Alternative Cementitious Materials for the Precast Industry

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With thanks to:

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Federal Highway Administration

- Georgia Institute of Technology
  - Kimberly Kurtis
  - Lisa Burris (me)
  - Prasanth Alapati
- Oklahoma State University
  - Tyler Ley

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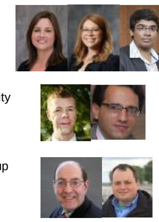

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What are Alternative Cements?

- Hardening systems with different chemistries than portland cement (OPC)
- Often lower CaO content ➔less Raw materials-derived CO_{2e}
- Often lower production temperatures ➔less Fuel-derived CO_{2e}
- Often radically different behavior/properties from OPC
- Many produced for decades (at least)

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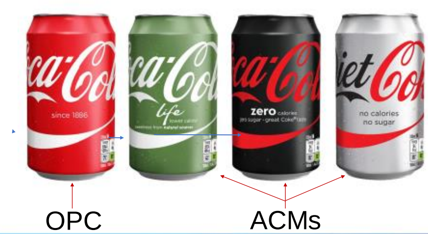
What are Alternative Cements?



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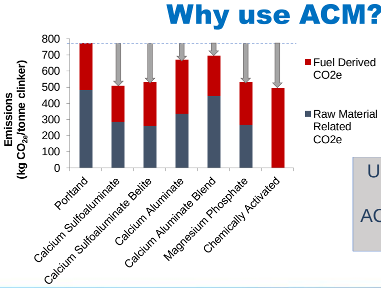
Why use ACM?



Up to 40% reduction in CO_{2e} by using ACMs instead of OPC (1:1)

Gartner, E., "Industrially interesting approaches to "low-CO2" cements," Cement and Concrete Research, 2004, 1489-1498.

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Why use ACMs?

In addition to sustainability benefits…

- Very rapid setting and strength gain: +5000 psi in 2 hrs possible
- Resistance to cold temperatures
- Reduced shrinkage (reduced cracking and prestress losses)
- Currently used for repairs and full-scale structures (typ. bridge decks)
- Established supply chain (Multiple U.S. suppliers including in VA, MO, and OK)
- Improved durability (in some cases)

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Why use ACMs?

ACMs will never replace OPC/PLC but they instead provide some specialized tools for accomplishing different tasks and goals

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6 Primary Types of Alternative Cements:

- Calcium Sulfoaluminate Cement (CSA1)
- Calcium Sulfoaluminate Belite Cement (CSAB, CSA2)
- Calcium Aluminate Cement (CAC)
- Portland-Calcium Aluminate-Calcium Sulfate Ternary Blend Cement Blend (CACB)
- Chemically/Alkali Activated Binder ('geopolymer') (AA1)
- Magnesium-based Cement (phosphate, oxychloride) (MPC)

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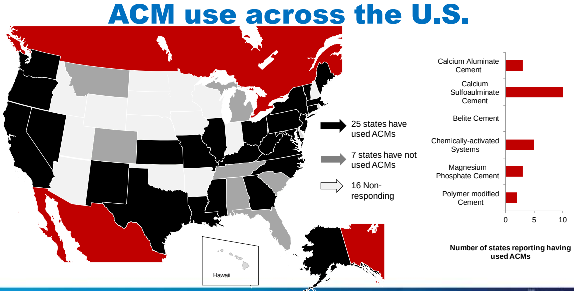
ACM use across the U.S.



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Basics of ACM Production, Reaction, and Composition

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Calcium Sulfoaluminate (CSA)
Calcium Sulfoaluminate Belite (CSAB)

- Raw materials:
  - Limestone
  - Bauxite
  - Gypsum
- Fabrication:
  - Rotary kiln
  - 1350°C
  - Large quantities of anhydrite are added to help control set time
- Mineral components:
  - Ye'elmelite – ($C_4A_3\bar{S}$), also called Klein's compound
  - Dicalcium silicate – belite (C_2S)
  - Calcium sulfate

CSA Type	Ye'elimite $C_4A_3\bar{S}$ (%)	Belite C_2S (%)	Calcium Sulfate $C\bar{S}$ (%)	Other (%)
Type A – Accelerating Additive	35-45	0-20	10-30	5-55
Type B – Belitic CSA (BCSA)	20-30	30-60	5-25	0-35
Type C – Expansive Additive	10-20	10-30	40-60	0-40
Type K – Shrinkage Compensating Cement	1-10	30-50	1-20	20-70

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How are CSAs different from OPC?

- Hydration process:

OPC

$$2C_3S + 6H \rightarrow C-S-H + 3CH$$

C = CaO
S = SiO_2
H = H_2O
A = Al_2O_3
S = SO_3

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How are CSAs different from OPC?

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OPC

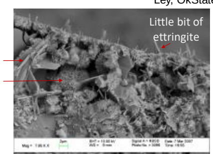
$$2C_3S + 6H \rightarrow C-S-H + 3CH$$

Image credit: Tyler Ley, OkState

CH

C-S-H

Concrete's strength-giving phase



3-5 hr lag between mixing and hardening

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How are CSAs different from OPC?

