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The Case for Concrete Pavement – Sustainable Attributes and Opportunities for the Future

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Principal

CPAM 2022 Annual Concrete Pavement Conference
Friday, March 11, 2022

Today's Topics

- Climate change – driving the conversation
- What is sustainability?
- The role played by portland cement and concrete
- Considering carbonation and the use phase
- Verification
- Some recent initiatives

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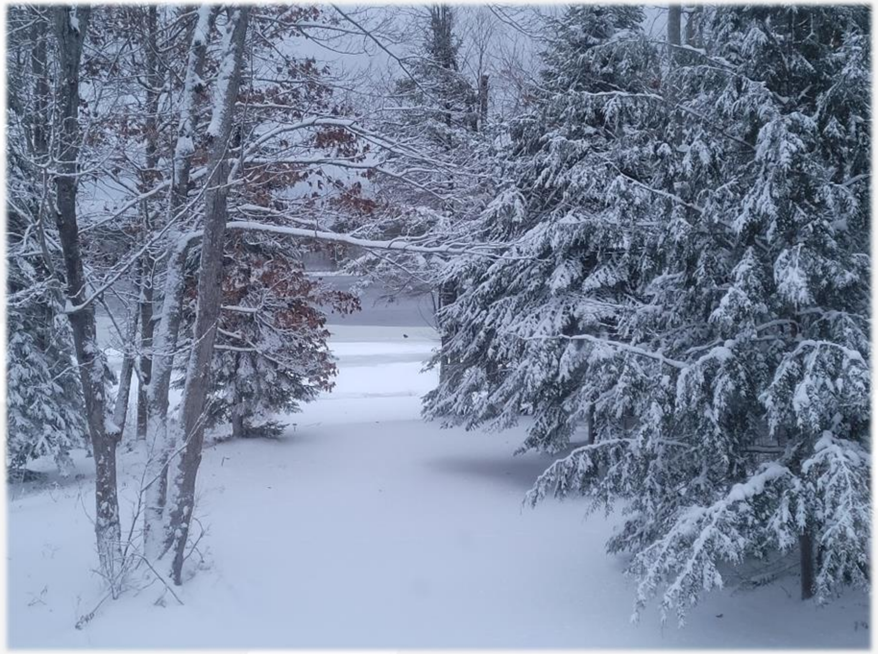
And Just Like That, Climate Change Is The Rage

- Politicians come and go, but scientific facts remain
  - GHG concentrations are increasing
  - Global temperatures are rising
  - The Arctic continues to melt, and sea levels are rising
- Current administration is emphasizing climate change
  - Climate change is a focal point in the new infrastructure bill (IIJA)
- Climate change is of great interest to many governmental agencies and industry
  - Clearly matters to Colorado as well as many others



Climate Change

- Changes in global climate from human activities are occurring
  - Supported by historical observations and climate modeling
- Optimistic models predict substantial climate change over the next century
  - Rate of change depends on what we do
  - Long life of emitted heat-trapping, greenhouse gases and slow feedback functions of atmospheric systems drive climate change

Certainty

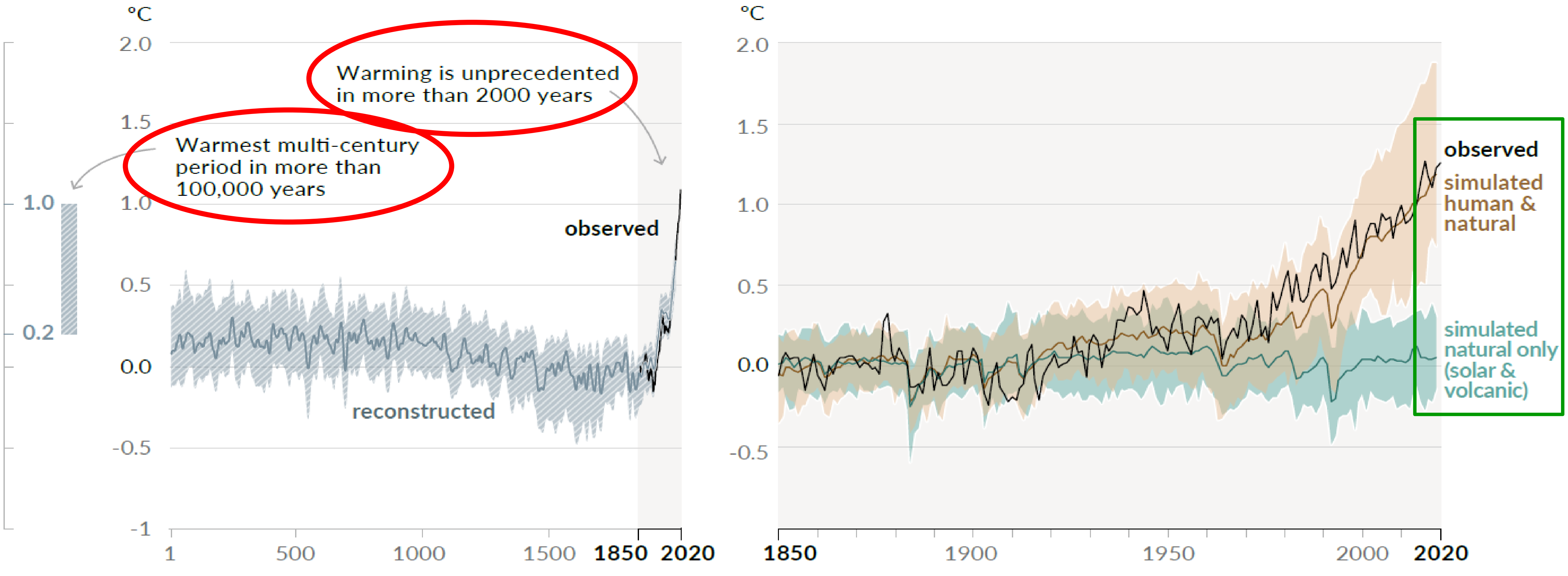
"It is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred"

IPCC, 2021: Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis*

Uncertainty

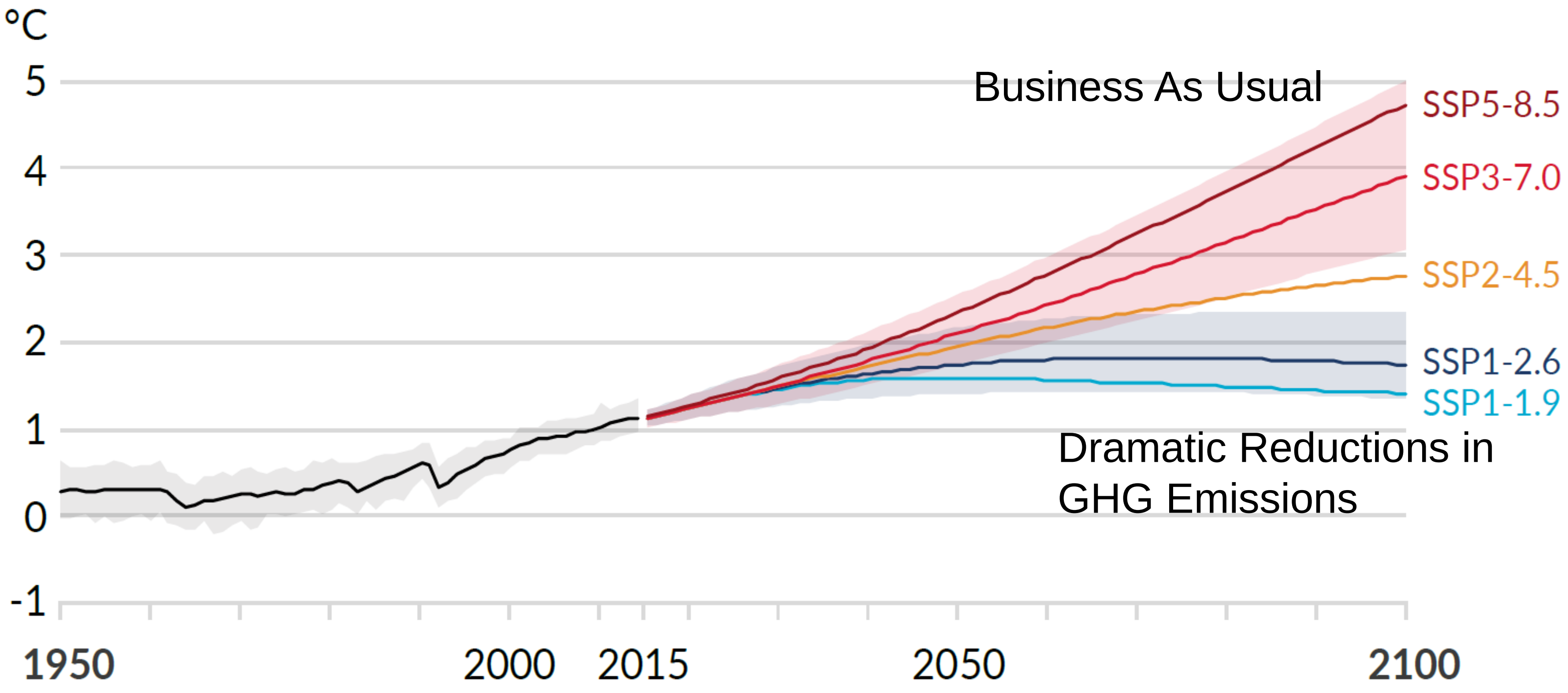
The degree of change is uncertain as many variables are important and as yet, undefined

Changes in Global Surface Temperatures Relative to 1850-1900 (IPCC 2021)



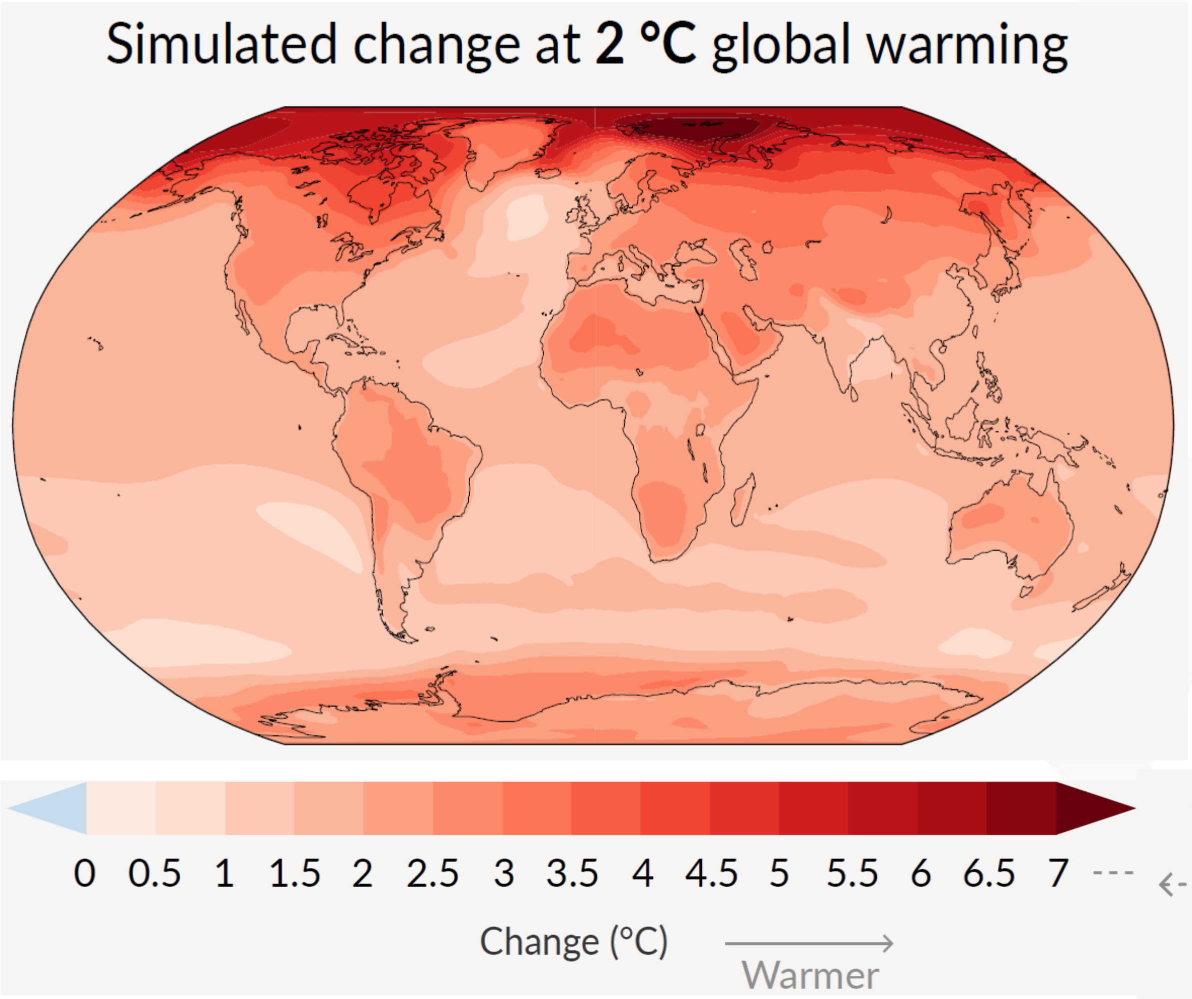
IPCC, 2021: Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis*

