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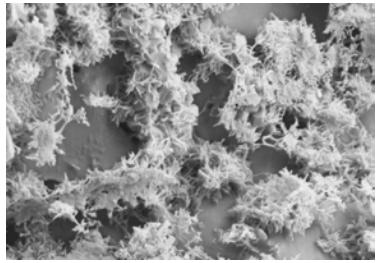

Enhancing Early-Age Concrete Strength through Nanotechnology

Pittsburgh ACI Area Chapter Meeting
Wednesday, December 4, 2019

AIA Registered Course No. ASNano001

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Description

- This course will cover the basics of cement hydration and strength development in concrete, the need for early-age strength enhancement, and options available to increase early-age strength, including the use of nanotechnology-based admixtures.
- Applications highlighting the successful use of nanotechnology-based strength-enhancing admixtures will also be presented.

Learning Objectives

Upon completing this course, you will:

- understand the basics of the hydration of portland cement, its effect on strength development and the need for enhanced early-age strength in some concrete applications;
- know the different options available for early-age strength enhancement;
- understand how nanotechnology-based strength-enhancing admixtures function;
- learn about the use of nanotechnology-based strength-enhancing admixtures in various concrete applications.

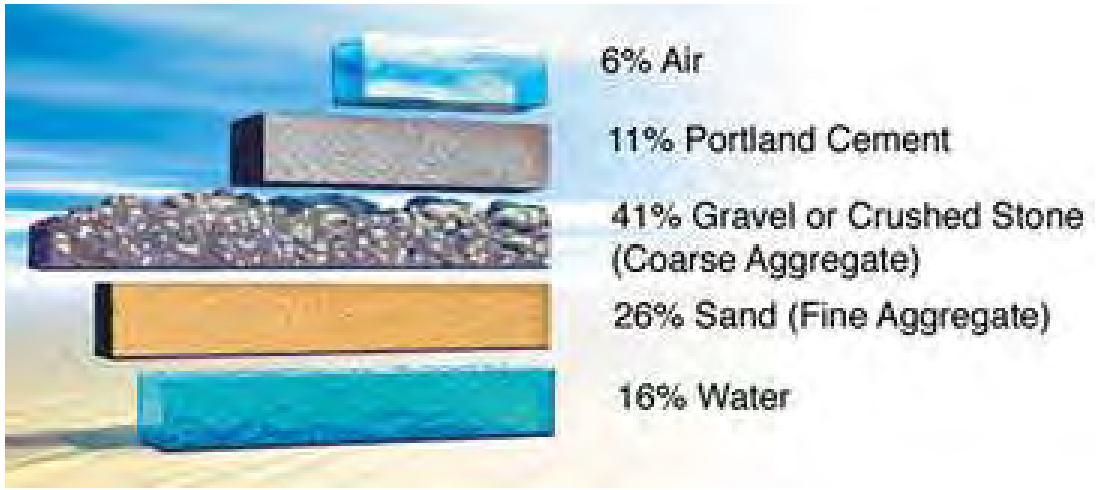
Outline

- Basic overview of portland cement hydration and the factors that affect strength development
- Enhanced early-age strength development
  - Why needed and typical options
- Nanotechnology-based strength-enhancing admixtures
  - Technology and applications
- Summary

Concrete As We Know It…

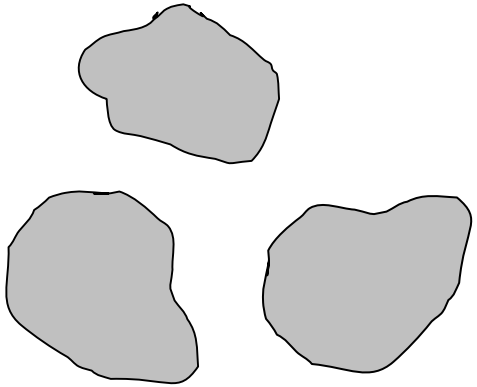
A Mixture of:

- Cementitious Materials
  - Portland Cement
  - Supplementary Cementitious Materials (SCMs)
- Fine & Coarse Aggregates
- Water
- Admixtures
- Fibers



Hydration of Portland Cement

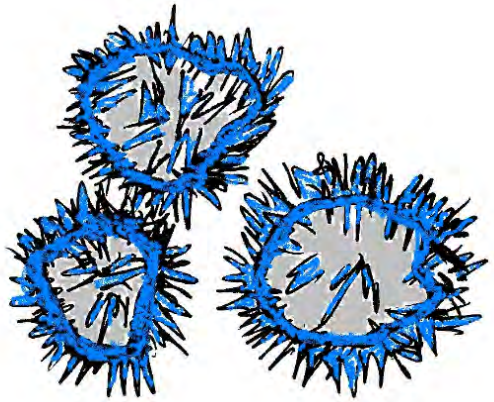
Portland Cement



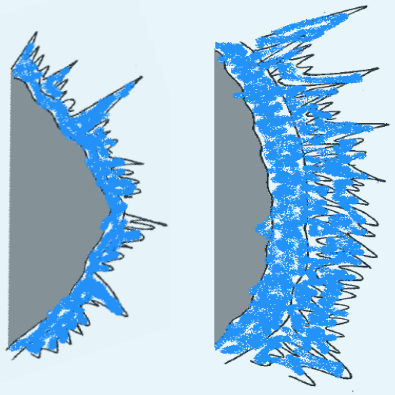
+ Water

Hydration

C-S-H gel + $Ca(OH)_2$ + Other

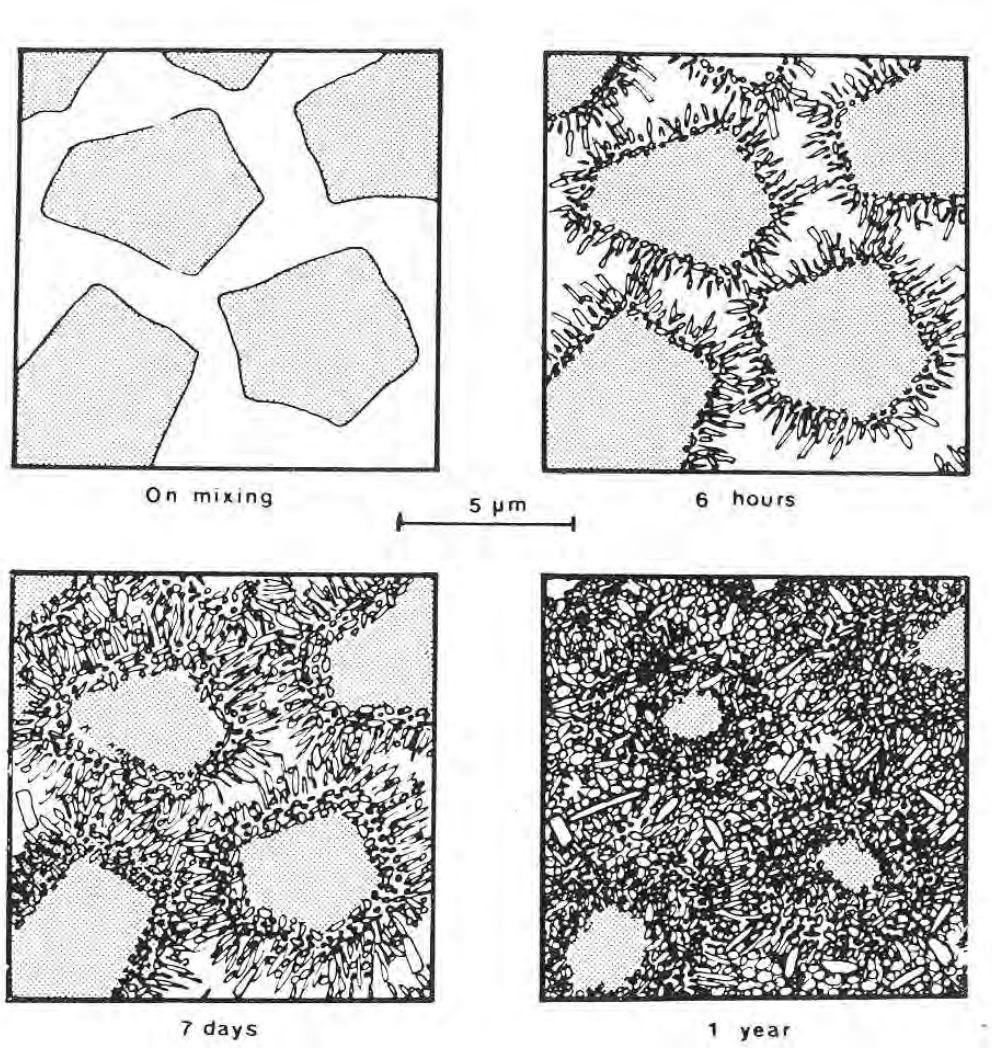


The crystallization of C-S-H occurs close to the surface or onto the surface itself creating a layer which slows down the diffusion of products and reactants (topochemical reaction)



After 28 days, the penetration of the granule hydration is about 4 microns, and after one year 8 microns.

Hydration of Portland Cement



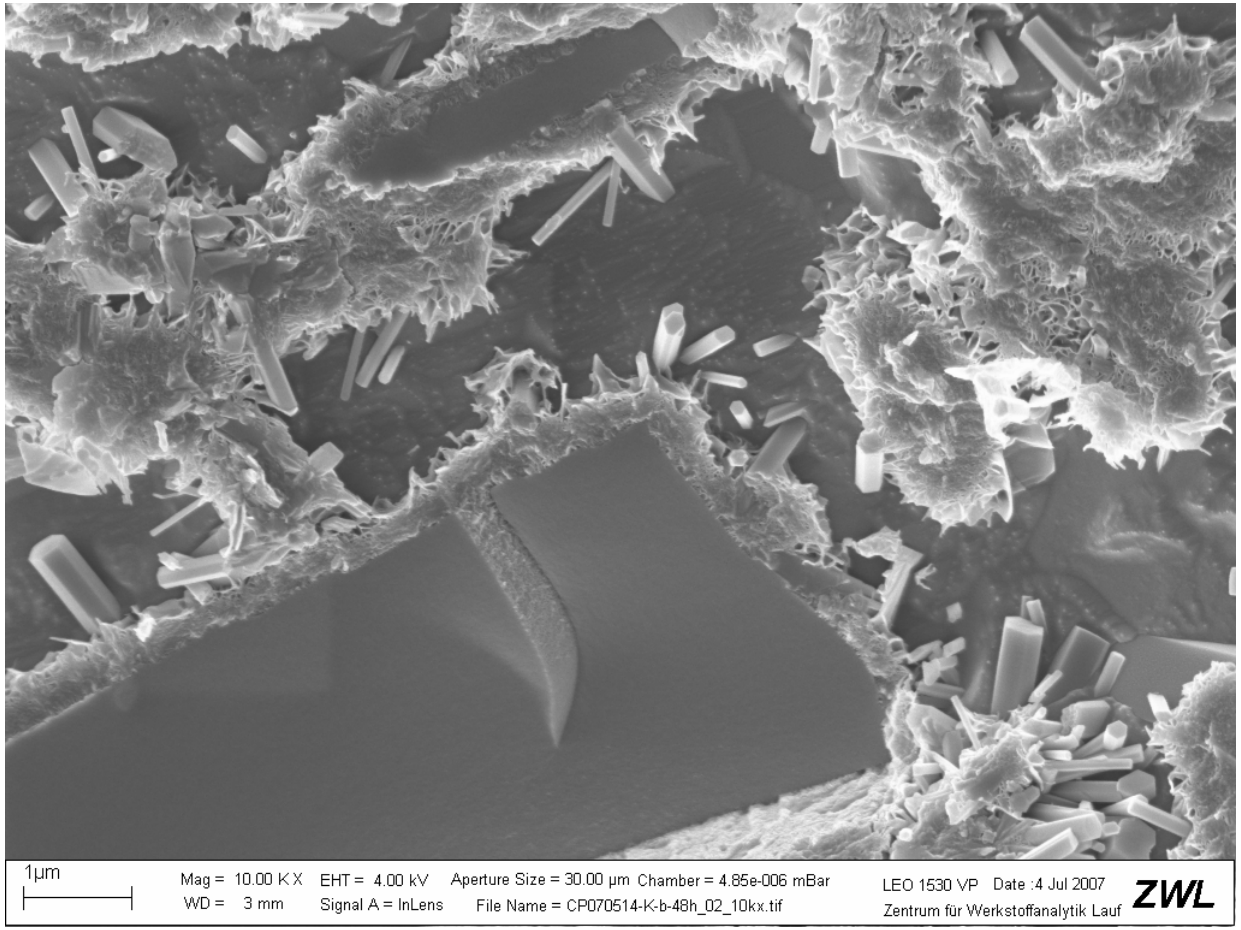


Fig. 1 from second module: *Instructional Modules in Cement Science* (Penn State, 1985)

