

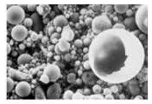

**Supplementary Cementitious Materials (SCMs)**

**Anthony F. Bentivegna, PhD, PE**

**May 8, 2018**

## References


- ASTM C109 / C109M-16a, Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens), ASTM International, West Conshohocken, PA, 2016, www.astm.org
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- ASTM C311 / C311M-17, Standard Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use in Portland-Cement Concrete, ASTM International, West Conshohocken, PA, 2017, www.astm.org
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- ASTM C618-17a, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete, ASTM International, West Conshohocken, PA, 2017, www.astm.org
- ASTM C989 / C989M-18, Standard Specification for Slag Cement for Use in Concrete and Mortars, ASTM International, West Conshohocken, PA, 2018, www.astm.org
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- ASTM C1202-17a, Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration, ASTM International, West Conshohocken, PA, 2017, www.astm.org
- ASTM C1240-15, Standard Specification for Silica Fume Used in Cementitious Mixtures, ASTM International, West Conshohocken, PA, 2015, www.astm.org
- ASTM C1556-11a(2016), Standard Test Method for Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion, ASTM International, West Conshohocken, PA, 2016, www.astm.org
- Portland Cement Association – 16th Edition, Design and Control of Concrete Mixtures
- Silica Fume Association – Presentation, “Silica Fume in Concrete”




## Agenda

Supplementary Cementitious Materials (SCMs)

- **Introduction to SCMs**
- Slag Cement:
  - Production, Specification, and Use in Concrete
- Fly Ash:
  - Production, Specification, and Use in Concrete
- Silica Fume:
  - Production, Specification, and Use in Concrete





## What are SCMs?

Supplementary Cementing Materials (SCMs)

- A material that, when used in conjunction with portland cement, contributes to the properties of the hardened concrete through hydraulic or pozzolanic activity.

From left to right:
- Fly ash (Class C)
- Metakaolin (calcined clay)
- Silica fume
- Fly ash (Class F)
- Slag
- Calcined shale



## Two Categories of SCMs

**Pozzolanic** – a siliceous or alumnino-siliceous material, chemically reacts at ordinary temperatures with calcium hydroxide released by hydration products of portland cement to form cementing properties.

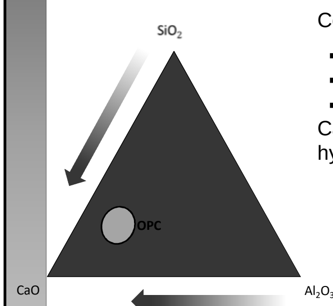
- Does **NOT** in itself produce hydration products

**Hydraulic** – a material that reacts chemically with water to form compounds that have cementing properties

- Forms hydration products in itself e.g. portland cement



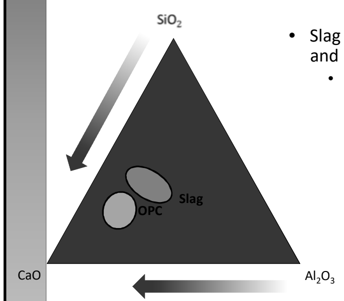
## Ordinary Portland Cement (OPC)



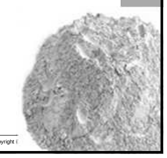

Composition:
- 60% CaO
- 20% $SiO_2$
- 5-10% $Al_2O_3$

CaO indicator of hydraulic product

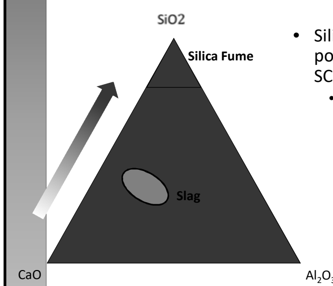
## Composition: Slag Cement



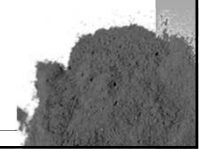

- Slag – Most cementitious and least pozzolanic SCM
  - Byproduct of the Steel industry