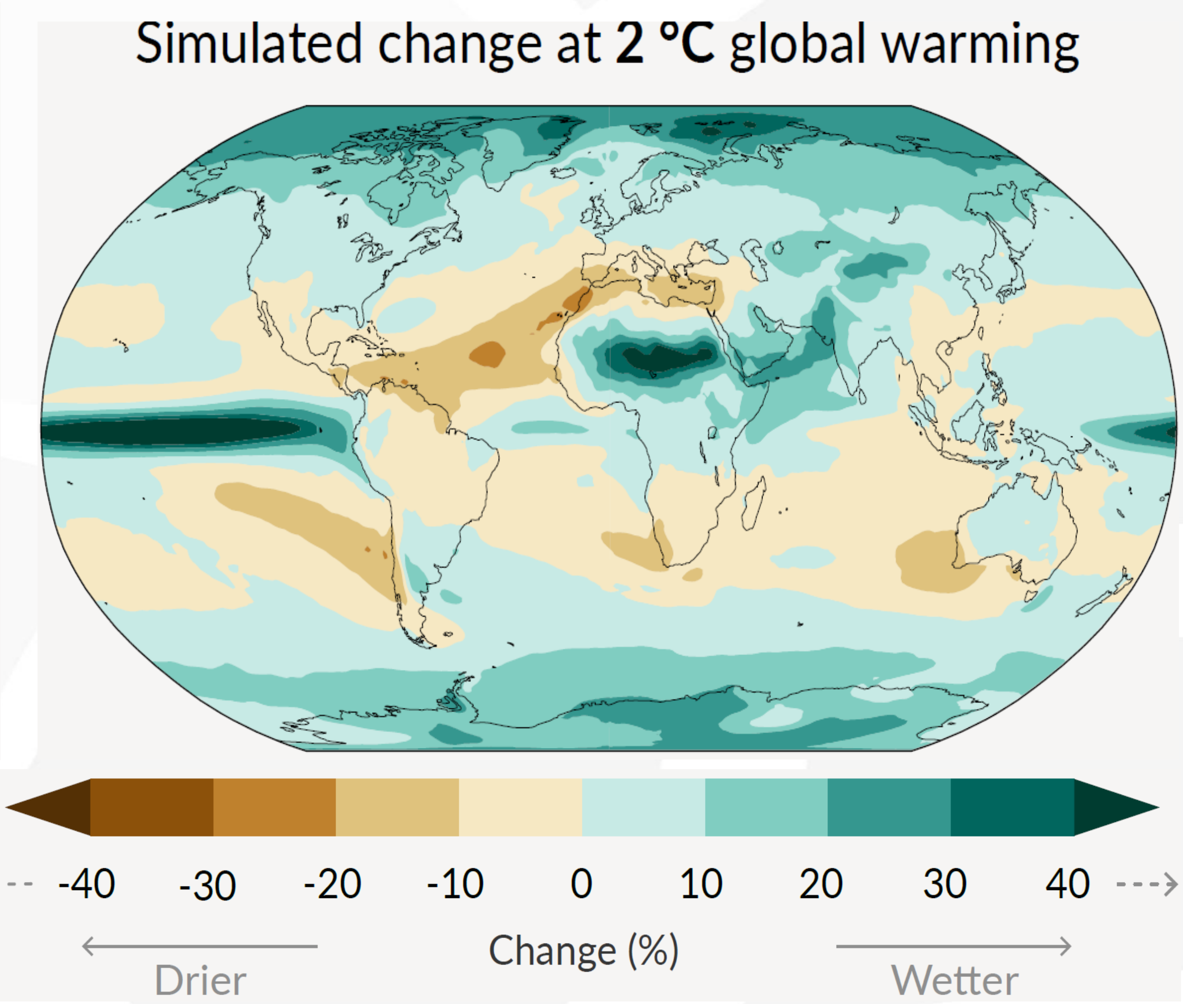
Global Surface Temperature Increases Compared to 1850-1900 Average



IPCC, 2021: Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis*

Regional Differences (IPCC 2021)





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The Sustainability Triple Bottom Line

Sustainable practices are simply good engineering

And not just GHG emissions or environmental impacts

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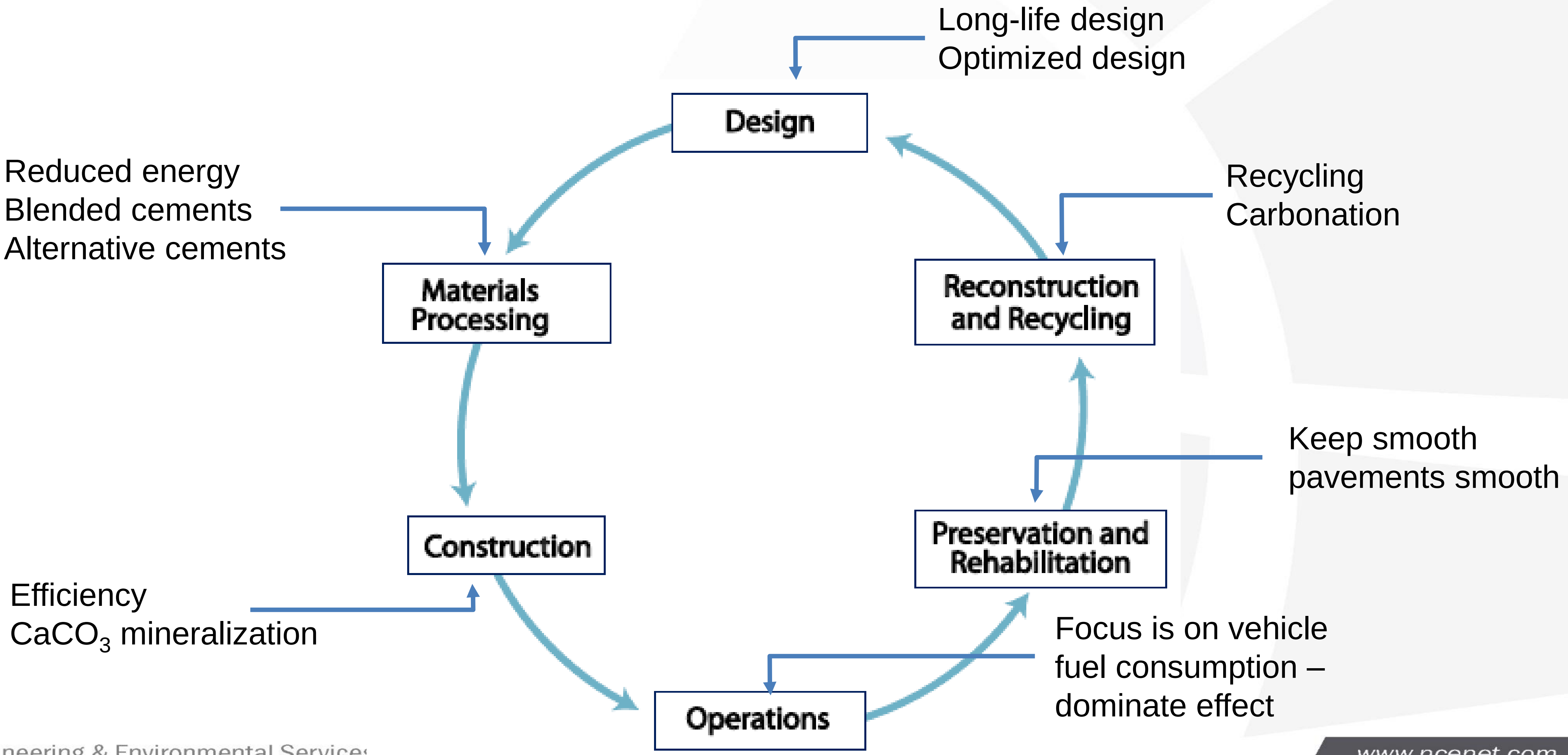
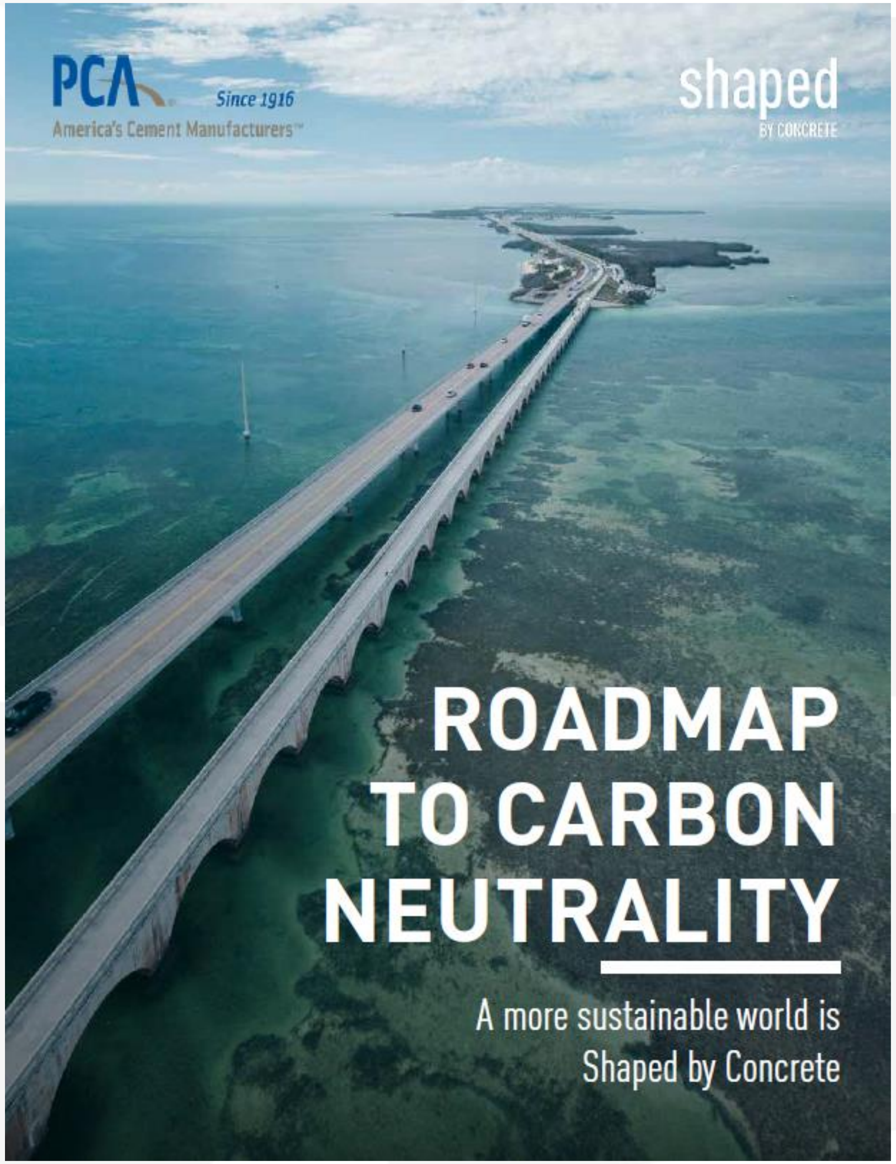
Sustainable Solutions Require Life-Cycle Thinking



Challenges In Front of Us

- Change is difficult
  - Must ween ourselves from business as usual
- Traditional cement and concrete are carbon intensive
- Designs and materials are dictated by the past and “conservatism” in codes, specifications, and standards

DON’T BE SAD – INNOVATE!



