Impacts of Alternative Materials: Advantages & Risk

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Special Thanks to

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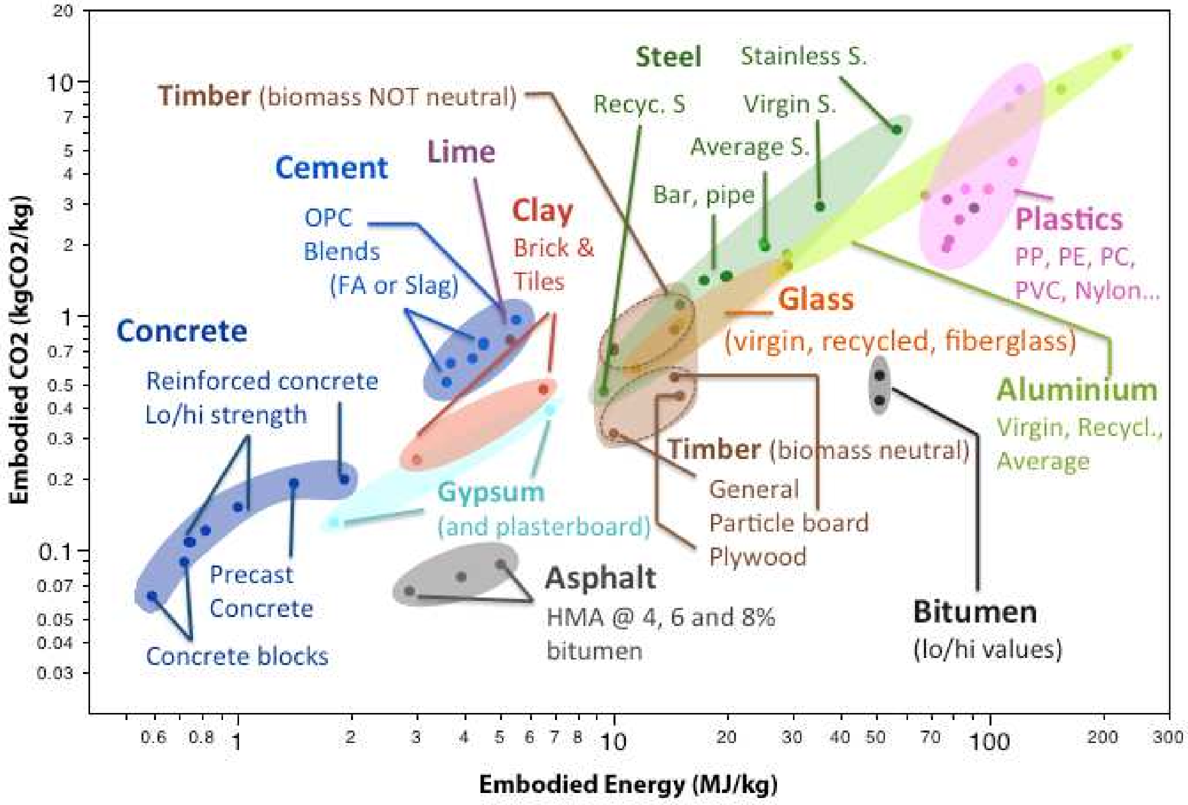
Why Alternative Materials

- Concrete has one of the lowest carbon footprints of any material… but…
- **We used ~4.5 billion tons world-wide in 2020, projected to double by 2050**
- **~1 cy/person/year**
- **~140 million tons of cement (U.S.) in 2023**
- Concrete greenhouse gas (GHG) emissions at the gate
  - ~1.5% acquiring raw materials
  - ~9.5% concrete production
  - **~89% cement production**
    - **~37% from burning fuel**
    - **~46% from calcination**



Goals

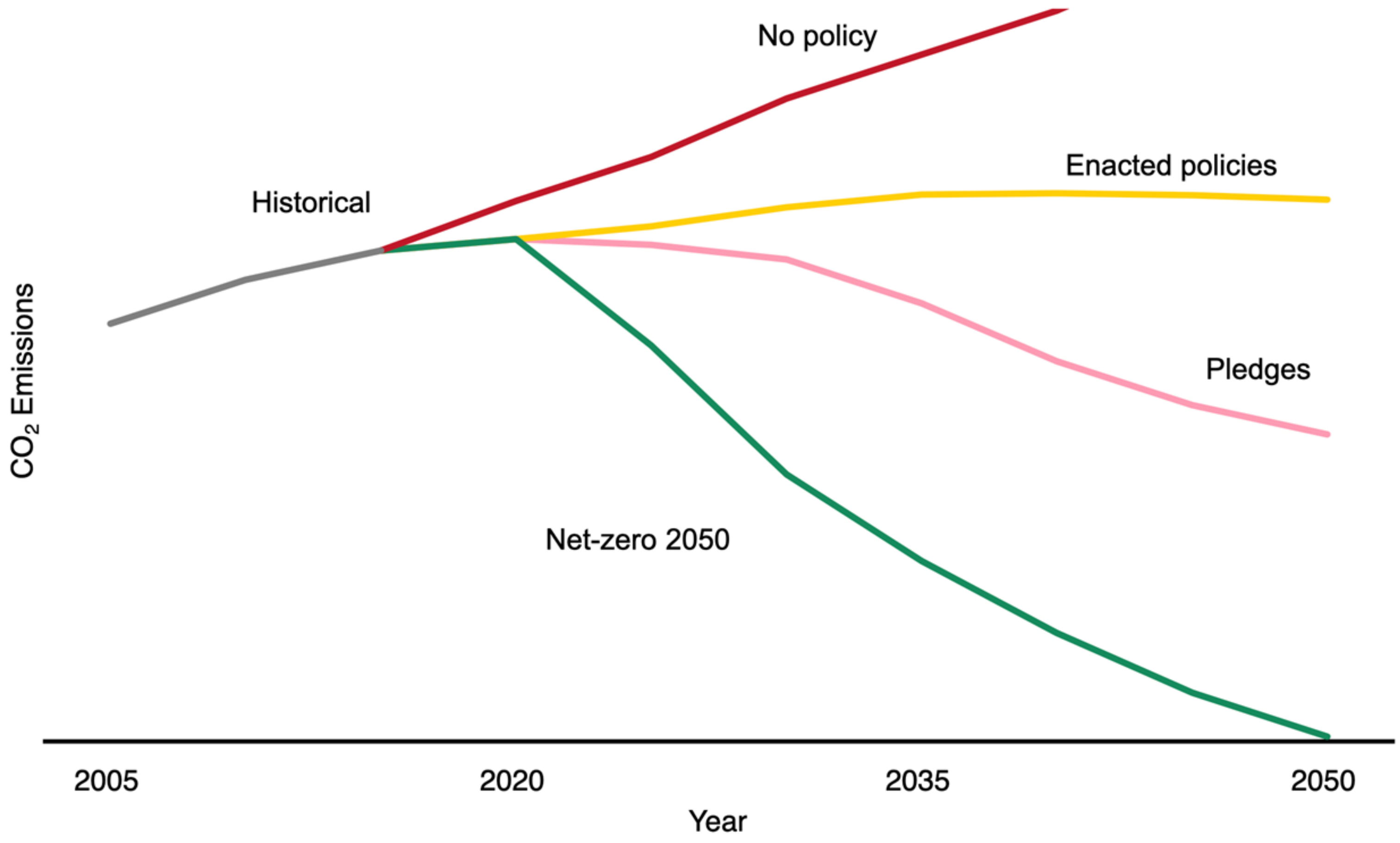
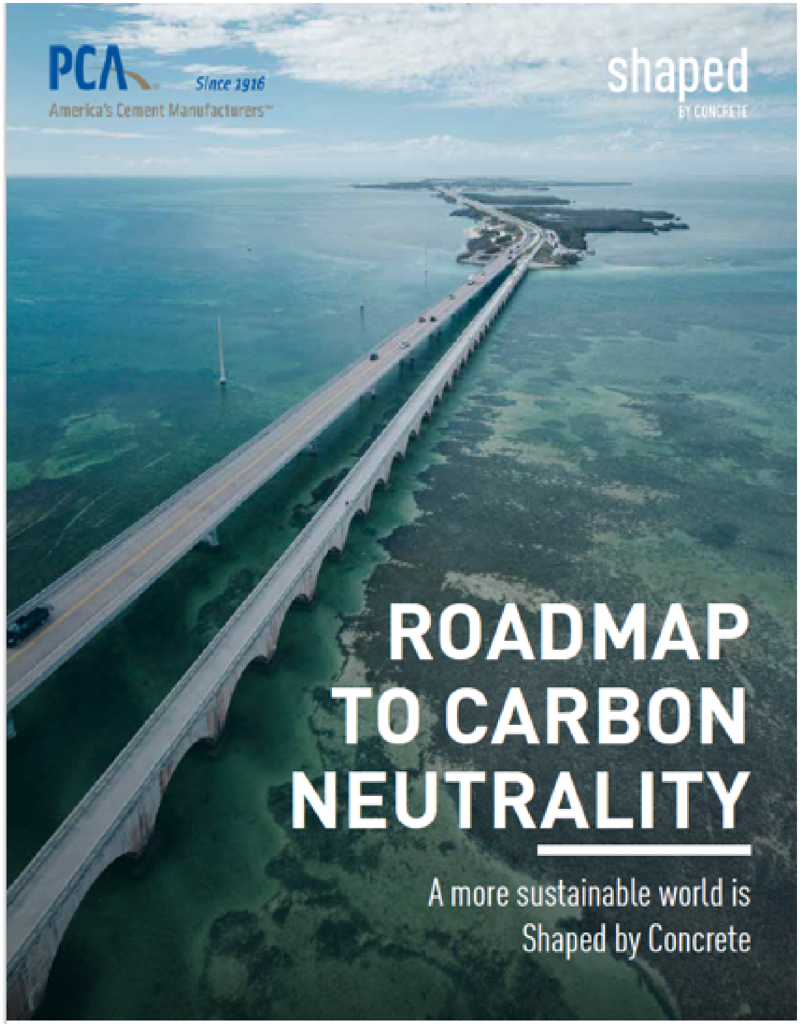