- Hydration process:

OPC

$$2C_3S + 6H \rightarrow C-S-H + 3CH$$

3-5 hr lag between mixing and hardening

CSA

$$C_4A_3\bar{S} + 2C\bar{S} + 38H \rightarrow C_6A\bar{S}_3H_{32} + 2AH_3$$

ye'elimite | anhydrite | Lots of water | ettringite | aluminum hydroxide

Hydrates and hardens rapidly → early and high strength gain

Can set in 10-15 min at w/c=0.40

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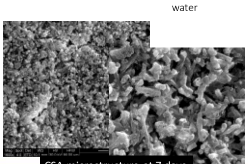
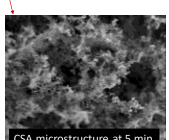


CSA microstructure at 7 days



CSA microstructure at 5 min

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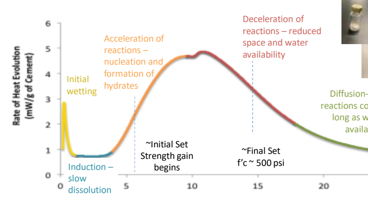
How are CSAs different from OPC?

Hydration Kinetics



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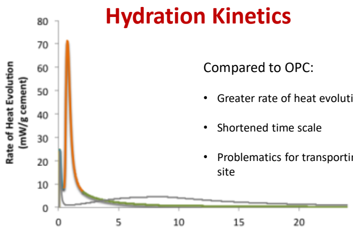
How are CSAs different from OPC?

Hydration Kinetics



Compared to OPC:

- Greater rate of heat evolution
- Shortened time scale
- Problematics for transporting materials to the site

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Calcium Sulfoaluminate (CSA)
Calcium Sulfoaluminate Belite (CSAB)

- Advantages:
  - HIGH early strengths (as high as 5000 psi @ 2 hrs)
  - Very low shrinkage, and expansive formulas available
  - Freeze-resistant
  - Many examples of in-place performance
  - Long-term strength development
  - Two U.S. suppliers

CTS | Rapid Set | Buzzi Unicem USA

- Disadvantages:
  - VERY fast set (5-35 min)
  - Rapid heat release

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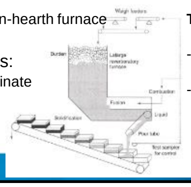
Calcium Aluminate Cement (CAC)

- Raw materials:
  - Limestone
  - Bauxite
- Fabrication:
  - Reverberatory open-hearth furnace
  - >1450°C
- Mineral components:
  - Monocalcium Aluminate
  - Ferrite

	Calcium Aluminates (%)	Belite C_2S (%)	Gehlenite (%)	Ferrite (%)	Other (%)
Calcium aluminate cement (ciment Fondu)	56	7	4	24	9



Two major types of CAC:

- Ciment Fondu ("pure" CAC)
- Ternal (Ternary blend: OPC + CAC + Calcium Sulfate)

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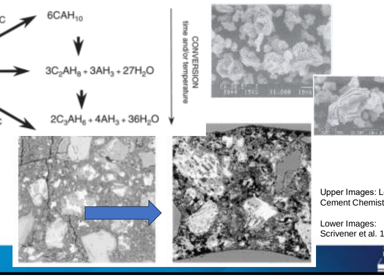
How are CACs different from OPC? Conversion

$6CA + 60H_2O$ → (T < 15°C) $6CAH_{10}$ → $3C_2AH_8 + 3AH_3 + 27H_2O$ → $2C_3AH_6 + 4AH_3 + 36H_2O$ (T > 70°C)

CONVERSION time and/or temperature



Upper Images: Lea's Cement Chemistry

Lower Images: Scrivener et al. 1999

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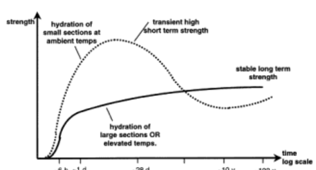
How are CACs different from OPC? Conversion

- Initial CAC hydrates are very strong
- Exposure to higher temperatures cause "conversion"
- New phases is denser, resulting in increased porosity and a drop in strength (40% of max)



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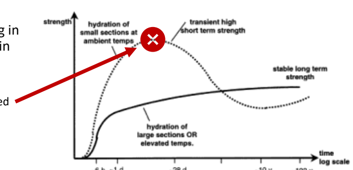
- Failure can be prevented by:
  - Designing based on the converted strength



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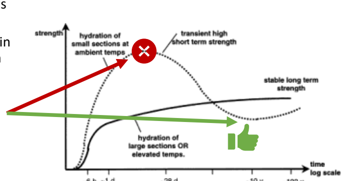

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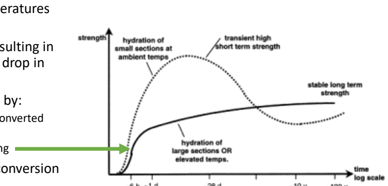
How are CACs different from OPC? Conversion

- Initial CAC hydrates are very strong
- Exposure to higher temperatures cause "conversion"
- New phases is denser, resulting in increased porosity and a drop in strength (40% of max)
- Failure can be prevented by:
  - Designing based on the converted strength
  - Utilizing heat during curing
- No need to be afraid of conversion
- Possible use to accelerate precast construction?