There is Hope!

- New policies and initiatives are focused on sustainability
  - New infrastructure bill (IIJA)
  - State and local initiatives
  - Private companies
- The cement and concrete industry is focused on change
  - PCA's Net Zero by 2050
  - ACI, ASTM and others
- Organizations and associations are responding to the need to innovate
  - ACPA, APWA, ASCE, etc.
  - Others (e.g., Breakthrough Energy)

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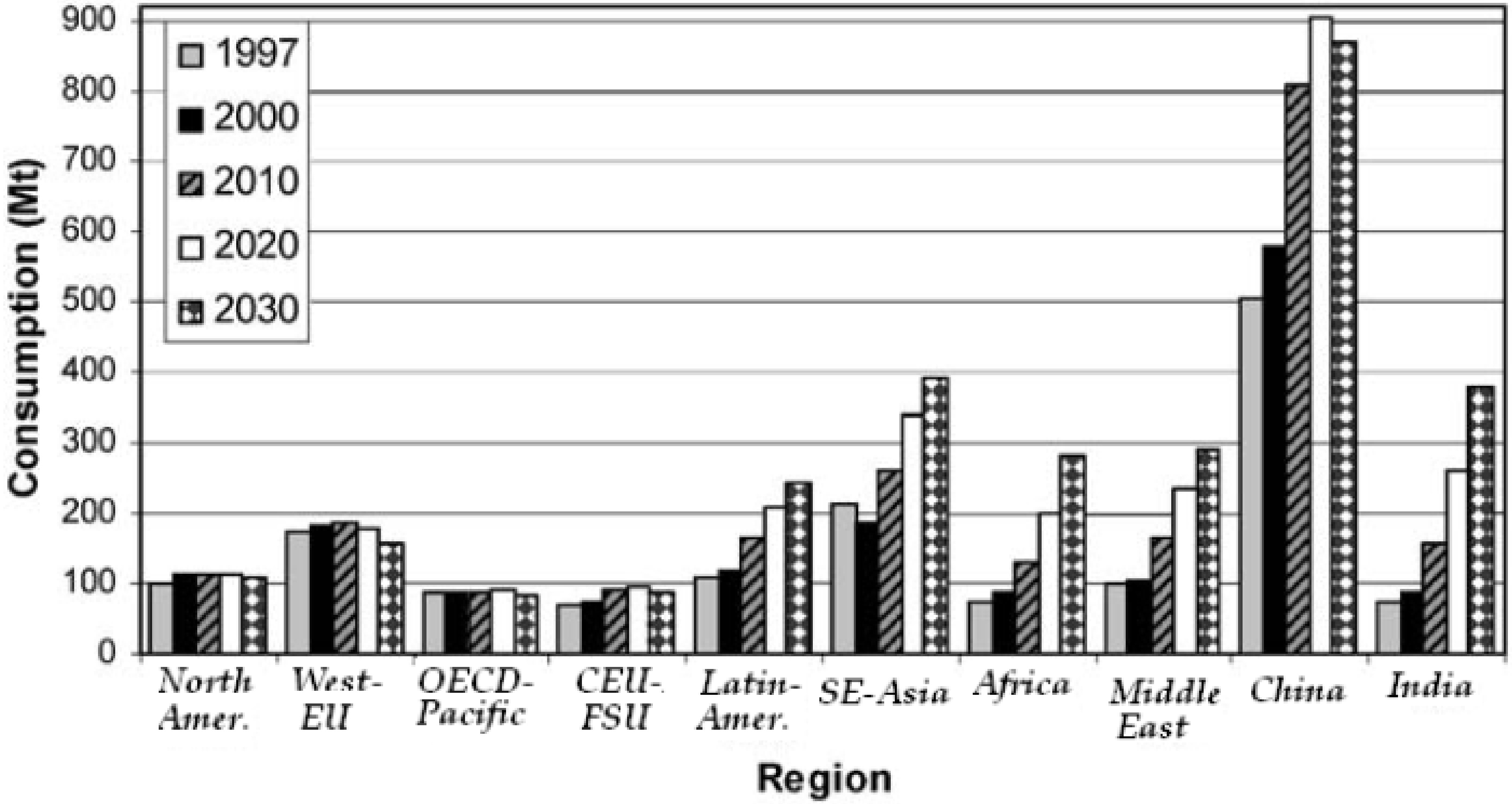
Hydraulic Cement and Concrete Mixtures

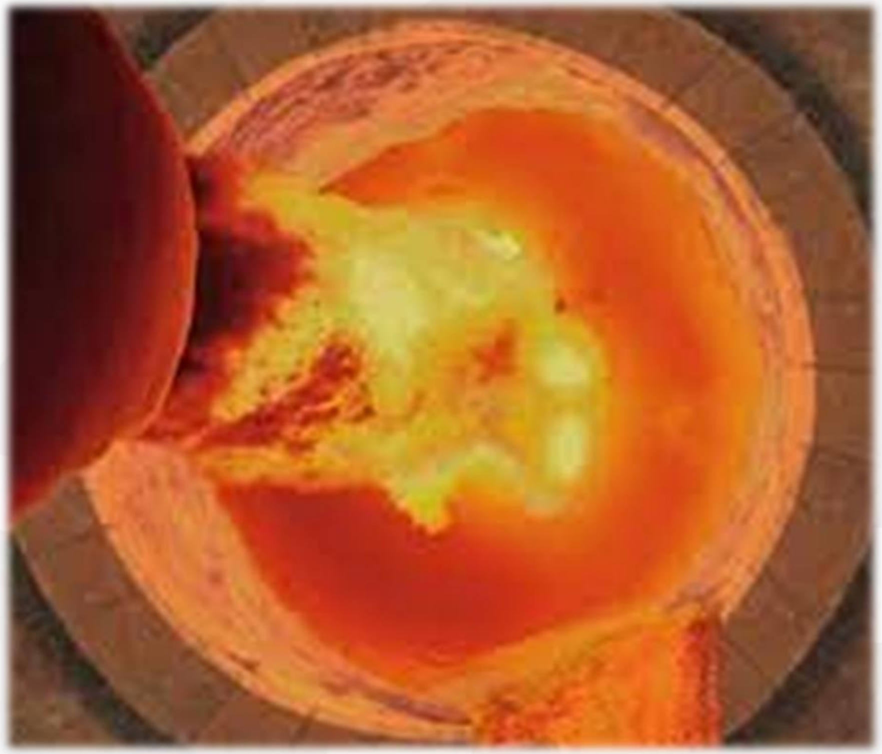
- Hydraulic cement concrete is humankind's most used material after water
  - Approximately 2.2 yd^3/person/year
  - Civilization is built on it – no exaggeration
  - 5% to 8% of global GHG emissions
- Massive economic, environmental, and social impacts
  - 90 million metric tons of cement manufactured in the U.S. in 2020 (4.1 billion MT worldwide)
  - In 2018, linked to 0.6% of US GHG emissions

Cement Consumption By Region



Altair and Kabir 2020

GHG Emissions Associated With Concrete at the Gate



- ~1.5% from acquiring and processing raw materials
- ~89% from cement manufacturing
  - ~37% from burning fuel
  - ~46% from calcination
- ~9.5% from making concrete

Net result: for every pound (kg, MT) of U.S. made ASTM C150 Type I cement, roughly 0.922 lbs (kg,MT) of GHG emissions are released

Total GHG Emissions Embodied in Concrete

Cement

Gravel
Sand
Water

Typical concrete at the gate:
~0.26 tons CO_2 /yd^3 concrete
~0.23 tons CO_2 from portland cement

Elements of PCA's Net Zero by 2050

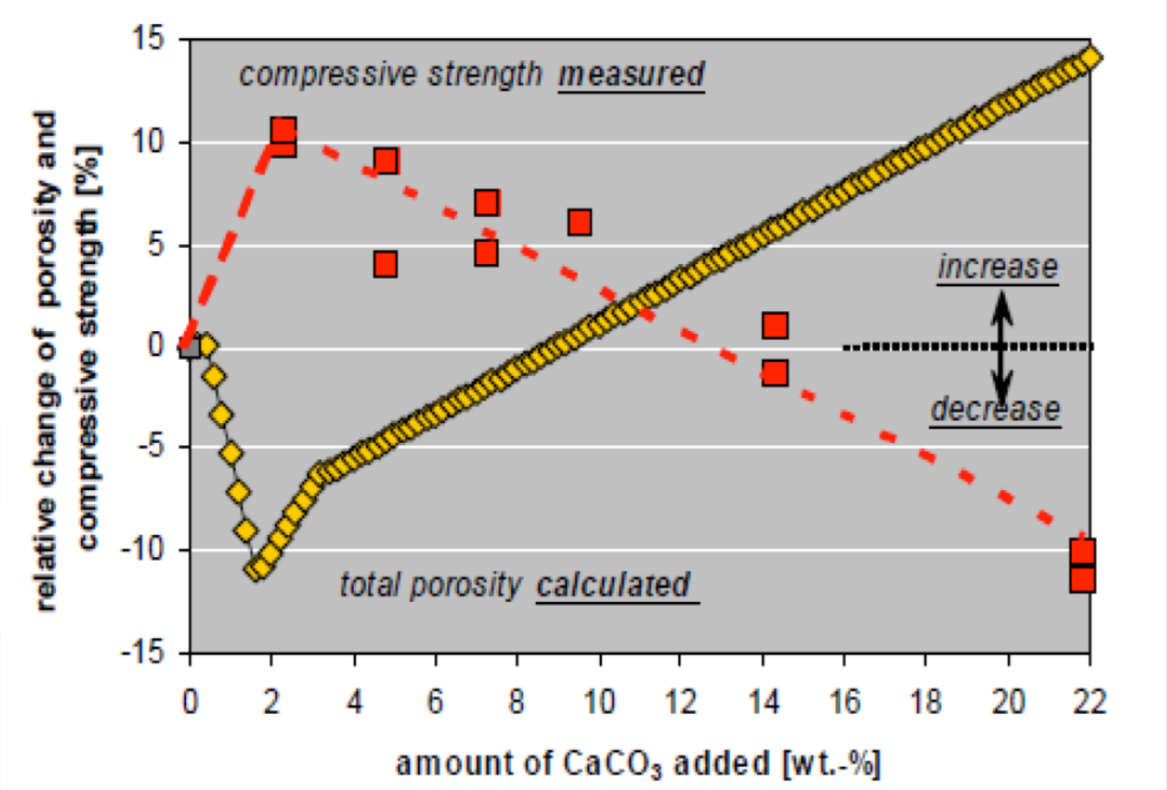
- Clinker optimization
  - Production enhancements
  - Sequestration
- Cement optimization
  - Blended portland cements
  - Alternative cements
- Concrete optimization
  - Reduced cementitious materials content
  - Longevity
- In-service and end-of-life carbonation
  - For structural concrete, small but still significant

Clinker Optimization

- Reduce GHG emissions during production
  - Make kilns super efficient
  - High efficiency grinding mills
  - Fuels including waste fuels and plasma
- Carbon dioxide sequestration
  - Kiln flue gas has high CO_2 concentration…typically about 25 mol% vs 14% for coal-fired power plant vs 0.033% in atmosphere
  - A "target-rich environment" for sequestering CO_2

Cement Optimization: What Can You Do Now?