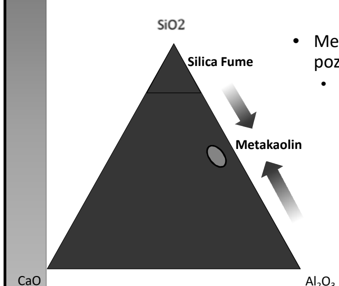
## Composition: Silica Fume




- Silica Fume – (SF) Purely pozzolanic and finest sized SCM
  - Byproduct of the silicone alloy industry



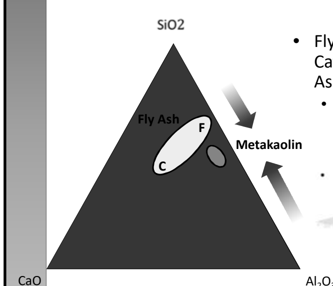
## Composition: Metakaolin




- Metakaolin - Purely pozzolanic SCM
  - Specific kind of clay



## Composition: Fly Ash




- Fly Ash – Two Different Categories F-Ash and C-Ash
  - Although Both are the byproducts of burning coal *their effects on Concrete differ greatly*
  - Both fly ashes improve work ability due to spherical nature

## Two Categories: Class F and C

**Class F Fly Ash**

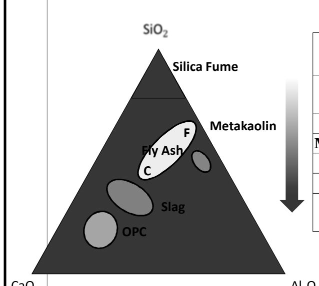
- Derived from anthracite or bituminous coals
- Pozzolanic reaction → slower rate of reaction that Class C fly ash
- Composition:
  - <20% CaO
  - >50% SiO$_2$

**Class C Fly Ash**

- Derived from lignite or sub-bituminous coals
- Pozzolanic and hydraulic reactions
- Composition:
  - >20% CaO
  - 30-50% SiO$_2$



## Pozzolanic vs. Hydraulic




| SCM | Pozzolanic | Hydraulic |
|---|---|---|
| Silica Fume | XXXXX | |
| F-Ash | XXXX | |
| Metakaolin | XXXX | |
| C-Ash | XX | XX |
| Slag | X | XXXX |
| Portland Cement | | XXXXX |

## Agenda

Supplementary Cementitious Materials (SCMs)

- Introduction to SCMs
- **Slag Cement:**
  - **Production, Specification, and Use in Concrete**
- Fly Ash:
  - Production, Specification, and Use in Concrete
- Silica Fume:
  - Production, Specification, and Use in Concrete

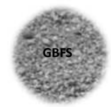



## Terminology

***Slag Cement***

Ground Granulated Blast Furnace Slag (GGBFS)

Granulated blast furnace slag (GBFS)







## Manufacturing

Byproduct of iron and steel manufacturing process

Materials fed into furnace:

- coke, natural gas, oxygen and pulverized coal and also limestone as a fluxing agent

Two Products:

- Molten iron metal
- Molten blast furnance slag

Slag Run-off from an Open Hearth Furnace



## Quenching Molten Slag and Grinding

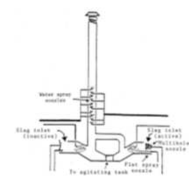
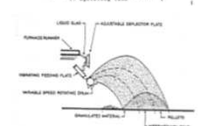
Two Methods:

- Water granulator
- Air granulator

Dried and Dewatered

Crushed Using Traditional Ball Mill

- Usually finer than cement



## Specifications and Grade of Ground Granulated Iron Blast-Furnace Slags

ASTM C 989 (AASHTO M 302)

Grade 80

- Slags with a low activity index

Grade 100

- Slags with a moderate activity index

Grade 120

- Slags with a high activity index



## Slag Cement

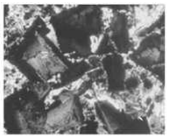
Glassy granular material formed when molten blast-furnace slag is rapidly chilled, as by immersion in water