Strength Development is Influenced By…

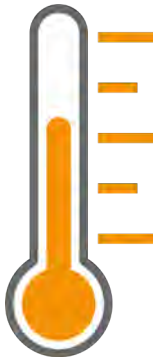
- Cementitious materials content
  - Portland cement type and amount
  - SCM type and amount
- Water-cementitious materials ratio (w/cm)
- Temperature
  - Ambient and concrete
- Admixtures
  - Set-control, other
- Curing

Biggest Influencers on Early Strength Development

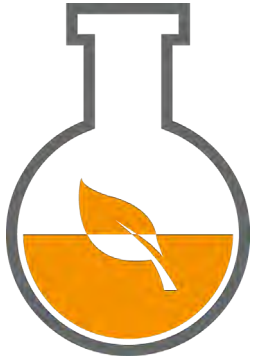
Cement Type & Amount; SCMs

w/cm

Ambient & Concrete Temperatures



Chemical Admixtures



Curing

Outline

- Basic overview of portland cement hydration and the factors that affect strength development
- **Enhanced early-age strength development**
  - Why needed and typical options
- Nanotechnology-based strength-enhancing admixtures
  - Technology and applications
- Summary

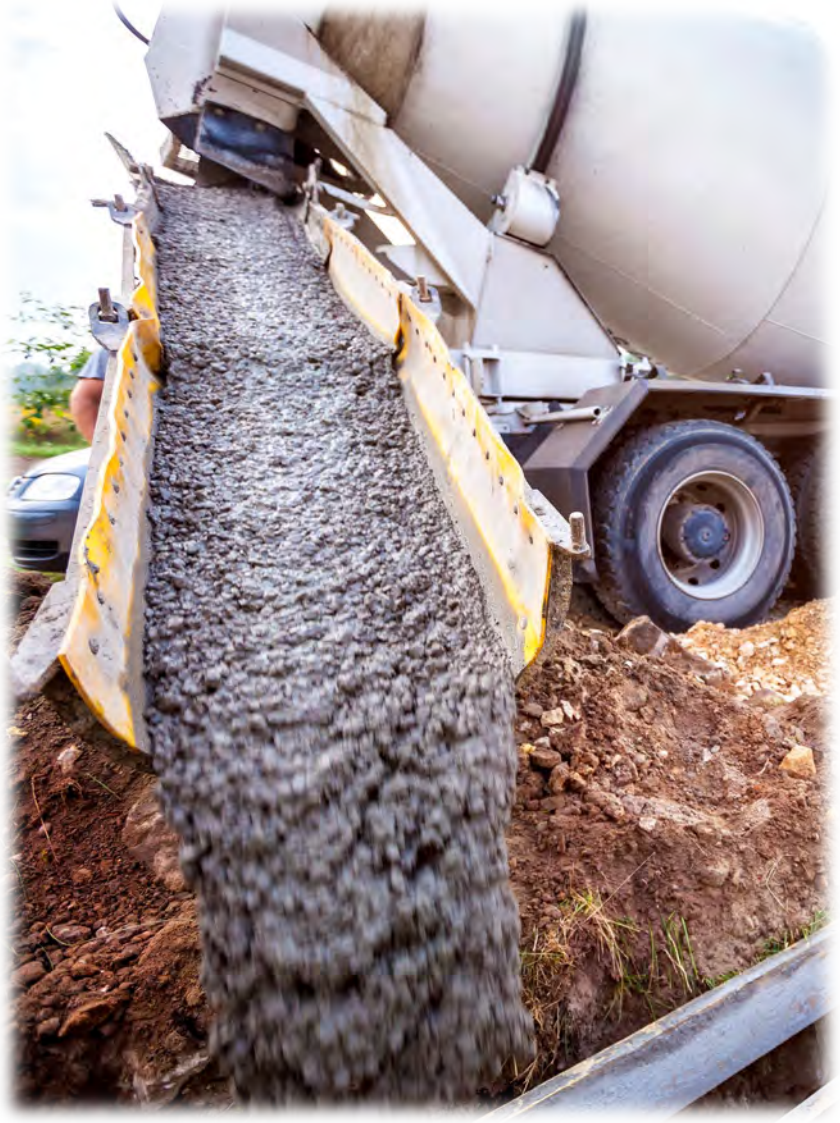
Enhanced Early-Age Strength Development

Typically needed to meet…

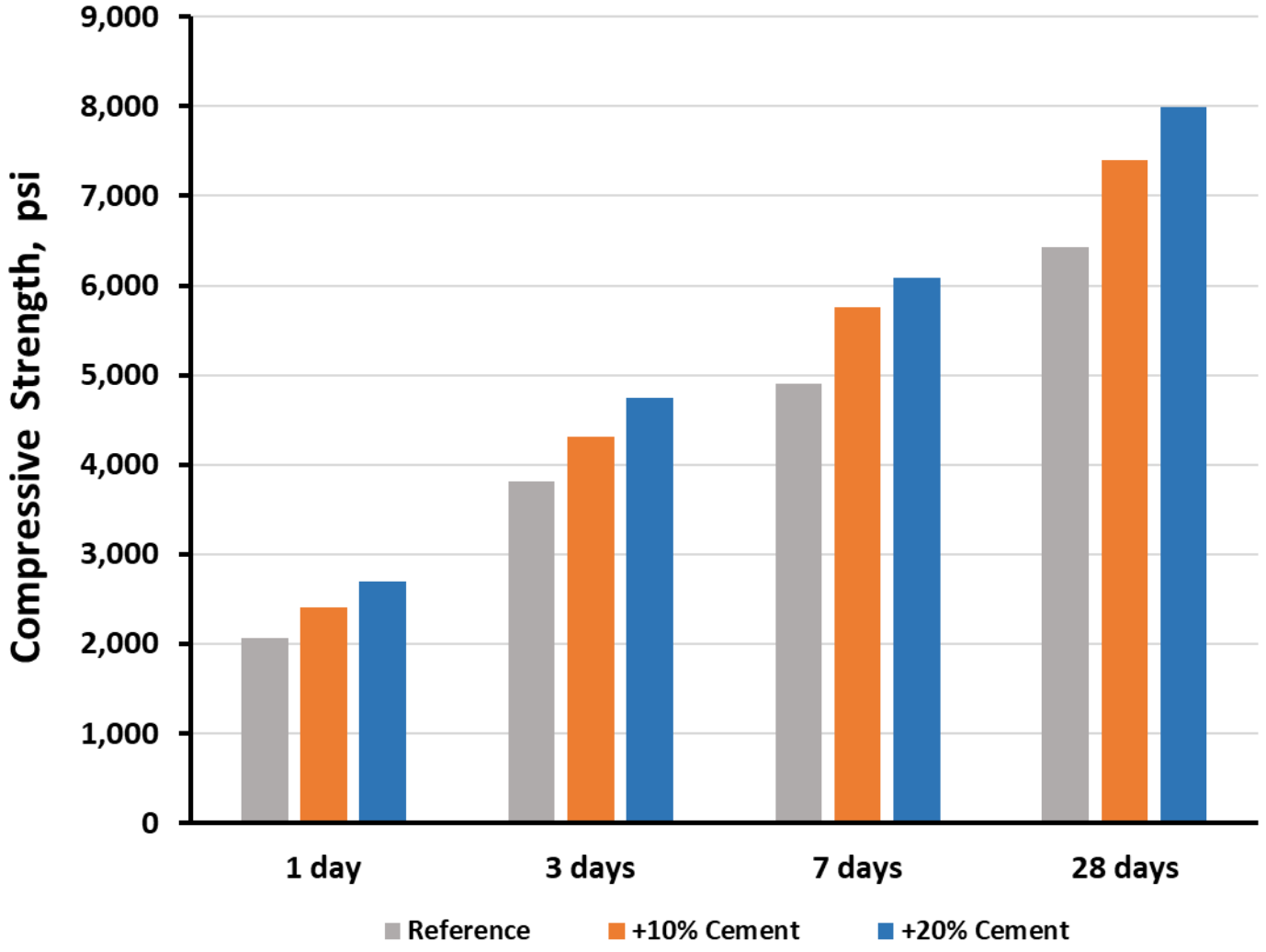
- Specification requirements
  - ex. time-to-opening, etc.
- Operational requirements
  - precast / prestressed concrete
- Construction needs
  - form stripping
  - post-tensioning
  - fast-track applications

Enhanced Early-Age Strength Development: Typical Options

- Increased portland cement content
  - Reduced SCM content
- Type III cement
- Lower w/cm
  - with high-range water-reducing admixtures
- Higher initial curing temperature
  - Heat (steam)
- Admixtures
  - Accelerating admixtures



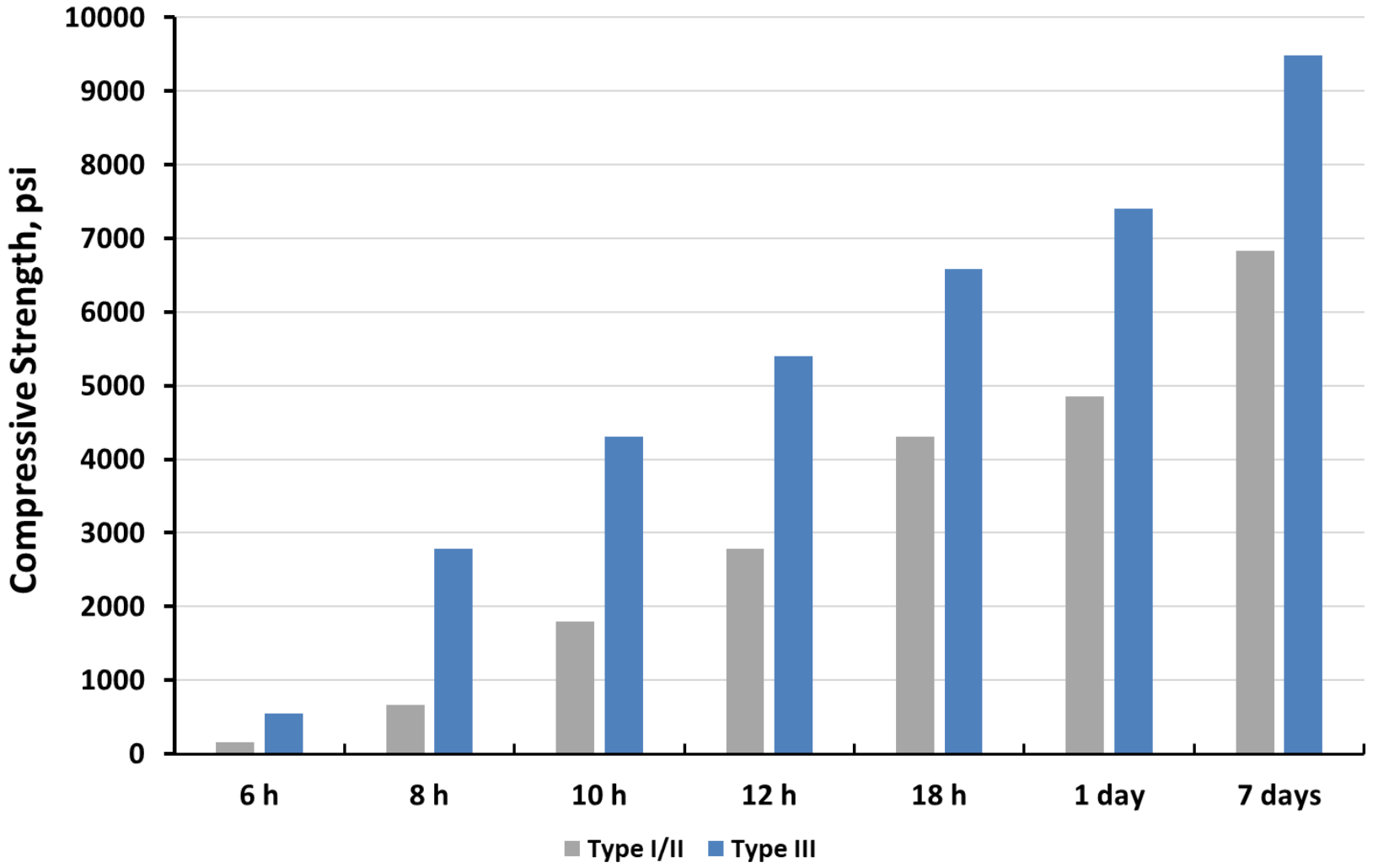
Enhanced Early-Age Strength Development: ↑↑ Cement Content



- Increased portland cement content
  - Higher strength at all ages
  - Increased heat of hydration
  - Higher carbon footprint