Image Credit: BlackRock

Roadmap to Carbon Nuetrality



CLINKER
Key chemically reactive ingredient

CEMENT
The binder

CONCRETE
Critically useful material to society

CONSTRUCTION
Service life / use phase impacts

CARBONATION
Concrete is a CO_2 sink

AT THE CEMENT PLANT

- Increase the use of decarbonated raw materials
- Decrease the use of traditional fossil fuels by 5X
- Increase the use of alternative fuels
- Push efficiency and decrease energy intensity for one metric ton of clinker
- Utilize carbon capture to avoid the release of CO_2 emissions
- Reduce clinker production emissions

OPTIMIZING THE DESIGN AND CONSTRUCTION OF THE BUILT ENVIRONMENT

- Lower concrete manufacturing emissions to zero at the plant
- Transition to zero emission fleets
- Optimize concrete mixes
- Reduce overdesign
- Construct concrete structures for durability, resiliency, stiffness, and thermal mass benefits

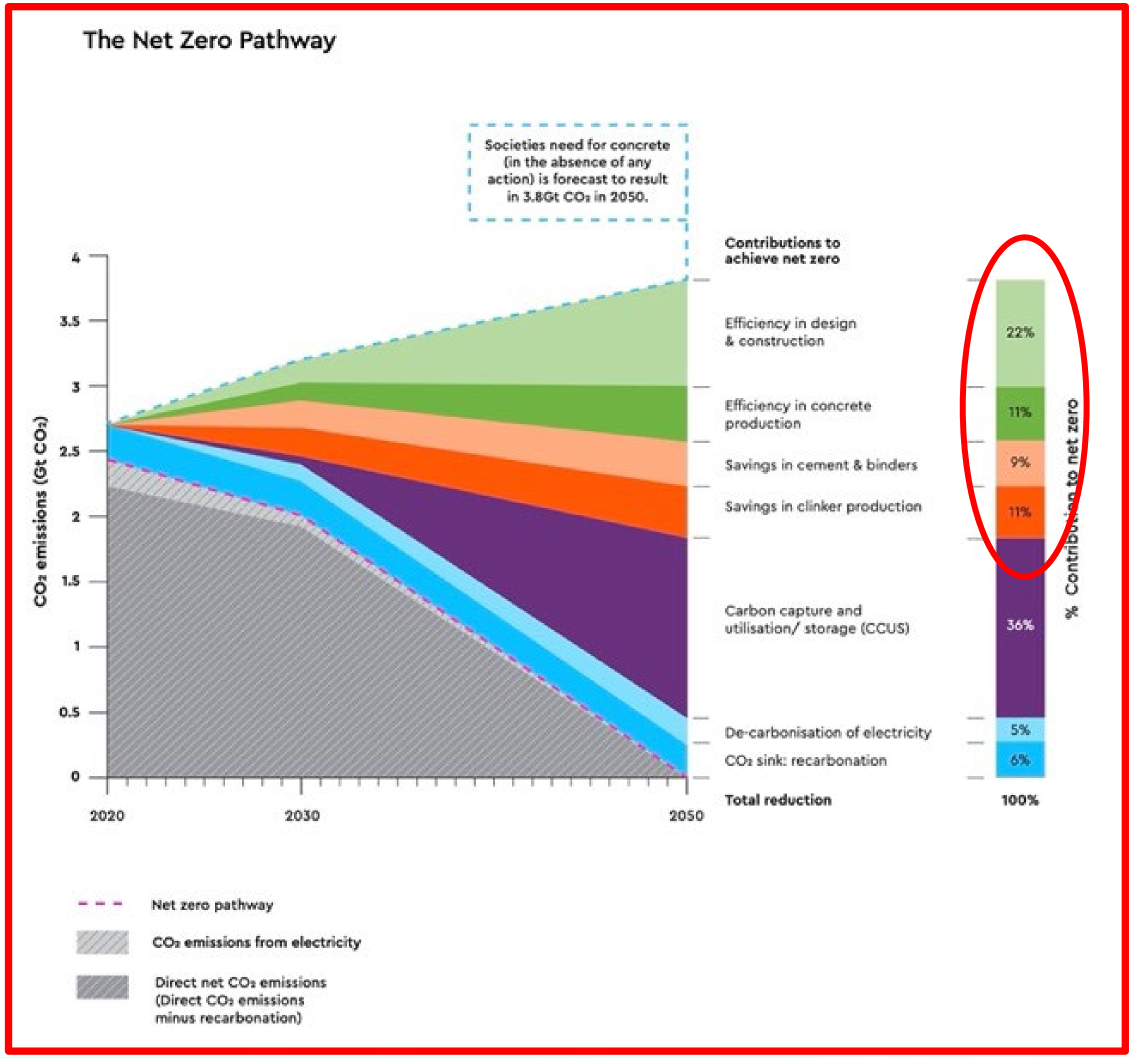
CONCRETE IN USE

10%

The amount of CO_2 that concrete buildings, structures, and pavements can permanently absorb from the air is 10%

A reduction of 46.5 million metric tons of GHG emissions per year could be realized if the entire U.S. road system used concrete pavement according to the MIT Concrete Sustainability Hub (MIT CSHUB)

Where Does CO2 Reduction Come From



CO2 Reduction

- Replace clinker content in cement
  - Use blended cement (ASTM C595), C1157 cements or replace clinker with supplementary cementitious materials (SCMs) at concrete plant
- Use less cementitious materials
  - Optimized aggregate grading
  - Lower cementitious content
- Optimize designs & new mixtures
- Use alternative SCMs and/or alternative cementitious materials

