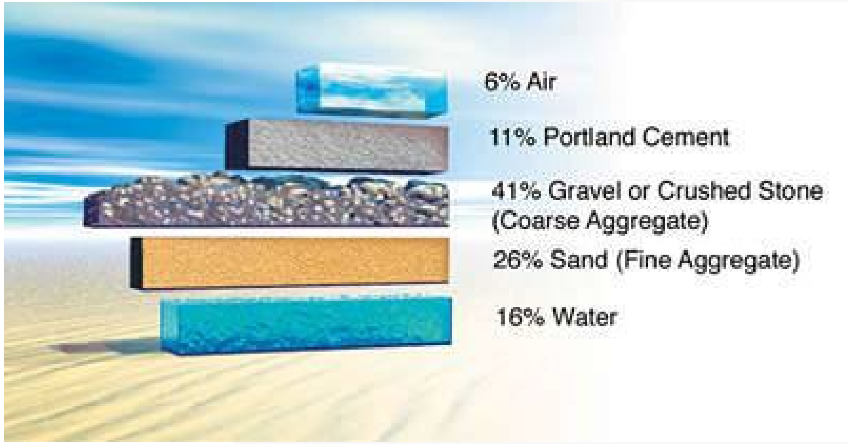
Sustainable environmental benefits of PLC (IL cement)

Legislation in Canada

- CO_2 emission to be reduced by 18% until 2010, over a 2006 baseline

- **Ecological footprint in quarries**
  - 1.6 times more limestone is required for clinker production compared to direct use of limestone in cement
- **Greenhouse gas emissions**
  - 15% limestone in cement results in more than 100 kg LESS CO_2 per ton of cement
  - Less fossil fuel and less clinker required to serve market with same amount of cement
  - Limestone is a local product, no need to transport material over long distances differently compared to some SCM's
- **Support for LEED projects**

Sustainability Initiative



Cement is around 10% to 17% of concrete's mass but 80% or more of the embodied energy & CO_2 footprint (due to clinker production)

- CONCERN – Is PLC a sustainable option if mix cement content must be increased due to water demand & strength performance?

Historical use of limestone cements

- 1965 Heidelberg produces 20% limestone cement in Germany for specialty applications
- 1983 CSA A5 allows 5% in Type 10 cement in Canada
- 1990, 15+/-5% limestone blended cements being used in Germany
- 1992, in UK, BS 7583 allows up to 20% in Limestone Cement
- 2000 EN 197-1 allows 5% MAC (Typ. Limestone) in all 27 common cements, as was commonly practiced in various European cement standards prior to that
- 2000 EN 197-1 creates CEM II/A-L (6-20%) and CEM II/B-L (21-35%) classes of cement
- 2003 CSA A3001 allows 5% in other Types than GU
- 2004 ASTM C 150 allows 5% in Types I-V cements
- 2007 AASHTO M85 allows 5% in all cements
- 2008 In Canada PLC no longer considered a blended cement
- 2012 AASHTO M240 , ASTM C595 updated for IL containing 5-15% limestone

Features Claimed by Cement Companies

- Possible increase in admixture demand (finer grind)
- Similar Strengths then the OPC it is derived from
- Similar Setting time (careful with ash of slag)
- Reduced shrinkage
- Better pumpability
- May reduced abrasion
- Finishing (careful with setting and bleed)
- Reduced excessive bleeding due to improved particle packing
- Reduced segregation

What are the downsides?

- Challenges for the cement industry
  - **<u>FINENESS</u> –** For similar performance, PLC must be ground finer
    - The higher the limestone %, the higher Blaine needs to be
    - Grinding finer slows production and uses more energy
    - This could cut into production for grinding-limited plants
    - Thus, most plants want to lower Blaine, but this may be at the expense of performance
    - Higher fineness does NOT necessarily increase water demand
- Challenges for concrete projects
  - Strengths, in some cases
  - Some changes in various concrete properties possible
  - Greater source variability, more mix verification testing
  - Certain flatwork finishing issues

Other caveats – PLC Fineness, grinding, properties

- Increasing Blaine slows grinding significantly
  - Increasing by 100 m^2/kg can reduce production 20% – 40%

- Slightly higher grinding energy costs are more than offset by the clinker savings

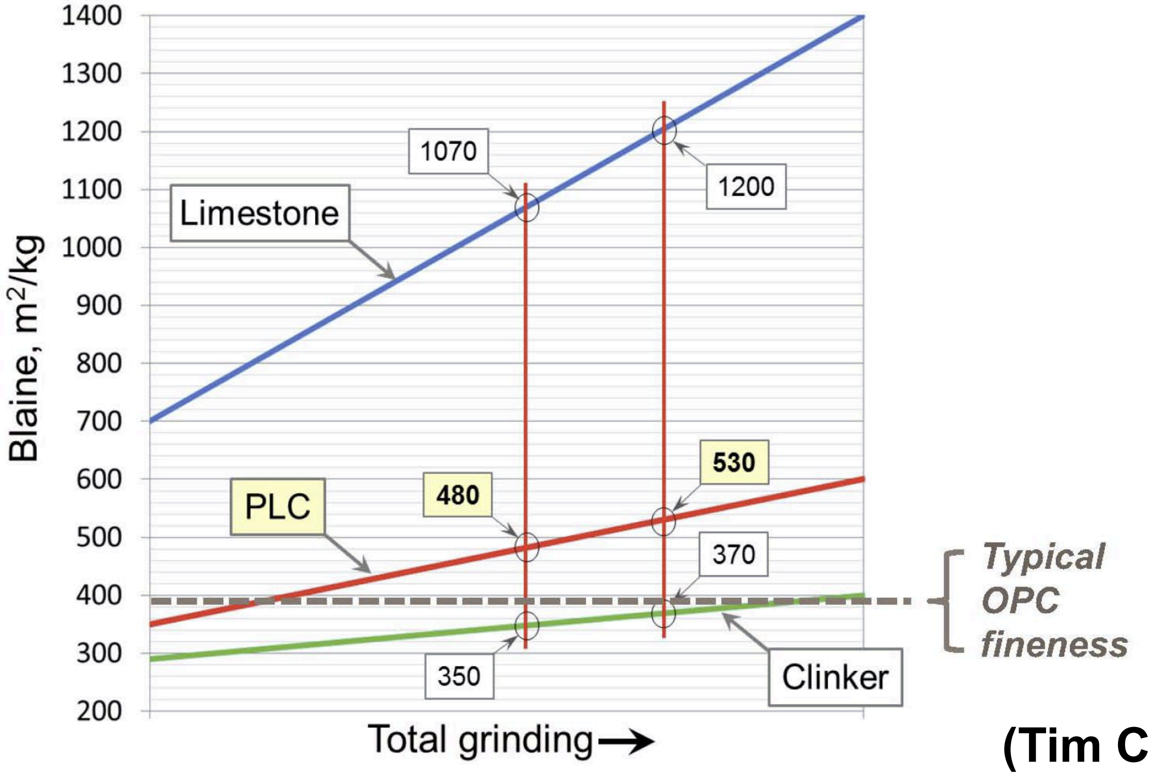
- Some plants now able to reduce fineness differential without (mortar) strength loss via grinding aids
  - Properties other than strength may be affected