Reference Mix: 564 lb/yd^3 portland cement; 305 lb/yd^3 water; nonair-entrained

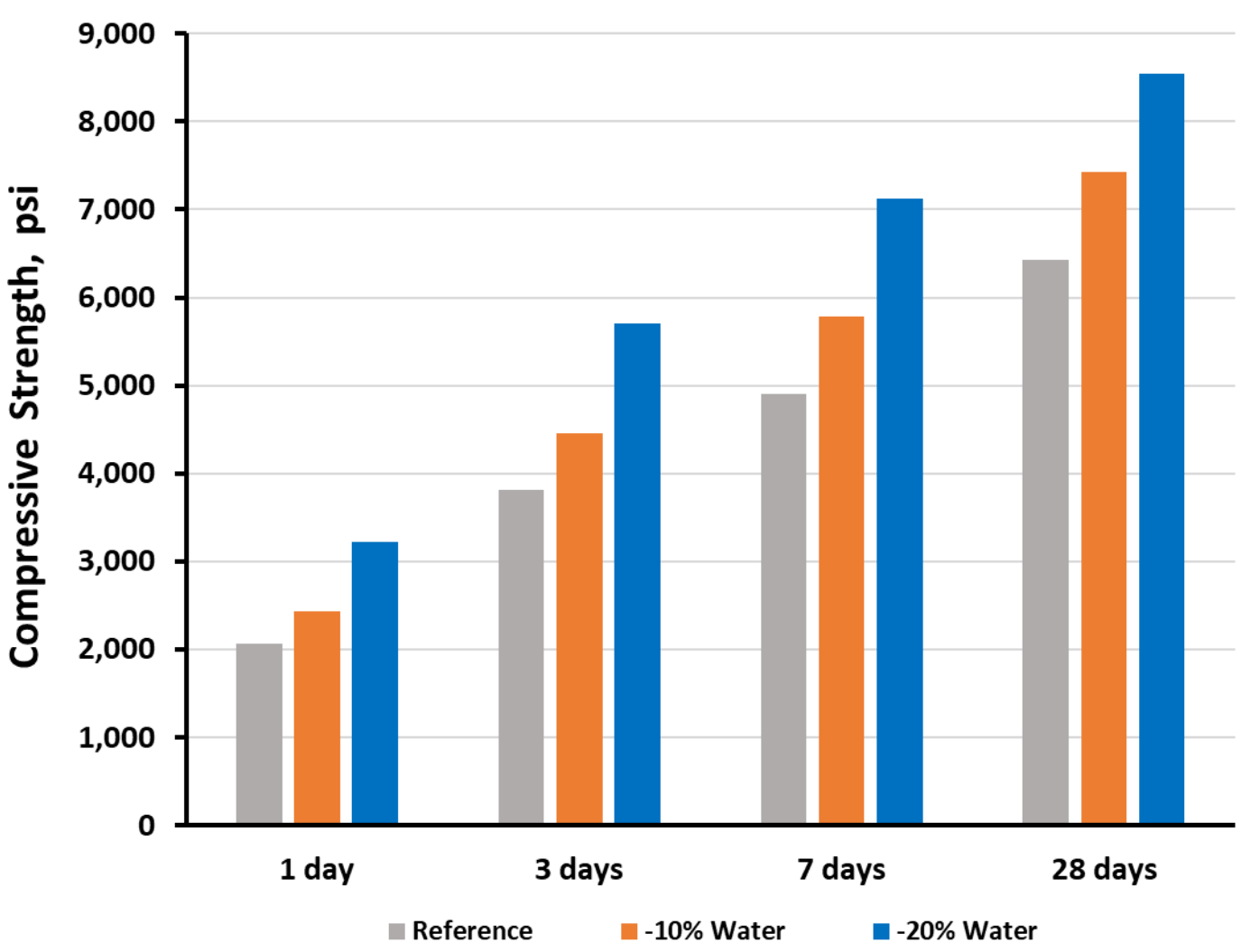
Enhanced Early-Age Strength Development: Type III Cement



- Type III Portland cement
  - Higher strength at all ages
  - Increased heat of hydration
  - Higher carbon footprint

Mix Info: 750 lb/yd^3 portland cement; 0.38 w/c; nonair-entrained; PCE HRWR

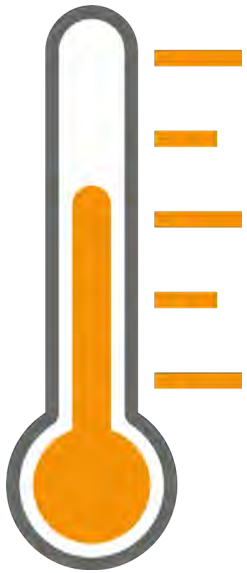
Enhanced Early-Age Strength Development: ↓↓ Water Content

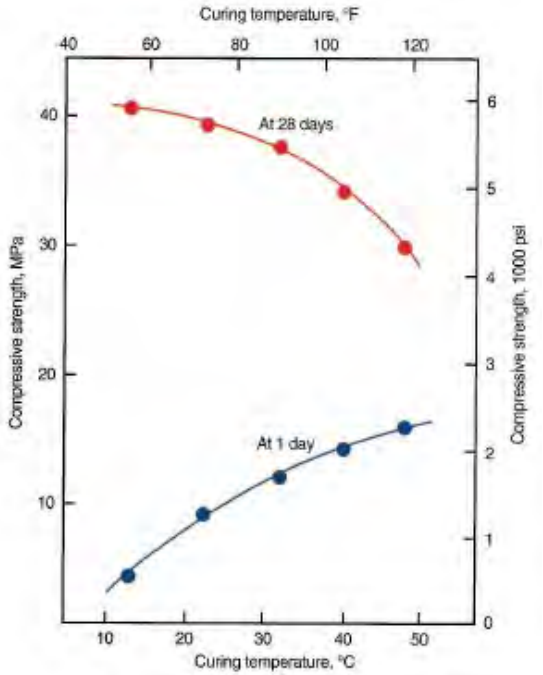


- Lower mix water content
  - Higher strength at all ages
  - HRWR required to achieve target slump
  - Increased mix stickiness

Reference Mix: 564 lb/yd^3 portland cement; 305 lb/yd^3 water; nonair-entrained

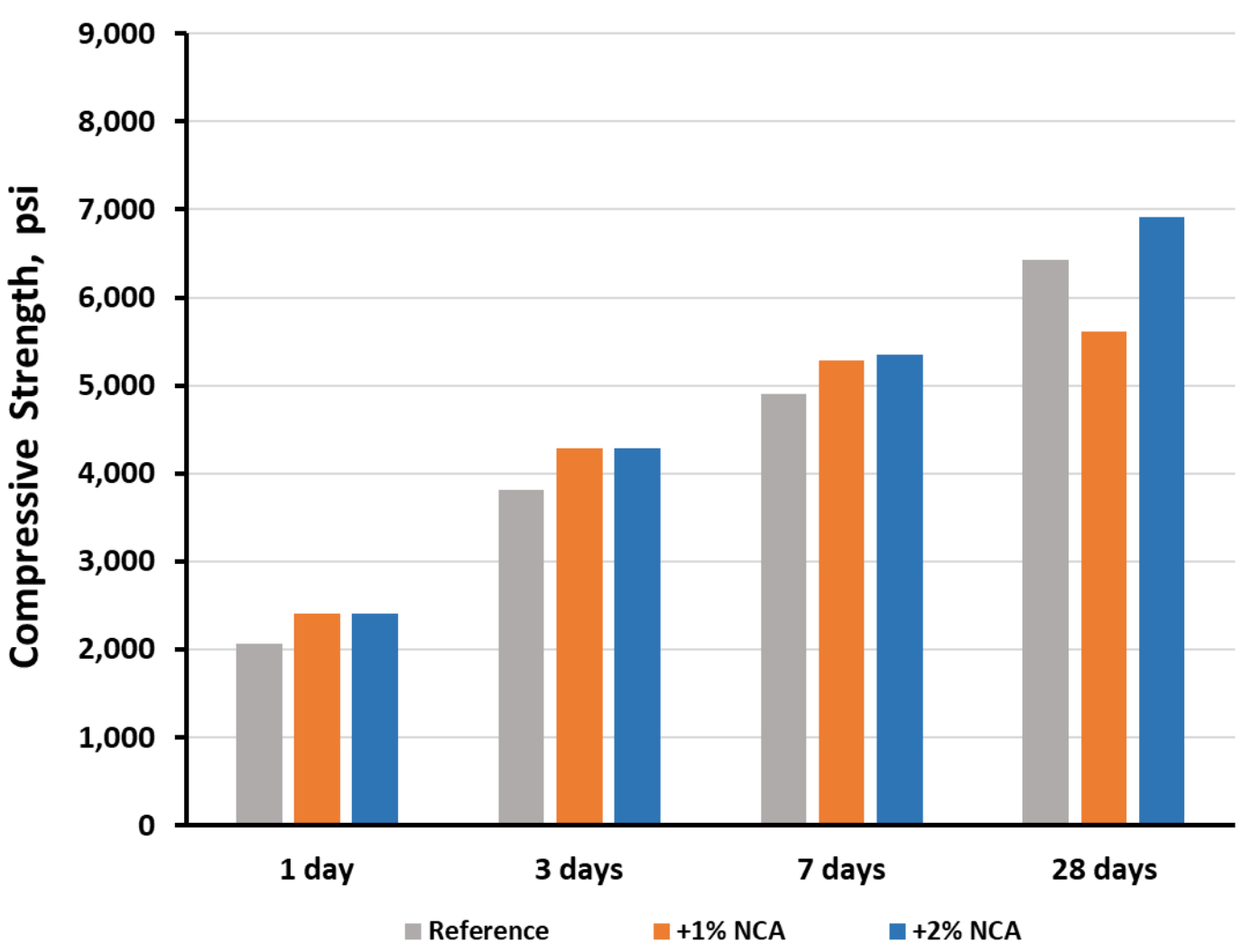
Effect of Temperature on Strength Development





- Both early and later age compressive strength are influenced by the concrete and curing temperatures
- Greater impact on early-age strength development
- Hot weather and cold weather concreting practices
- Maturity – degree hours relationship to compressive strength

Enhanced Early-Age Strength Development: **Accelerating Admixture**



- Increasing accelerating admixture dosage
  - Higher strength early ages
  - Increased heat of hydration
  - Shorter time-of-set

Reference Mix: 564 lb/yd^3 portland cement; 305 lb/yd^3 water; nonair-entrained

Outline

- Basic overview of portland cement hydration and the factors that affect strength development
- Enhanced early-age strength development
  - Why needed and typical options
- **Nanotechnology-based strength-enhancing admixtures**
  - Technology and applications
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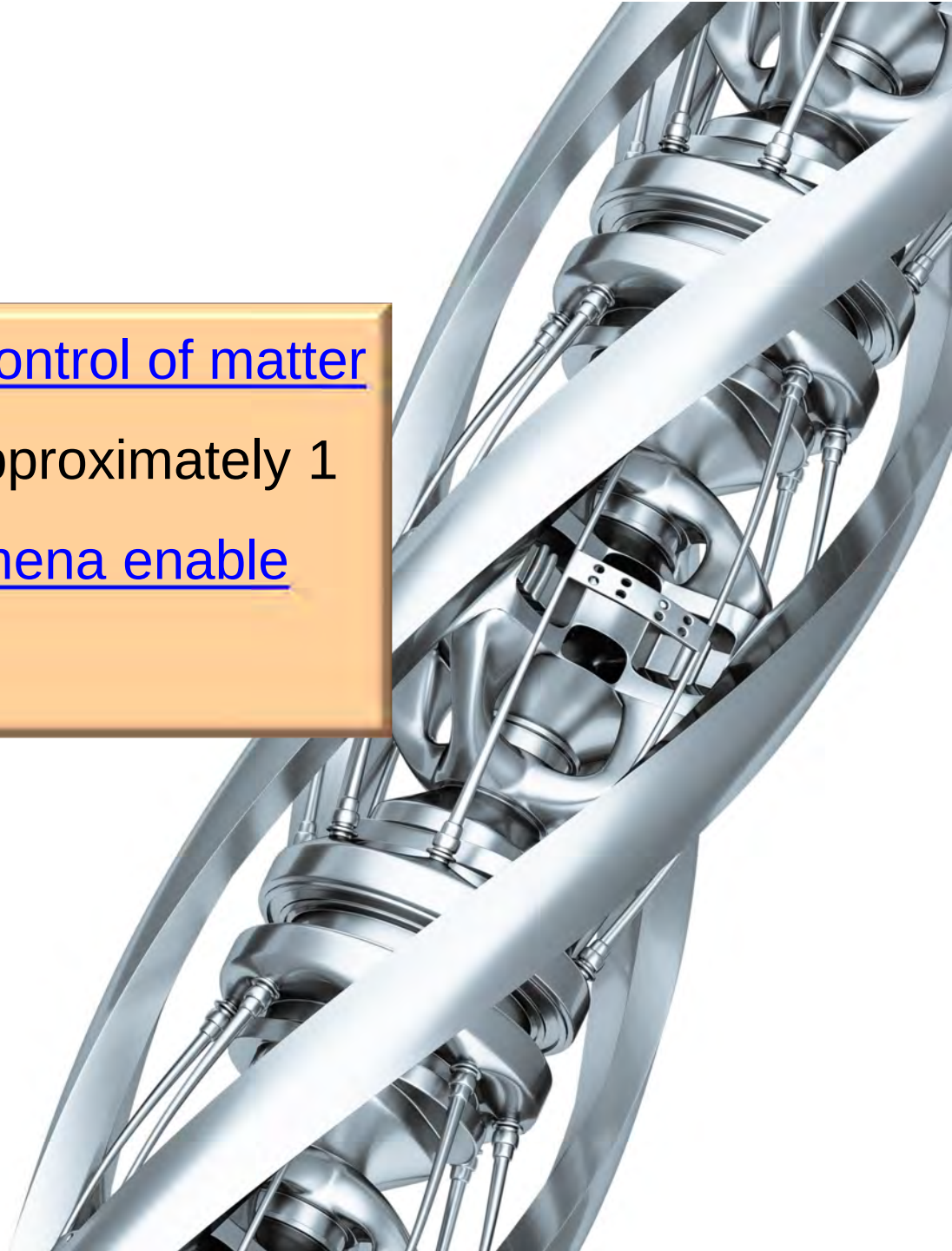
Nanotechnology Defined

- Nanotechnology is the understanding and control of matter at the nanoscale, at dimensions between approximately 1 and 100 nanometers, where unique phenomena enable novel applications.