Where We've Been

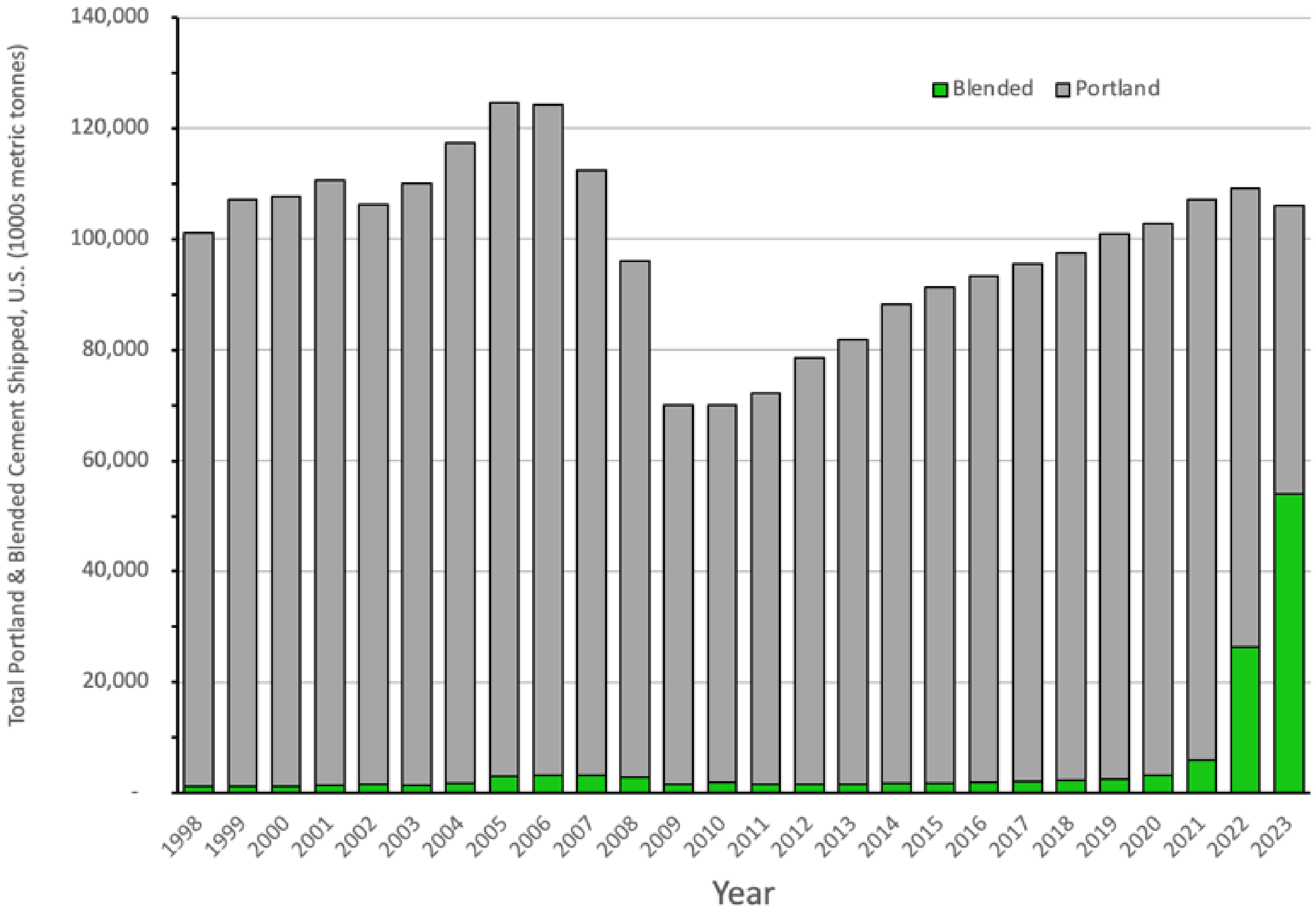
- Types I or I/II, IP, IS, III and V
- Class F and C Flyash
- Slag
- Silica Fume
- Metakaolin

Where We Are

- Type I/II, Type III, Type IL, IS, IP, IT, LC3, Type V
- C1157 Cements
- Class F and C Coal Ash
- Slag
- Silica Fume
- Metakaolin
- Ground Glass Pozzolans
- Raw or Calcined Natural Pozzolans

Increased Complexity

Blended Cement Usage



C595 Type IL Cement

- 5 to 15% limestone compared to 5% for type I/II or III
- Impact
  - Higher Blaine (finer)
    - Water Demand Higher
    - Bleed is different
    - Response to Admixtures
  - Lower Early Strength
  - Lower Ultimate Strength
  - Sticky
  - Different response to SCM (particularly Coal Ash)
  - Inconsistent
  - Type A Admixtures & IL

C595 IL Cement

- Opportunities
  - Lower Carbon Footprint
  - Mix Optimization – SCM, Admixtures,
  - Improve Control
    - Pre-testing
    - More Frequent Adjustments
  - Better Prepared for “What’s Next”

C595 IT Cement

- 5 to 15% Plus another component(NP, Ash, Slag, ?)
- Impact
  - Higher Blaine (finer)
    - Water Demand Higher
    - Bleed is different
    - Response to Admixtures
  - Lower Early Strength
  - Sticky
  - Different response to SCM (particularly Coal Ash)
  - Inconsistent

C595 or C1157

- Old materials used differently
- Significant clinker reductions
- Specify under ASTM C1157?

HFLW

30% cement

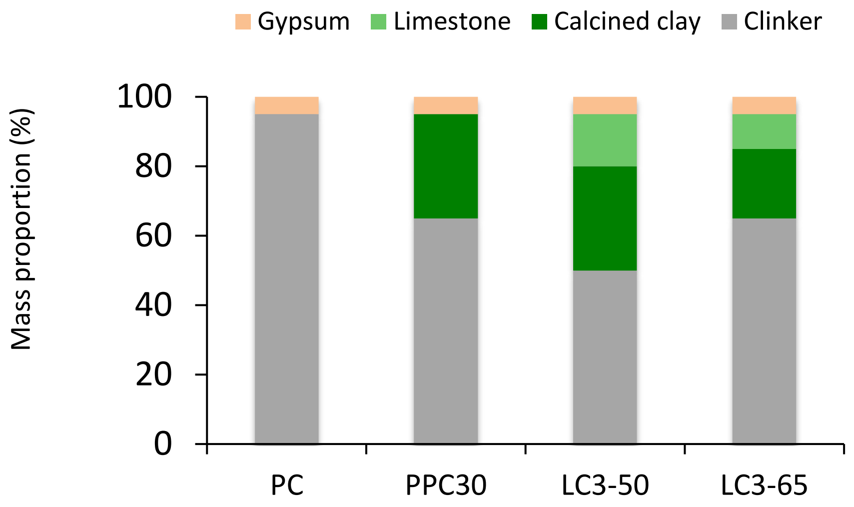
20% – 30% slag

40% – 50% limestone

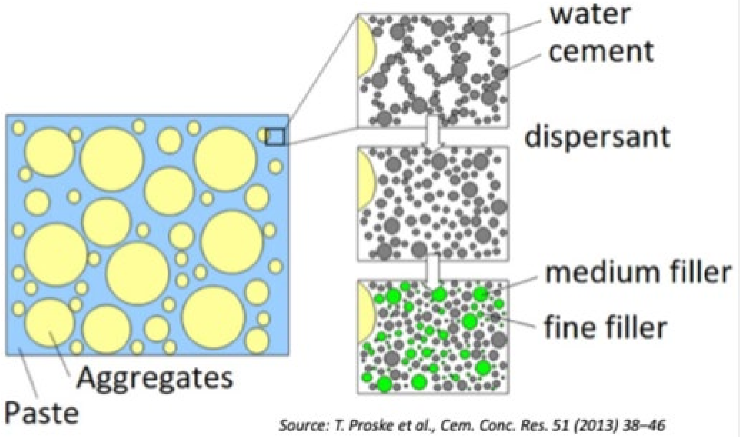
Proprietary admixtures

Calcined clay, ~45% kaolinite

Limestone Calcined Clay Cement LC3



High-Filler Low-Water (HFLW)



Source: T. Proske et al., Cem. Conc. Res. 51 (2013) 38–46

C1157 Cements

INTERNATIONAL

Designation: C1157/C1157M – 23

Standard Performance Specification for Hydraulic Cement[1]

This standard is issued under the fixed designation C1157/C1157M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 This performance specification covers hydraulic cements for both general and special applications. There are no restrictions on the composition of the cement or its constituents (see Note 1).