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Calcium Aluminate Cement (CAC)

- Advantages:
  - HIGH early strengths
  - Multiple formulations available depending on needs
  - Very high heat resistance – often used in refractory applications
  - High corrosion and abrasion resistance
  - 2 U.S. Suppliers
- Disadvantages:
  - VERY fast set (5-35 min)
  - Very high initial heat release
  - Must use proprietary chemical admixtures
  - Must have understanding of conversion process and methods of estimating long term strength

IMERYS

RWC ROYAL WHITE CEMENT

Table 2. Strength Gain of CAC Versus RHPC

Temperature °F (°C)	Cement	Strength, psi (MPa)* 6 h	16 h	1 day	2 days
64.4 (18)	CAC	3480 (24)	5655 (39)	5800 (40)	6525 (45)
64.4 (18)	RHPC	0 (0)	580 (4)	1740 (12)	3335 (23)
53.6 (12)	CAC	3045 (21)	5220 (36)	5655 (39)	5945 (41)
53.6 (12)	RHPC	0 (0)	145 (1)	435 (3)	6235 (43)
42.8 (6)	CAC	2755 (19)	5220 (36)	5365 (37)	5655 (39)
42.8 (6)	RHPC	0 (0)	145 (1)	145 (1)	1015 (7)
32 (0)	CAC	725 (5)	4785 (33)	5075 (35)	5655 (39)
32 (0)	RHPC	0 (0)	0 (0)	145 (1)	290 (2)

* Concrete prisms 2.75 x 2.75 x 11 in (70 x 70 x 280 mm) cement content 590 lb/yd³ (350 kg/m³), w/c = 0.5.)
Source: Scrivener and Capmas (1998)

TxDOT Tech Note on CAC: https://ftp.dot.state.tx.us/pub/txdot-info/cst/tips/calcium_concrete.pdf

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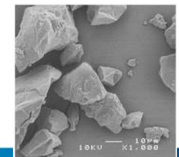
Magnesia Cements

- Raw materials:
  - Magnesium-bearing rocks ($MgCO_3$)
  - Phosphate activator solution
- Fabrication:
  - Magnesia ground, then calcined in a kiln (sometimes twice).
  - Reactivity is increased with longer burn time and hotter burn temperatures.
- Very very fast setting time (my experience)
- Very white binder
- Very low w/c required

Mag Cement Types	Hydration Process
Sorel (Magnesium Oxychloride) cement	$3MgO + MgCl_2 + 11\ H_2O \rightarrow 3Mg(OH)_2 \cdot MgCl_2 \cdot 8H_2O$
Magnesium Phosphate	$MgO + NH_4H_2PO_4 + 5H_2O \rightarrow NH_4MgPO_4 \cdot 6H_2O$
Magnesium Silicate Hydrate (M-S-H)	$C\text{-}S\text{-}H + MgSO_4 \rightarrow CaSO_4 + SiO_2 + Mg(OH)_2 \rightarrow CaSO_4 + M\text{-}S\text{-}H$
Magnesium Oxysulfate	$3MgO + MgSO_4 + 11\ H_2O \rightarrow 3Mg(OH)_2 \cdot MgSO_4 \cdot 8H_2O$



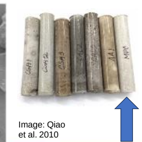


Image: Qiao et al. 2010

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Magnesium Phosphate Cement

- Advantages:
  - HIGH strengths (as high as 7250 psi @ 3 hrs!!!)
  - VERY heat resistant
  - No shrinkage
  - Low water requirement
  - Beautiful concrete
- Disadvantages:
  - VERY fast set (5-35 min)
  - VERY high retarder dosing requirements
  - Currently primarily available from China
    - Shipping costs
    - Availability issues (phosphate is in high demand at the beginning of the growing season)
    - Weird material consistency
    - Very different materials and microstructure

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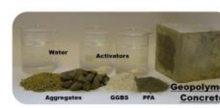
Alkali Activated Materials (Geopolymers)

- Developed first in the 1940s?
- Refined by Joseph Davidovits (1979) – coined the term "Geopolymer"
- Raw materials:
  - Aluminosiliceous materials (most commonly metakaolin, slag, fly ash)
  - Alkali hydroxide or alkali silicate solutions, for example: NaOH
- Fabrication:
  - No real 'fabrication' process besides mixing and placing the materials.



https://dasco.co/en/geopolymer-concrete/

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Alkali Activated Cement Reactions

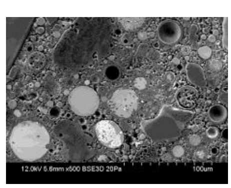
Si or Al based material: kaolinite-based clay, slag, natural pozzolan, fly ash

↓

Mixed with alkaline solution: sodium hydroxide, sodium silicate

↓

Solution dissolves the starting material and reforms into solid binder matrix



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Alkali Activated Cements

- Advantages:
  - Heat resistant
  - Low shrinkage
  - No risk of prehydration during storage
  - Can achieve very high strengths
  - Several U.S. suppliers established recently
- Disadvantages:
  - Requires use of either a proprietary activation formula or caustic solution
  - Many formulations require heat curing (autoclave or steam cure)
  - No consistent dosing requirement – activation formula dosage varies with materials
  - No current supplier in the U.S.