- Fineness influences <u>all</u> concrete properties, not just
  - strength, and many potential PLC benefits depend heavily on fineness

Notably higher fineness of PLC does <u>not</u> inherently share the side effects of finer OPC (Type III) – heat of hydration & water demand

How fine Should PLC be ground?

Example fineness trends, PLC vs. clinker and limestone component fractions



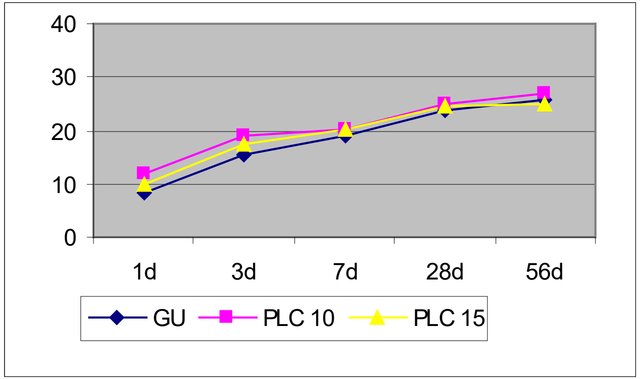
(Tim Cost, HOLCIM)

Reactions with Portland Cement

- Limestone (primarily $CaCO_3$) reacts with C_3A to form carboaluminates
- Fills voids between clinker particles improving grain packing of cement
- Acts as nucleation sites of calcium hydroxide crystals at early hydration ages accelerating hydration and consequently improves early strength

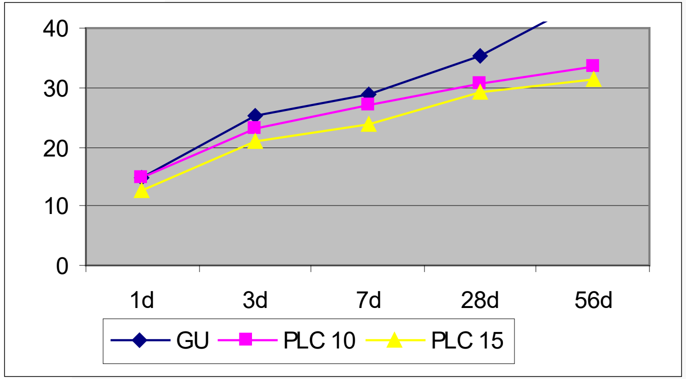
Let’s look at some results

Initial concrete test results – straight cement (Holcim Canada)

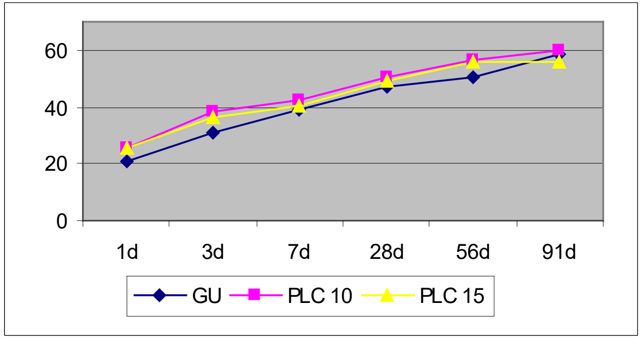


w/c 0.7 Res. Wall

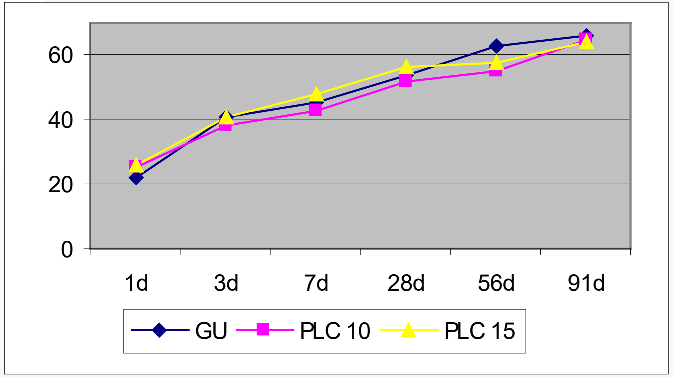
[MPa]



w/c 0.65 Res. Floor



w/c 0.40 C1



w/c 0.37 HPC

NRC results using Lafarge PLC/1L

Properties	Cement		Limestone	
	GU	GUL	3 µm	17 µm
Blaine fineness (m^2/kg)	380	472		
Specific Surface (m^2/g)	2.92	3.31	5.04	1.26
Passing 45µm, %	97	99	100	96
Specific gravity	3.13	3.08	2.70	2.70
Compressive Strength				
7 day	33.5 MPa	36.0 MPa		
28 day	41.4 MPa	41.8 MPa		