Non-metallic product, consisting of silicates and aluminosilicates of calcium and other bases

| Component | Mass (%) |
|---|---|
| CaO | 30-50 |
| $SiO_2$ | 28-38 |
| $Al_2O_3$ | 8-24 |
| MgO | 1-18 |

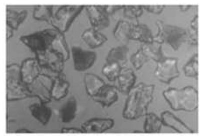
## Slag Cement

**Air-Cooled Slag**



- Crystallin Structure
  - Little to No Cementitious behavior

**Quenched Slag**



- Amorphous/ Glassy structure
  - Reactive and similar to PC



## Classification

Slag is Classified as Grade 80, 100, and 120

- Determined from compressive strength

ASTM C109 and ASTM C1437 (2 Mixes)

- Slag mixture 50/50 slag and reference cement
- Reference mixture – only reference cement

| | | |
|---|---|---|
| Total Alkalies ($Na_2O + 0.658\ K_2O$) | min % | 0.60 |
| | max % | 0.90 |
| Compressive Strength, MPa, min, 28 days[A] | | 35 [5000 psi] |



## Classification

Slag Activity Index, % = (SP / P) X 100

SP = Average compressive strength of slag–cement mortar cubes, Mpa

P = Average compressive strength of cement mortar cubes, MPa

| | Average of Last Five Consecutive Samples | Any Individual Sample |
|---|---|---|
| Slag Activity Index | | |
| 28-Day Index, min.% | | |
| Grade 80 | 75 | 70 |
| Grade 100 | 95 | 90 |
| Grade 120 | 115 | 120 |



## Physical Requirements

| | Item |
|---|---|
| Fineness: | |
| Amount retained when wet screened on a 45-µm Sieve, max. % | 20 |
| Specific surface by air permeability, Test Methods C204 shall be determined and reported although no limits are requried. | … |
| Air Content of Slag Mortar, max. % | 12 |



## Chemical Requirements

Composition Depends mainly on the composition blast furnace oxides

Variability between sources exist, but relatively low within the same plant

ASTM C989 Limits

- Sulfide sulfur content (S), to 2.55
- Determined per ASTM C114



## Typical Dosage

| Application | Dosage (% by wt.) |
|---|---|
| Exterior Flatwork | ≤ 35% |
| General Usage | 35 to 50% |
| Mass Concrete | 60 to 80% |
| Sulfate Resistance | |
| ASTM C150 – Type II Equivalent | ≥ 35% |
| ASTM C150 – Type V Equivalent | ≥ 50% |
| Marine Exposure | > 50% < 80% |

## Mixture Proportioning

Concrete Properties

- Typical Dosage – 35-50%
- w/c ratio – w/(cement + slag) ratio
- Water Demand – 1 to 5% lower

Admixture dosage

- Similar for air-entraining admixtures
- Slightly lower for other admixtures

SG 2.90



## Slag Benefits – Water Demand

Reduces Water Demand

Improved Pumpability



## Slag Benefits – Workability

Improved Workability Due To:

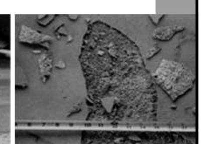
- Smooth surface creating slip planes
- Low absorption of water (unlike OPC)
- Better particle dispersion
- Consolidates better under mechanical vibration



## Slag Benefits – Finishability and Increase Setting Time

Delayed Bleeding

- Latent free water to the surface
- Potential for trapping water just below finished surface





## Slag Benefits – Finishability and Increase Setting Time

Improve Finishability Extends Setting Time

- Latent hydraulic material
- Benefit in weather environments



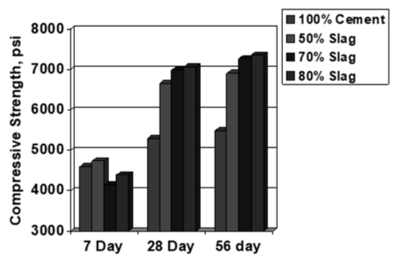
## Effects of Slag Cement on Fresh Concrete