Note 1—There are two related hydraulic cement standards, Specification C150/C150M for portland cement and Specifications C595/C595M for blended cements, both of which contain prescriptive and performance requirements

ization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

C109/C109M Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50 mm] Cube

C1157 Cements

TABLE 1 Standard Physical Requirements

Cement Type	Applicable Test Method	GU	HE	MS	HS	MH	LH
Fineness	C204, and C430 or C1891	[A]	[A]	[A]	[A]	[A]	[A]
Time of setting, Vicat test[B]	C191						
Initial, not less than, minutes		45	45	45	45	45	45
Initial, not more than, minutes		420	420	420	420	420	420
Air content of mortar volume, max, %[C]	C185	12	12	12	12	12	12
Compressive strength minimum, MPa [psi][D]	C109/C109M						
1 day		...	12.0 [1740]	...	...	...	...
3 days		13.0 [1890]	24.0 [3480]	11.0 [1600]	11.0 [1600]	5.0 [725]	...
7 days		20.0 [2900]	...	18.0 [2610]	18.0 [2610]	11.0 [1600]	11.0 [1600]
28 days		28.0 [4060]	...	...	25.0 [3620]	...	21.0 [3050]
Heat of hydration, max, kJ/kg [cal/g]	C1702						
3 days		...	...	...	...	335 [80]	200 [50]
7 days		...	...	...	...	...	225 [55]
Mortar bar expansion	C1038/C1038M						
14 days, % max		0.020	0.020	0.020	0.020	0.020	0.020
Sulfate expansion (sulfate resistance)[E]	C1012/C1012M						
6 months, max, %		...	...	0.10	0.05	...	...
1 year, max, %		...	...	...	0.10	...	...
Optional Physical Requirements							
Option A—Air entraining[C,F]	C185						
Air content of mortar, vol %							
max		22	22	22	22	22	22
min		16	16	16	16	16	16
Option R—Low reactivity with alkali-silica-reactive aggregates[G]	C227						
Expansion at							
14 days, max, %		0.020	0.020	0.020	0.020	0.020	0.020
56 days, max, %		0.060	0.060	0.060	0.060	0.060	0.060
Early stiffening, final penetration, min,%	C451	50	50	50	50	50	50
Compressive strength,[D] 28 days, min, MPa	C109/C109M	...	...	28.0	...	22.0	...

[A] Both amount retained on the 45 µm (No. 325) sieve and specific surface area by air permeability apparatus in m^2/kg shall be reported on all certificates of test results requested from the manufacturer.
[B] Time of setting refers to initial setting time in Test Method C191.
[C] A given value of air content in mortar does not necessarily assure that the desired air content will be obtained in concrete.
[D] Cements may be shipped prior to later-age test data being available. In such cases, the test value may be left blank. Alternatively, the manufacturer can generally provide estimates based on historical production data. The report shall indicate if such estimates are provided.
[E] In the testing of HS cement, testing at one year shall not be required when the cement meets the six-month limit. An HS cement failing the six-month limit shall not be rejected unless it also fails the one-year limit.
[F] When this option is invoked, it replaces the maximum air content of mortar listed in the default table requirements. The minimum compressive strength of air-entraining cements shall be no less than 80 % of that of the comparable non-air-entraining cement type.
[G] Compliance with this requirement shall not be requested unless the cement will be used with alkali-reactive aggregate.

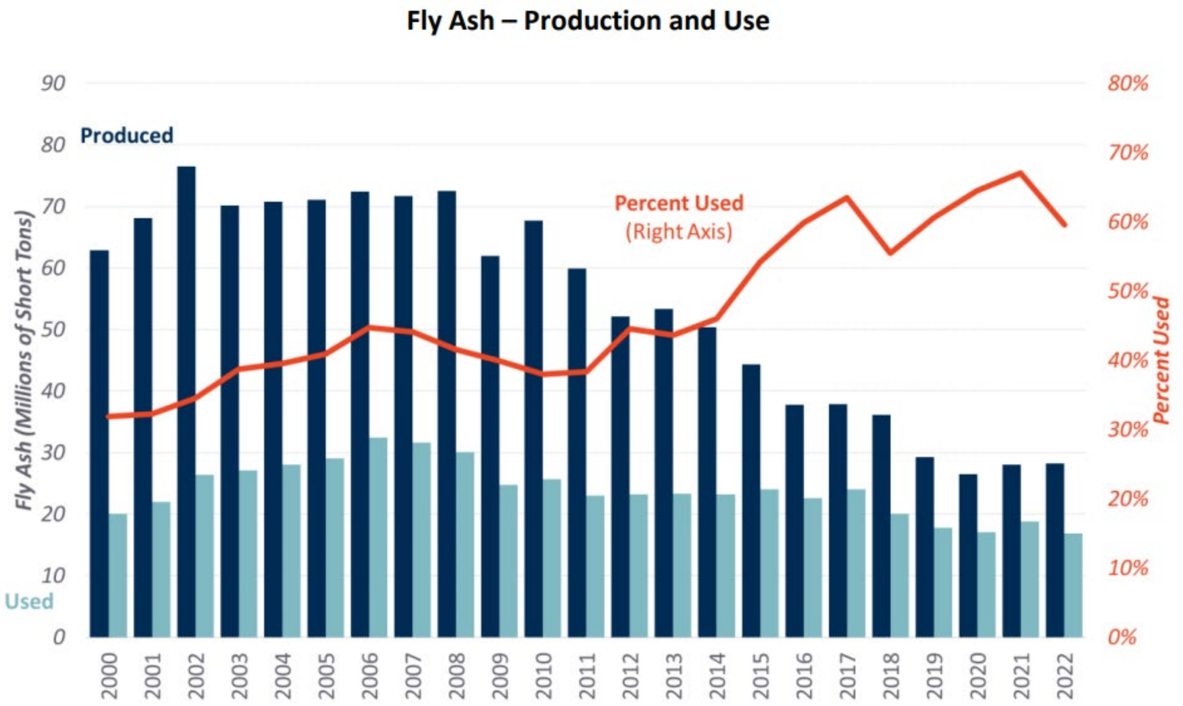
C618 Coal Ash

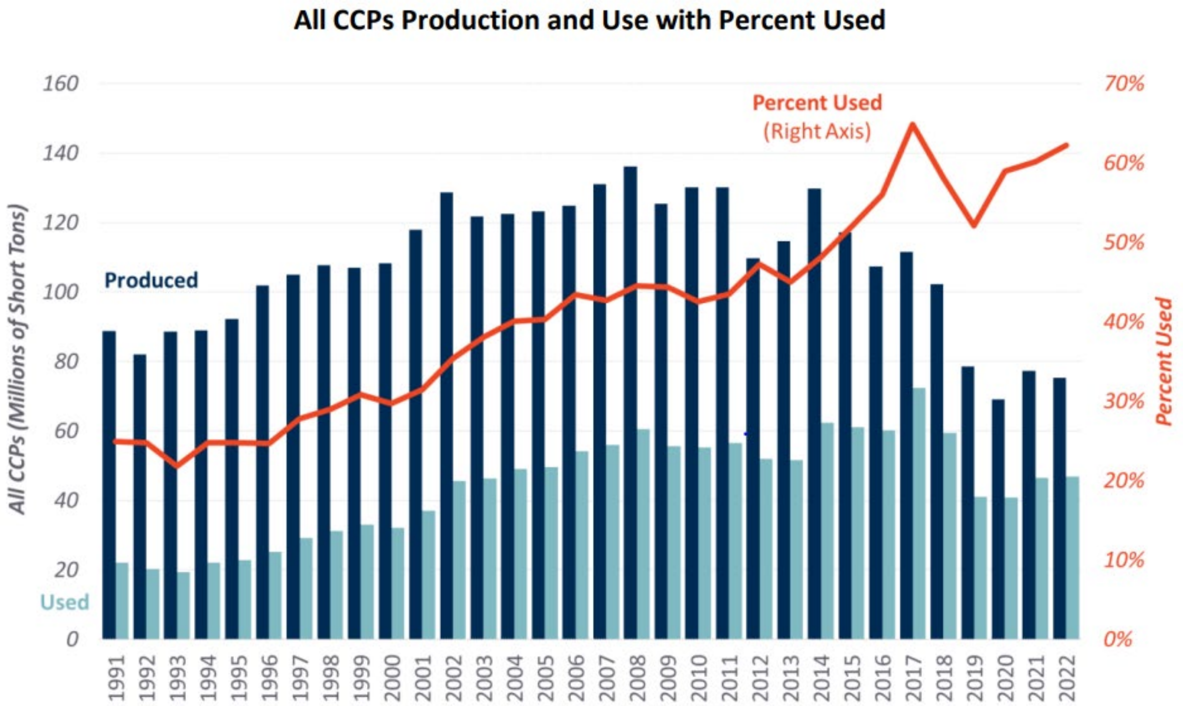
- Why Coal Ash
- From C618 - 13.2 The supplier's report shall disclose whether the source of the material represented in the certificate is fly ash, bottom ash, or commingled fly ash and bottom ash, and if the material is harvested coal ash.
- We are beyond Class C and F
  - Testing for optimal % of ash is necessary for Strength
  - Other requirements may determine percentage replacement