EU

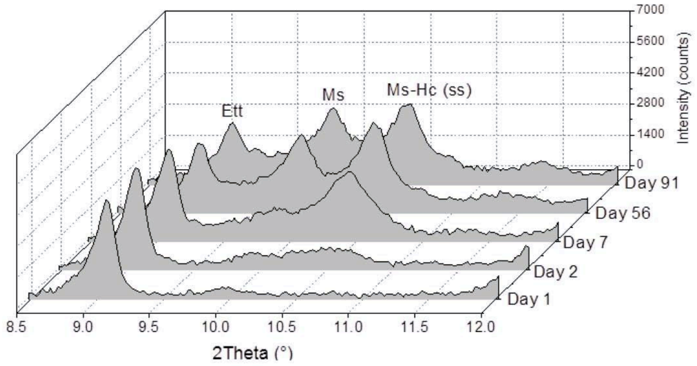
NRC Concrete

Concrete Type	W/C	Durability Factor (%) Freeze/Thaw *>300 cycles*	Compressive Strength, MPa		Chloride-ion Penetration, Coulombs	
			1d	*28d*	*28d*	*91d*
GU-CTL	0.33	100	34.2	56.8	2458	1558
GUL-CTL	0.33	100	34.0	56.0	2461	1804
BC 3µ 10%	0.33	100	31.7	55.7	2609	1597
BC 17µ 10%	0.32	100	31.3	54.4	2864	1659

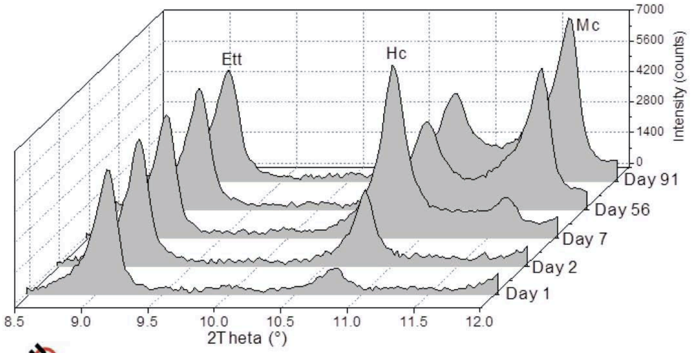
Hardened Properties

- Properly air entrained concrete exhibit similar F/T and Scaling properties
- Shrinkage is similar or reduced
- Coulombs number very similar
- ASR: Test not design to show effect of lower alkalies
- Permeability usually reduced

When used with SCM



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



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

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

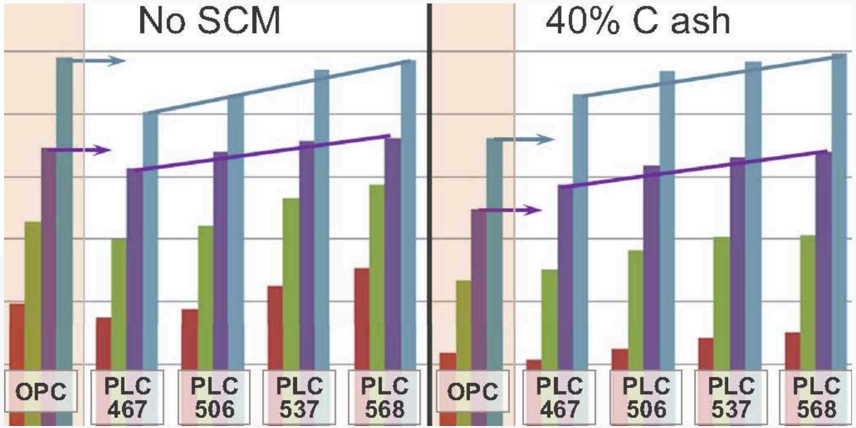
(Tim Cost, HOLCIM)

How fine should PLC be ground? (at a certain % of filler)

Fineness of the grind is typically used to "tune" 28-day strength to equal that of OPC in C109 mortar and/or simple concrete mixtures (mild or no SCM use)

Benefits of synergies with SCMs become increasingly significant with higher fineness and higher SCM replacement of cement

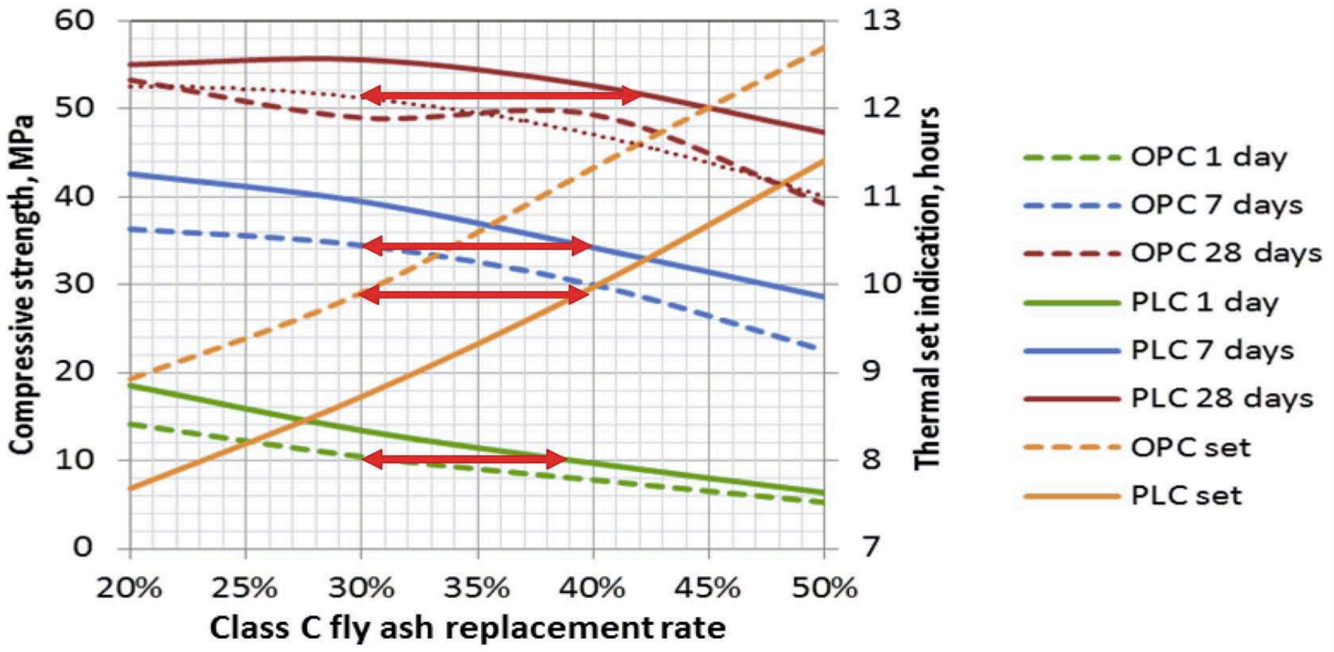
Practical limits of increased fineness benefits vary for each plant