↓ *Reduced* ⇨ *No/Little Effect*

↑ *Increased* ↕ *Varies*

| | Slag |
|---|---|
| Water Requirements | ↓ |
| Workability | ↑ |
| Bleeding and Segregation | ↕ |
| Air Content | ↕ |
| Heat of Hydration | ↓ |
| Setting Time | ↑ |
| Finishability | ↑ |
| Pumpability | ↑ |
| Plastic Shrinkage Cracking | ⇨ |

## Slag and Higher Strengths






## Effects of Supplementary Cementing Materials on Hardened Concrete

↓ *Reduced* ➡ *No/Little Effect*
↑ *Increased* ⬍ *Varies*

| | Slag |
|---|---|
| Strength Gain | ⬍ |
| Abrasion Resistance | ➡ |
| Freeze-Thaw and Deicer-Scaling Resistance | ➡ |
| Drying Shrinkage and Creep | ➡ |
| Permeability | ↓ |
| Alkali-Silica Reactivity | ↓ |
| Sulphate Resistance | ↑ |
| Carbonation | ➡ |
| Concrete Colour | ⬍ |

## Agenda

Supplementary Cementitious Materials (SCMs)

- Introduction to SCMs
- Slag Cement:
  - Production, Specification, and Use in Concrete
- **Fly Ash:**
  - **Production, Specification, and Use in Concrete**
- Silica Fume:
  - Production, Specification, and Use in Concrete



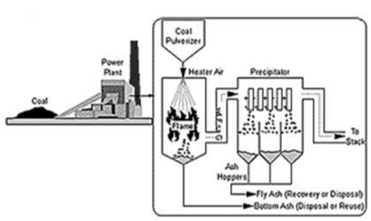

## What is Fly Ash?

Fly ash is the ***finely-divided*** residue produced in coal-fired ***electric power*** generating plants as an industrial by-product of the combustion of ground or powdered ***coal***.



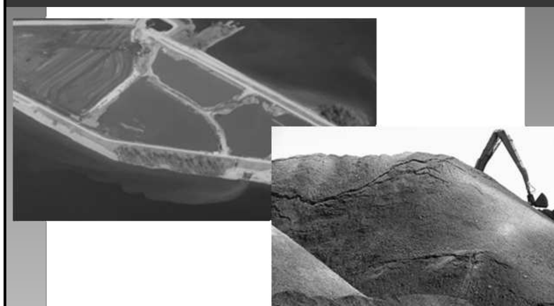
## Boiler Layout – Fly Ash "Production"

- Dry-Bottom Boiler
- Fly ash and bottom ash created
- 80% of ash leaves the furnace as fly ash

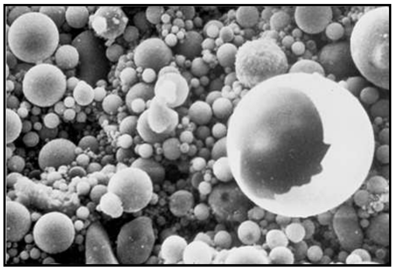





## Storage

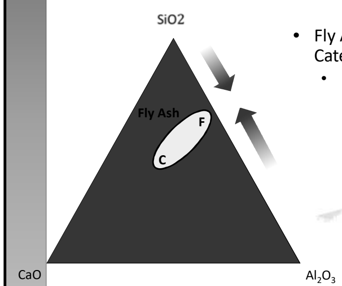


## SEM Micrograph of Fly Ash Particles





## Composition: Fly Ash




- Fly Ash – Two Different Categories F-Ash and C-Ash
  - Although Both are the byproducts of burning coal their effects on concrete differ greatly



## Two Categories: Class F and C

**Class F Fly Ash**

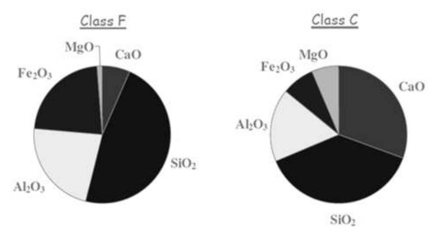
- Derived from anthracite or bituminous coals
- Pozzolanic reaction → slower rate of reaction that Class C fly ash
- Composition:
  - $SiO_2 + Al_2O_3 + Fe_2O_3 \geq 70\%$
  - <20% CaO
  - >50% $SiO_2$