21% of ash used in 2024 was harvested ash

C618 Coal Ash

- Why Coal Ash





C618 Coal Ash

	10% Cement Replacement						15% Cement Replacement						20% Cement Replacement					
	Control	1:1	1.25:1	1.5:1	1.75:1	2:1	Control	1:1	1.25:1	1.5:1	1.75:1	2:1	Control	1:1	1.25:1	1.5:1	1.75:1	2:1
Water/Binder																		
485	0.635	0.635	0.619	0.603	0.589	0.576	0.635	0.635	0.613	0.590	0.571	0.552	0.635	0.635	0.606	0.567	0.552	0.530
555	0.563	0.563	0.549	0.536	0.523	0.512	0.563	0.563	0.542	0.523	0.505	0.490	0.563	0.563	0.536	0.511	0.489	0.469
625	0.493	0.493	0.481	0.470	0.459	0.448	0.493	0.493	0.475	0.459	0.443	0.429	0.493	0.493	0.470	0.448	0.429	0.411
Cement/Ash																		
485	485/0	437/49	437/61	437/74	437/86	437/98	485/0	412/73	412/91	412/110	412/128	412/146	485/0	388/97	388/121	388/156	388/170	388/194
555	555/0	500/55	500/69	500/83	500/97	500/110	555/0	472/83	472/104	472/125	472/146	472/166	555/0	444/111	444/139	444/167	444/195	444/222
625	625/0	563/63	563/78	563/93	563/110	563/125	625/0	531/94	531/118	531/141	531/165	531/188	625/0	500/125	500/156	500/188	500/219	500/250
True Ash %																		
485	0.0%	10.1%	12.2%	14.5%	16.4%	18.3%	0.0%	15.1%	18.1%	21.1%	23.7%	26.2%	0.0%	20.0%	23.8%	28.7%	30.5%	33.3%
555	0.0%	9.9%	12.1%	14.2%	16.2%	18.0%	0.0%	15.0%	18.1%	20.9%	23.6%	26.0%	0.0%	20.0%	23.8%	27.3%	30.5%	33.3%
625	0.0%	10.1%	12.2%	14.2%	16.4%	18.2%	0.0%	15.0%	18.2%	21.0%	23.7%	26.1%	0.0%	20.0%	23.8%	27.3%	30.5%	33.3%
Slump																		
485	3.75	4.00	4.25	4.50	4.75	4.75	3.00	3.50	3.75	4.25	4.50	4.75	3.75	4.50	5.00	5.50	5.50	5.25
555	4.00	4.75	5.25	5.00	5.50	5.25	4.25	4.75	4.75	5.75	5.25	5.75	4.25	5.00	5.50	6.00	5.50	5.50
625	5.00	5.00	5.50	5.50	5.50	5.25	4.75	5.75	5.50	5.00	5.00	4.75	4.50	4.75	6.00	5.00	5.00	4.75
7-Day																		
485	3200	2550	3000	3010	2960	2890	3300	2500	2660	2540	2700	2770	3280	2350	2380	2700	2510	2520
555	4160	3550	3610	3660	3670	3690	4170	3280	3280	3140	3540	3630	4000	3050	2990	3120	3270	3170
625	5090	4280	4280	4280	4650	4470	4910	3660	3960	4140	4190	4120	4770	3700	4000	3890	4000	4010
28-Day																		
485	4460	3710	4170	4120	4050	4210	4500	3690	4170	4110	4260	4350	4560	3630	3490	4070	3950	4250
555	5390	4680	4770	5000	5150	5210	5040	4260	4530	4670	4640	4940	4960	3970	4300	4430	4720	4940
625	6070	5440	5450	5520	6040	5920	5990	5230	5510	5530	5710	6180	6080	4930	5170	5340	5650	5760
56-Day																		
485	4640	4360	4440	4730	4810	4850	4750	4380	4640	4770	5310	5260	4710	4220	4270	4870	4520	4930
555	5680	5370	5470	6010	6090	6140	5190	4740	5030	5470	5420	5750	5120	4790	4950	5140	5700	5890
625	6430	5970	6260	6350	6710	6900	6090	5850	6210	6470	6620	6830	6090	6050	6230	6440	6780	6870

C618 Coal Ash

Benefits

- Improved workability
- Improved later age strength
- ASR Mitigation (Class F)
- Sulfate Mitigation (Class F)
- Reduced permeability

Challenges

- Lower early strength
- Controlling air

C1866 Ground Glass Pozzolan

Designation: C1866/C1866M – 22

Standard Specification for Ground-Glass Pozzolan for Use in Concrete[1]

This standard is issued under the fixed designation C1866/C1866M; the number immediately following the designa… year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicate… reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

4. Classification

4.1 *Type GS*—Ground soda-lime-silica glass that meets the applicable requirements for this Type as given herein. Typical sources of Type GS glass are container glass and plate glass.

NOTE 1—Total equivalent alkali range of this ground glass type is 10-15%, reported as Na_2O_{eq}. See Appendix X1 for information on alkali-silica reactivity.

4.2 *Type GE*—Ground glass that meets the applicable requirements for this Type as given herein. The typical source of Type GE glass is waste fibers from producers of glass fiber reinforcement.

NOTE 2—Total equivalent alkali range of this ground glass type is 0-1%, reported as Na_2O_{eq}.

TABLE 1 Chemical Requirements

	Classification	
	Type GS	Type GE
Silicon dioxide (SiO_2), min %	60.0	55.0
Aluminum oxide (Al_2O_3), max %	5.0	15.0
Calcium oxide (CaO), max %	15.0	25.0
Iron oxide (Fe_2O_3), max %	1.0	1.0
Sulfur trioxide (SO_3), max %	1.0	1.0
Total equivalent alkalies, Na_2O_{eq}, max %[A]	15.0	4.0
Moisture content, max %	0.5	0.5
Loss on ignition, max %[B]	0.5	0.5

[A] Na_2O_{eq} % = Na_2O + 0.658K_2O. See Notes 1 and 2 for total equivalent alkali content ranges.
[B] Loss on ignition shall be conducted at 600° C in accordance with CSA A3003.

Test Methods C311/C311M. Optional chemical requirements are shown in Table 2, tested in accordance with CSA A3004-A4 modified McMaster method.

TABLE 2 Optional Chemical Requirements[A]

	Classification	
	Type GS	Type GE
Amorphous Content[B], min %	95	95

[A] This optional requirement applies only if requested by the purchaser.
[B] Testing in accordance with CSA A3004-A4 modified McMaster method.