(Tim Cost, HOLCIM USA south)

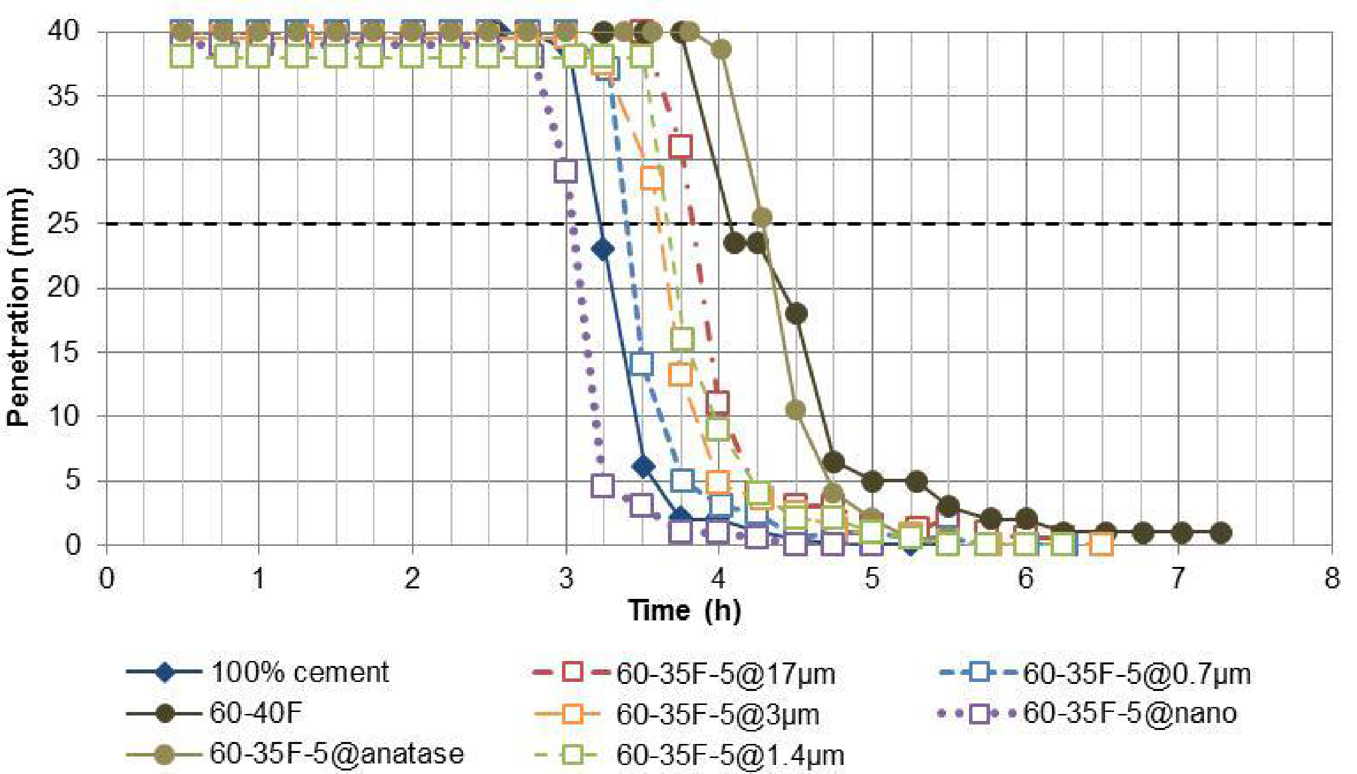
It becomes a game of how much filler versus grinding time versus strength