**Class C Fly Ash**

- Derived from lignite or sub-bituminous coals
- Pozzolanic and hydraulic reactions
- Composition:
  - $SiO_2 + Al_2O_3 + Fe_2O_3 \geq 50\%$
  - >20% CaO
  - 30-50% $SiO_2$



## Classification






## Fly Ash and Setting Time

Fly ash slows setting time of concrete

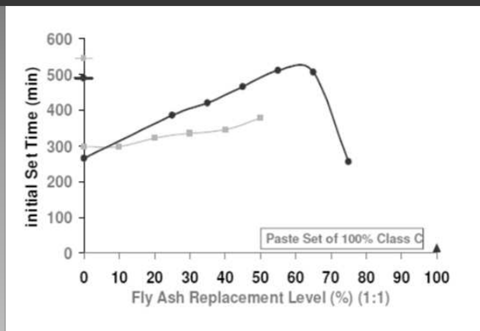
Class C fly ash (at typical dosages) tends to retard more than Class F fly ash (work is needed to understand the mechanism)



## Effect of Fly Ash on Concrete: Setting Time

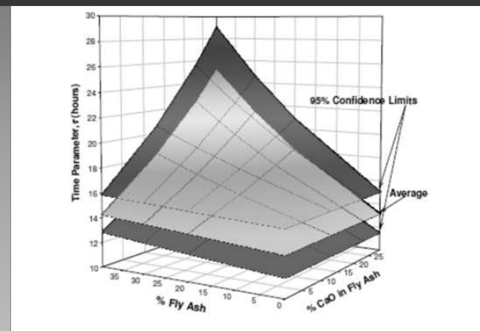
| Fly ash test mixtures | | Setting time, hr:min | | Retardation relative to control, hr:min | |
|---|---|---|---|---|---|
| | | **Initial** | **Final** | **Initial** | **Final** |
| Average of: | Class C | 4:40 | 6:15 | 0:30 | 0:45 |
| | Class F | 4:50 | 6:45 | 0:35 | 1:15 |
| Control mixture | | 4:15 | 5:30 | — | — |

## Class C Ash Influence on Setting Time






## Modeling of Fly Ash Setting Time



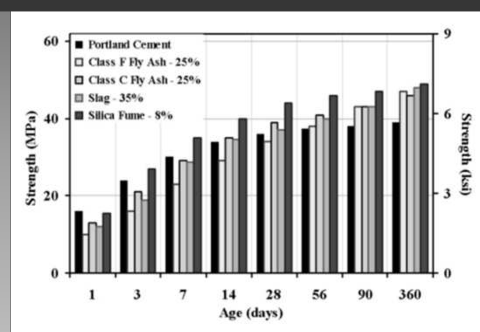



## Effects of Supplementary Cementing Materials on Freshly Mixed Concrete

⬇ *Reduced* ➡ *No/Little Effect*
⬆ *Increased* ⬍ *Varies*

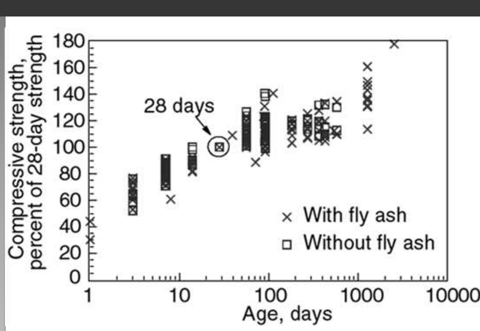
| | Fly ash |
|---|---|
| **Water Requirements** | ⬇ |
| **Workability** | ⬆ |
| **Bleeding and Segregation** | ⬇ |
| **Air Content** | ⬇ |
| **Heat of Hydration** | ⬇ |
| **Setting Time** | ⬆ |
| **Finishability** | ⬆ |
| **Pumpability** | ⬆ |
| **Plastic Shrinkage Cracking** | ➡ |

