3D Concrete Printing:
From Materials Selection to Testing

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Approach: 3D Concrete Printing

- Innovative design and construction practices are looking at additive manufacturing to improve sustainability of construction.
- Aim: reduce environmental impact at the same time as reducing economic costs

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Materials Requirements

- Raw materials influence the fresh and hardened proprieties of concrete
- Easily-flowing and easily-extrudable
- Comprise mainly of powder materials to meet the required printability
- Chemical admixtures provide positive contributions the fresh properties of concrete

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Materials for 3D Printing

- Cement
  - Portland Cement
  - Calcium Aluminate Cement
- Supplementary Cementitious Materials (SCMs)
  - Fly Ash
  - Silica Fume
  - Slag Cement
  - Limestone

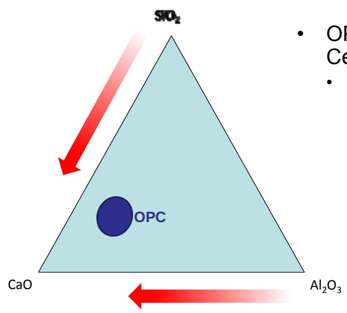
What are SCMs?

- 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.

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** – cement that reacts chemically with water to form compounds that have cementing properties
  - Forms hydration products in itself e.g. portland cement

Composition: Portland Cement



- OPC – Ordinary Portland Cement (60% CaO)
  - Calcium (Ca) is a strong indicator of a hydraulic product

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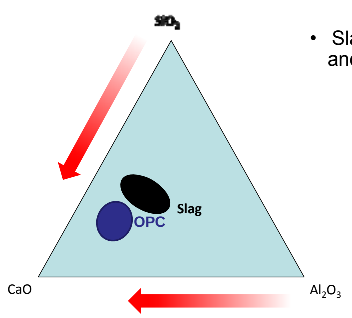
Composition: Slag Cement



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

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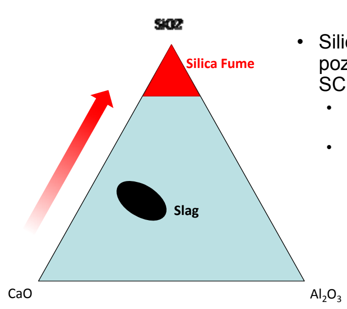
Composition: Silica Fume



- Silica Fume – (SF) Purely pozzolanic and finest sized SCM
  - Byproduct of the smelting industry
  - Improve concrete through pozzolanic reactions with free lime and fills voids

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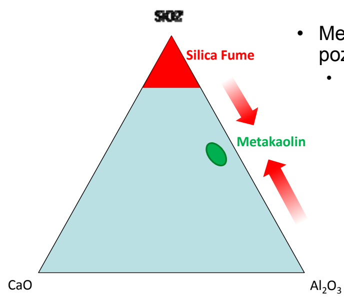
Composition: Metakaolin



- Metakaolin - Purely pozzolanic SCM
  - Specific kind of clay

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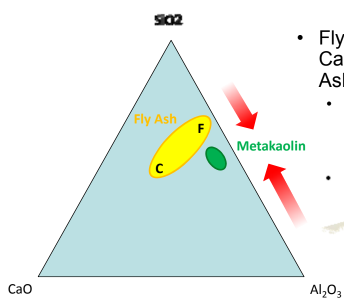
Composition: Fly Ash



- 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

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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

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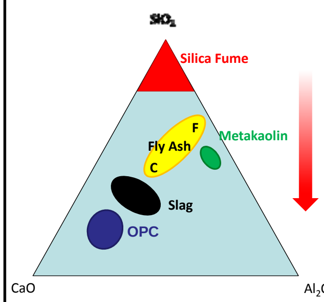
Composition: Fly Ash



SCM	Pozzolanic	Hydration
Silica Fume	XXXXX	
F-Ash	XXXX	
F/C-Ash	XXX	X
C-Ash	XX	XX
Slag	X	XXXX
Portland Cement		XXXXX

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Effect of SCMs on Concrete Durability

- Pozzolanic Materials Improve Durability due to:
  - Refined Pore Structure
    - Particle Packing
    - Formation of C-S-H
  - Improved Transition Zone Properties
  - Reduction in soluble transition zone hydrates (e.g. CH)

(Refined Pore Structure and Improved Transition Zone Properties → Improved Permeability)

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What is Calcium Aluminate Cement (CAC)?