Source: https://www.nano.gov/nanotech-101/what
(Official website of the United States National Nanotechnology Initiative)

Nanotechnology Defined

Nanotechnology

- Addressing ‘big problems’ with ‘tiny solutions.’
- In 2006, ASTM International Committee E56 on Nanotechnology approved its first standard

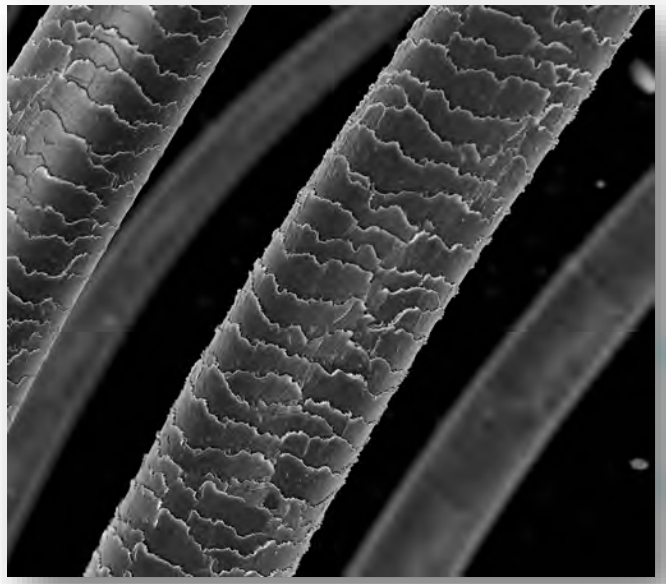
nanoparticle, n — in nanotechnology, a sub-classification of ultrafine particle with lengths in two or three dimensions greater than 0.001 micrometer (1 nanometer) and smaller than about 0.1 micrometer (100 nanometers) and which may or may not exhibit a size-related intensive property.

Source: ASTM - E 2456, Terminology for Nanotechnology

Scale of Things – Nanometers and More

How big is a nanometer?

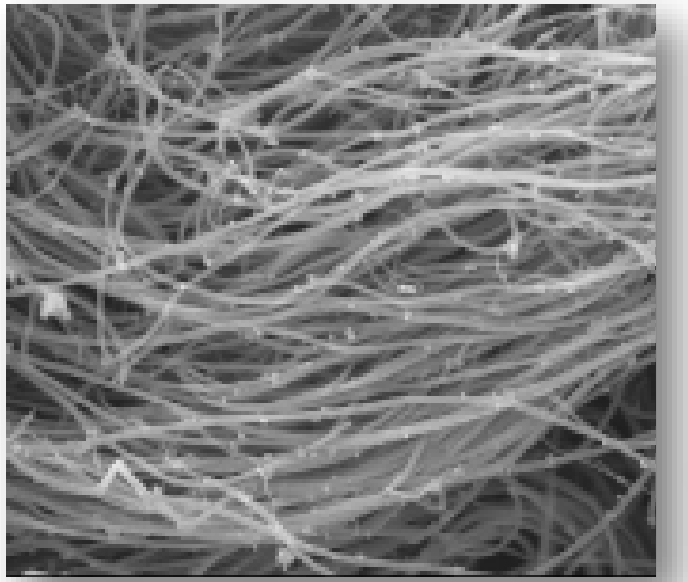
It is a million times smaller than the smallest measurement you can see on a tape measure!



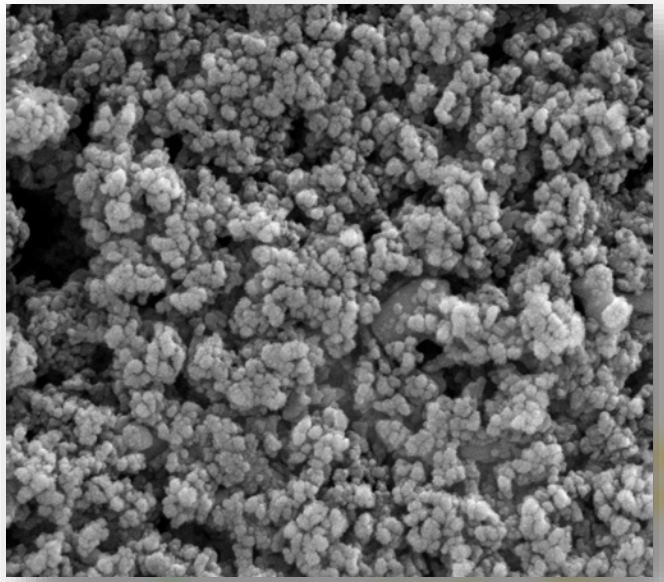
Human Hair
~ 50,000 to 150,000 nm

A millionth of a millimeter…

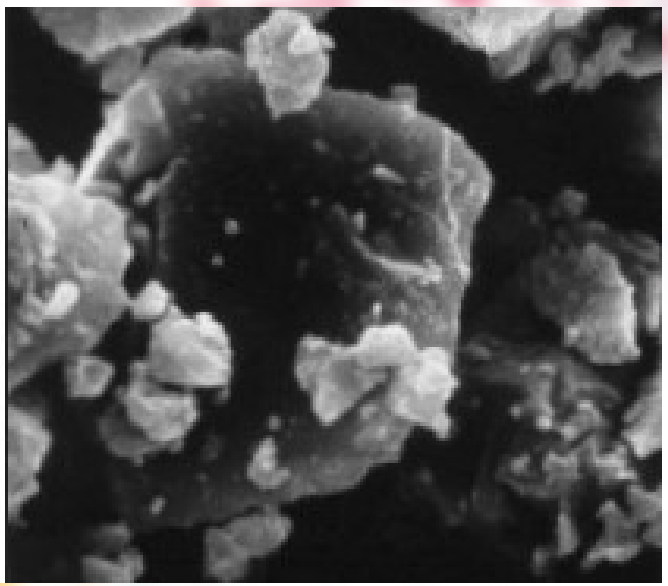
Historical Use of Nanotechnology to Improve Concrete Performance



Carbon Nanotube Nanoparticles
~ 40-80 nm

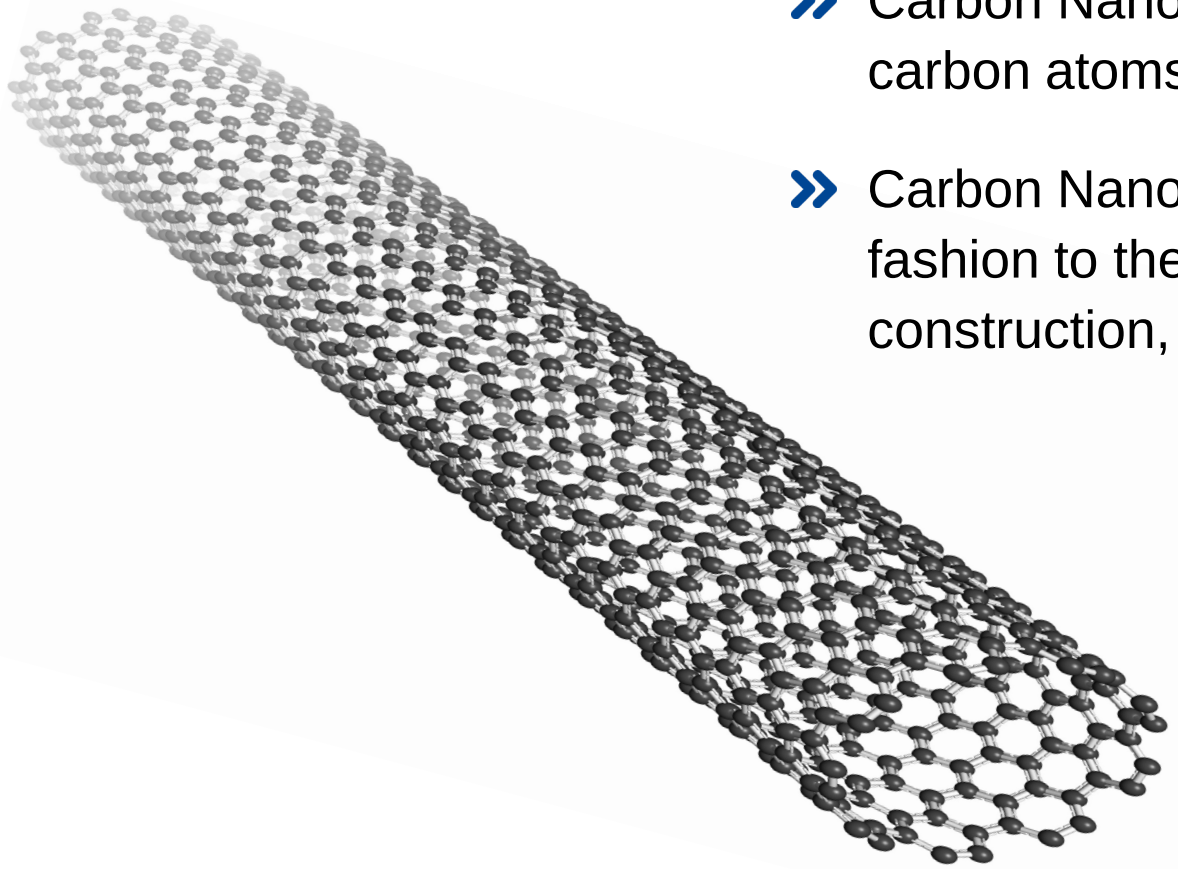


Titanium Dioxide (TiO_2) Nanoparticles
~ 4-8 nm



Portland Cement
~ 20,000 to 45,000 nm
(for reference)

Carbon Nanotubes



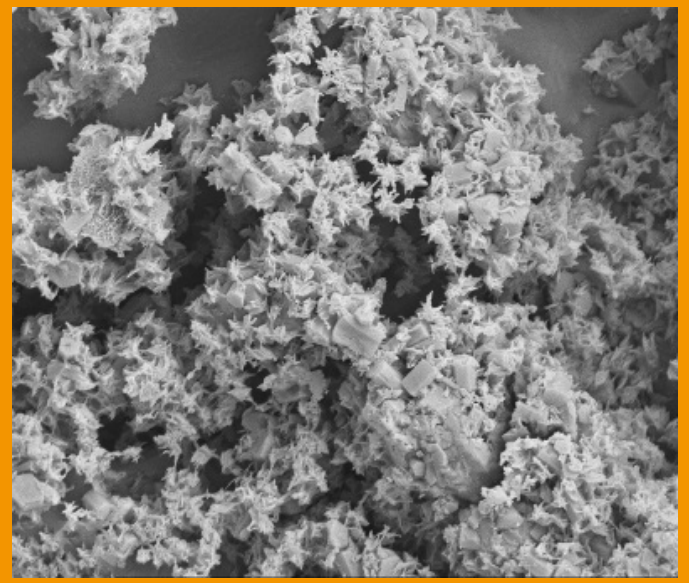
- Carbon Nanotubes are incredibly strong hollow strings of carbon atoms that bond together in a tube
- Carbon Nanotubes can be added to concrete in a similar fashion to the way steel reinforcement is used in modern construction, greatly increasing the structural strength