## Compressive Strength Development



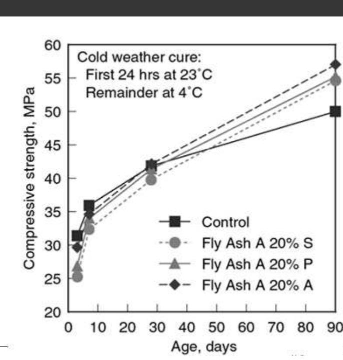



## Long Term Strength Development

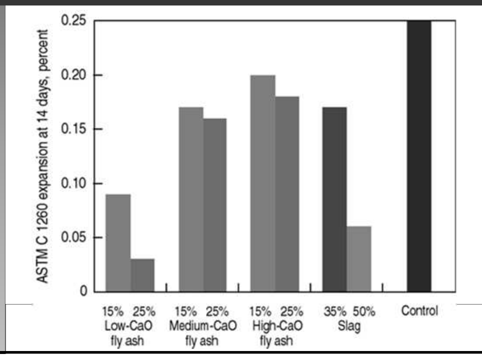





## Cold Weather Strength Development



## Effect of Fly Ash and Slag on Alkali-Silica Reactivity




## Effects of Supplementary Cementing Materials on Hardened Concrete

Key: ↓ *Reduced* · ↑ *Increased* · ⇨ *No/Little Effect* · ⬍ *Varies*

| | Fly ash |
|---|---|
| Strength Gain | Varies |
| Abrasion Resistance | No/Little Effect |
| Freeze-Thaw and Deicer-Scaling Resistance | No/Little Effect |
| Drying Shrinkage and Creep | No/Little Effect |
| Permeability | Reduced |
| Alkali-Silica Reactivity | Reduced |
| Sulphate Resistance | Increased |
| Carbonation | No/Little Effect |
| Concrete Colour | Varies |

## Agenda

Supplementary Cementitious Materials (SCMs)

- Introduction to SCMs
- Slag Cement:
  - Production, Specification, and Use in Concrete
- Fly Ash:
  - Production, Specification, and Use in Concrete
- **Silica Fume:**
  - **Production, Specification, and Use in Concrete**

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## Terminology

Silica Fume

- Condensed silica Fume
- Microsilica
- Silica dust
- "Micropoz" (trademark)
- Silica dust
- Volatilized silica

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## Terminology

Silica Fume is **NOT:**

- Precipitated silica
- Fumed silica
- Gel silica
- Colloidal silica
- Silica flour

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## Specifications for Silica Fume

ASTM C1240

- Finely divided residue resulting from the production of silicon, ferro-silicon, or other silicon-containing alloys that is carried from the burning surface area of an electric-arc furnace by exhaust gases.

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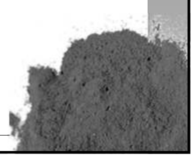
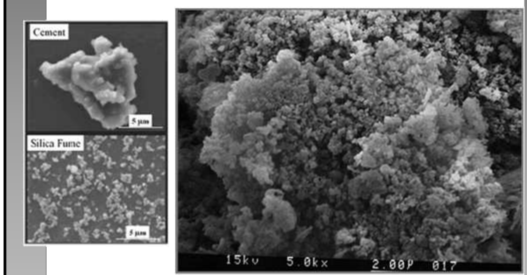
## Composition: Silica Fume


- Silica Fume – (SF) Purely pozzolanic and finest sized SCM
  - Byproduct of the silicone alloy industry



## SEM Micrograph Silica Fume



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## Applications for Silica Fume



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## Silica Fume

Production

- Silica fume is the ultra fine non-crystalline silica produced in electric-arc furnaces as an industrial by-product of the production of silicon metals and ferrosilicon alloys.



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## How it Helps

How it helps….

- 100X smaller than avg. cement particle
- Reduces permeability of hardened concrete
- Less segregation and bleeding
- Used to control reactive aggregates

Implications….