6. Physical Properties

6.1 Ground-glass pozzolans shall conform to the physical…

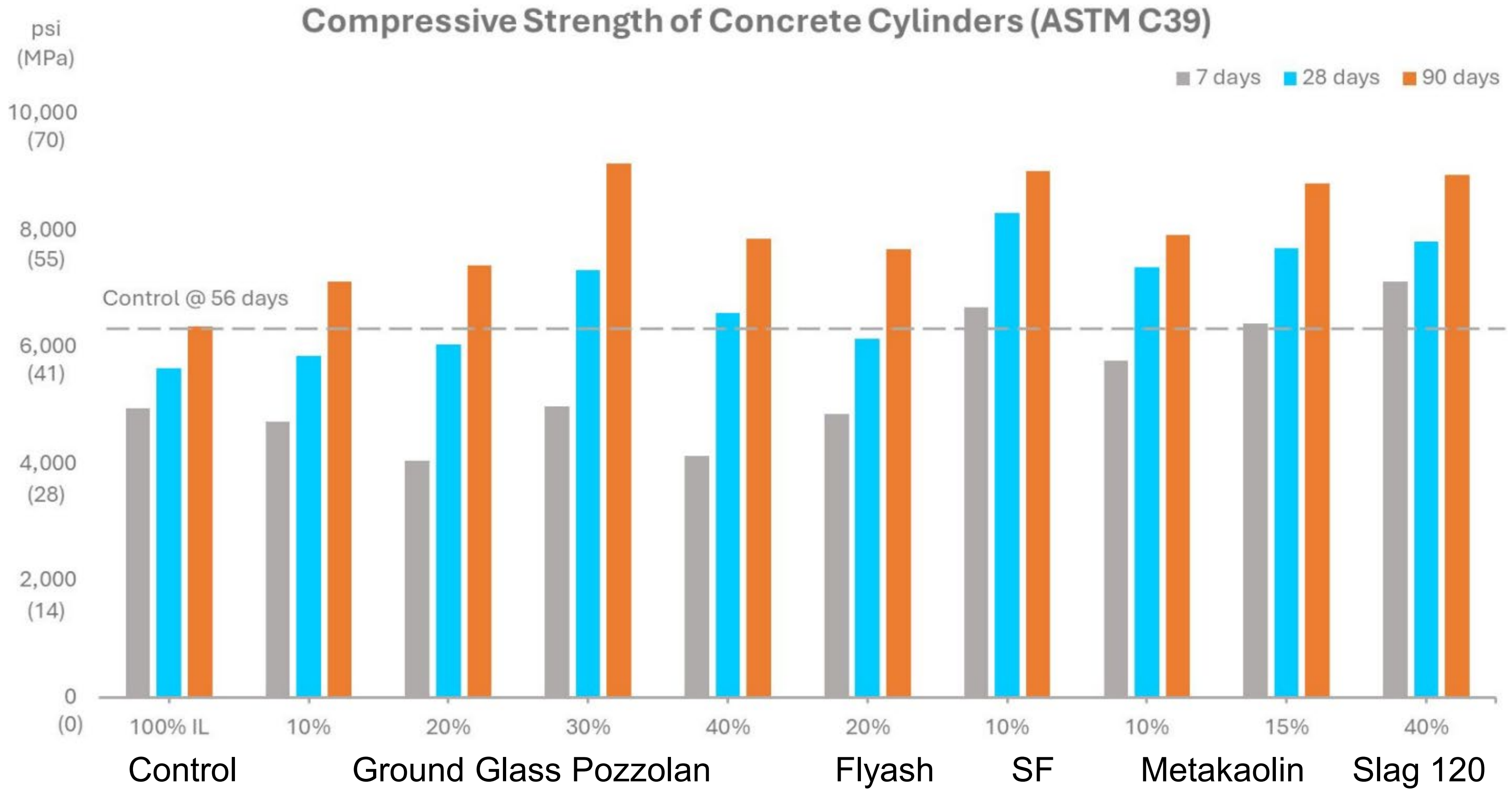
TABLE 3 Physical Requirements

	Classification	
	Type GS	Type GE
Fineness		
Amount retained when wet-sieved on 45 µm (No. 325 sieve), max %	5.0	5.0
Strength activity index		
With portland cement, at 7 days, min % of control	75[A]	75[A]
With portland cement, at 28 days, min % of control	85[A]	85[A]
Water requirement, max % of control	Report Only	Report Only
Relative Density	Report Only	Report Only

[A] Meeting both the 7-day and 28-day strength activity index is required for specification compliance.

NOTE 3—The strength activity index with portland cement is not to be considered a measure of the compressive strength of concrete containing the ground-glass pozzolan. The mass of ground-glass pozzolan specified for the test to determine the strength activity index with portland cement is not necessarily the proportion to be used in the concrete for the work. The optimum amount of ground-glass pozzolan for any specific project is determined by the required properties of the concrete and other constituents of the concrete and is to be established by testing. Strength activity index with portland cement is a measure of reactivity with a given cement and is subject to variation depending on the source of both the ground-glass pozzolan and the cement.

C1866 Ground Glass Pozzolan



C1866 Ground Glass Pozzolan

Benefits

- Increased strength
- Reduced Permeability
- ASR Mitigation
- Sulfate Mitigation
- White color