- Replace clinker with supplementary cementitious materials (SCMs)
  - Blend at concrete plant
  - Obtained as blended cement (ASTM C595)
- Replace clinker with ground limestone
  - ASTM C595 Type IL blended cement can have up to 15% limestone
    - Widespread acceptance
  - On-going work to look at higher limestone content
    - 25% or more w/ SCM



Traditional Supplementary Cementitious Materials (SCMs)

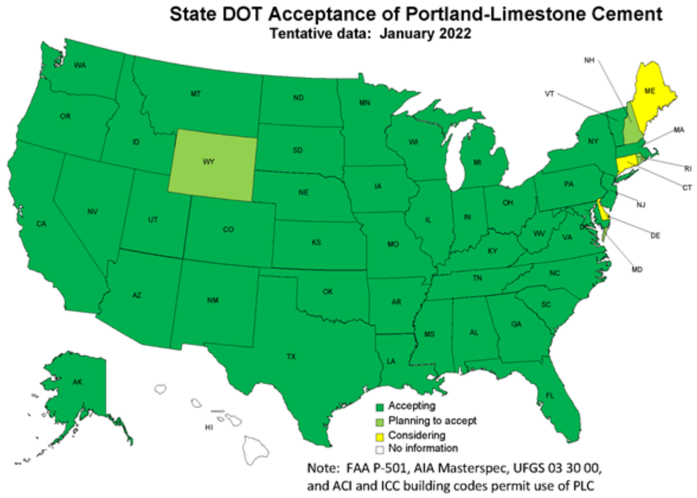
- Fly ash
  - Collected from flue gases of coal burning power plant
- Slag cement
  - From iron blast furnace
- Natural pozzolan
  - Calcined clay, volcanic ash, ground pumice, etc.

Alternative SCMs

- Reclaimed coal ash
  - From landfills and ponds
  - Mix of fly ash and bottom ash
  - Requires processing
- Ground glass pozzolan
- SCM produced by sequestering carbon dioxide
- ASTM is working to develop standards based on reactivity

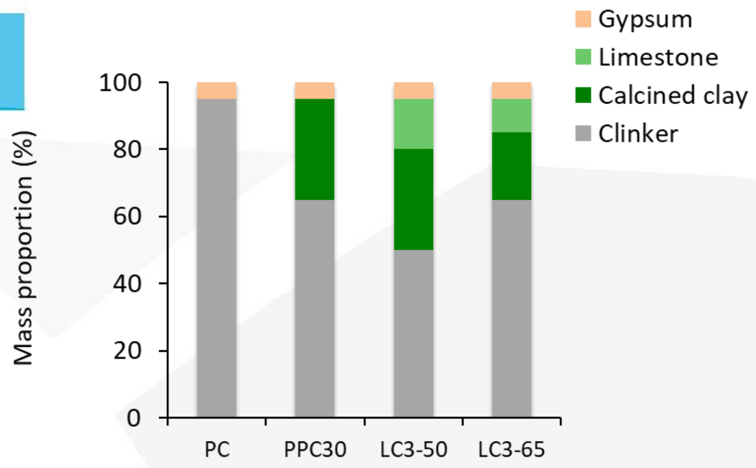
ASTM C595 Blended Cements

- Produced by cement manufacturers
- Type IP(X), Type IS(X), and Type IT (X)(Y)
  - Blended with pozzolan, slag cement, limestone or ternary blend
- Type IL will reduce carbon footprint by 8 to 10 percent with little impact on behavior
  - Pretty much all you're going to get going forward?
- Can be designated as moderate sulfate resistance (MS), high sulfate resistance (HS), moderate heat (MH), or low heat (LH)

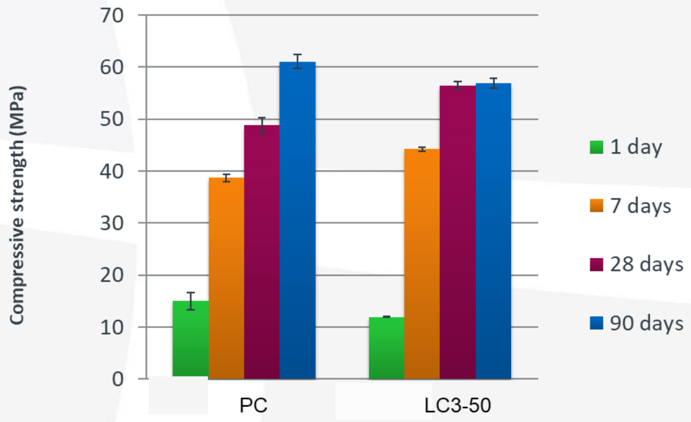


Alternative Cementitious Materials

- Non-traditional blended hydraulic cements
  - LC3 – portland cement, calcined clay, limestone
- Alkali-activated hydraulic cements
  - Alkali activator – liquid or powder
  - Precursor containing calcium and alumino-silica minerals
    - e.g., Class C fly ash, slag cement
- Geopolymers
  - Alkali-activated non-hydraulic reaction based on low calcium alumino-silica minerals
  - Dissolution and polymerization process



LC^3 is a family of cements, the figure refers to the **clinker** content

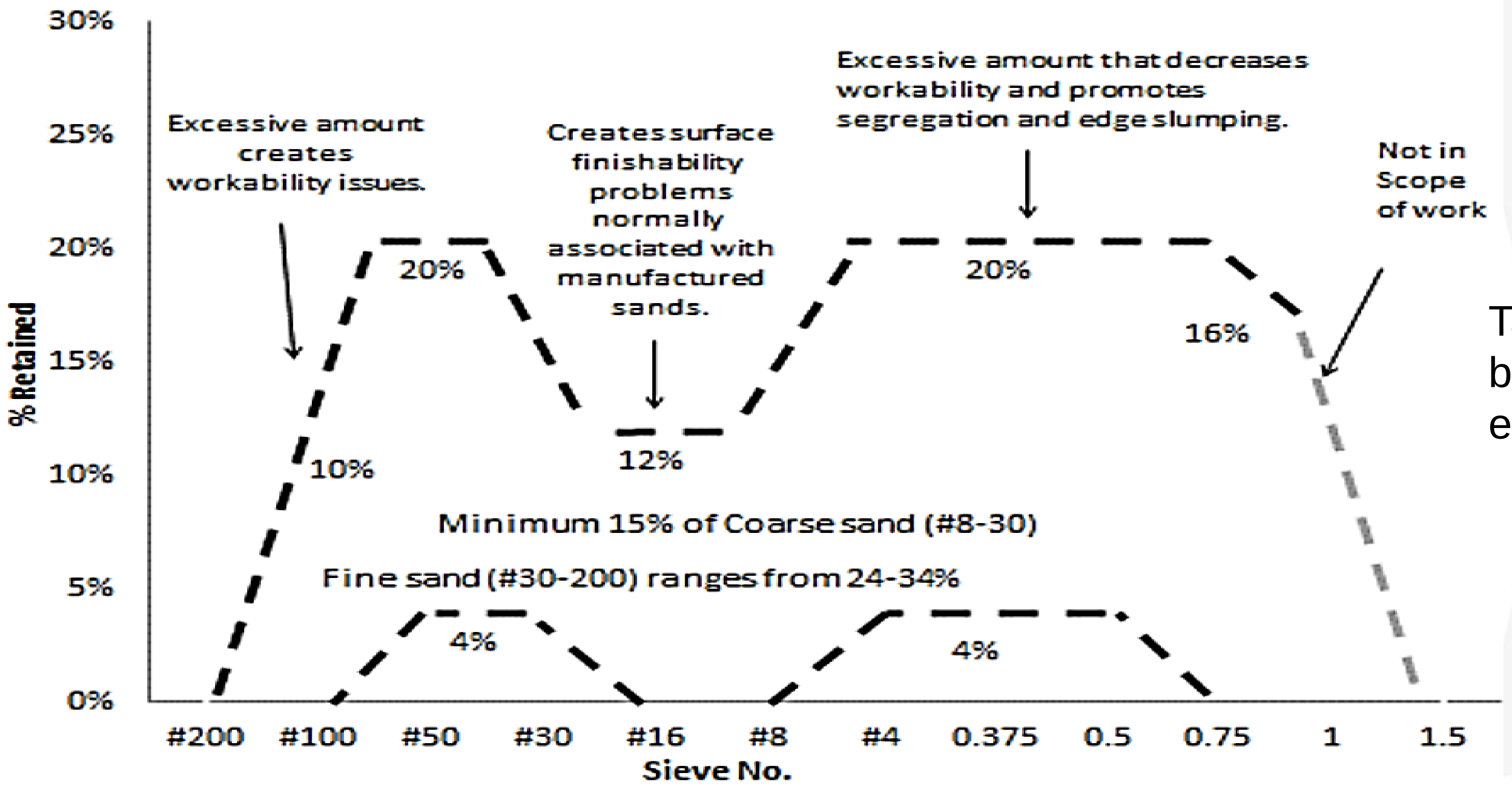


- 50% less clinker
- 40% less CO_2
- Similar strength
- Better chloride resistance
- Resistant to alkali silica reaction