GEOPOLYMERSOLUTIONS

GEOPOLYMER INTERNATIONAL (GPI)

AGS Alchemy Geopolymer SOLUTIONS

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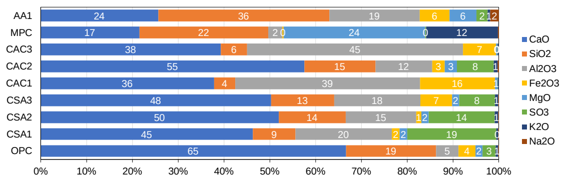
ACM Chemistry

- Typically, lower calcium systems (= naturally lower materials-derived CO_2)
- Many have higher alumina and sulfate contents



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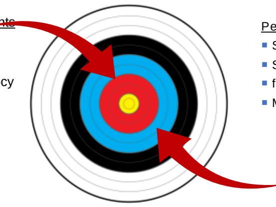
Mixture Criteria

- Prescriptive Requirements
  - w/b ≥ 0.40
  - Binder content ≥ 765 pcy
  - #67 coarse aggregate



Performance Targets

- Set time ≥ I hour
- $\text{Slump}_{60min} \geq$ 3in
- $f_{c7d} \geq$ 3500 psi
- $\text{MOR}_{28d} \geq$ 700 psi

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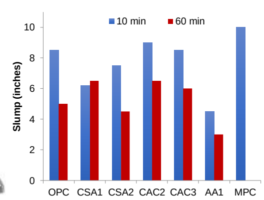
Constructability - Slump

All materials can be formulated to achieve reasonable slumps

Slump loss mirror that of OPC except:

- When using high retarder dosages with CSA (lower slump loss)
- MPC formulations (rapid slump loss)



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Constructability - Slump

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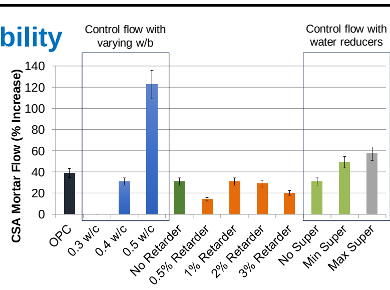
Constructability

Reduction in flow relative to OPC

Flow can be adjusted with changes in w/c or use of water reducing admixtures, similar to OPC

Note this data is CSA only



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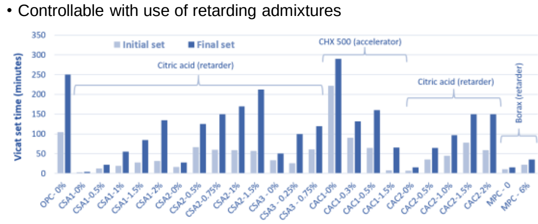
Constructability

- Rapid setting and strength gain
- Controllable with use of retarding admixtures



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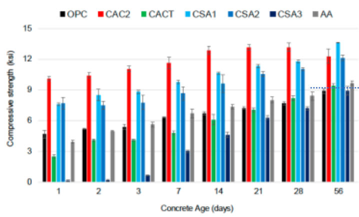
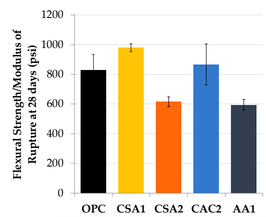
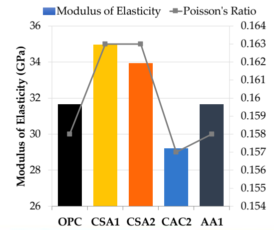
Compressive Strengths

- All mixtures: 765 lbs/cy cement
- All cement reached >7000 psi by 28d
- Strength development varied relative to OPC, but can be tailored by adjusting mixture cement content
- Possibility of reduced cement requirements for CSA mixtures to achieve similar strengths as OPC?



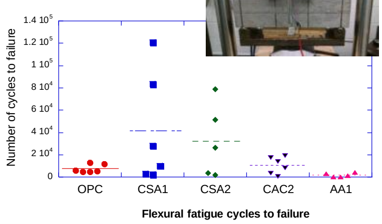
MOR and MOE





Flexural Fatigue

- Samples loaded at 28 days to 40% of ultimate strength
- Fatigue testing has significant levels of variability, but
- Most ACMs, on average, outperformed OPC



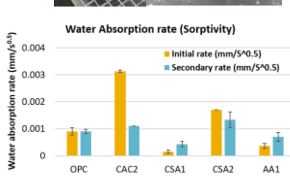
ACM Durability

Tested parameters:

- Carbonation
- Sorptivity and Chloride Diffusion
- Resistance to Freezing and Thawing
- Sulfate attack
- Alkali Silica Reaction
- Shrinkage

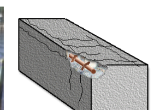
Sorptivity

- Sorption: suggestive of surface porosity and permeability levels → increased sorption = increased permeability
- All samples prepared at same w/b
- Dissimilar pore structures across the material test set
- Expect differences in water uptake, shrinkage, and carbonation, and chloride permeability



Chloride Diffusion & Corrosion

- Biggest durability problem in infrastructure: $20B/yr spent by US to repair corrosion issues in concrete

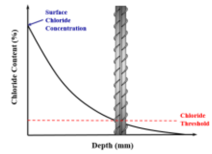


Chloride Diffusion

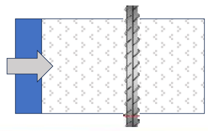
- Controls time to initiation of corrosion

When enough chlorides reach the surface of the steel, concrete's protective 'passivating layer' will fail and corrosion will initiate.