- Reduced workability… HRWR (1-2 times)
- Requires more water
- Requires more air (1-4 times)
- “Sticky” mixes
- Increased cost



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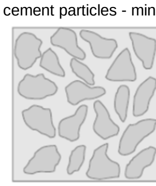
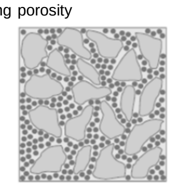
## Role of Silica Fume

Micro-filler Effect (Physical Effect)

- Average particle size of silica fume is 0.1 µm (1/100th average size of a cement grain)
- Leads to “dense packing” of the silica fume particles between the cement particles - minimizing porosity



Cement Only



with Silica Fume



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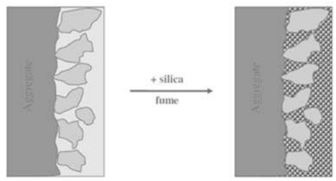
## Role of Silica Fume

Wall Effect

- Transition zone along aggregate interface is minimized
  - Decreasing permeability and increasing the strength of the mix




Cement Only — with Silica Fume



## Typical Dosage

Limit Silica Fume Dosage to 6-8% by volume

- ACI 318 limit is <= 10% based on freeze thaw resistance
- Increased cost of concrete
- Requires more admixtures to compensate impact on workability
  - HRWR
  - Air Entrainment




## Production of Silica Fume Concrete

Addition

- Batch in cement hopper and weighed with cement
- Added in bags (when small amount is required)




## Central Batch Mix Plant (Preferred)

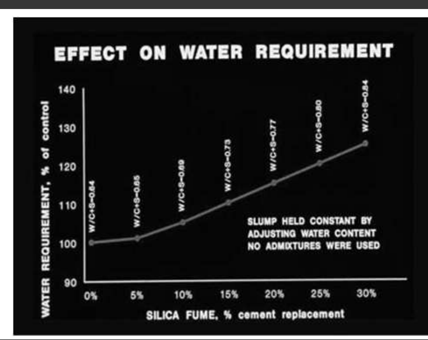



## Truck Mixed Concrete (Not Preferred)





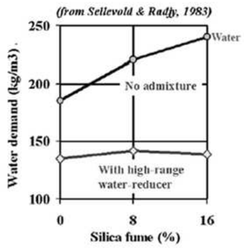
## Water Demand



## Water Demand

Silica fumes small particle size and large surface area imposes a very high water demand.

- Do not compensate with water along. That would offset the durability benefits. Must use water reducing agent to get desired workability.






## Finishability

Due to it’s high surface area more water is needed typically paired with a high range water reducer.

Mixes with silica fume are naturally sticky, making it a perfect application for shotcrete and overhead applications in the field

## Early-age Volume Change

Plastic Shrinkage:

- Shrinkage that takes place before cement paste, mortar, grout, or concrete sets.

## Early-age Volume Change (1/2)

Silica Fume:

- Silica fume has little effect on initial or final set.
- However, it is very difficult to finish or determine finishing time based upon observed bleeding.
- Plastic Shrinkage cracks often occur due to improper finishing or curing when dealing with silica fume

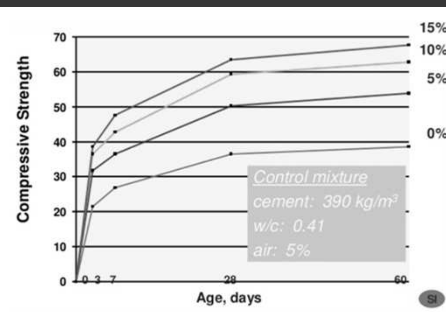
 

## Effects of Silica Fume on fresh concrete

Legend: ⬇ *Reduced* ⬆ *Increased* ➡ *No/Little Effect* ⬍ *Varies*

| | Silica fume |
|---|---|
| Water Requirements | ⬆ |
| Workability | ⬇ |
| Bleeding and Segregation | ⬇ |
| Air Content | ⬇ |
| Heat of Hydration | ⬍ |
| Setting Time | ➡ |
| Finishability | ⬍ |
| Pumpability | ⬆ |
| Plastic Shrinkage Cracking | ⬆ |