K. Scrivener, 2020

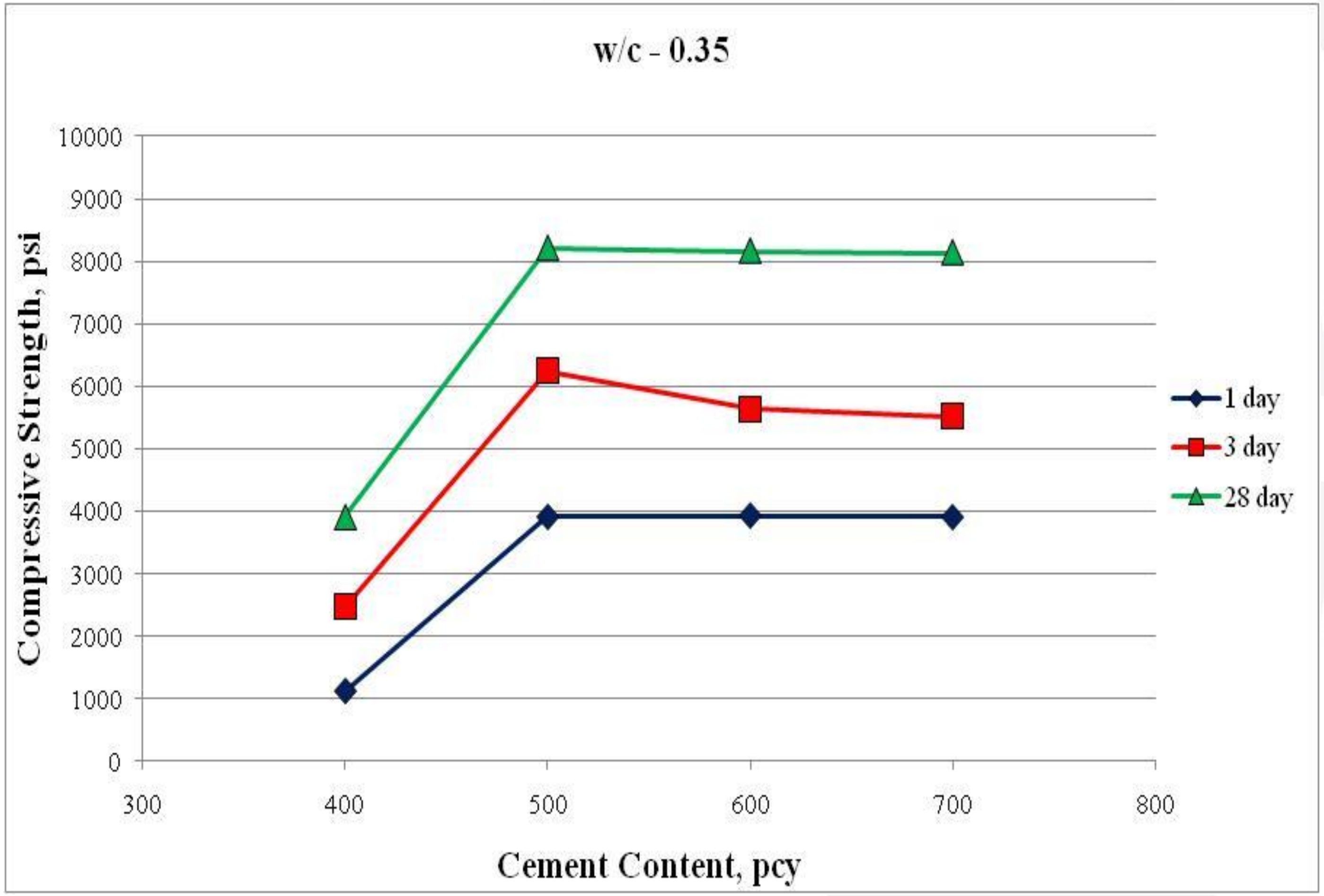
Reduce Cementitious Content in Concrete

- Use optimized aggregate grading to maximize aggregate content



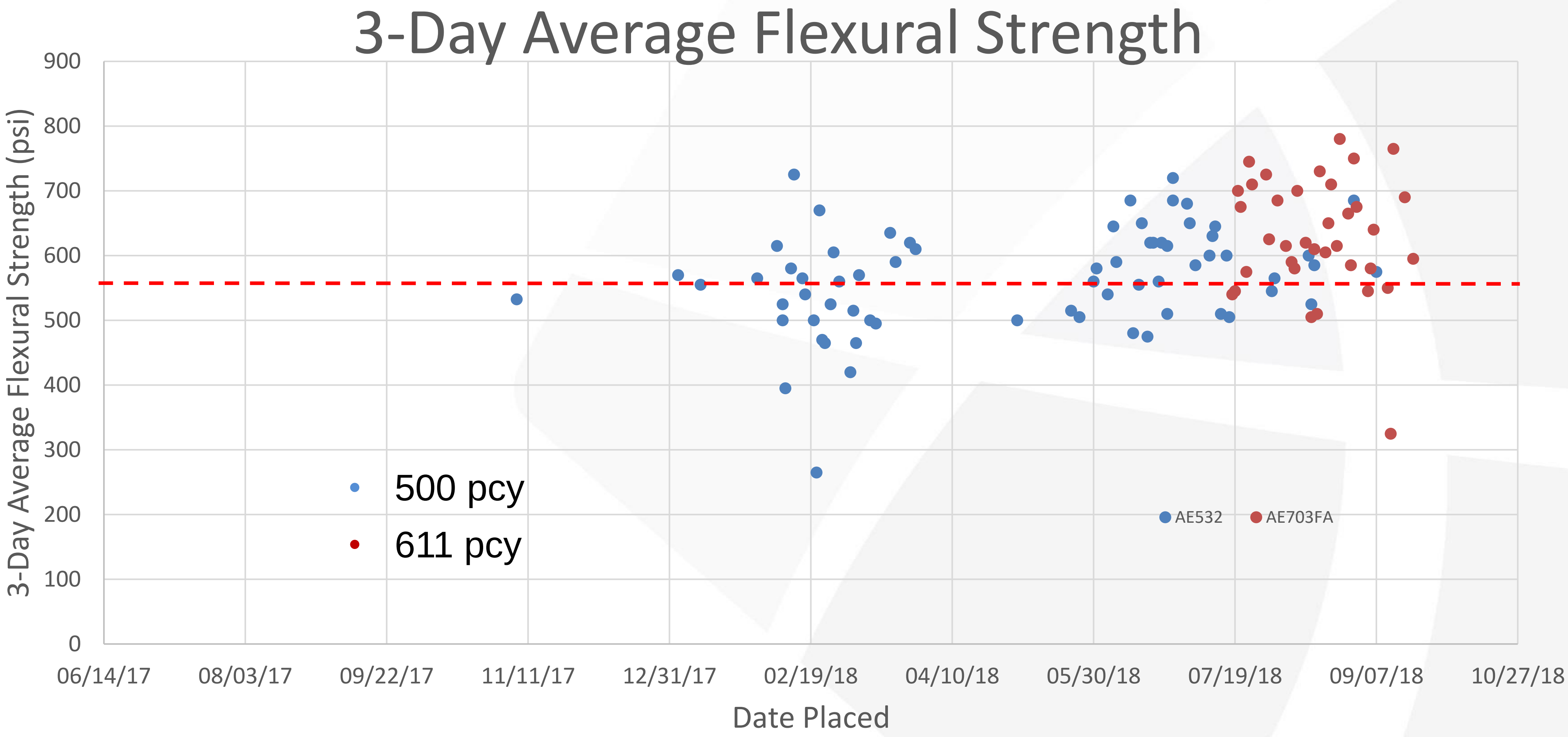
Tarantula curved based on Tyler Ley et al.

A Common Fallacy: Increasing Cement Content Increases Strength

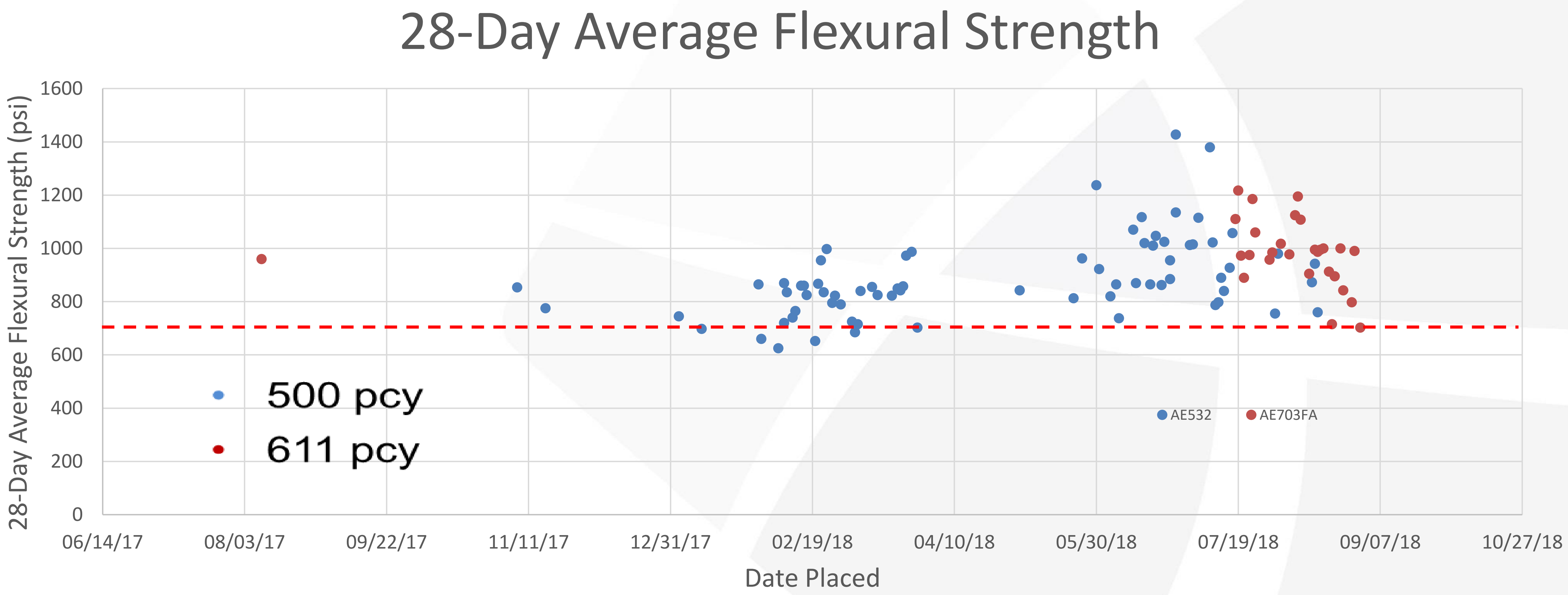


Based on Taylor and Wilson

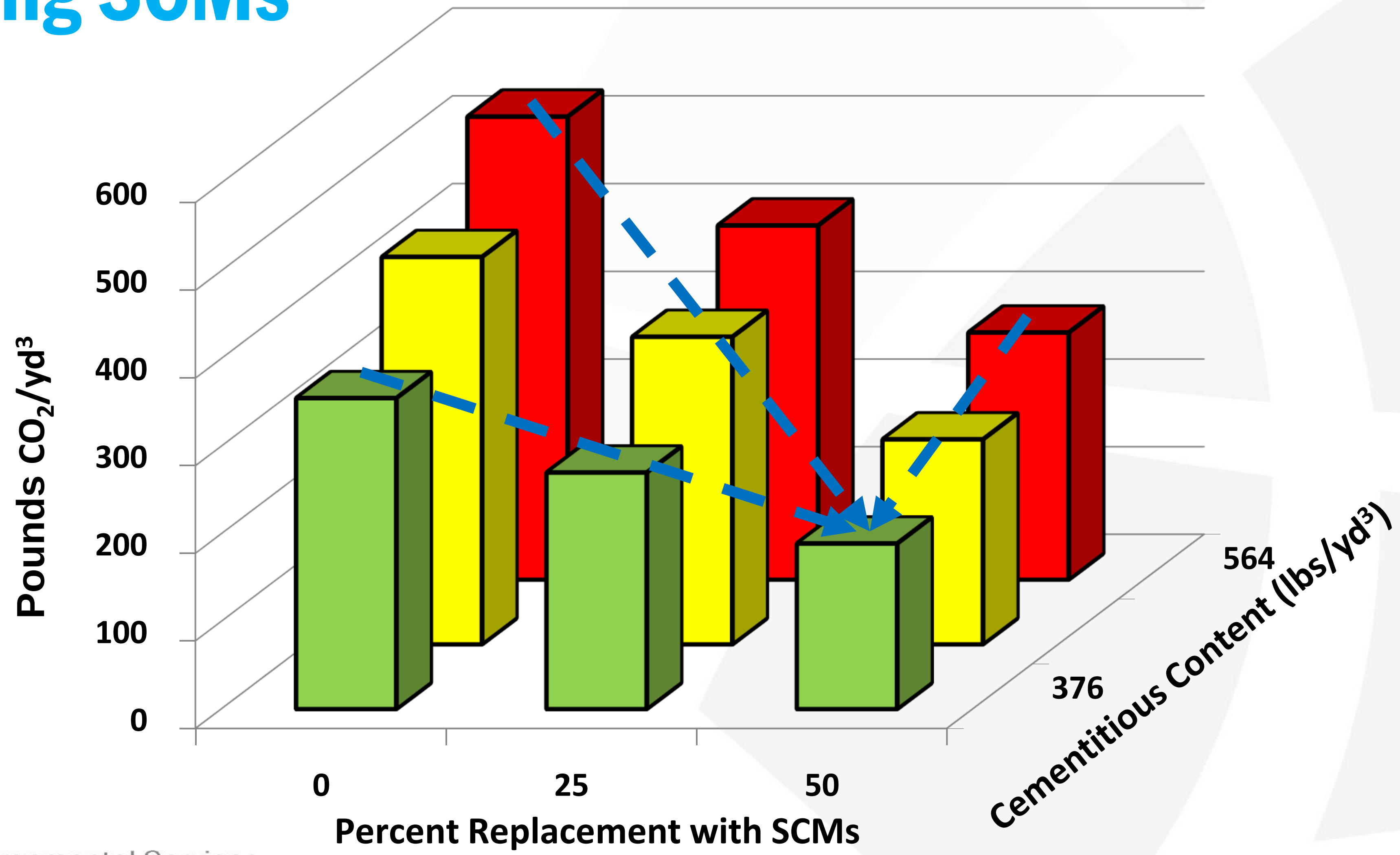
Real Data from Project NEON in Las Vegas



Project NEON Concrete



Reducing GHG Emissions by Minimizing Cement Content and Increasing SCMs



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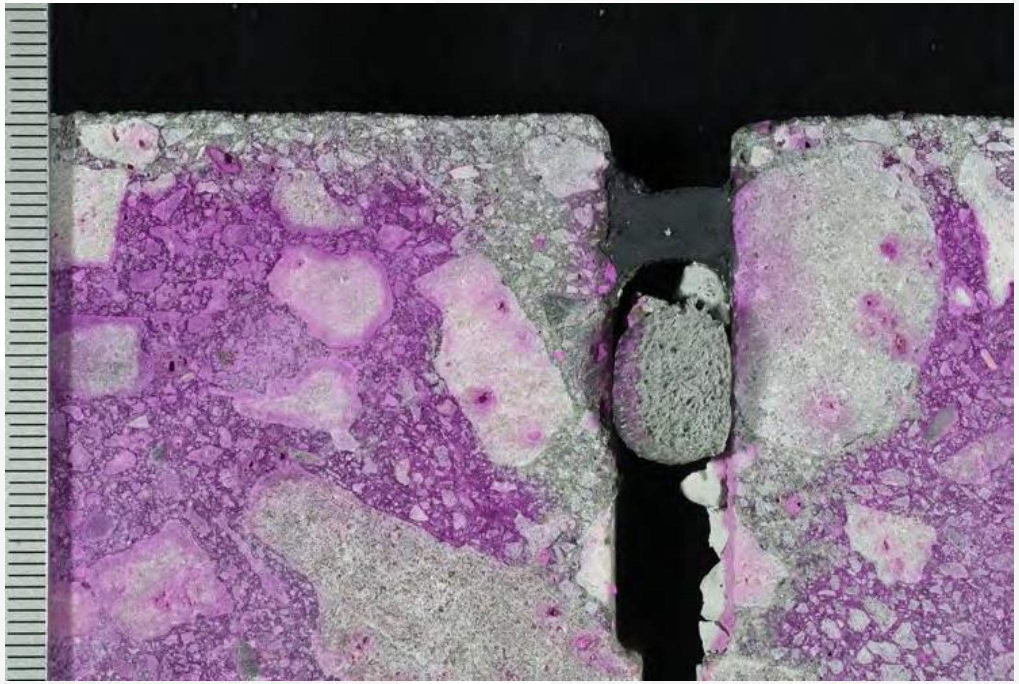
What About CO_2 Sequestration Through Carbonation?