6 years from corrosion initiation to spalling of concrete



Chloride movement



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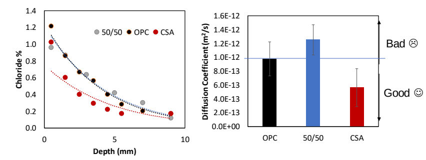
Chloride Diffusion

- Lower diffusivity in CSA materials compared to OPC



* Note that OPC Air% was 6.5% compared to 4 ± 0.5% for other mixes

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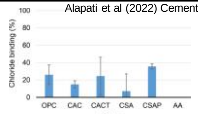
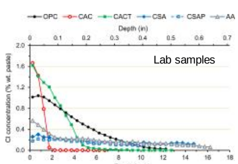
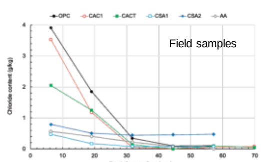
Chloride Diffusion

Alapati et al (2022) Cement

- Most ACMs:
  - Similar chloride binding
  - Lower chloride infiltration levels than OPC







* Note that OPC Air% was 6.5% compared to 4 ± 0.5% for other mixes

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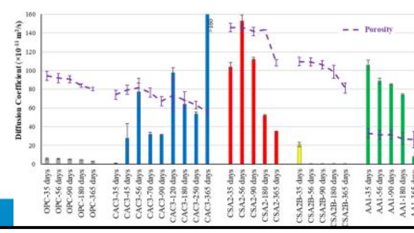
Chloride Diffusion

Behravan (2021) Materials & Design

- Most ACMs:
  - Higher diffusion coefficients (faster infiltration rate) ☹
  - Use of a polymeric sealant SIGNIFICANTLY improved diffusivity



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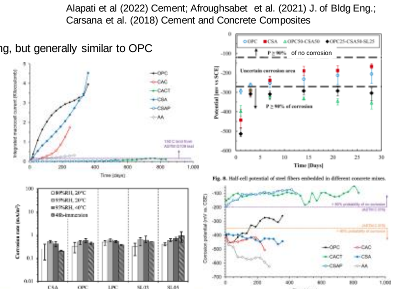
Corrosion

Alapati et al (2022) Cement; Afroughsabet et al. (2021) J. of Bldg Eng.; Carsana et al. (2018) Cement and Concrete Composites

- Varying results for corrosion testing, but generally similar to OPC performance



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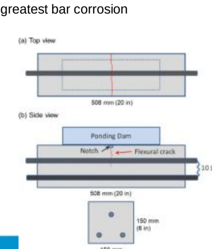
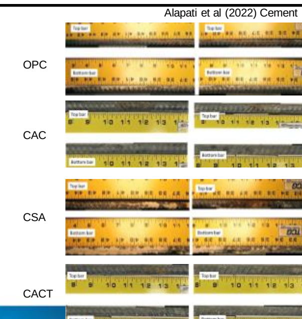
Corrosion

Alapati et al (2022) Cement

- In cracked section tests CSA showed the greatest bar corrosion





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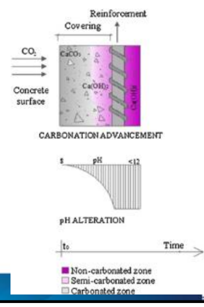
Carbonation

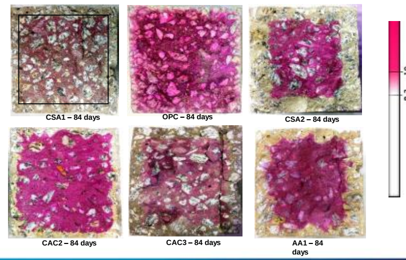
Possan et al (2017) Case Studies in Construction Materials

- CO_2 from the atmosphere consumes CH and lowers concrete pH
- Lower pH leads to initiation of corrosion
- After CH is consumed C-S-H can be decalcified – leading to strength reduction
- Carbonation sequesters CO_2 from the atmosphere…
- Use of phenolphthalien solution can be sprayed onto broken samples to ID areas with pH >10 → pink = not carbonated



50

Carbonation



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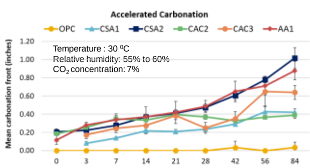
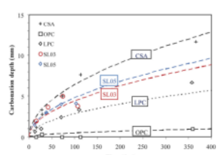
Carbonation

- All ACMs carbonated MUCH faster than OPC
- Accelerated carbonation was likely related to lower calcium content and lack of CH

	Carbonation Rate – in/yr$^{0.5}$	Carbonated pH
OPC		0.06
CSA		1.72
CAC		1.16
CACT		0.35
AA1		1.54





Carsana et al (2018) Cement and Concrete Composites

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Carbonation – pH Change

- Greater reduction in pH in ACMs compared to OPC
- Increased likelihood of carbonation-driven corrosion

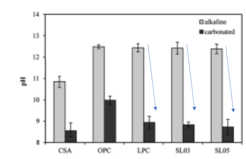

Fig. 4. Evaluation of the alkalinity of the pore solution: (a) phenolphthalein test on fracture surface of non-carbonated concrete, (b) pH of the aqueous extract of alkaline and carbonated concrete (the higher value obtained for carbonated OPC concrete was due to incomplete carbonation of the sample, as shown by phenolphthalein test of the solution).