Titanium Dioxide (TiO_2) Nanoparticles

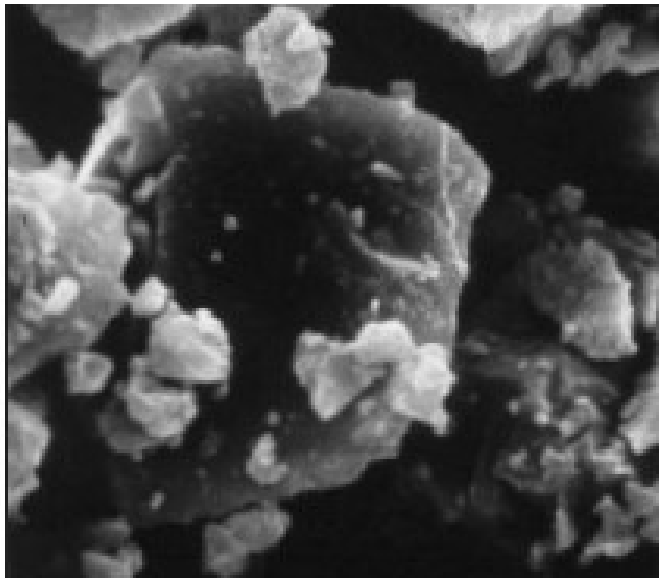
- Titanium Dioxide occurs in nature as the minerals rutile, anatase, and brookite. These oxides are the source of commercial titanium
- Due to its brightness and high refractive index, TiO_2 is a widely used white pigment
- Approximately four million tons of pigmentary TiO_2 are consumed annually worldwide
  - **Not all TiO_2 are in nanoparticle form**
- Applications include paints, coatings, plastics, foods, medicine, toothpaste… portland cement, and **self-cleaning concrete***

* Photocatalytic type

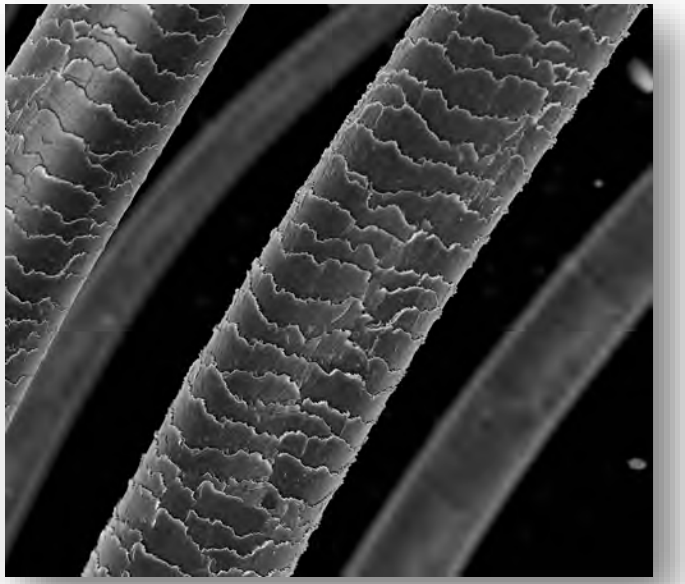
Nanotechnology to Improve Concrete Performance: What's New?



C-S-H Nanoparticles
~ 50 to 100 nm



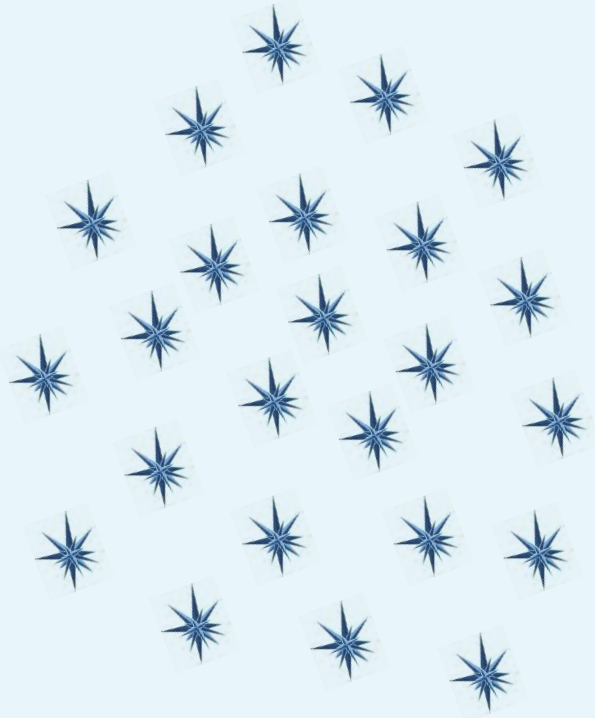
Portland Cement
~ 20,000 to 45,000 nm
(for reference)

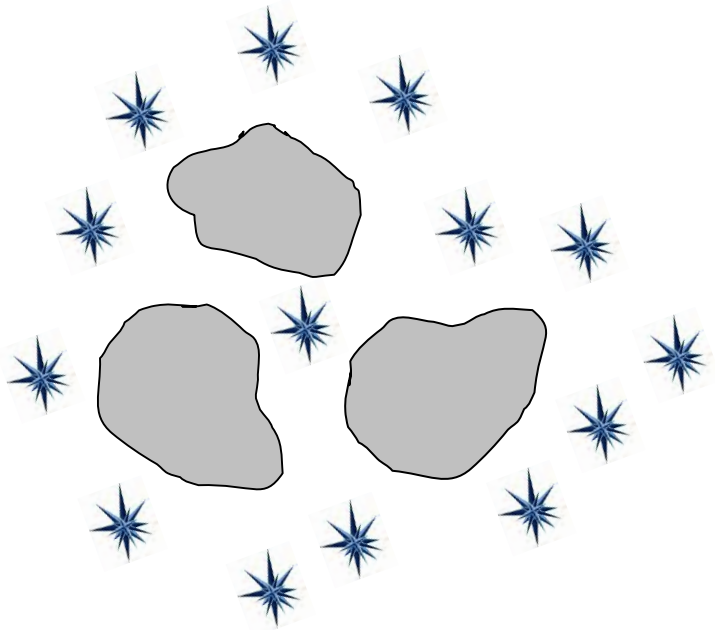


Human Hair
~ 50,000 to 150,000 nm
(for reference)

Portland Cement Hydration Process: What If?

Suspended C-S-H nanoparticles

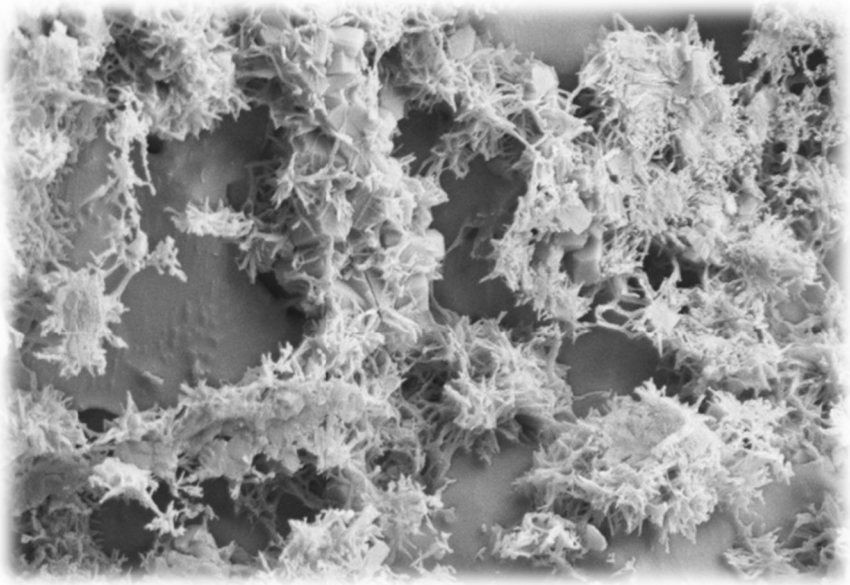




Why wait for the crystallization of the nuclei to be formed if C-S-H nanoparticles can be added to the concrete mixture?

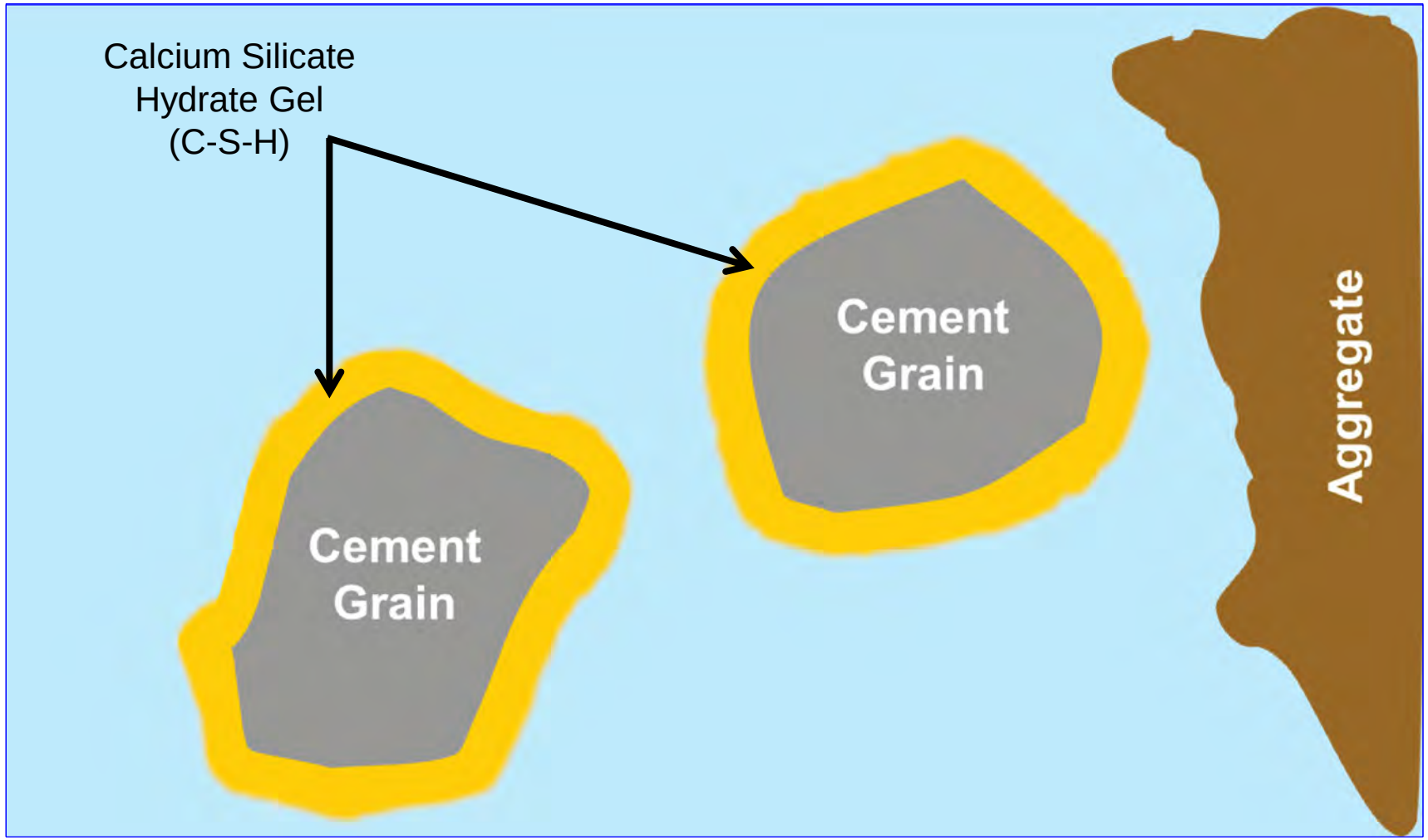
Time to Innovate…

The **challenge** is how to introduce nanoscale particles into concrete – the best option is to use a **liquid admixture!**