Challenges

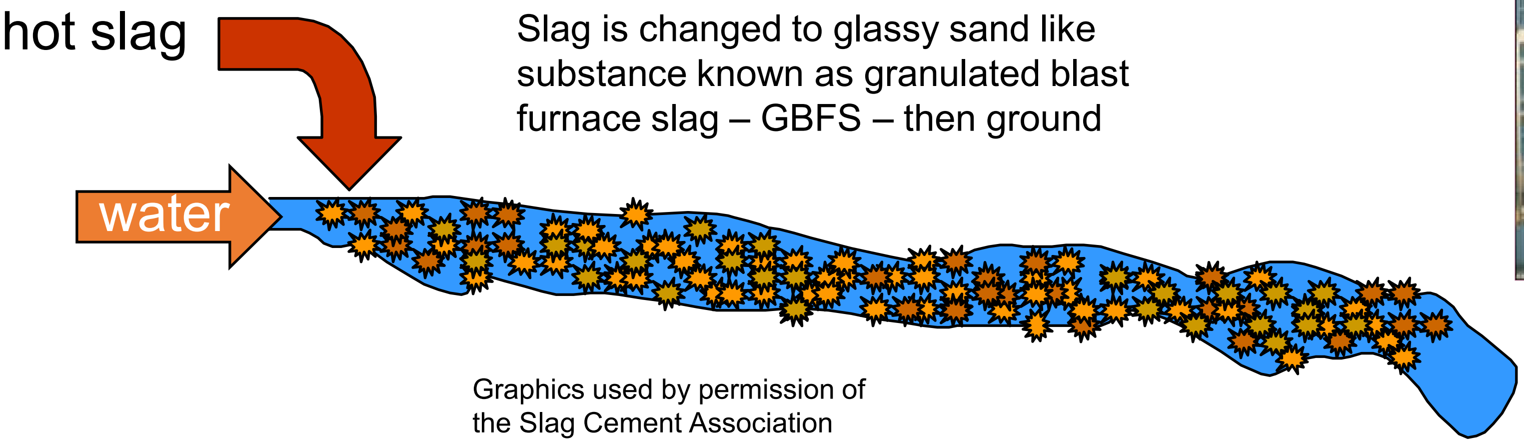
- Early strength

C1866 Ground Glass Pozzolan

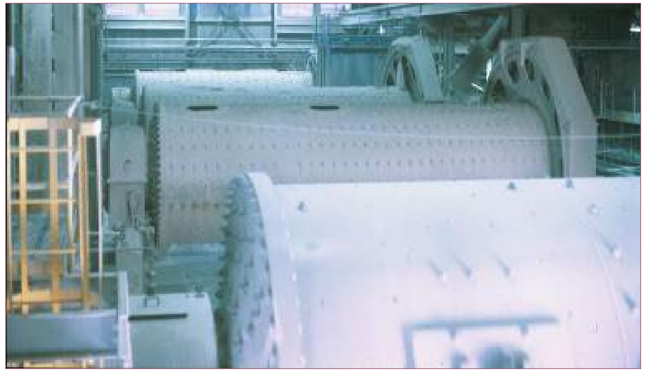
Control	20% Glass Pozz	30% Glass Pozz	30% Slag
Qty-lb (SSD)	Qty-lb (SSD)	Qty-lb (SSD)	Qty-lb (SSD)
675	540	473	473
0	0	0	203
0	135	203	0
1300	1274	1261	1288
1750	1750	1750	1750
263	263	263	263
oz/cwt	oz/cwt	oz/cwt	oz/cwt
0.25	0.62	0.21	0.29
4.00	4.00	4.00	4.10
0.50	0.50	0.50	0.50
0.39	0.39	0.39	0.39
0:11 Hr	0:10 Hr	0:10 Hr	0:10 Hr
1:00 PM	2:20 PM	3:42 PM	4:53 PM
148.76	142.56	149.06	149.08
5.2%	8.6%	4.1%	4.7%
5.5%	9.5%	4.5%	4.5%
6.50	7.00	7.00	6.75
0.00	0.00	0.00	0.00
72	72	71	71
5240.0	4460.0	3960.0	3920.0
6100.0	5320.0	5080.0	5960.0
7650.0	7950.0	8320.0	8540.0

C989 Slag Cement

- Produced from blast-furnace slag (reduction of iron ore) in a blast furnace
- Slag cement is hydraulic and produces calcium silicate hydrate (CSH) as a hydration product
- Slag cement is not projected to increase in supply



Slag is changed to glassy sand like substance known as granulated blast furnace slag – GBFS – then ground



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C989 Slag Cement

Benefits

- Higher later age strength
- Reduced Permeability
- Lower Shrinkage
- Sulfate Mitigation
- ASR Mitigation
- Mass Concrete
- White Color

Challenges

- Early Strength
- “Greening”

C989 Slag Cement

Tools

- Heat
- NCA
- HRWR
- Strength Enhancers

C1945 Metakaolin

Benefits

- Improved early & late strength
- Greatly reduced permeability
- Improved durability
- Light color

Challenges

- Water demand / workability
- Curing requirements

C1945 Metakaolin

Tools

- Water
- HRWR
- Rheology Modifiers

C1240 Silica Fume

- Produced in arc furnaces during the production of silicon alloys

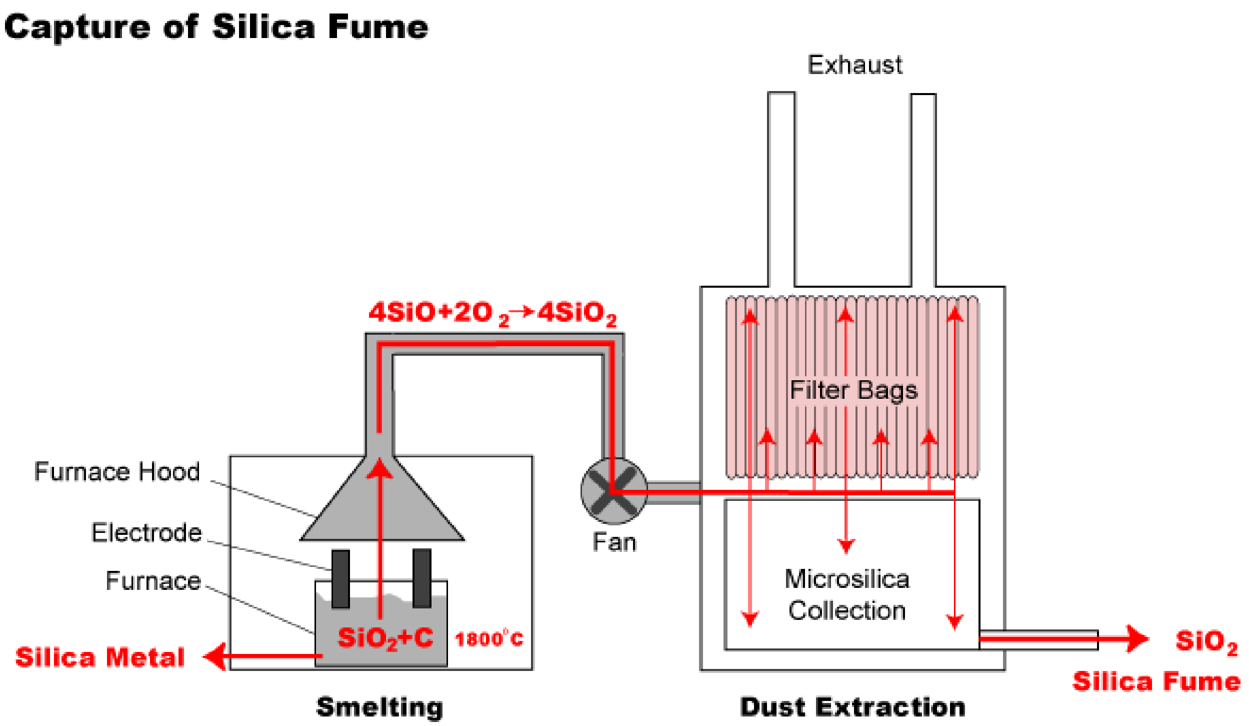


Image Source: http://www.bulkmaterialsinternational.net/bmi_silica_fume.html

- Extremely fine particle size (i.e., particle size averaging 0.1 to 0.2 micron in diameter)
- 100% Amorphous silica that is highly pozzolanic

Silica Fume

Benefits

- Improved early & late strength
- Greatly reduced permeability
- Improved durability

Challenges

- Water demand / workability
- Dark color
- Mixing requirements
- Curing requirements

Silica Fume

Tools

- Water
- HRWR
- Rheology Modifiers

C1945 Raw or Calcined Natural Pozzolans

Types of Natural Pozzolans

- **Raw** – Includes volcanic materials and DE
- **Calcined** – Includes Metakaolin, other calcined Clays, calcined Shales and Slates; other siliceous rocks.

C1945 Raw or Calcined Natural Pozzolans

- 95% of Natural Pozzolans are raw (not calcined)
- Most Natural Pozzolans are in the West and are volcanic (pumice, perlite, obsidian, rhyolite, volcanic ash)
- Most reactive clays are in the East and need to be calcined
- Current NP use is 70% concrete, 30% Cement; that will likely reverse in the next 10 years (IP, IT)

C1945 Raw or Calcined Natural Pozzolans

General Properties of Raw Natural Pozzolan

- High in Silica and alumina (70+ %)
- Mostly non-crystalline amorphous material
- Porous with similar or higher water demand than cement
- Typical Median Particle size between 10~15µ micron
- Strength Activity Index – relative to cement – of 75~100%+
- at 7d and 28d breaks (C618)