LPC = PLC
SL03 = 60/40 CSA/OPC
SL05 = 60/40 CSA/PLC

From FHWA project:

	Uncarbonated pH	Carbonated pH
OPC	>13	< 13
CSA	>13	9 - 11
CAC	9 - 11	< 9
AA1	> 13	< 9

Carsana et al (2018) Cement and Concrete Composites

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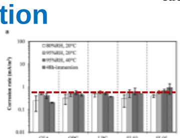
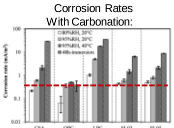
Carbonation

Carsana et al (2018) Cement and Concrete Composites

Corrosion Rates Without Carbonation:



Corrosion Rates With Carbonation:



LPC = PLC
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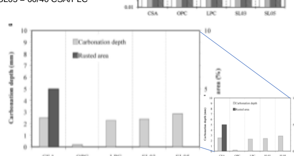

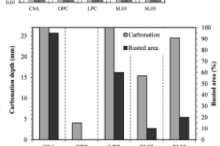

Carbonation SIGINIFICANTLY increases liklihood of corrosion in ACM systems

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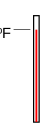
Freezing and Thawing

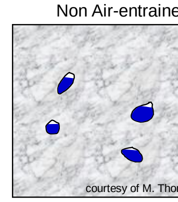
"Dry concrete (generally below ~ 75 to 80% internal relative humidity) is normally immune to damage from freezing." ACI 201

- Water expands 9% as it freezes
- Water will move from paste to pores to provide space for this expansion
- When concrete is at a critical saturation level (91%) or does not have enough entrained air, expansion results in cracking of the concrete

Mechanism of Frost Damage in Concrete



Non Air-entrained



Saturation < 91.7%

55

Freezing and Thawing

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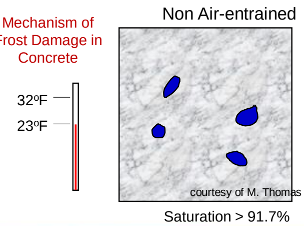

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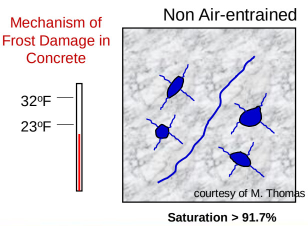

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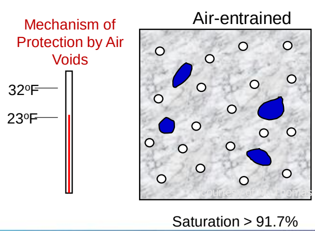
Mechanism of Protection by Air Voids



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Freezing and Thawing

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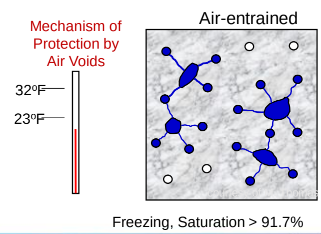

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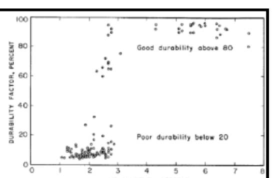
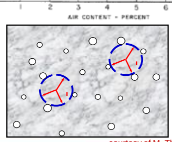
Freezing and Thawing

- Entrained air in concrete provides:
  - Extra pore space for expansion of water
  - Reduced distance for water to travel to reach the voids
- Does this phenomenon work similarly with ACMs?
- Testing was performed with ACMs using systematic dosages of synthetic AEA (e.g., 3%, 4%, 5% air)





courtesy of M. Thomas

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Bruyn (2017) International J. of Concrete Structures and Materials

Freezing and Thawing

- Reduced uptake of water in CSA samples compared to PC

→Longer time to reach critical saturation levels in CSA concretes

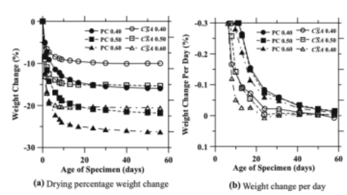

Fig. 1 Percent weight change and rate of weight change of the portland and CSA cement pastes.

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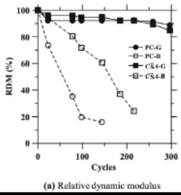
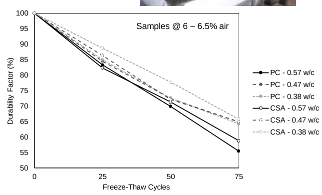
Freezing and Thawing

Zhao (2014) Construction and Building Materials
Bruyn (2017) International J. of Concrete Structures and Materials

- Varying changes in ASTM C666 Freeze-thaw durability, but CSA was AT LEAST as durable as the PC





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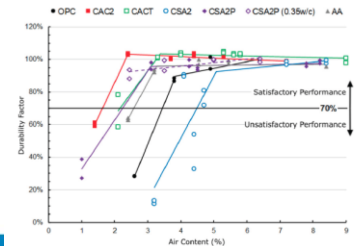
Freezing and Thawing

- With varying air contents, all samples with > 5% air performed satisfactorily, and similarly to OPC
- Some CAC mixtures needed much lower AEA



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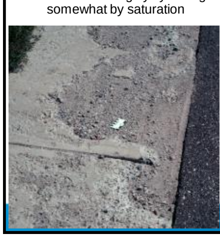
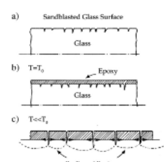
Scaling