C-S-H nanoparticles

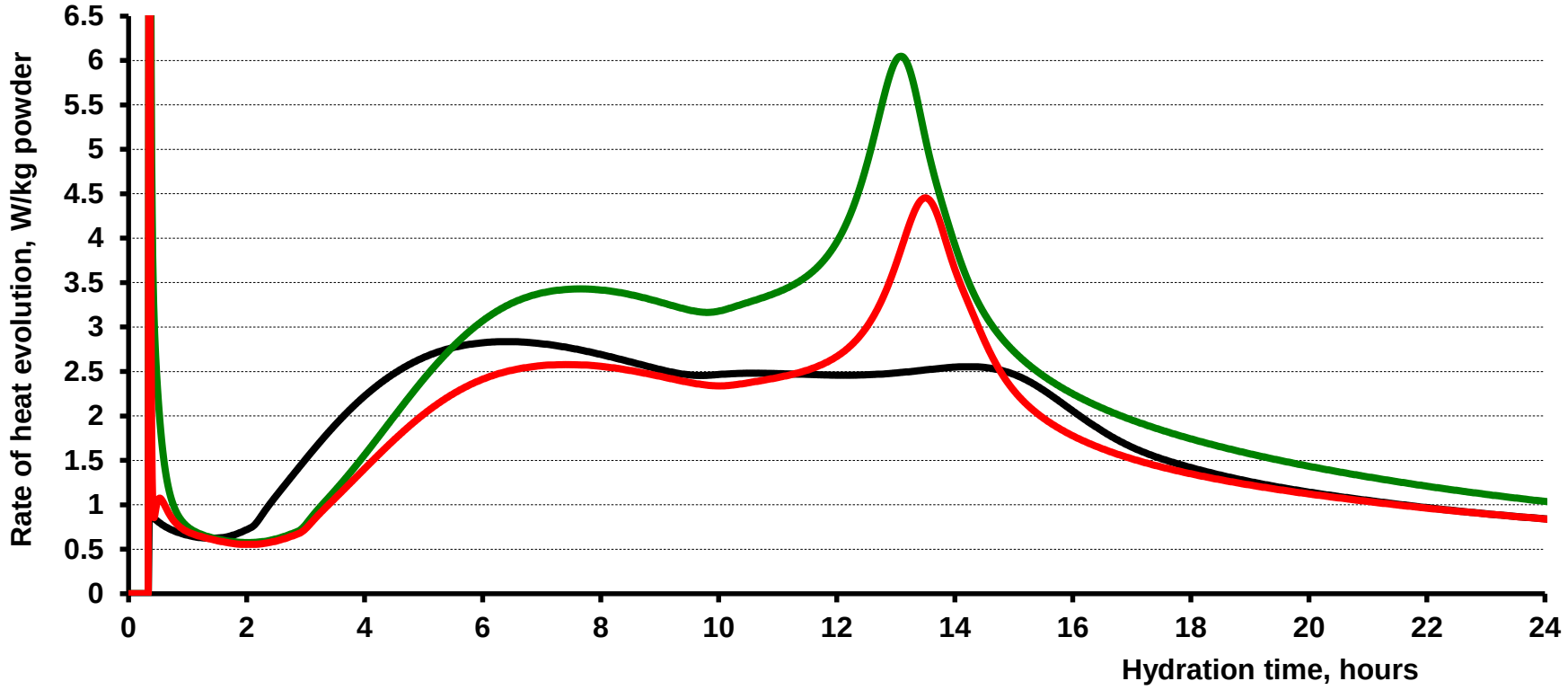
Jump-Starting the Hydration Process



Master X-Seed® 55:
Increase the Speed of Construction

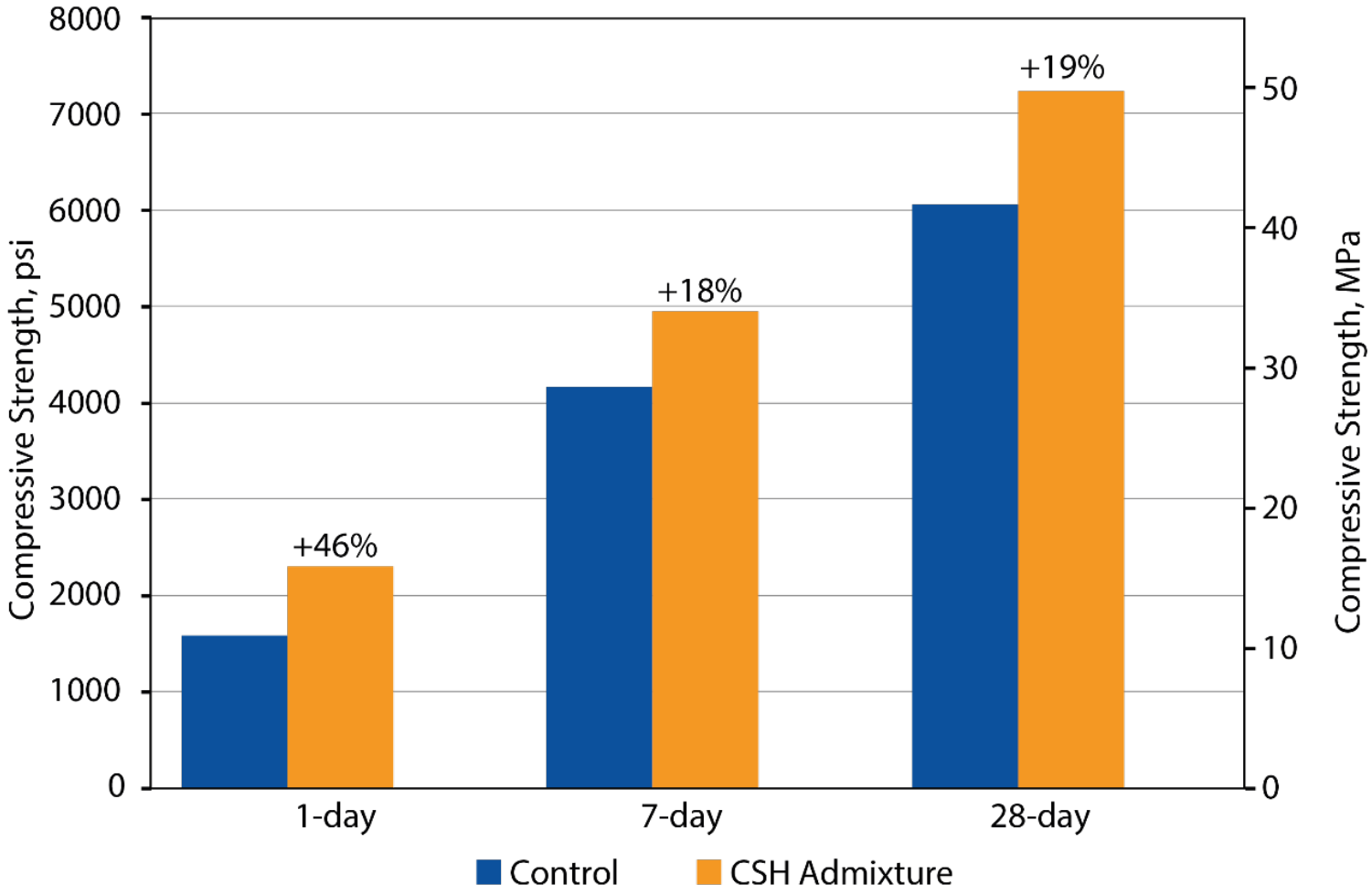
https://youtu.be/6qLXzs9M-iI

C-S-H Nanoparticle-Based Admixtures: Calorimetry Data



Strength-Enhancing Admixture (SEA)

Increases Early-Age Compressive Strength



(Nominal cementitious materials content of 611 lb/yd^3 [362 kg/m^3] with 20 percent fly ash, w/cm of 0.47; CSH-based Strength-Enhancing Admixture dosage of 10 fl oz/cwt [650 mL/100 kg])

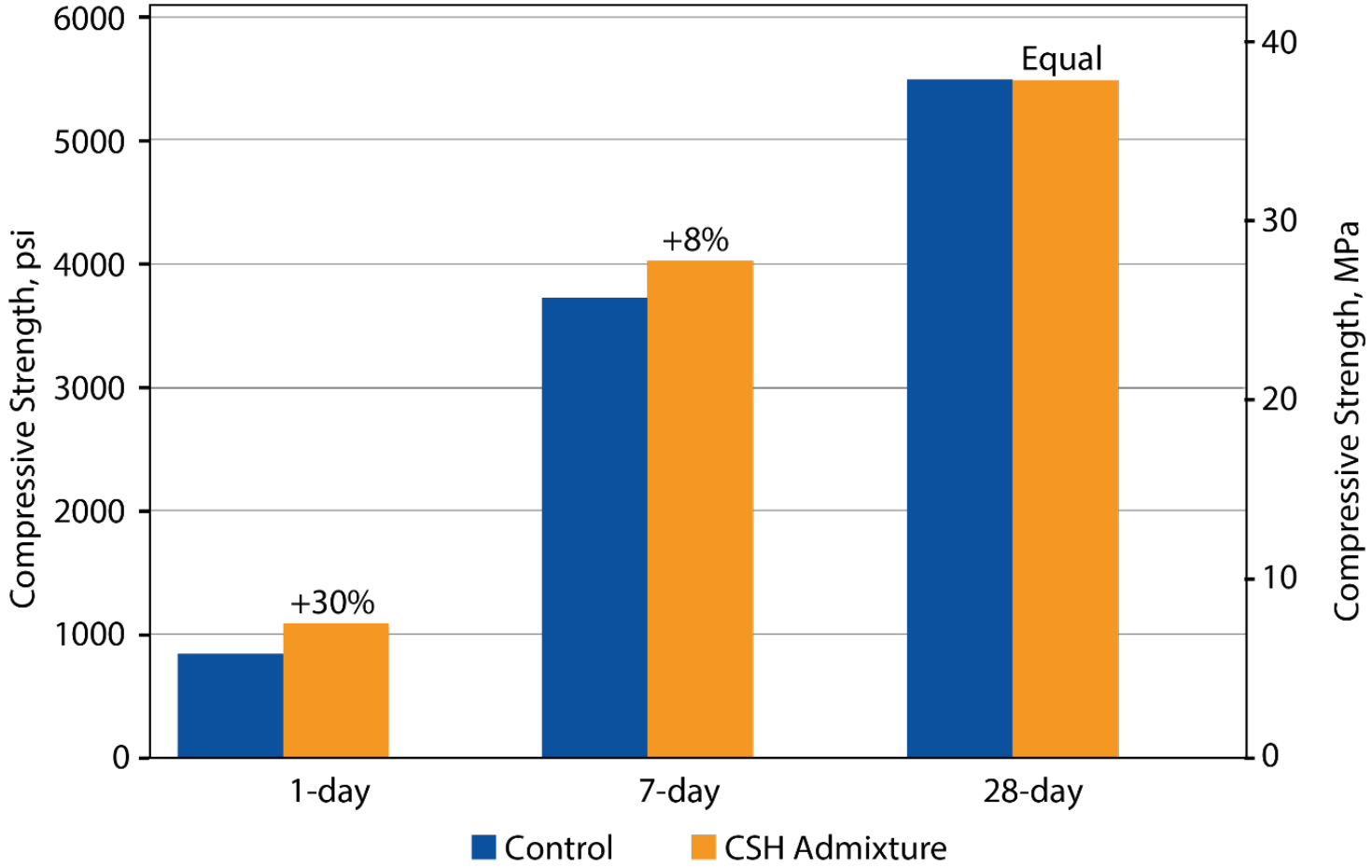
Strength-Enhancing Admixture (SEA)

Permits Reduction in Cementitious Materials Content

	Reference	CSH-Based SEA
Total Binder Content	705 lb/yd^3 (418 kg/m^3)	629 lb/yd^3 (373 kg/m^3)
Fly Ash	25 percent	25 percent
Limestone Powder	21 percent	21 percent
w/cm	0.39	0.40
CSH-Based SEA	--	**7.3 fl oz/cwt (475 mL/100 kg)**

Strength-Enhancing Admixture (SEA)