- Rapid hardening cementitious material
- Niche concrete repair applications
  - High early-age strength
  - Durability are required
- What makes it different?
  - Raw materials – limestone and alumina bauxite
  - Cost - (~4-6 X ordinary portland cement)
  - Hydration – temperature dependent and sometimes not monotonic (Conversion)

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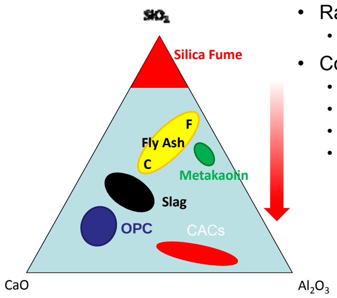
Composition: Calcium Aluminate Cement



- Raw materials
  - Limestone and bauxite
- Composition
  - 36 – 42% Al_2O_3
  - 36 – 42% CaO
  - < 6% SiO_2
  - ≤ 20% Fe_2O_3

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CAC Applications Today

- Low temperature placement
- Rapid hardening
- Refractory resistance
- Durability
  - Acid resistant
  - Abrasion resistant
  - Sulfate resistant
  - Chloride resistant
- Non-structural applications

Source: http://www.chicagobreakingnews.com/_fixed640.jpg

Source: http://www.cimentfondu.com/gb/entreprises/PDF/Gebidem.pdf

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Hydration of CACs

- Type of hydration products is dependent on temperature

$6CA + 60H_2O \rightarrow$

- T < 15°C: $6CAH_{10}$
- $3C_2AH_8 + 3AH_3 + 27H_2O$
- T > 70°C: $2C_3AH_6 + 4AH_3 + 60H_2O$

(Red) Indicates metastable hydration product

(Green) Indicates stable hydration product

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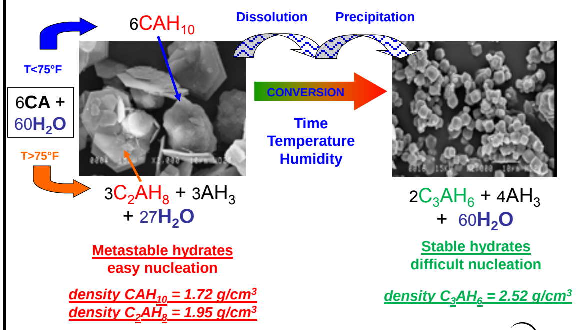
Metastable and Stable Hydrates



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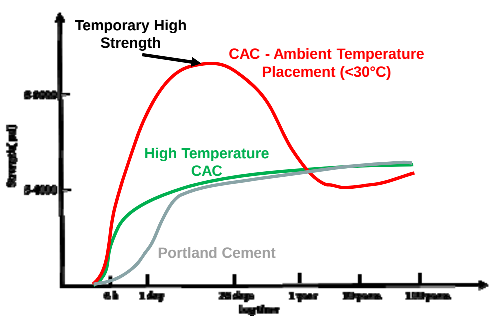
CAC Hydration and Strength Development



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Chemical Admixtures

- Water-reducing Admixtures
- Accelerator Admixtures
- Retarding Admixtures
- Viscosity Modifying Admixtures

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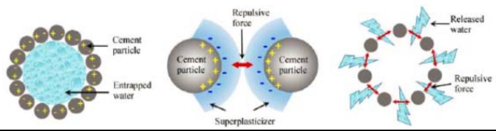
Water-reducing Admixtures

- Admixtures that either increase slump of freshly-mixed without increasing water content OR maintain slump with a reduced amount of water.
- Cement particles are dispersed by repulsive force generated by negatively charged superplasticizers and the entrapped water would be released.



Set-controlling Admixtures

- **Accelerator:** Short setting time required to promote the material to acquire enough early strength right after being deposited from nozzles
- Setting accelerators are a class of admixtures commonly used for concrete to produce an immediate set.
- Shortening the setting time and promote the speed of early stiffness development

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Set-controlling Admixtures

- **Retarder:** can be adsorbed on the surface of cement particles to form an insoluble layer, which delays the hydration of cement.
- Sodium gluconate (SG), tartaric acid (TA), citric acid (CA) are usually adopted retarders which perform favorable retarding effect

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Viscosity Modifier Admixture (VMA)

- Water soluble polymers control the flow characteristics and rheological performance
- Reduce segregation and enhance the dimensional stability
- VMA polymer chains leads to an increase in the mixture plastic viscosity.

Mixture Optimization for 3D Printing

- Flowability Control
- Extrudability Control
- Buildability Control
- Setting Time Control
- Mechanical Property Control
- Shrinkage Control

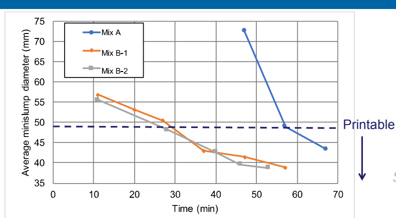
Mixture Optimization for 3D Printing

- **Flowability Control**: easy-pumpable in the delivery system and easy-depositable in the deposition system.
- Particle grading of concrete paste is a main factor that governs its rheology and fluidity in the fresh state.
- Wider particle size distribution contributes to a higher packing density and yield a better flowability

Mixture Optimization for 3D Printing

- **<u>ASTM C1437 – Flow of Hydraulic Mortar</u>**

Mini Slump Test



Source: S. Jones - NIST

- Mini slump measurements were performed during printing
- Mixture A could not be printed until ~ 50 min after mixing. Rapid reduction in mini slump – print intervals approximately 5 min
- Mixture B was printable from the beginning – only able to support 4 layers