Trends with SCM

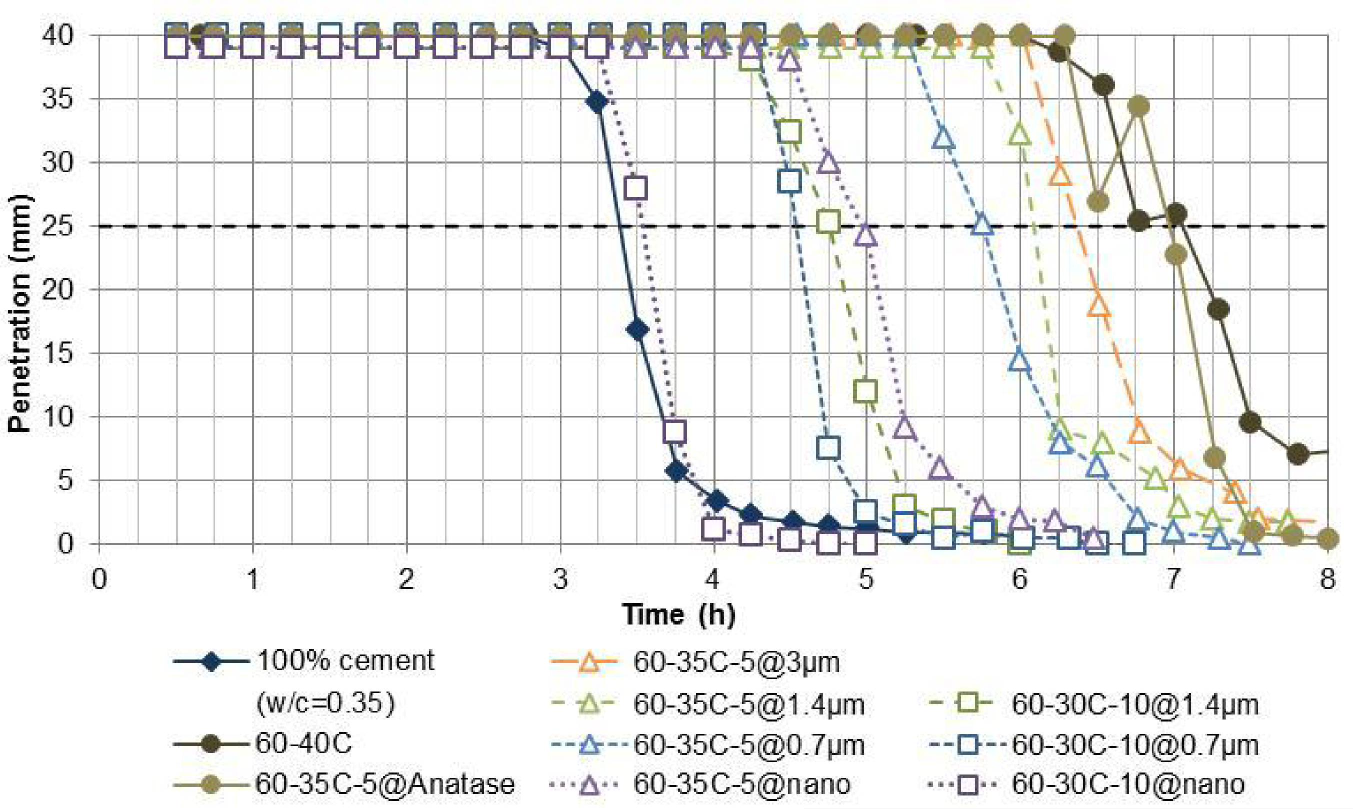


Observed trends suggest that equivalent performance should be possible with at least 10% higher fly ash replacement, using PLC.

Study conducted at NIST (D Bentz) Type F



Study conducted at NIST (D Bentz) Type C



Role of Limestone in Greater Hydration Efficiency

(Tim Cost, HOLCIM)

Limestone is not inert, but contributes to hydration both physically and chemically.

Physical mechanisms:

Enhanced particle packing and paste density due to enhanced PSD

"Nucleation site" phenomenon – limestone particles between clinker grains become intermediate sites for CSH crystal growth

Chemical mechanisms:

- Limestone contributes calcium compounds that go into solution and become available for hydration interaction.
- Calcium carbonate reacts with aluminate compounds to produce durable mono-and hemi-carboaluminate hydrate crystals.

– De Weerdt , Kjellsen, Sellevold, and Justnes, "Synergy Between Fly Ash and Limestone Powder in Ternary Cements," *Cement and Concrete Composites*, Vol. 33, Issue 1, January 2011, pp 30-38.

Cements used in MSU research comparisons

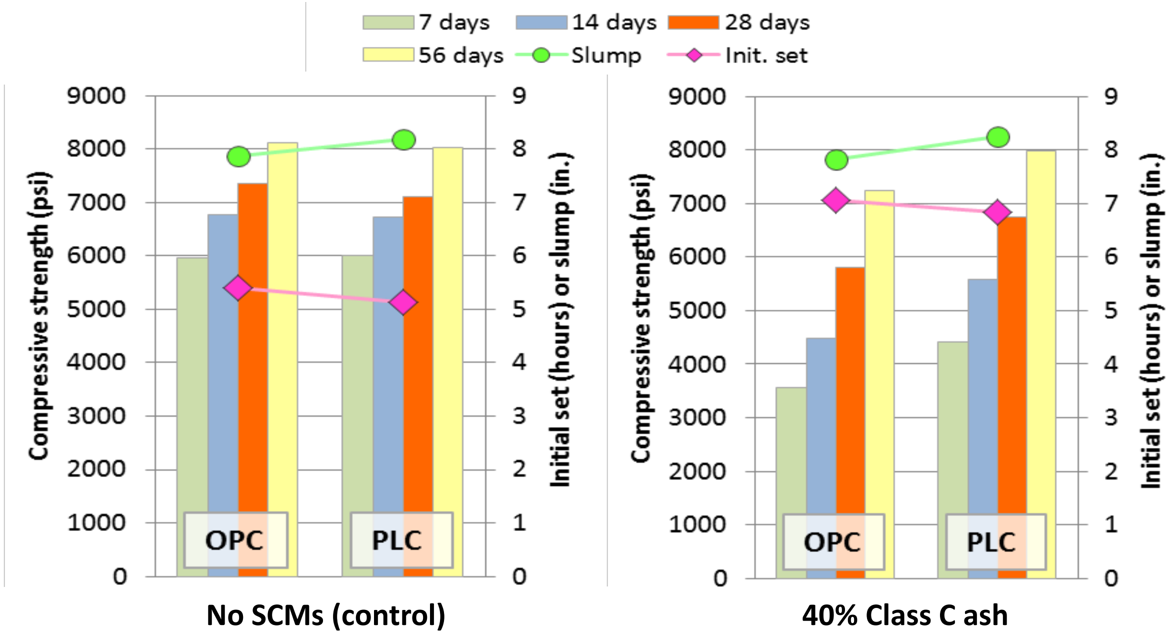
- OPCs and PLCs from 4 sources
- 8 cement samples used in groups of identical concrete mixtures with and without aggressive SCM replacement