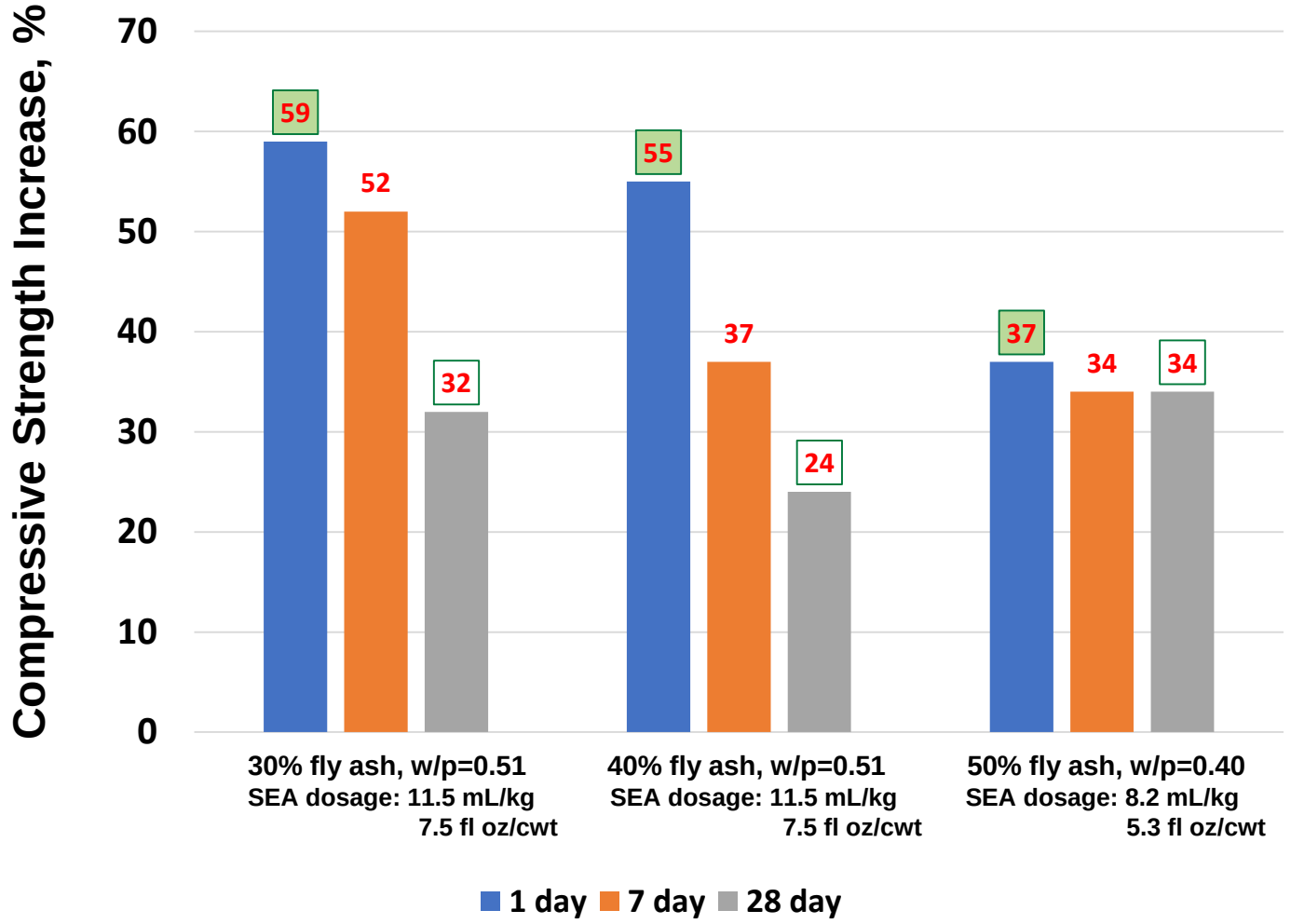
Permits Reduction in Cementitious Materials Content



Control: Total binder content - 705 lb/yd^3 [418 kg/m^3] with 25% fly ash, 21% limestone powder, 0.39 w/cm;
C-S-H Admixture: Dosage of 7.3 fl oz/cwt [475 mL/100 kg], Total binder content - 629 lb/yd^3 [373 kg/m^3] with 25% fly ash, 21% limestone powder, w/cm of 0.40

Strength-Enhancing Admixture (SEA)

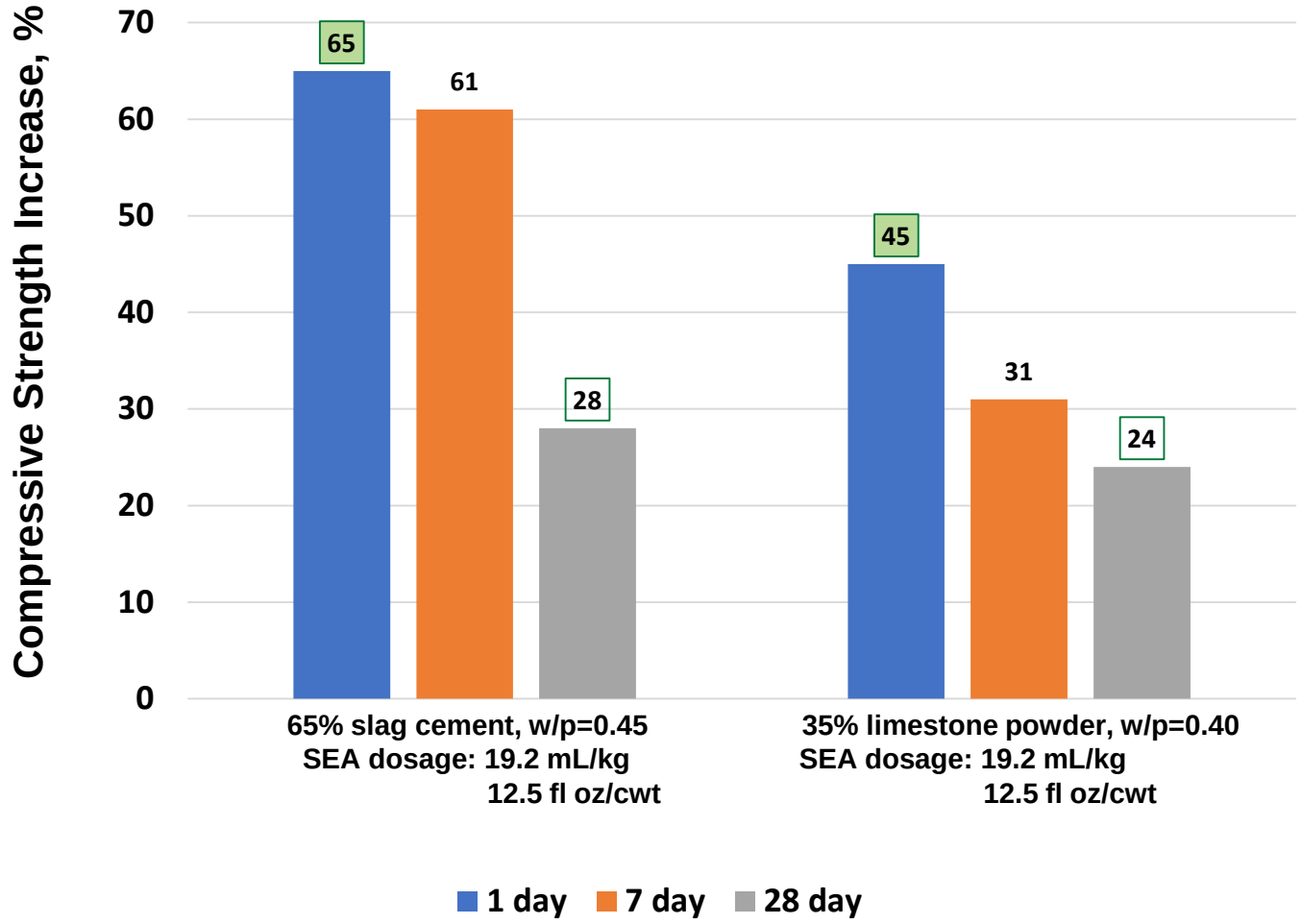
Offers Potential for Increased Replacement of Portland Cement



Cement Reduction & Higher Fly Ash Amounts

Strength-Enhancing Admixture (SEA)

Offers Potential for Increased Replacement of Portland Cement



Cement Reduction & High Amounts of Slag Cement or Limestone Powder

C-S-H Nanoparticle-Based Admixtures: **Typical Applications**

Precast Concrete

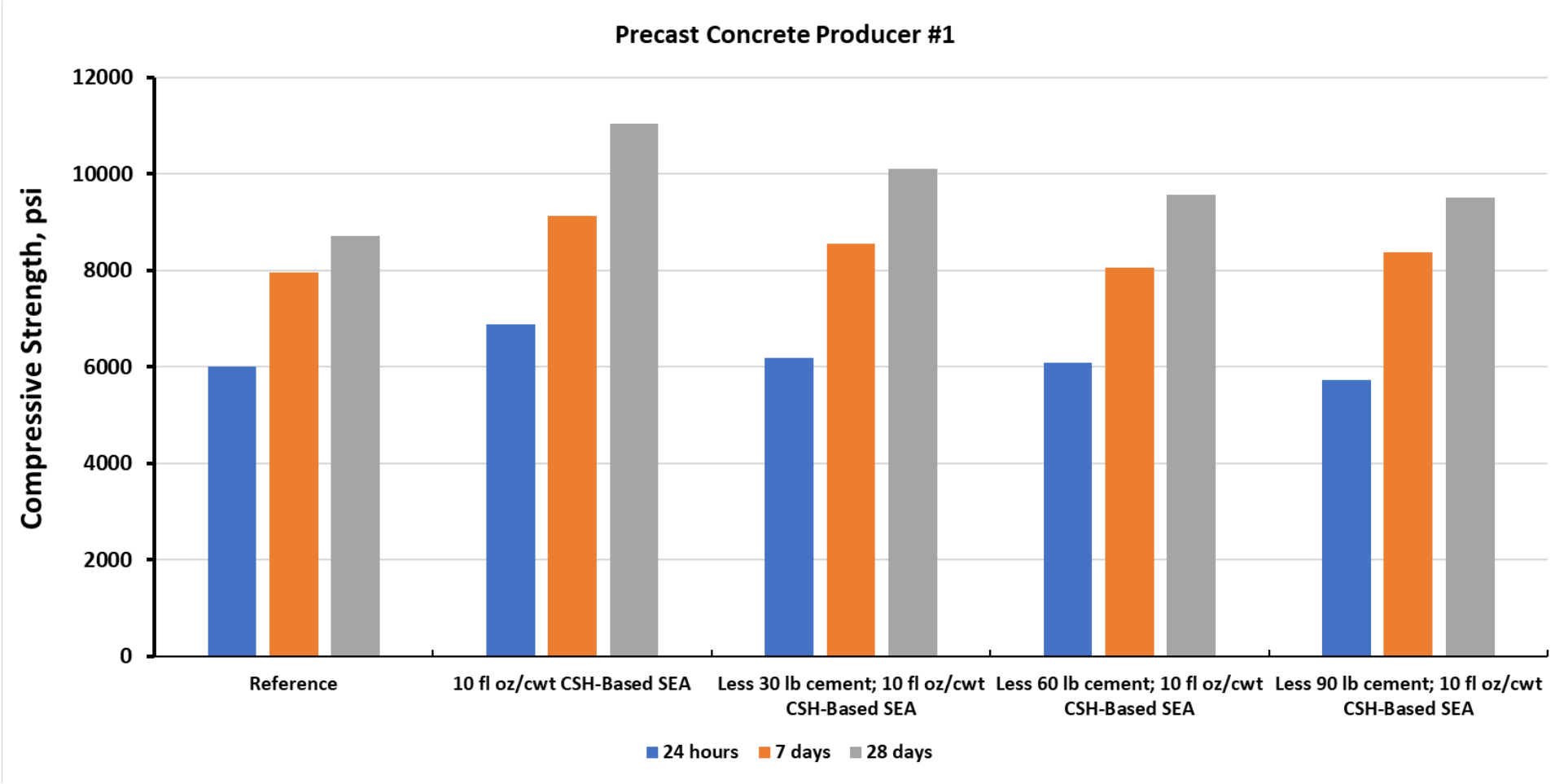
- Reduce cycle times
- Enhance product aesthetics

Cast-in-Place Concrete

- Expedite construction
- Optimize concrete mixture to reduce carbon footprint

Strength-Enhancing Admixture

Potential Benefits in Concrete Pipe Production



Benefits in Production of Concrete Pipe

- **Mix Cost Reduction:** Permits reduction of cementitious materials content, normally eliminating surfactant admixtures without strength reduction, while improving pipe appearance.
- **Inventory Reduction Flexibility:** Reduces duration of storage in the production yard until 80% of the design strength is achieved.
- **Reduction in Post-Production Defects:** Higher early strengths reduce potential for chipping or cracking when the pipes are moved.
- **Mixture Simplification:** Makes it possible to meet strength requirements for both Class 3 and Class 5 pipes with only one mixture proportion.
- **Improved Aesthetics:** Enhances surface appearance.
- **Energy Savings:** Offers potential to either reduce or eliminate heat curing.

Improved Surface Appearance

Reference Pipes

With C-S-H Nanoparticle-Based Strength-Enhancing Admixture

Improved Surface Appearance

Tilt-Up Construction

Stripping and Lifting Considerations from the Concrete Perspective

- Faster development of concrete strength to facilitate construction

Construction in the 21st Century…

Owners / Design Team often ask:

"Do your products address my sustainability requirements?"