- Formation of ice lenses at the surface of the concrete causes surface-level cracking due to ice spall effect
- Controlled largely by strength of the concrete and somewhat by saturation





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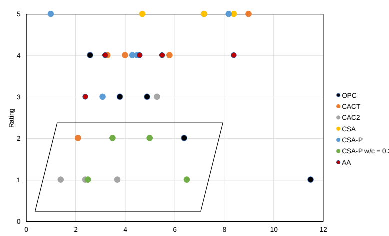
Scaling

- ACMs and OPC performed overall poorly against scaling, except:
- CAC and low w/c CSA-P did well
- Air content did not correlate with scaling performance



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Scaling

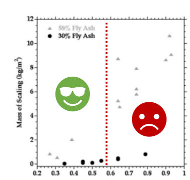
OPC
30 cycles

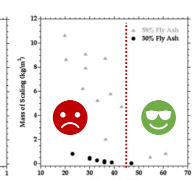
CSA 2
5 cycles
30 cycles

66

Scaling

- Strongest correlator with scaling is strength of materials.
- How to improve scaling resistance:
  - Lower w/c
- ACMs may increase scaling resistance at early ages as a result of rapid strength development





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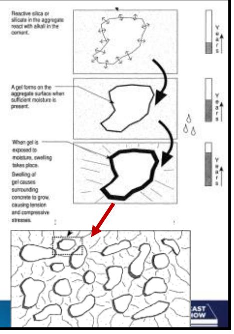
Alkali Silica Reaction

- Some silica aggregates dissolve when in contact with alkaline concrete pore solution and form a gel
- Higher alkali content in the pore solution and higher presence of calcium lead to increased risk of reaction
- Exposure to water and humidity lead to expansion of the gel and cracking in concrete structures



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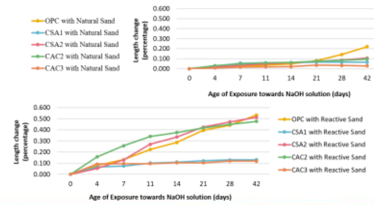
Alkali Silica Reaction – AMBT Results:

- No ACMs found to CAUSE ASR
- CAC and CSA found to control reactive aggregate better than OPC



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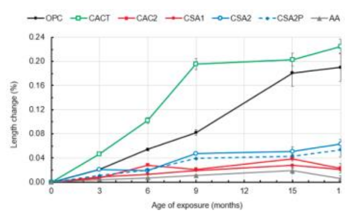
Alkali Silica Reaction – CPT Results:

- All ACMs, except the ternary-blend CAC improved ASR resistance



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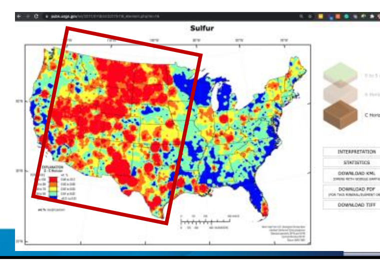
Sulfate Attack – Where is this an issue?

Sulfates in soil attack concrete resulting in decalcification, strength loss, and expansive compound formation



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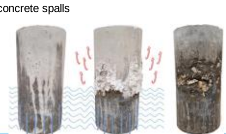
Sulfate Attack – Types

Two types :

Chemical – sulfate reacts with calcium in samples, converts to ettringite (causes expansion) or gypsum (results in section loss)

Physical – salts build up in pores of concrete, create stress – when that stress exceeds the tensile stress of the concrete, concrete spalls



Alyami et al. (2019) Construction and Building Materials

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Sulfate Attack Mechanisms

In OPC, chemical sulfate attack typically occurs through:

(1) reaction of sulfate with monosulfate hydrate, calcium aluminate hydrate, and/or unhydrated C_3A, producing ettringite

–OR–

(2) through reaction of sulfate with CH, producing gypsum, lowers pore solution alkalinity and results in a destabilization of C-S-H

- Most ACMs do not have CH as a hydration product → Less susceptible to sulfate attack?
- However, many do have calcium aluminate hydrates and monosulfate → Susceptible to sulfate attack?

ARE ACMs SUSCEPTIBLE TO SULFATE ATTACK?

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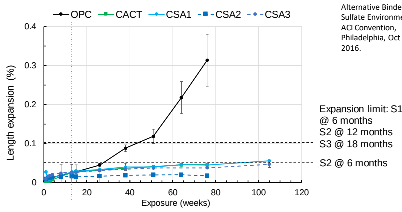
ASTM C1012 Expansion Test Results

- Concentrated sodium sulfate solution (50 g of Na_2SO_4 in 1 L of solution)
- All ACMs significantly outperform OPC



L.E. Burris and K.E. Kurtis, "Performance of Alternative Binders in Sulfate Environments," ACI Convention, Philadelphia, Oct 23, 2016.