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

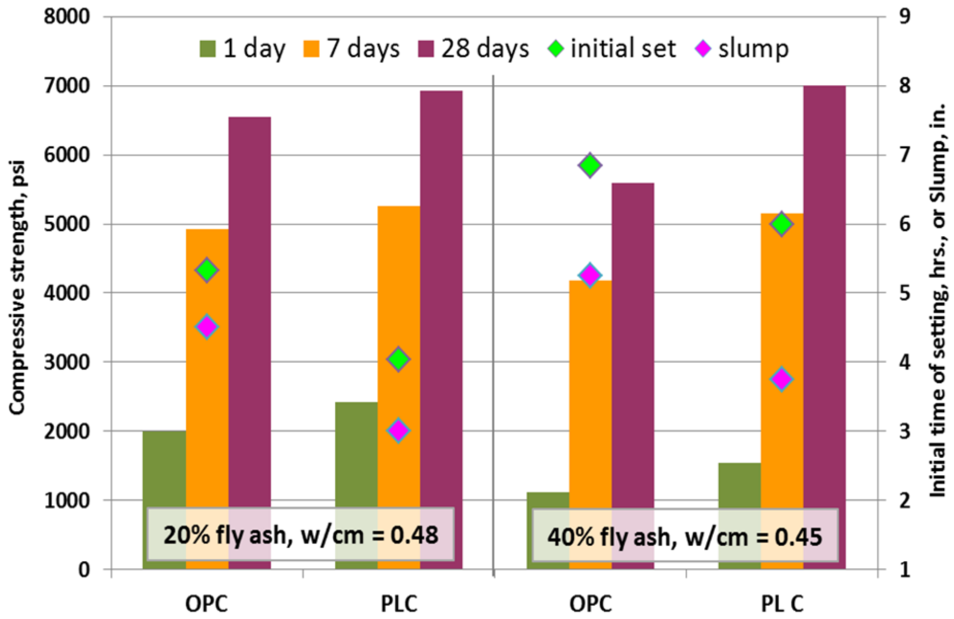
Example data from MSU study, performance synergies with high-replacement C ash

Each bar group shows the average of 4 mixes – 1 with each cement source



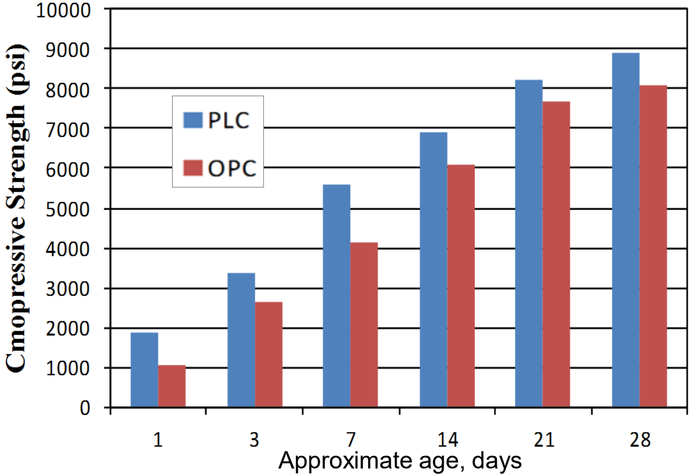
Otherwise identical concrete batches using limestone coarse aggregate, 540 lb/ft^3 total cementitious content, w/cm = 0.43. The PLC strength advantage at 28 days in 40% fly ash mixtures ranged from 13% to 22%, averaging 16%.

Example data from MSU study, performance synergies, 20% vs. 40% C ash replacement

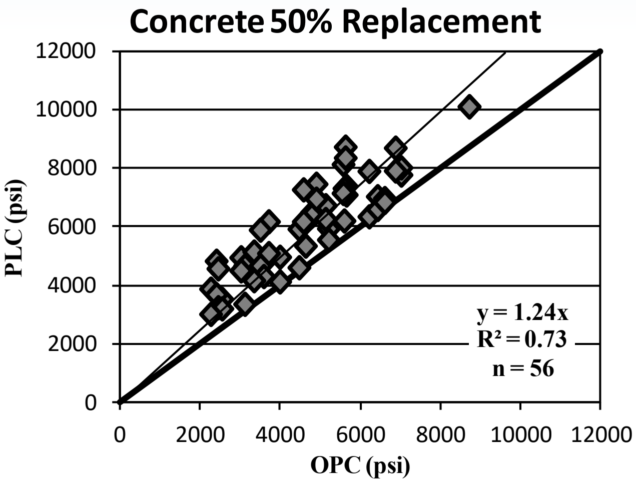


Otherwise identical mixes comparing OPC and PLC, 20% or 40% Class C fly ash, 540 pcf total cementitious content, non-AE, #57 gravel CA, 4 oz/cwt MRWR. Bleeding (via ASTM C232) averaged 34% less in PLC mixes.

MSU 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

Other PLC performance synergies: gravel aggregates

- Rounded smooth-textured gravel coarse aggregates can pose concrete strength challenges
  - Especially in mixtures using fly ash
  - Lower inherent paste-aggregate bond (PAB)
  - Evidenced by fracture planes of broken cylinders (lots of
    - aggregate sockets, no broken aggregate pieces
- PLC has been found to help mitigate loss of PAB
  - Other cementitious components with very high fineness have also been found useful in improving PAB

CAUTION – Don’t assume you’ll see all these benefits!