C1945 Raw or Calcined Natural Pozzolans

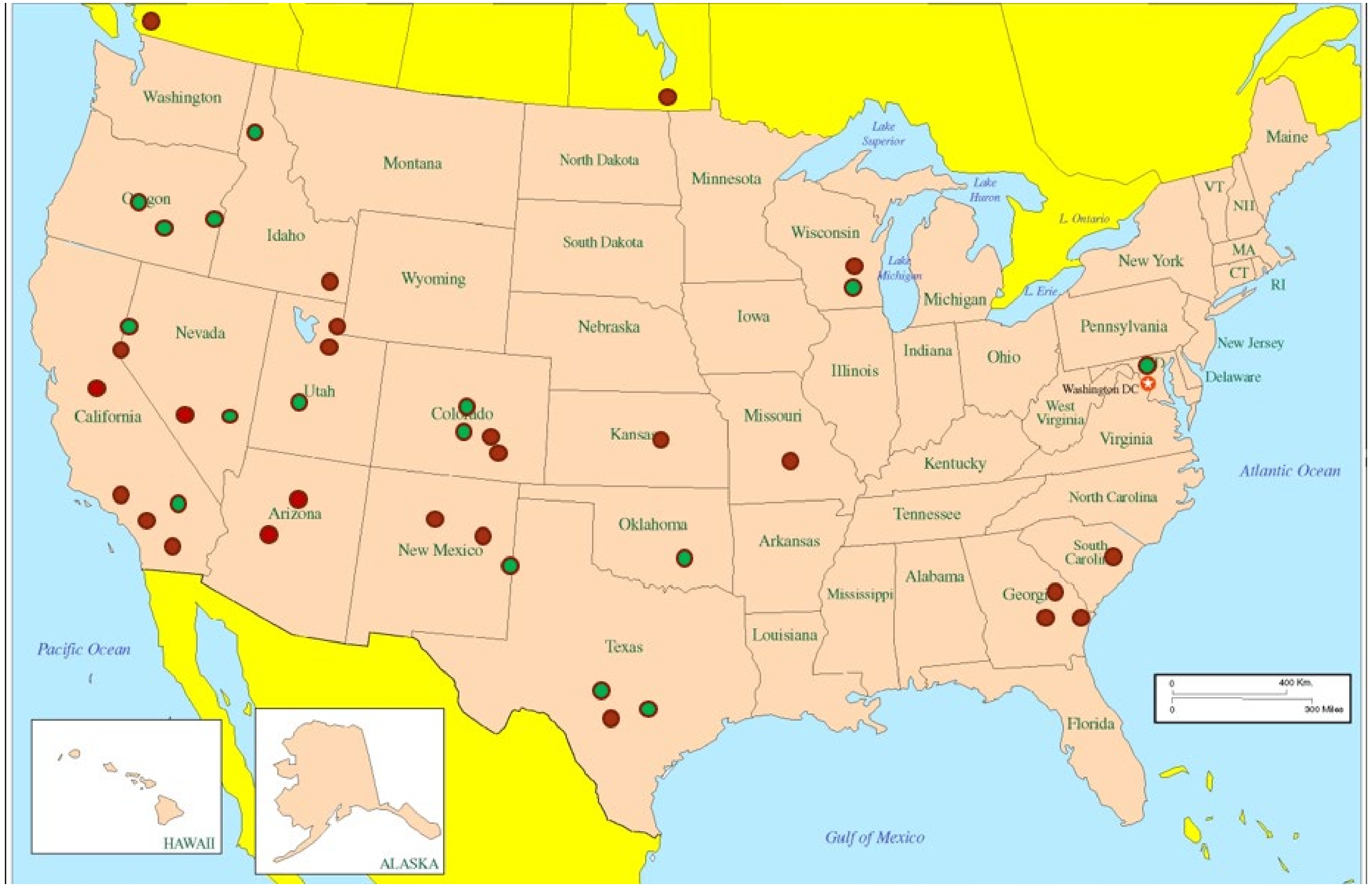
Benefits of Natural Pozzolan

- Reduction in Carbon footprint compared to cement
- Reduction in concrete permeability/increased resistivity
- Mitigates ASR
- Mitigates Sulfate attack
- Reduces Heat of Hydration
- Significant long-term strength add to concrete
- Reduces or eliminates Efflorescence

C1945 Raw or Calcined Natural Pozzolans

<u>2023</u>

- Operating or Permitted
- Under Development



C1945 Raw or Calcined Natural Pozzolans

<u>Benefits of Natural Pozzolan</u>

- Increased water demand
- Lower strength
- Sticky
-

Challenging Aggregates

- Changing to manufactured sand from natural
- Gradation issues
- Clay issues
- Particle shape
- Water demand
- Too fine or too coarse

Challenging Aggregates

Solutions

- Rheology Modifiers
- Viscosity Modifiers
- MRWR – Built in rheology improvement
- Mix Optimization

General Solutions

High-Range Water Reducers

- Reduced water content / w/c to improve early and later age strengths
- Improved flow
- Overcome increased water demand to maintain strength

Non-Chloride Accelerators

- Improve early age strengths

General Solutions

Rheology Modifiers

- Reduced stickiness
- Improved flow

Strength Enhancers

- Improve early and later age strengths

General Solutions

Calorimetry

- Set times
- Relative Strength

Mortar Testing ASTM C1810

- Quicker than concrete
- Test more materials in a short period of time
- Compare materials
- Reduce the number of concrete tes
- Use as a QC tool

General Solutions

Rheology Modifiers

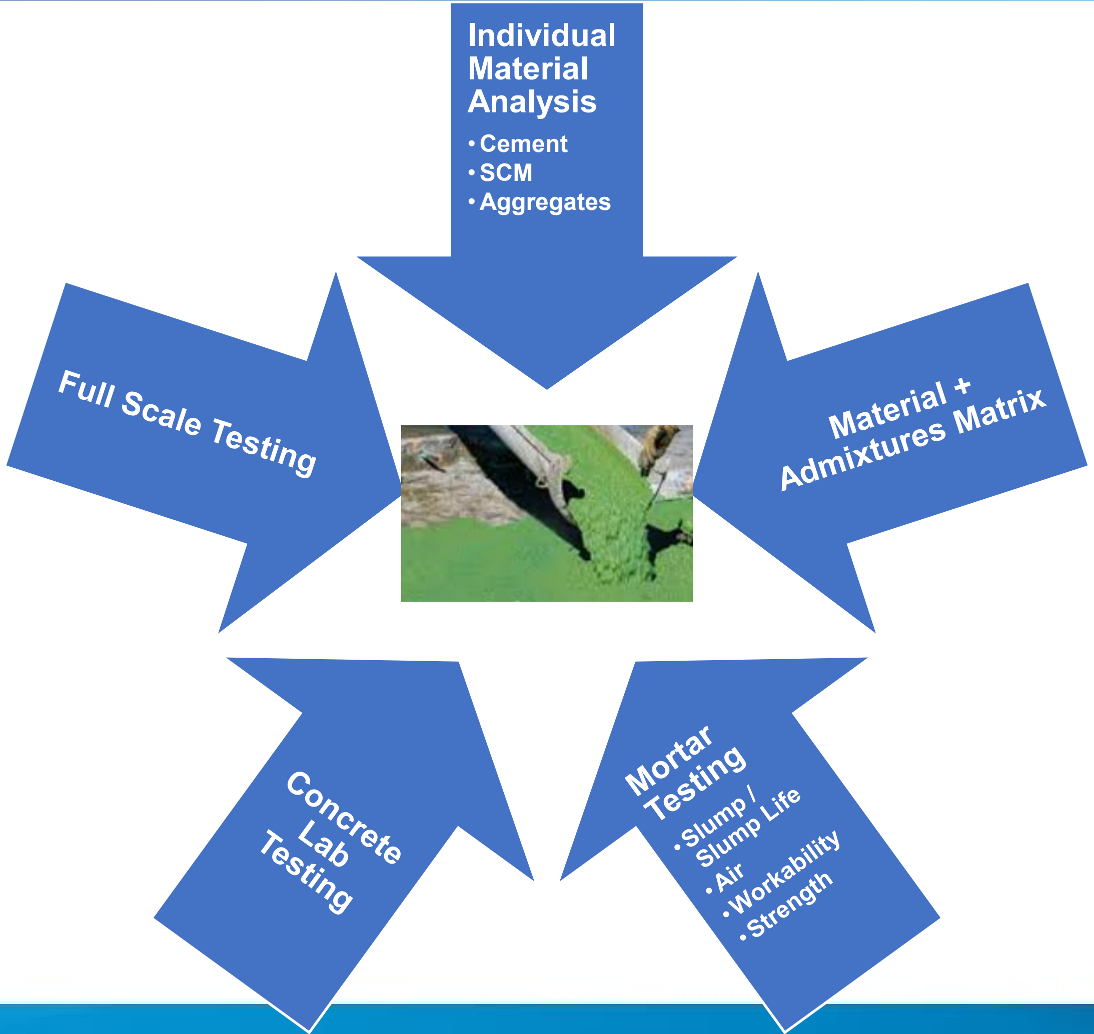
- Reduced stickiness
- Improved flow

Strength Enhancers

- Improve early and later age strengths

Material Evaluation Process

Material Impact Analysis



Impacts of Alternative Materials: Advantages & Risk

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