## Compressive Strength

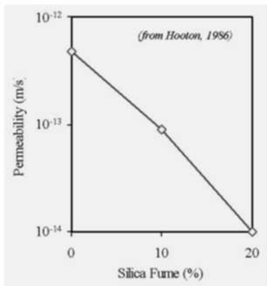


## Permeability of Concrete

Effect of Silica Fume:

- Significant reductions (~ 5 times) being observed when 10% of the cement is replaced with silica fume.

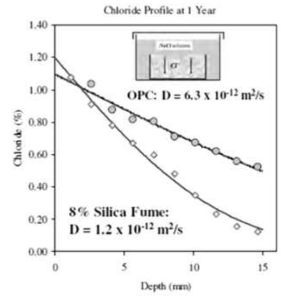






## Evaluating the Benefits of Silica Fume

ASTM C 1556 Bulk Diffusion Test







## Ternary Blends

The blending of 2 or more SCM's can provide additional benefit to the concrete material fresh and hardened properties

- Silica fume + Class F Fly Ash
  - The silica fume compensates for the low early-strength of Class F Fly Ash
- Fly Ash + Slag + Silica Fume
  - Fly Ash and Slag increase long-term strength development
  - Fly Ash and Slag help offset the increased water demad of the silica fume




## Ternary Blends (Continued)

- Silica fume + Class C Fly Ash or Slag
  - The silica fume compensates for high quantities of Class C Ash or Slag typically required for ASR resistance
- Class F Fly Ash and Slag with Silica Fume
  - Fly Ash and Slag offset the high heat of hydration created by silica fume




## Effects of SCMs on fresh concrete

| ↓ *Reduced* → *No/Little Effect* ↑ *Increased* ↕ *Varies* | Fly ash | Slag | Silica fume | Nat. Pozzolans |
|---|---|---|---|---|
| Water Requirements | ↓ | ↓ | ↑ | → |
| Workability | ↑ | ↑ | ↓ | ↑ |
| Bleeding and Segregation | ↓ | ↕ | ↓ | → |
| Air Content | ↓ | ↕ | ↓ | → |
| Heat of Hydration | ↓ | ↓ | ↕ | ↓ |
| Setting Time | ↑ | ↑ | → | → |
| Finishability | ↑ | ↑ | ↕ | ↑ |
| Pumpability | ↑ | ↑ | ↑ | ↑ |
| Plastic Shrinkage Cracking | → | → | ↑ | → |

## Effects of Supplementary Cementing Materials on Hardened Concrete

| ↓ *Reduced* → *No/Little Effect* ↑ *Increased* ↕ *Varies* | Fly ash | Slag | Silica fume | Nat. Pozzolans |
|---|---|---|---|---|
| Strength Gain | ↕ | ↕ | ↑ | ↕ |
| Abrasion Resistance | → | → | → | → |
| Freeze-Thaw and Deicer-Scaling Resistance | → | → | → | → |
| Drying Shrinkage and Creep | → | → | → | → |
| Permeability | ↓ | ↓ | ↓ | ↓ |
| Alkali-Silica Reactivity | ↓ | ↓ | ↓ | ↓ |
| Chemical Resistance | ↑ | ↑ | ↑ | ↑ |
| Carbonation | → | → | → | → |
| Concrete Color | ↕ | ↕ | ↕ | ↕ |

## Standards

| | |
|---|---|
| ASTM C 618 | Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete |
| ASTM C 989 | Standard Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars |
| ASTM C 1240 | Standard Specification for Silica Fume for Use as a Mineral Admixture in Hydraulic-Cement Concrete, Mortar, and Grout |
| ASTM C 595 | Standard Specification for Blended Hydraulic Cements Has PC+SCM grounded and blended together |
| ASTM C 1157 | Standard Performance Specification for Blended Hydraulic Cement |




## QUESTIONS?

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