Mixture Optimization for 3D Printing

- **<u>Extrudability Control</u>**: ability to continuously be delivered through the small pipes and deposited form nozzles at the printing head
- Smooth grading of materials is essential
- Aggregates should be rounded and not crushed
- Requires substantial volume of cementitious paste to fill the voids formed between smooth graded aggregate particles

Mixture Optimization for 3D Printing

- **Extrudability Control**:

Source: S. Jones - NIST

Discontinuities resulting from poor pumping performance caused layer instability

Pumping difficulties: air bubbles present in piping

- Pumping – many air bubbles
- Printed 6 layers before collapse of first layer
- Difficulty with start stop – indicated by discontinuous purge layer

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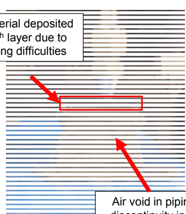
Mixture Optimization for 3D Printing

- **Extrudability Control**:

Source: S. Jones - NIST

No material deposited on 14th layer due to pumping difficulties



Air void in piping caused discontinuity in deposited layer

- Print 9 layers before first void.
- Print 13 layers before first missing 14th layer

- Pumping challenges caused several missed layers at beginning of print.

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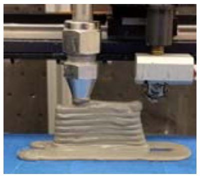
Mixture Optimization for 3D Printing

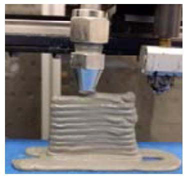
- **Buildability Control:** ability of material to retain its extruded shape under self-weight and pressure from upper layers.
- Must have enough buildability to guarantee it being lay down accurately keep the form right after deposition, be hard enough to bear the weight of subsequent layers without collapsing and still be capable to binding adjacent layers.

Mixture Optimization for 3D Printing

Source: S. Jones - NIST

- **Buildability Control (Continued)**





- No pumping issues – no air bubbles
- Printed 15 layers before collapse of first layer
- First layer collapse

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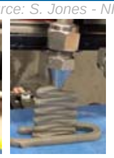
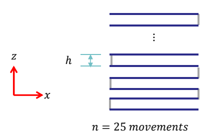
Extrudability and Buildability Test

Source: S. Jones - NIST

- Determine:
  - Retain shape after deposition
  - Number of layers it can support
- Print quality is dependent on both material formulation and printing parameters
- Proposed test print – a tall, thin structure
  - Print 25 layers, h = 3 mm
  - Wall Width – 45 mm
  - Filament width – w = 4 mm





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Mixture Optimization for 3D Printing

- **Setting Time Control**: material requires a long setting time to maintain a continuous flow
- Printable material requires a short setting time to promote the material acquire enough early strength right after being deposited out from nozzles

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Vicat Testing – Determine Time of Set

- Penetration Test
  - Place fresh sample below rod
  - Release the rod quickly
  - Allow the needle to settle
  - Take a reading to determine penetration
  - Initial Set = 25 mm
  - Final Set = No Penetration

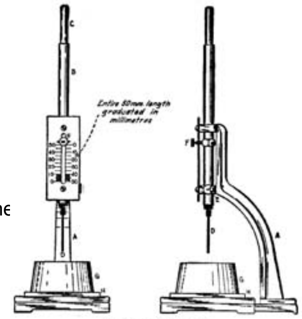

FIG. A1.1 Vicat Apparatus

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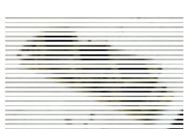
Mixture Optimization for 3D Printing

- **Mechanical Property Control**: SCMs fill voids and increase the packing density of cement matrix, resulting in higher stiffness and strength of concrete.
- High pozzolanic activity of silica fume and fly ash increase mechanical properties

Mechanical Property Testing

- ASTM C109 - Compressive Strength Cubes Specimens
  - Test Materials
- ASTM C42 - Testing Drilled Cores
  - Destructive
  - Test Materials and Constructability



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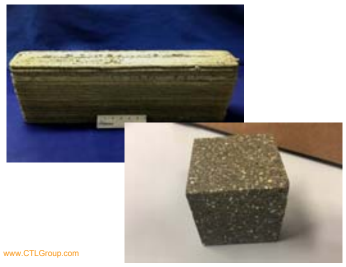
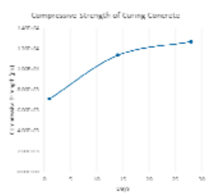
Mechanical Property Testing

- Modified Test Method
  - Test Materials and Constructability





Mixture Optimization for 3D Printing

- **<u>Shrinkage Control</u>**: affects the dimensional accuracy and stability of printed structures.
- 3D Printing requires high water and cement content to ensure good flowability and extrudability.
- 3D printed components always have larger area of surfaces directly exposed to ambient conditions than conventionally casted structures using mould or formworks. This case would promote the evaporation of free water

Mixture Optimization for 3D Printing

- Flowability Control
- Extrudability Control
- Buildability Control
- Setting Time Control
- Mechanical Property Control
- Shrinkage Control

Questions & Answers