- It is a real thing
  - Anderson, et. al. 2019. "Carbonation as a method to improve climate performance for cement based materials." Cement and Concrete Research (2019)
- Paper quantifies uptake of CO_2 by concrete through carbonation
  - $Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$
  - Calcium silicate hydrate also undergoes carbonation
  - Uses Fick's law



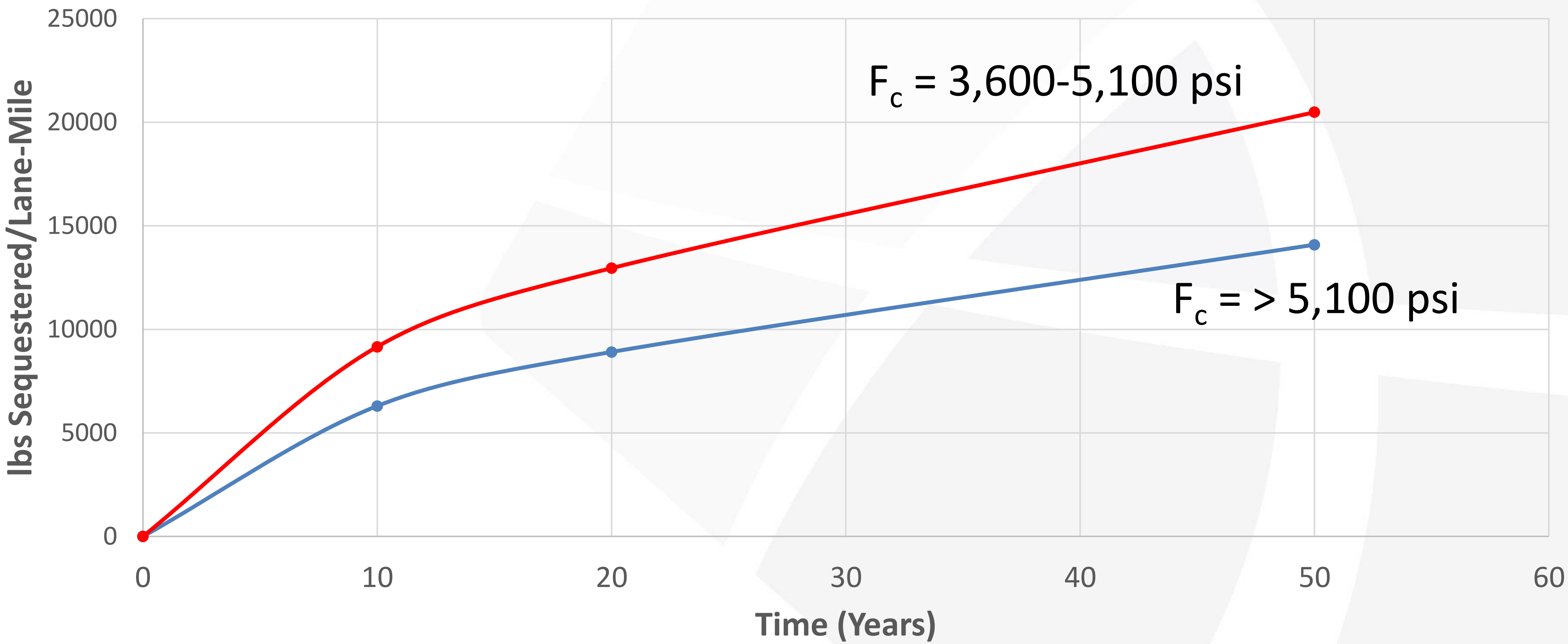
How Much Carbonation Occurs in Typical U.S. Concrete?

- Depends on exposure and quality of concrete
  - Is climate wet or dry? Is it exposed to rain?
- Quality of concrete
  - In the paper, is related to strength, but it is permeability that matters
  - Related to w/cm
- In general, dry concrete that is permeable (low strength) will have a higher degree of carbonation than wet concrete that has low permeability (high strength)

Applying This to a Typical U.S. Pavement

- Assume 564 lbs/yd^3 portland cement in concrete with a compressive strength of 4000 psi that is exposed to rain
  - Less carbonation would occur if less cement and/or SCMs used
- The amount of CO_2 sequestered through carbonation is calculated to be between 0.2-0.3 lbs/ft^2 of surface area in 50 years
  - Roughly 14,000-20,000 lbs CO_2 per lane-mile, or equivalent to 700 to 1000 gallons of fuel consumed

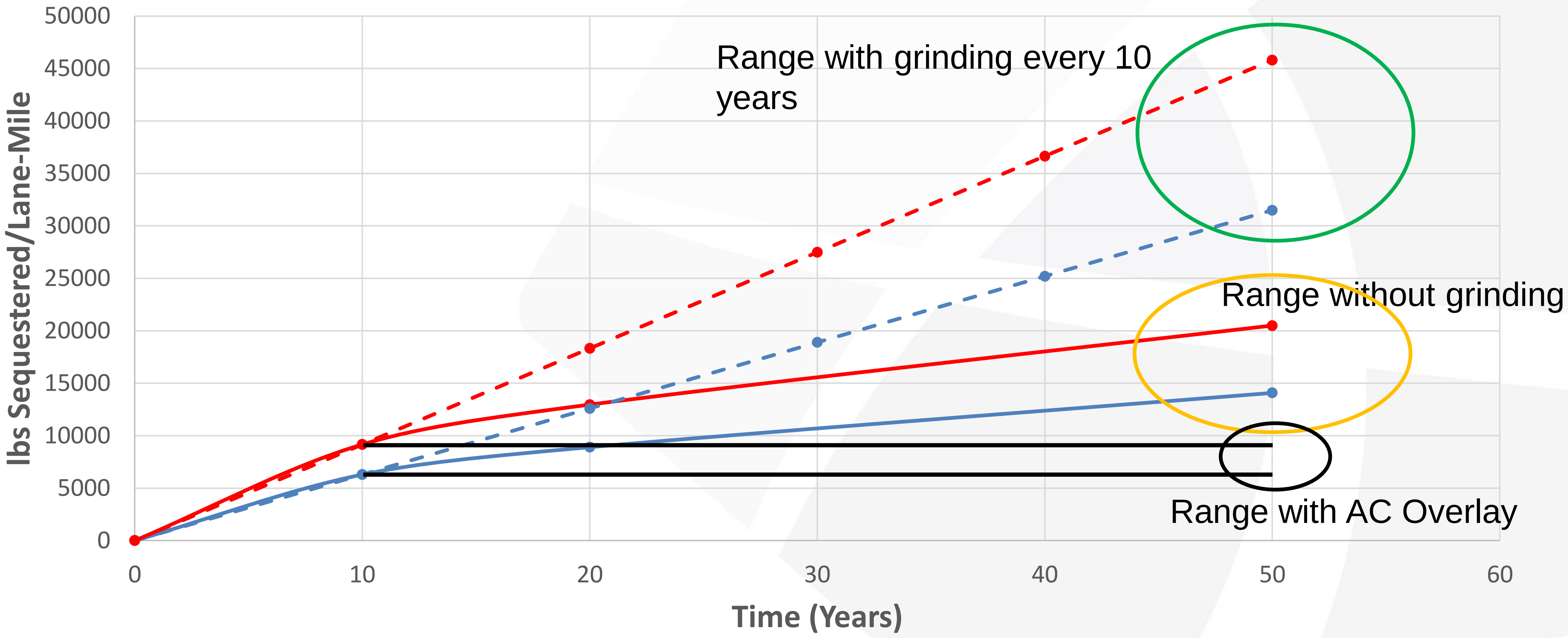
Pounds CO_2 Sequestered Over Time per Lane-Mile



Diamond Grinding Increases Carbonation

- Rate of carbonation decreases with time
  - Roughly 45% of 50 year of carbonation over occurs by Year 10
- Diamond grinding exposes a "fresh", uncarbonated surface to the atmosphere
- Grinding every 10 years will more than double the amount of sequestered CO_2
- Overlaying concrete with asphalt will shut out atmospheric CO_2 and terminate sequestration

Pounds CO_2 Sequestered Over Time per Lane-Mile



Diamond Grinding has Close to Net Zero GHG Emissions

- Diamond grinding every 10 years results in 17,400 to 25,300 lbs of additional CO_2 being sequestered over 50 years per lane-mile
  - This is equivalent to 870 to 1,270 gallons of diesel fuel consumed over 50 years
- Four diamond grindings consumes between 1,000 and 1,600 gallons of diesel
  - 250-400 gallons per lane-mile of grinding
- In addition, vehicle fuel efficiency is improved due to improved smoothness resulting in greater than net zero GHG emissions
  - HDM-4, NCHRP 720, MIT, NAPA

IRI Trigger Values (Wang et al. 2012)

Traffic group	Daily PCE of lane-segments range	Total lane-miles	Percentile of lane-mile	Optimal IRI triggering value (m/km, inch/mile in parentheses)	Annualized CO_2-e reductions (MMT)	Modified total cost-effectiveness ($/t$CO_2$-e)
1	<2,517	12,068	<25	-----	0	N/A
2	2,517 to 11,704	12,068	25~50	2.8 (177)	0.141	1,169
3	11,704 to 19,108	4,827	50~60	2.0 (127)	0.096	857
4	19,108 to 33,908	4,827	60~70	2.0 (127)	0.128	503
5	33,908 to 64,656	4,827	70~80	1.6 (101)	0.264	516
6	64,656 to 95,184	4,827	80~90	1.6 (101)	0.297	259
7	>95,184	4,827	90~100	1.6 (101)	0.45	104
Total					**1.38**	**416**

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Assessing Sustainability

- Use unbiased, factually-based tools/resources to assess life cycle impacts
  - There is A LOT of greenwashing going on
- A life cycle assessment (LCA) meeting ISO standards is the best way to assess environmental impact
  - Request environmental product declarations (EPDs) based on approved product category rules (PCR)
  - Stay informed
  - Seek help as needed

What is an EPD?

- EPDs are published by product manufacturers to communicate potential environmental impacts of a product or process
- ISO has established processes that use life-cycle assessment (LCA) methods to declare the environmental impacts on product labels (Type III declarations = EPDs)
- EPDs are preferred because they provide a high level of confidence as the information provided has followed a standardized and transparent scientific process

SUSTAINABLE PAVEMENTS PROGRAM

U.S. Department of Transportation
Federal Highway Administration

TECH BRIEF: ENVIRONMENTAL PRODUCT DECLARATIONS

Communicating Environmental Impact for Transportation Products

State Departments of Transportation (DOTs) are continually assessing and choosing materials or technologies to meet their transportation needs. As part of this assessment, DOTs are turning to Environmental Product Declarations (EPDs) to quantify the environmental impacts associated with those products.

What Are Environmental Product Declarations?