- These benefits depend on PLC fineness
- MSU research was done with high fineness PLCs and no strength-enhancing grinding aids
- Most PLCs today are not as fine
- Synergies depend heavily on SCM C_3A content, usually insignificant for F ash

Challenges reported with high-spec floor finishing

- Less bleed water may be a problem for some finishing
  - Less total bleeding is universally true with PLC
  - Timing of bleed water, progression of set may be quite different
  - More surface crusting and blistering reported by some
- Trial placements and ASTM C 232 testing recommended
- Adjustment of bleed water may be possible
  - Experiment with aggregate grading, mix proportions, sand FM, etc.
  - VMAs have been found useful

PLC-related concrete performance variability

Reports & observations

- Variation of PLC physical properties
  - Fineness & % limestone
  - PSD effects of different mills and separators
  - Limestone characteristics differ
- Reports of differences in admixture effectiveness
- Extreme temperature sensitivity
- ***There are lots of physical property differences among PLC sources – much more than for OPC!***

PLC-related concrete performance variability

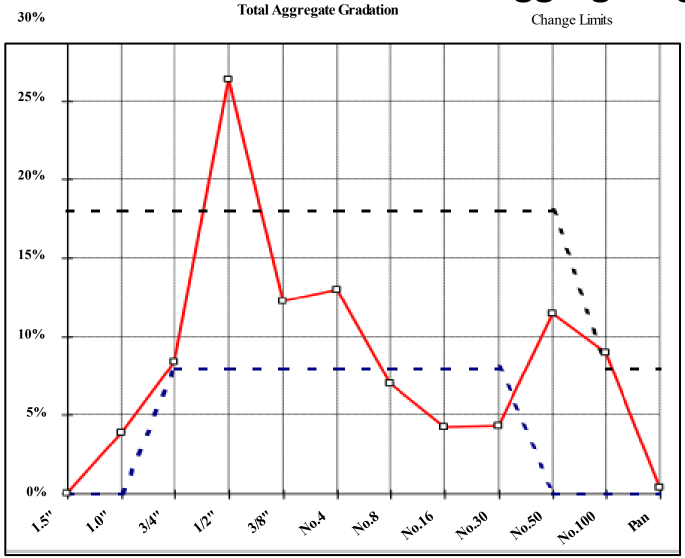
Effects of limestone characteristics

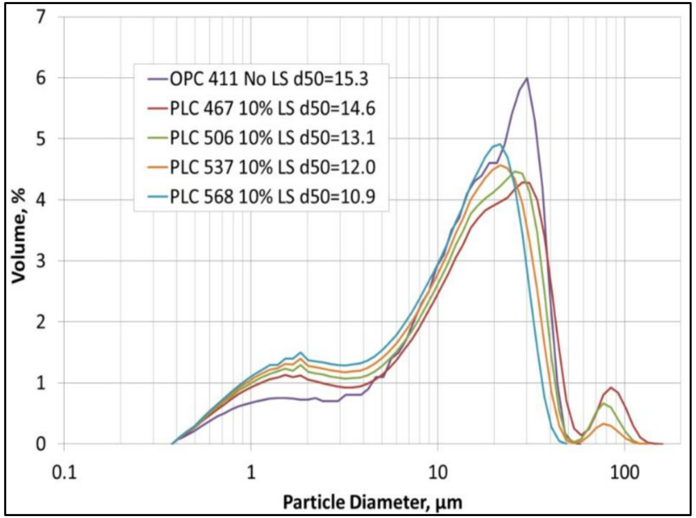
- The limestone used in PLC is almost always the plant raw material limestone
- Cement-making limestone hardness varies
  - Materials softer than aggregate-quality LS preferred
- Harder limestones result in less-ideal PSDs
- Limestone hardness differs in the same quarry
- Limestone chemistry (esp. % $CaCO_3$) also varies

PLC-related concrete performance variability

More on PSD influences

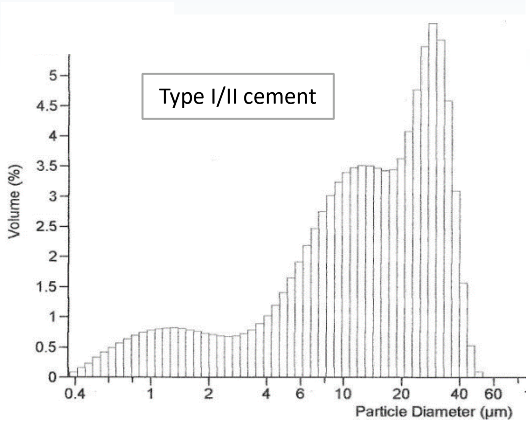
- Cement PSD is like aggregate grading for concrete performance