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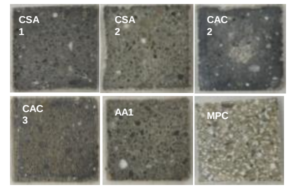
Visual Changes

- Despite minimal shrinkage most ACM mortars showed evidence of chemical reaction around the rim of samples cut from the mortar bars



75

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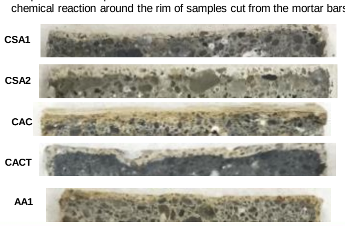

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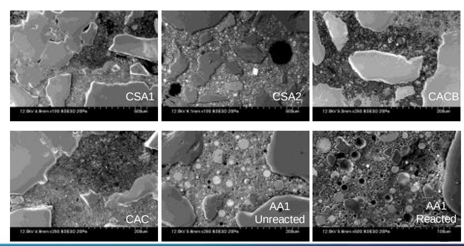
Microstructural Changes

Colors in BSE are indicative of changes to either density or chemistry



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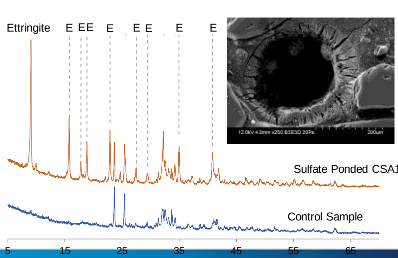
Phase Changes – CSA1



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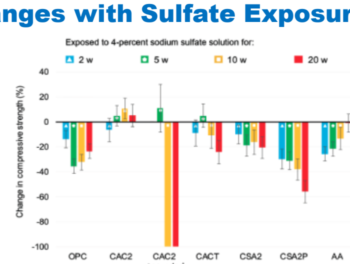
Strength Changes with Sulfate Exposure

20 – 40% loss of strength in all samples

Similar to OPC, but without expansion



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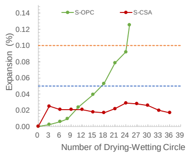
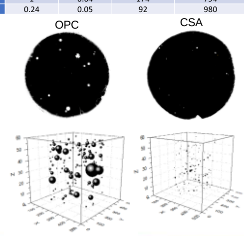
Physical Sulfate Attack

Yang, S., Acarturk, B. C., & Burris, L. E. (2022). *Cement and Concrete Research*

- CSA does not appear to be affected by physical sulfate attack
- Likely a result of SIGNIFICANTLY reduced porosity

	Area Porosity (%)	Volume porosity (%)	Average pore diameter (µm)	Average surface distance (µm)
OPC	1	0.64	174	794
CSAB	0.24	0.05	92	980





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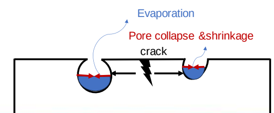
Drying Shrinkage Basics

Results from removal of water from (2.50-5.0 nm) pores in hardened paste due to external drying – water leaving pores due to drying

- Shrinkage of concrete results in cracking and can also cause prestress loss
- Can cause curling when it occurs only on one side of the specimen
- Time scale: hours to years after water-contact
- Dependent on exposure, but also on sample porosity and surface area



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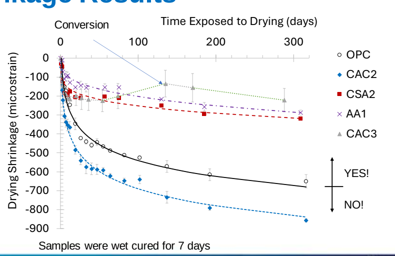
Drying Shrinkage Results

- Except the CAC, all samples had significantly less drying shrinkage
- This likely translates to reduced liklihood of cracking



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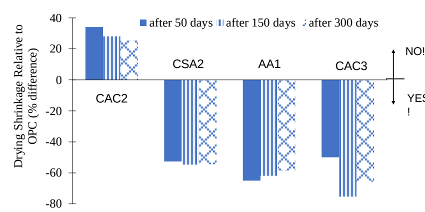
Drying Shrinkage Results



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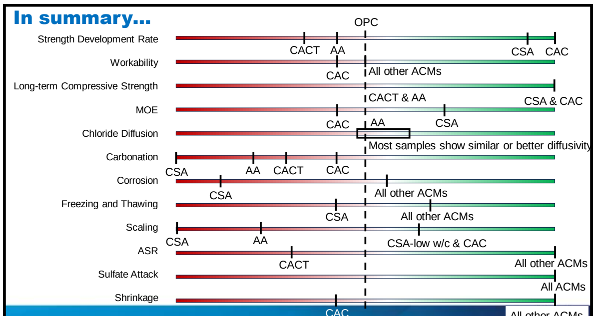
In summary…



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Conclusions

- ➢ACMs are new 'tools' for the construction toolbox
- ➢Each has various strengths:
  1. Accelerated strength gain rates
  2. Potential for reduced cement content requirements
  3. Reduced shrinkage
  4. Reduced susceptibility to ASR and Sulfate Attack
  5. Somewhat improved F/T resistance
- ➢…and challenges:
  1. Accelerated setting and finishing schedules
  2. Differing requirements for durable mixtures
  3. Increased carbonation rates (and corrosion?)
  4. Increased scaling liklihood
  5. Undefined requirements for design of durable mixtures

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For more Information…

- Dr. Burris' contact information: burris.189@osu.edu or:
- Two FHWA technotes:

http://www.fhwa.dot.gov/advancedresearch/pubs/16017/index.cfm
https://highways.dot.gov/sites/fhwa.dot.gov/files/FHWA-HRT-24-012.pdf

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Questions?

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