An Environmental Product Declaration (EPD) is a transparent, verified report used to communicate the environmental impact (e.g., resource use, energy, emissions) associated with the manufacture or production of construction materials such as asphalt, cement, asphalt mixtures, concrete mixtures, or steel reinforcement. EPDs, also called Type III Environmental Declarations, are product labels developed by industry in accordance with International Organization for Standardization (ISO) Standard 14025. ISO Standard 14025 includes a critical review process to ensure that the ISO standards and the industry consensus standards described in the Product Category Rule (PCR) document were followed.

EPDs and PCRs are not required by law or Federal regulation.

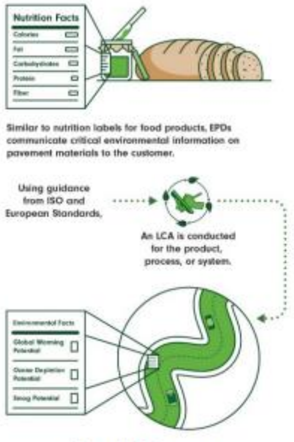

Figure 1. EPD concepts.

What Are the Benefits of EPDs?

- Provide verifiable and transparent information on life-cycle environmental impact data for materials or products.
- Allow meaningful comparisons of the environmental performance of materials (if they were developed using the same product category rules, PCRs, which are industry consensus standards and guidelines used in developing and reporting EPDs).
- Identify areas for environmental performance improvement, encouraging industry efficiency.

Table 1. Environmental impacts reported in an EPD for an asphalt mix design (based on a hypothetical scenario from National Asphalt Pavement Association).

TRACI Impact Indicator	Unit	Materials	Transport	Production
Global Warming Potential	kg CO_2-Equiv.	83.4	11.8	168
Ozone Depletion	kg CFC-11-Equiv.	1.81e-08	5e-10	8.55e-11
Acidification	kg SO_2-Equiv.	0.486	0.0577	1.08
Eutrophication	kg N-Equiv.	0.0263	0.00373	0.0207
Smog Air	kg O_3-Equiv.	8.23	1.81	13.3

Note: Impacts for Test Mix 1, a dense-graded Superpave asphalt mixture, categorized as a hot-mix asphalt mixture, produced within a temperature range of 100 to 250°F.

How Are EPDs Used?

- **Green Procurement**. An EPD encourages the demand for (and supply of) those products that promote the more sustainable use of finite resources and that create less stress on the environment.
- **Environmental Stewardship**. An EPD is a statement that the manufacturer is paying attention to the environmental aspects of sustainability.
- **Progress Measurement**. Periodic updating of EPDs can show the progress being made by a manufacturer or an industry. Agencies can use this information to track supplier progress in meeting agency goals.
- **Pavement Design**. EPDs provide critical information for use in conceptual- and project-level full (i.e., cradle-to-cradle) LCAs or less rigorous types of environmental assessment of alternative design decisions.
- **Pavement Management**. Industry-average EPD data can be included in databases used in pavement management systems to perform network-level LCA.

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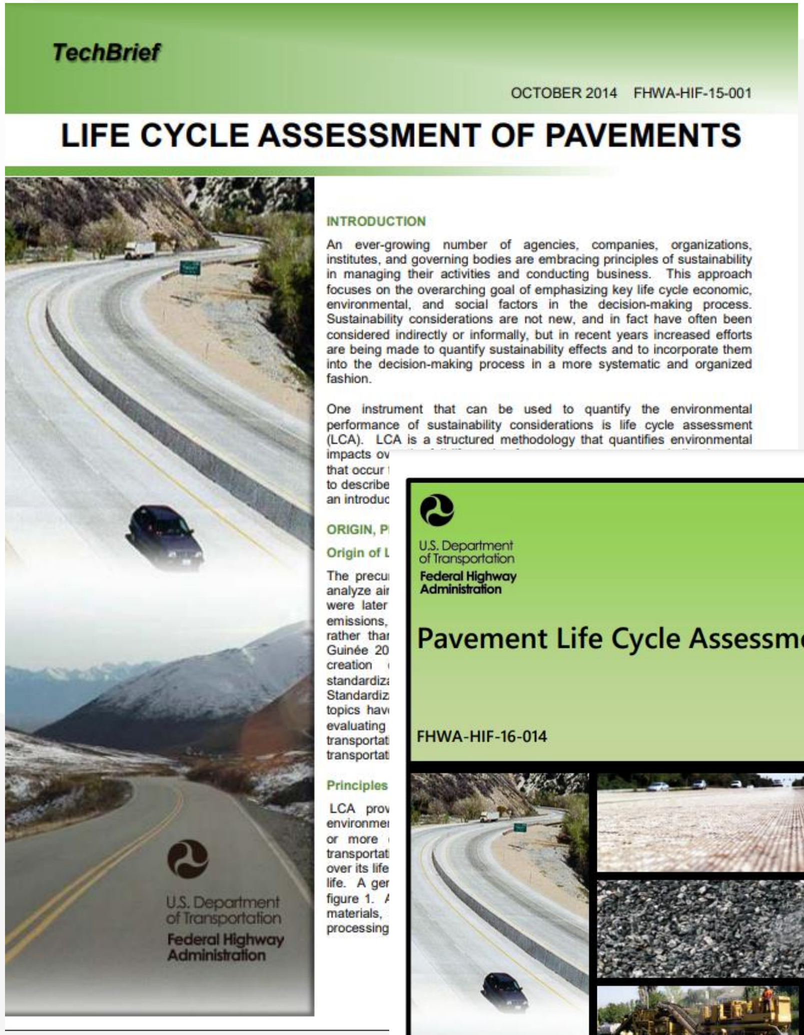
https://www.fhwa.dot.gov/pavement/sustainability/hif19087.pdf

An EPD Requires a Life Cycle Assessment (LCA)

- LCA is standardized and rigorously enforced process to quantitatively assess impact over multiple environmental impact categories
  - From cradle to gate, cradle to placement, or cradle to grave
- Implementable for civil infrastructure
  - Basis for EPDs


TechBrief

OCTOBER 2014 FHWA-HIF-15-001

LIFE CYCLE ASSESSMENT OF PAVEMENTS

INTRODUCTION

An ever-growing number of agencies, companies, organizations, institutes, and governing bodies are embracing principles of sustainability in managing their activities and conducting business. This approach focuses on the overarching goal of emphasizing key life cycle economic, environmental, and social factors in the decision-making process. Sustainability considerations are not new, and in fact have often been considered indirectly or informally, but in recent years increased efforts are being made to quantify sustainability effects and to incorporate them into the decision-making process in a more systematic and organized fashion.

One instrument that can be used to quantify the environmental performance of sustainability considerations is life cycle assessment (LCA). LCA is a structured methodology that quantifies environmental impacts ov

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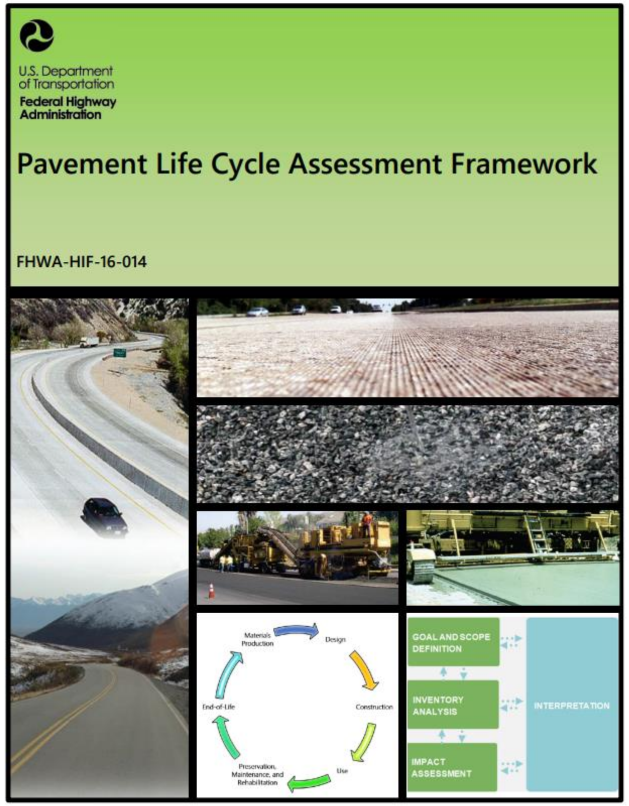
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Pavement Life Cycle Assessment Framework

FHWA-HIF-16-014

Development of EPDs

Adapted from N. Santero by John Harvey

PCR: the framework

Product Category Rule (PCR)
"Set of specific rules, requirements, and guidelines for developing Type III environmental product declarations for one or more product categories" (ISO 14025)

LCA: the analysis

Life Cycle Assessment (LCA)
"Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO 14040)

EPD: the declaration

Environmental Product Declaration (EPD)
"Providing quantified environmental data using predetermined parameters and, where relevant, additional environmental information" (ISO 14025) as defined in a PCR which is based on LCA

Example: Specific Concrete EPD

Summary of
Environmental Product Declaration

Central Concrete

Mix 340PG9Q1

San Jose Service Area

EF V2 Gen Use P4000 3" Line 50% SCM

Performance Metrics

28-day compressive strength	4,000 psi
Slump	4.0 in

Environmental Impacts

Impact name	Unit	Impact per m3	Impact per cyd
Total primary energy consumption	MJ	2,491	1,906
Concrete water use (batch)	m3	6.66E-2	5.10E-2
Concrete water use (wash)	m3	8.56E-3	6.55E-3
Global warming potential	kg CO2-eq	271	207
Ozone depletion	kg CFC-11-eq	5.40E-6	4.14E-6
Acidification	kg SO2-eq	2.26	1.73
Eutrophication	kg N-eq	1.31E-1	1.00E-1
Photochemical ozone creation	kg O3-eq	46.6	35.7

A sample EPD for a concrete mix design by Central Concrete Supply Co.

Credit: Central Concrete Supply

https://www.fhwa.dot.gov/pavement/sustainability/articles/environmental.cfm

Case Example

- Peña Boulevard is the four-lane divided highway providing access to Denver International Airport
- Required reconstruction to replace ASR-affected concrete pavement
- Various alternatives considered
- Several innovative strategies were used to reduce cost and environmental impact

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SUSTAINABLE PAVEMENTS PROGRAM

CONCRETE MATERIAL AND CONSTRUCTION INNOVATIONS PROVIDE SUSTAINABILITY BENEFITS IN COLORADO AGENCY

FHWA-HIF-19-077

BACKGROUND

Shrewd modifications to concrete mixtures and resourceful construction practices led to cost savings of more than 50 percent, time savings of several weeks, and significant reductions in various environmental impacts. This was demonstrated on a concrete pavement reconstruction project on Peña Boulevard, a four-lane divided highway that connects the City of Denver (via I-70) to Denver International Airport (DIA).

WHAT WAS THE MOTIVATION?

Constructed in the early 1990s, the jointed plain concrete pavement (JPCP) on Peña Boulevard exhibited severe alkali-silica reactivity (ASR) distress that required increasing amounts of expensive repair. Given the on-going maintenance issues and the overall severity of distress, in 2011 authorities at DIA proposed a pavement reconstruction calling for an 11-inch (279-mm) doweled JPCP placed on a 12-inch (305-mm) Colorado Department of Transportation (CDOT) Class 6 aggregate base. However, because of concerns related to the overall reconstruction cost and the adverse impacts of a prolonged construction period, DIA was interested in pursuing an alternative approach that would reduce costs and minimize the overall duration of construction. The project was completed in 2014.

WHAT WAS DONE?

DIA worked with its contractor to develop a cheaper and quicker design alternative, one that featured the rubblization of the existing JPCP to serve as a foundation for the new pavement. This approach reduced removal and hauling costs and expedited the overall construction operations while providing a strong, stable foundation for the new pavement (see figure 1 [Cloud 2015]).

© 2015 Denver International Airport

Figure 1. Rubblized surface prior to placement of the 2-inch CDOT Class 6 aggregate base.