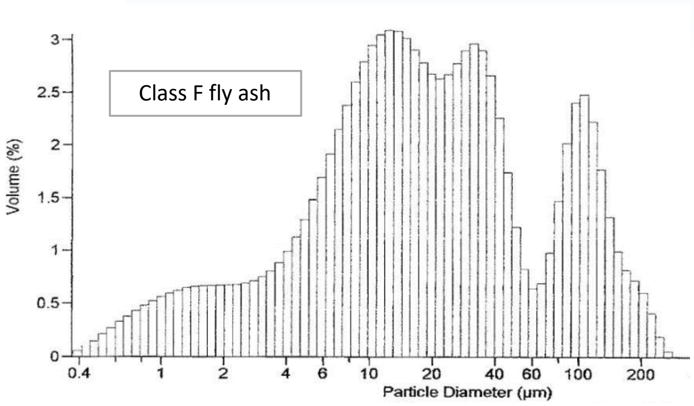


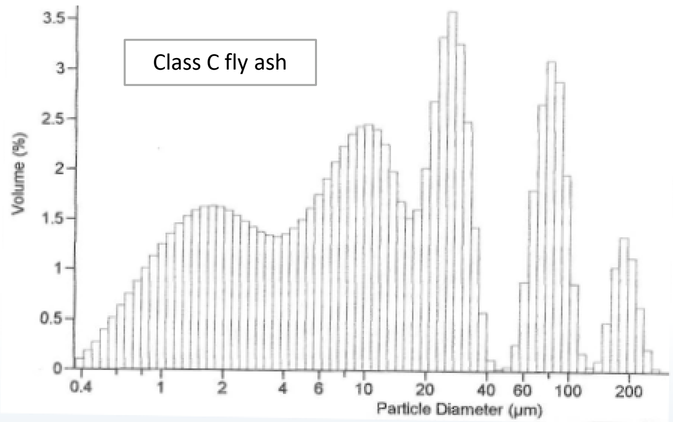


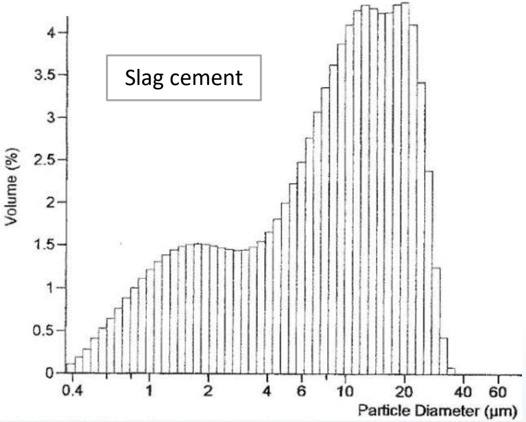
Rheology, water demand, particle packing, and other performance attributes improve as the effects of limestone fineness enhance PSD.

Example PSDs for traditional cementitious materials

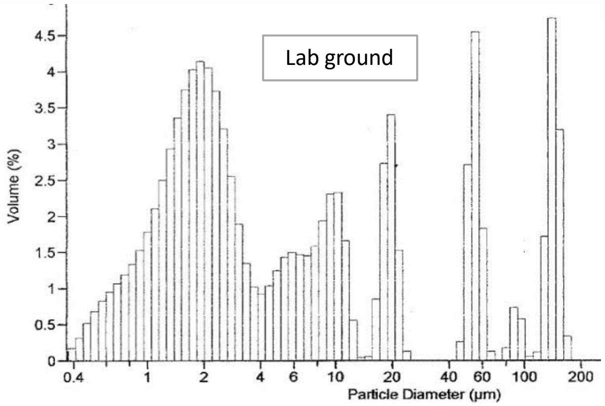


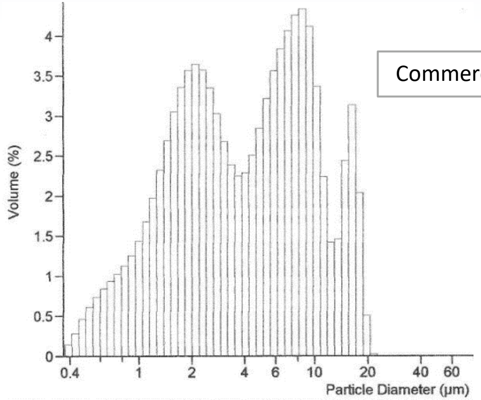


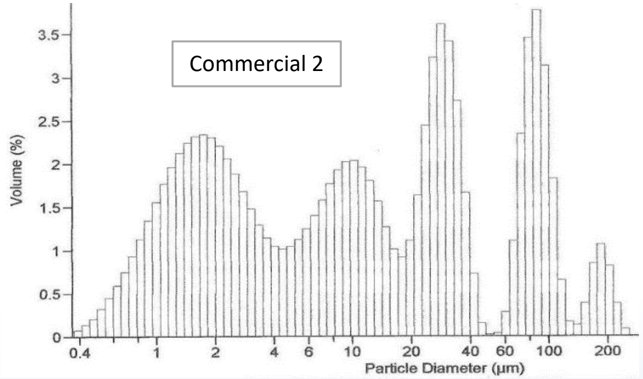


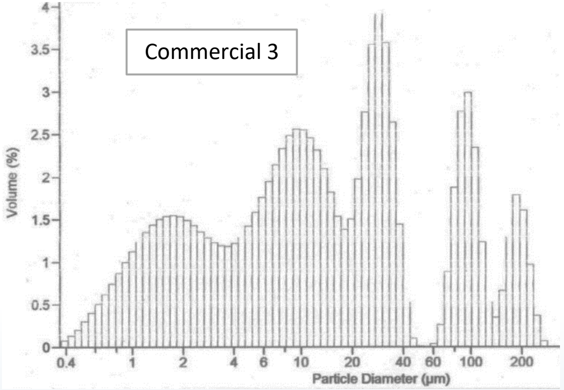


Example PSDs, lab-ground and commercial ground LS









Summary, PLC-related performance variability

- Type IL is more variable, source to source, than OPC
  - Overall fineness varies significantly, source to source
  - In turn, PSD and particle packing trends vary, as well as dissolved $CaCO_3$ contributions
  - Limestone hardness and grindability vary, also impacting PSD
  - Insufficient fineness could mean clinker particles are coarser, on average, than in OPC
- Resulting concrete performance variability:
  - Water demand could be anywhere from slightly lower to notably (and problematically) higher
  - Setting effects could be accelerated or retarded
  - Temp sensitivity could be made more extreme
  - Bleeding is always reduced, but extent and timing varies
  - Some other concrete properties & interactions influenced

Conclusions, recommendations

- Don't expect everything to be the same
  - Concrete performance will likely differ in unchanged mix designs
  - And may differ significantly when changing PLC sources
  - Pay attention to Blaine, relative to source's OPC
    - Also consistency of Blaine, load to load
  - Do the testing and be prepared for proportion modifications
- Enhanced properties and performance are possible
  - But depend heavily on PLC fineness and SCMs
- Special precautions warranted in certain cases
  - High-spec floor finishes, other bleed water-sensitive applications
  - Water demand, certain basic properties, temp sensitivity

My recommendations for the cement industry

Acknowledge that there may be a problem

Review and modify any marketing message for PLC as a seamless 1:1 OPC replacement in existing mix designs

Consider investing in grinding capacity improvements for grinding-limited plants

- The numbers will still be favorable
- Production can be extended, more product options possible
- Performance in concrete and customer acceptance will benefit
- Sustainability will benefit

Conclusion

- Do your homework
- No 2 cements are alike
  - Water demand (or admixture)
  - Set time
  - Strength development
  - Slump Retention
- It is being done elsewhere with success
- DOE in our lab for Holcim now CRH: all the mixes implemented