BASF EPD for Concrete

https://youtu.be/1492bds3UEY

Nutrition labels provide information on health impacts from food while an EPD…

Nutrition Facts

Serving Size ½ Cup (31g/1.1 oz.)
Servings Per Container About 17

Amount Per Serving	Cereal	Cereal with ½ Cup Vitamins A&D Fat Free Milk
Calories	80	120
Calories from Fat	10	10
	% Daily Value**	
Total Fat 1g*	2%	2%
Saturated Fat 0g	0%	0%
Trans Fat 0g		
Cholesterol 0mg	0%	0%
Sodium 80mg	3%	6%
Potassium 350mg	10%	16%
Total Carbohydrate 23g	8%	10%
Dietary Fiber 10g	40%	40%
Soluble Fiber 1g		
Sugars 6g		
Other Carbohydrate 7g		
Protein 4g		
Vitamin A	10%	15%
Vitamin C	10%	10%
Calcium	10%	25%
Iron	25%	25%
Vitamin D	10%	25%
Thiamin	25%	30%
Riboflavin	25%	35%
Niacin	25%	25%
Vitamin B_6	100%	100%
Folic Acid	100%	100%
Vitamin B_{12}	100%	110%

Nutrition Facts

Serving Size ¾ cup (47g)
Servings Per Container About 8

Amount Per Serving	Wheat Chex	with ½ cup skim milk
Calories	160	200
Calories from Fat	10	10
	% Daily Value**	
Total Fat 1g*	1%	2%
Saturated Fat 0g	0%	3%
Trans Fat 0g		
Polyunsaturated Fat 0.5g		
Monounsaturated Fat 0g		
Cholesterol 0mg	0%	1%
Sodium 300mg	12%	15%
Potassium 170mg	5%	11%
Total Carbohydrate 39g	13%	15%
Dietary Fiber 5g	21%	21%
Soluble Fiber 1g		
Sugars 5g		
Other Carbohydrate 33g		
Protein 4g		
Vitamin A	10%	15%
Vitamin C	10%	10%
Calcium	10%	25%
Iron	80%	80%
Vitamin D	10%	25%
Thiamin	25%	30%
Riboflavin	25%	35%

Life Cycle Impact Results

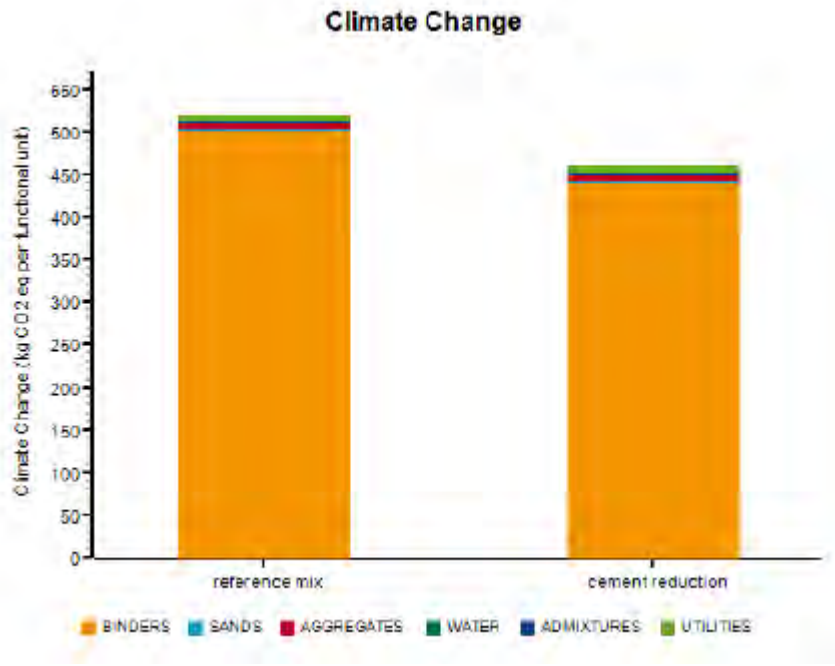
Declared Unit: 1 yd^3 of 5,000 psi (35 MPa) concrete at 28 days, 8,000 psi (40 MPa) at 56 days.

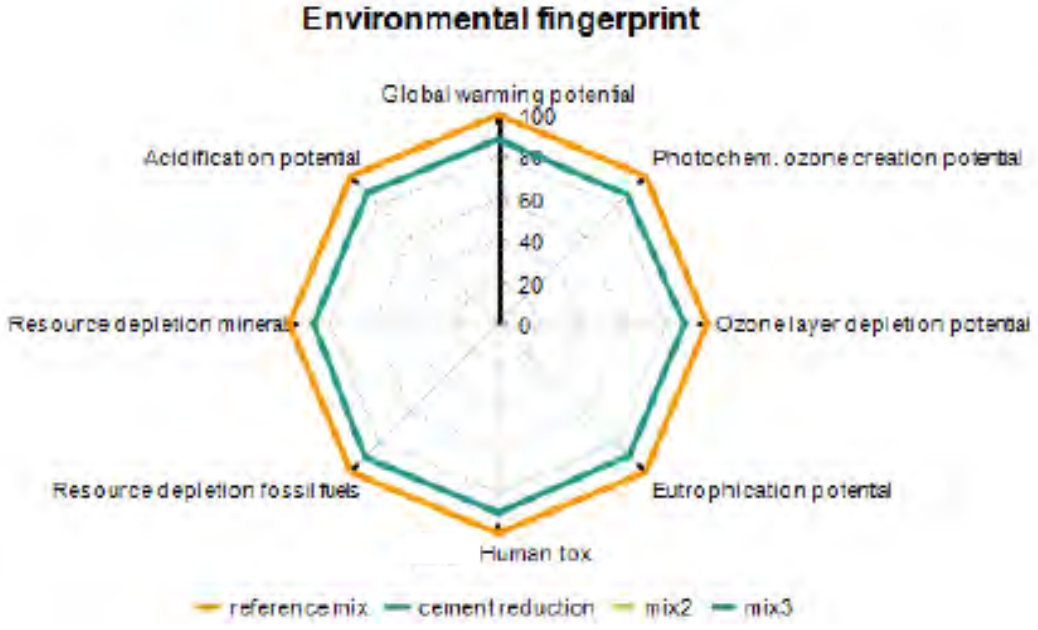
LIFE CYCLE INVENTORY DATA (per m^3)	*Product ID 4MFT438*
Total Primary Energy consumption (MJ)	1,961
Concrete batching water consumption (m^3)	1.60E-01
Concrete washing water consumption (m^3)	1.82E-02
Total water consumption (m^3)	1.78E-01
Use of renewable primary energy (MJ)	61
Depletion of non-renewable energy resources (MJ)	1,900
Use of renewable material resources (kg)	0.0
Depletion of non-renewable material resources (kg)	2,291
Hazardous waste (kg)	0.0
Non-hazardous waste (kg)	2.4
LIFE CYCLE IMPACT ASSESSMENT (per m^3)	
Climate change* (kg CO_2 eq)	270
Ozone depletion* (kg CFC 11 eq)	1.00 E-08
Acidification** (kg SO_2 eq)	1.8
Eutrophication** (kg N eq)	0.058
Photochemical ozone creation/smog** (kg O_3 eq)	16.6

*CML characterization **TRACI characterization

Sustainability Benefits of Nanoparticle CSH-Based SEAs can be Quantified with EEA

Sustainability Benefits of CSH Nanoparticle-Based Admixture





Overall reduction in environmental footprint

Pier 27 Residential Building - Toronto, Canada

- 35-storey residential building completed Summer 2019;
- ~ 32,700 yd^3 (25,000 m^3) of concrete;
- 3,900 yd^3 (3,000 m^3) of concrete optimized to achieve high-early strength in 16 – 18 h;
  - lower cementitious materials content
  - workable and pumpable; slump loss minimized
- Will receive the "Material Development & Innovation Award" from Ontario Concrete Awards in Dec. 2019.

Outline

- Basic overview of portland cement hydration and the factors that affect strength development
- Enhanced early-age strength development
  - Why needed and typical options
- Nanotechnology-based strength-enhancing admixtures
  - Technology and applications
- **Summary**

C-S-H Nanoparticle-Based Admixtures: **Summary**

- Increased desire for sustainable offerings drives innovations
- Technology exists to solve ‘big problems’ with ‘tiny solutions’
- Challenge is to effectively deliver and distribute small particles into concrete
- Liquid chemical admixture technology offers such a pathway to delivery

C-S-H Nanoparticle-Based Strength-Enhancing Admixtures (SEAs)

Admixtures Contain C-S-H Seeds

- Strength-enhancing admixtures contain nanoparticles
- Nanoparticles provide C-S-H ‘seeding’

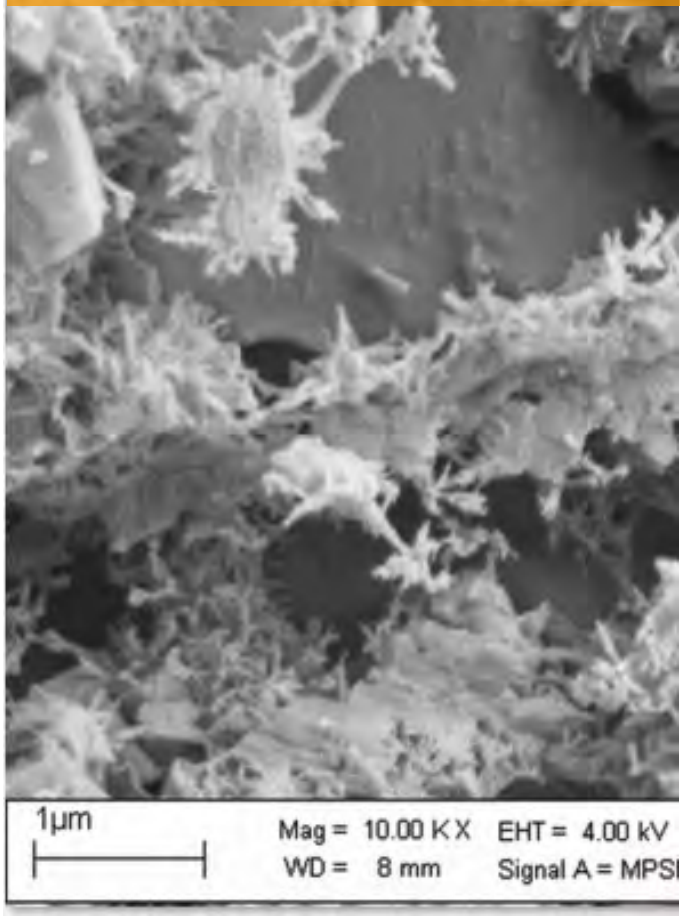
Unmatched Strength Enhancement

- C-S-H nanoparticles improve cement hydration
- Increase early- and late-age strength development

Value to Producers & Engineers

- C-S-H nanoparticles allow for design flexibility
- Facilitates mixture optimization and cement reduction without strength loss

Cryo-SEM imaging shows crystal growth between cement grains in early stages of hydration



Thank You!

This concludes the Continuing Education Program.

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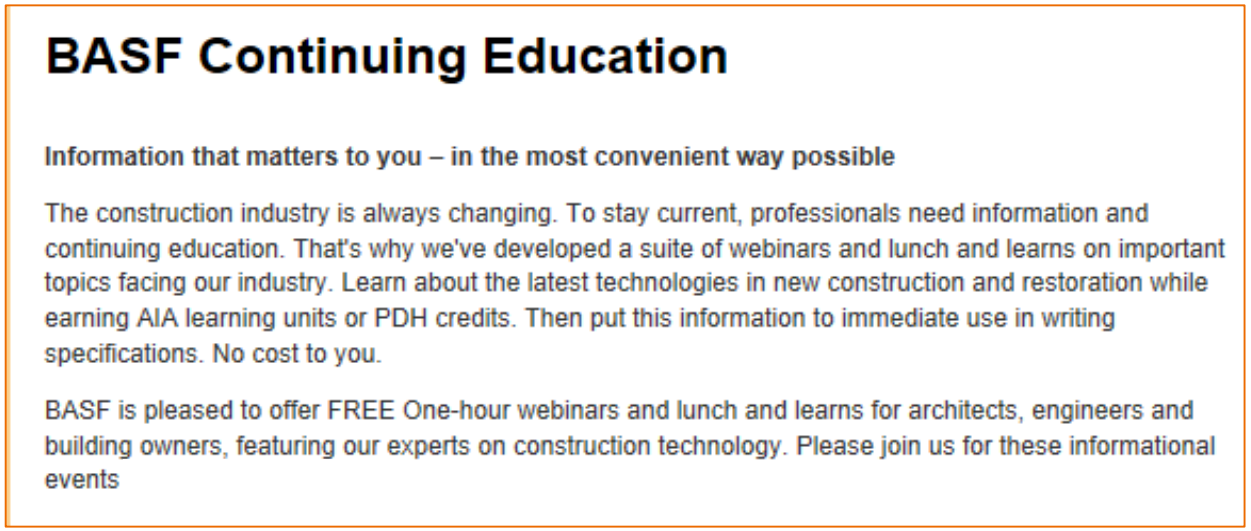

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