In addition, the contractor incorporated innovations in the concrete paving mixture to reduce both

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JUNE 2019
FHWA-HIF-19-077

Illustrative Case Study

- Innovative strategies included:
  - In-place recycling of existing JPCP through rubblization
  - Optimized concrete aggregate grading with reduced cementitious content
  - The use of an ASTM C595 Type IL cement with fly ash
- An LCA was used to assess reduced environmental impact

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Example LCA: Denver, Colorado

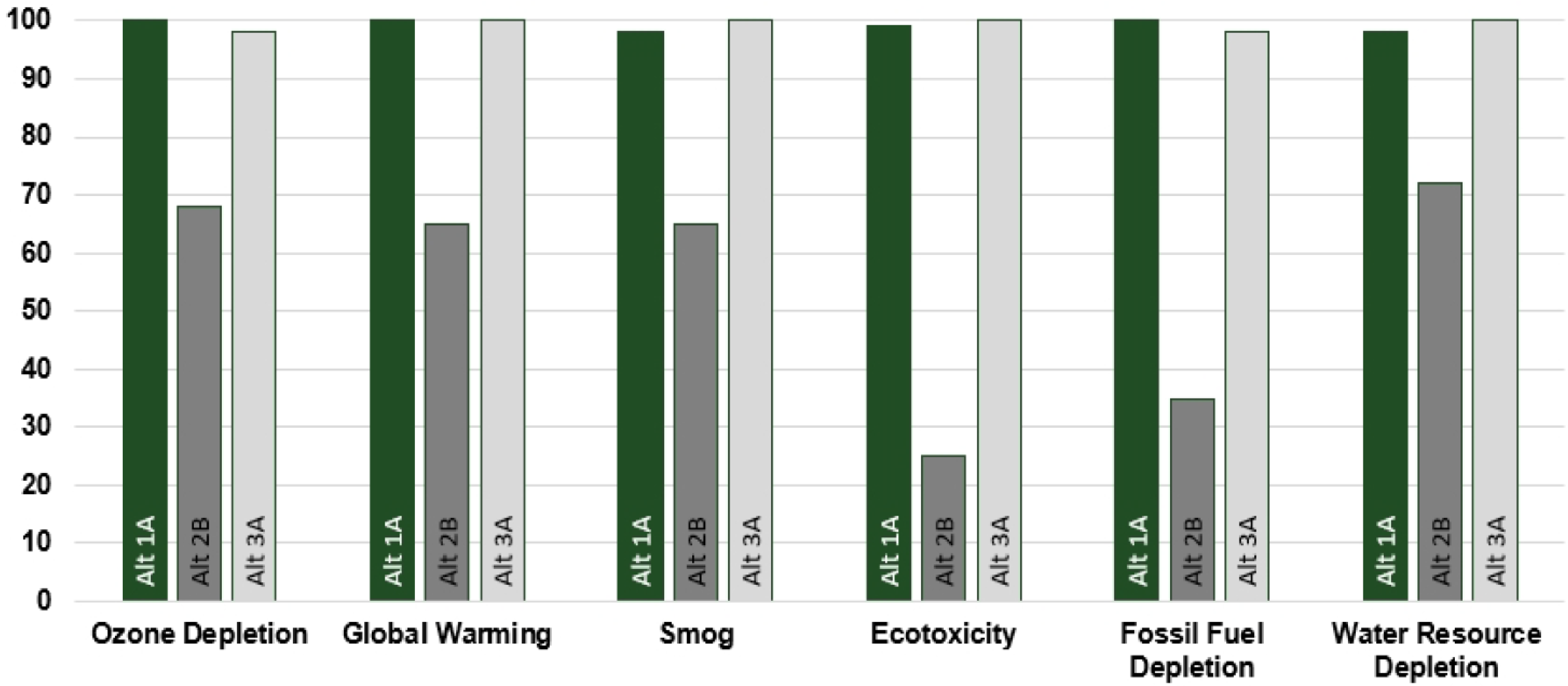
Mixture Constituent	Mixture A: Typical CDOT Class P (CDOT 2017)	Mixture B: Optimized (Ungerman 2015)
ASTM C150 Cement	452 lb/yd^3	–
ASTM C595 Blended Cement[1]	–	422 lb/yd^3
ASTM C618 Class F Fly Ash	113 lb/yd^3	108 lb/yd^3
ASTM C33 Coarse Aggregate #4	–	440 lb/yd^3
ASTM C33 Coarse Aggr		
ASTM C33 Intermediate		
ASTM C33 Fine Aggreg		
Water		
Air		
w/cm		

1 It is assumed that the AS

Alternative	Existing Pavement	Base	New Pavement
1A. Remove & Replace	Remove existing pavement and 12 inches (305 mm) of lime-treated subgrade	Reapply broken up existing pavement, 4 inches (102 mm) of RCA, geotextile, 12 inches (305 mm) of RCA	11-inch (279-mm) JPCP (CDOT Class P mix)
2B. Rubblized	Rubblized and compacted	2-inch (51-mm) RCA (from other stockpiles)	11-inch (279-mm) JPCP (Optimized mix)
3A. Reconstruct	Remove existing pavement and 12 inches (305 mm) of lime-treated subgrade, recondition and compact 18 inch (457 mm) of subgrade	Geotextile, 12-inch (305-mm) virgin aggregate	11-inch (279-mm) JPCP (CDOT Class P mix)

https://www.fhwa.dot.gov/pavement/sustainability/case_studies/hif19077.pdf

Example LCA Results



https://www.fhwa.dot.gov/pavement/sustainability/case_studies/hif19077.pdf

Today's Topics

- Climate change – driving the conversation
- What is sustainability?
- The role played by portland cement and concrete
- Cement and concrete materials
- Considering carbonation
- Verification
- Some recent initiatives

Current Initiative: MnROAD Reduced GHG Emissions Test Site

- A test site is under development at MnROAD to evaluate strategies to reduce GHG emission in concrete paving
- 16 test cells
  - 1 control cell
  - 3 carbon mineralization cells
  - 1 optimized concrete
  - 6 alternative SCM cells
  - 5 alkali-activated cements
- Construction scheduled for summer 2022

Current Initiative – Breakthrough Energy Foundation

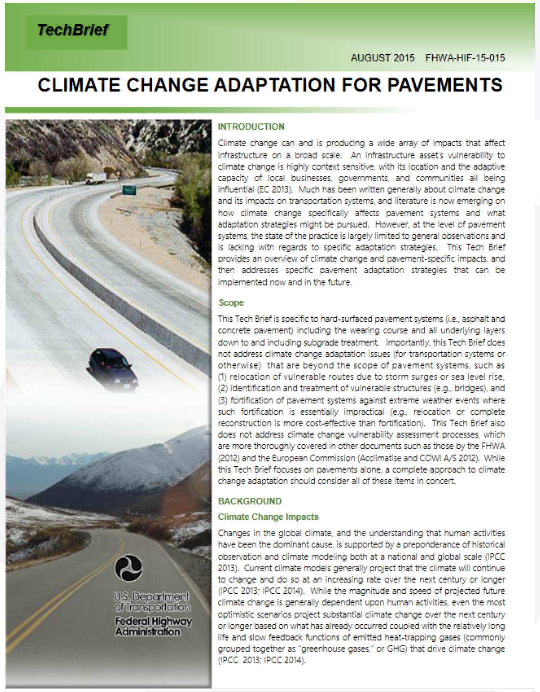
- BTE Foundation is focused on reducing global GHG emissions and fighting climate change
- Identification and elimination of barriers restricting carbon reduction strategies in concrete construction
  - Tracking the follow of clinker through the U.S. and Canadian economies
  - Evaluating codes, specifications, and standards dictating use
  - Identifying barriers and developing strategies to overcome barriers

Summary

- Sustainable concrete pavement practices are available for all phases of life
- Sustainable solutions require a life cycle perspective
  - Evaluating cradle to construction only will result in short-sighted decisions
- Strive to optimize your cement and concrete
- Use rigorous verification to avoid “greenwashing”
- As an industry, the future is bright

FHWA Sustainable Pavement Program: Work Products

- Sustainable Pavements Program Roadmap
- Toward Sustainable Pavement Systems: A Reference Document
- LCA framework document
- Tech briefs
- Case studies



TechBrief

AUGUST 2015 FHWA-HIF-15-015

CLIMATE CHANGE ADAPTATION FOR PAVEMENTS

INTRODUCTION

Climate change can and is producing a wide array of impacts that affect infrastructure on a broad scale. An infrastructure asset's vulnerability to climate change is highly context sensitive, with its location and the adaptive capacity of local businesses, governments, and communities all being influential (EC 2013). Much has been written generally about climate change and its impacts on transportation systems, and literature is now emerging on how climate change specifically affects pavement systems and what adaptation strategies might be pursued. However, at the level of pavement systems, the state of the practice is largely limited to general observations and is lacking with regards to specific adaptation strategies. This Tech Brief provides an overview of climate change and pavement-specific impacts, and then addresses specific pavement adaptation strategies that can be implemented now and in the future.

Scope

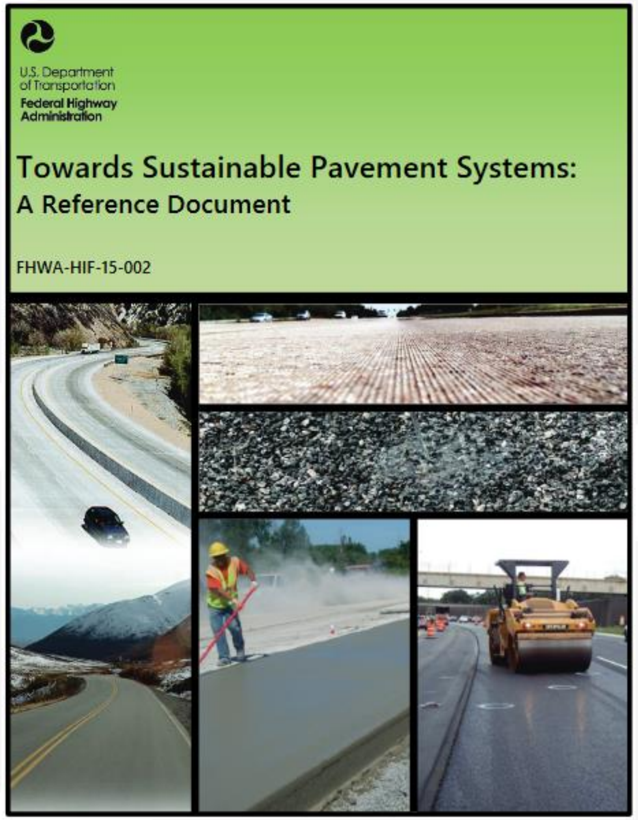
This Tech Brief is specific to hard-surfaced pavement systems (i.e., asphalt and concrete pavement) including the wearing course and all underlying layers down to and including subgrade treatment. Importantly, this Tech Brief does not address climate change adaptation issues (for transportation systems or otherwise) that are beyond the scope of pavement systems, such as (1) relocation of vulnerable routes due to storm surges or sea level rise, (2) identification and treatment of vulnerable structures (e.g., bridges), and (3) fortification of pavement systems against extreme weather events where such fortification is essentially impractical (e.g., relocation or complete reconstruction is more cost-effective than fortification). This Tech Brief also does not address climate change vulnerability assessment processes, which are more thoroughly covered in other documents such as those by the FHWA (2012) and the European Commission (Acclimatise and COWI A/S 2012). While this Tech Brief focuses on pavements alone, a complete approach to climate change adaptation should consider all of these items in concert.

BACKGROUND

Climate Change Impacts

Changes in the global climate, and the understanding that human activities have been the dominant cause, is supported by a preponderance of historical observation and climate modeling both at a national and global scale (IPCC 2013). Current climate models generally project that the climate will continue to change and do so at an increasing rate over the next century or longer (IPCC 2013; IPCC 2014). While the magnitude and speed of projected future climate change is generally dependent upon human activities, even the most optimistic scenarios project substantial climate change over the next century or longer based on what has already occurred coupled with the relatively long life and slow feedback functions of emitted heat-trapping gases (commonly grouped together as "greenhouse gases," or GHG) that drive climate change (IPCC 2013; IPCC 2014).

U.S. Department of Transportation
Federal Highway Administration



U.S. Department of Transportation
Federal Highway Administration

Towards Sustainable Pavement Systems: A Reference Document

FHWA-HIF-15-002

Questions?

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