

Innovations in SCMs and Sustainable Construction

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Today's Presentation

- Introduction to SCMs
- Future of SCMs
- 2024 MnROAD Concrete Pavement Test Sections
- Constructability Evaluation
- Early-Age Properties
- Field Performance (so far)

Acknowledgments

- Interim reports with full results (to date) from the 2024 sustainable concrete pavement test sections at MnROAD can be found on NRRRA's website



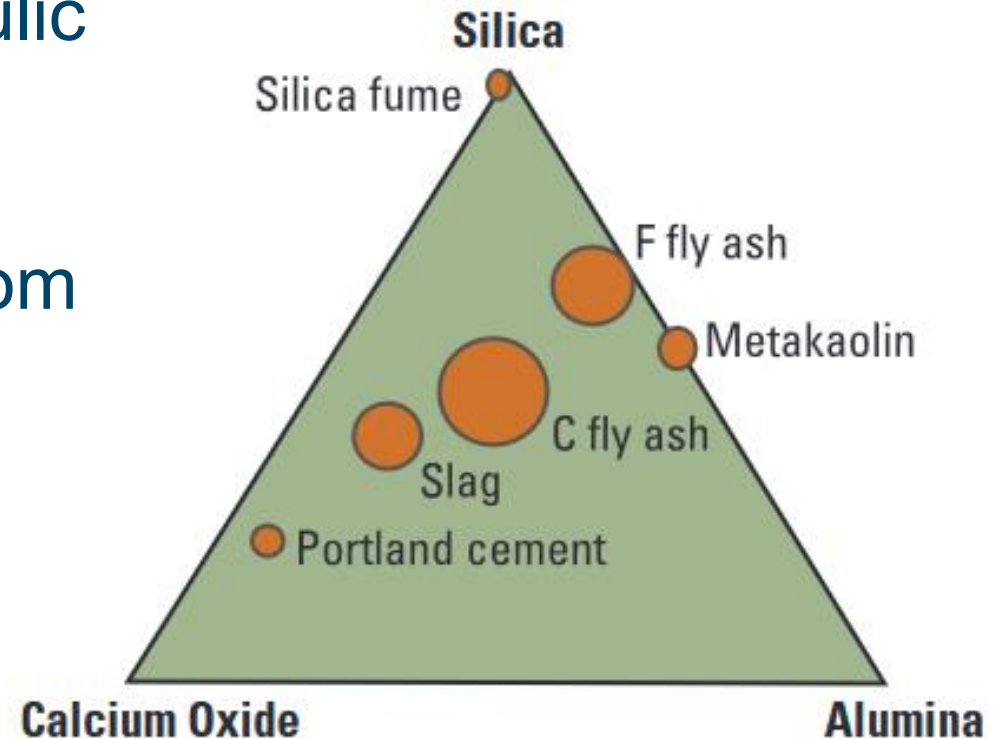
Acknowledgments

- Special thanks to:
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 - Amrize
 - American Engineering Testing
 - FHWA Mobile Concrete Technology Center
 - Braun Intertec

Introduction to SCMs

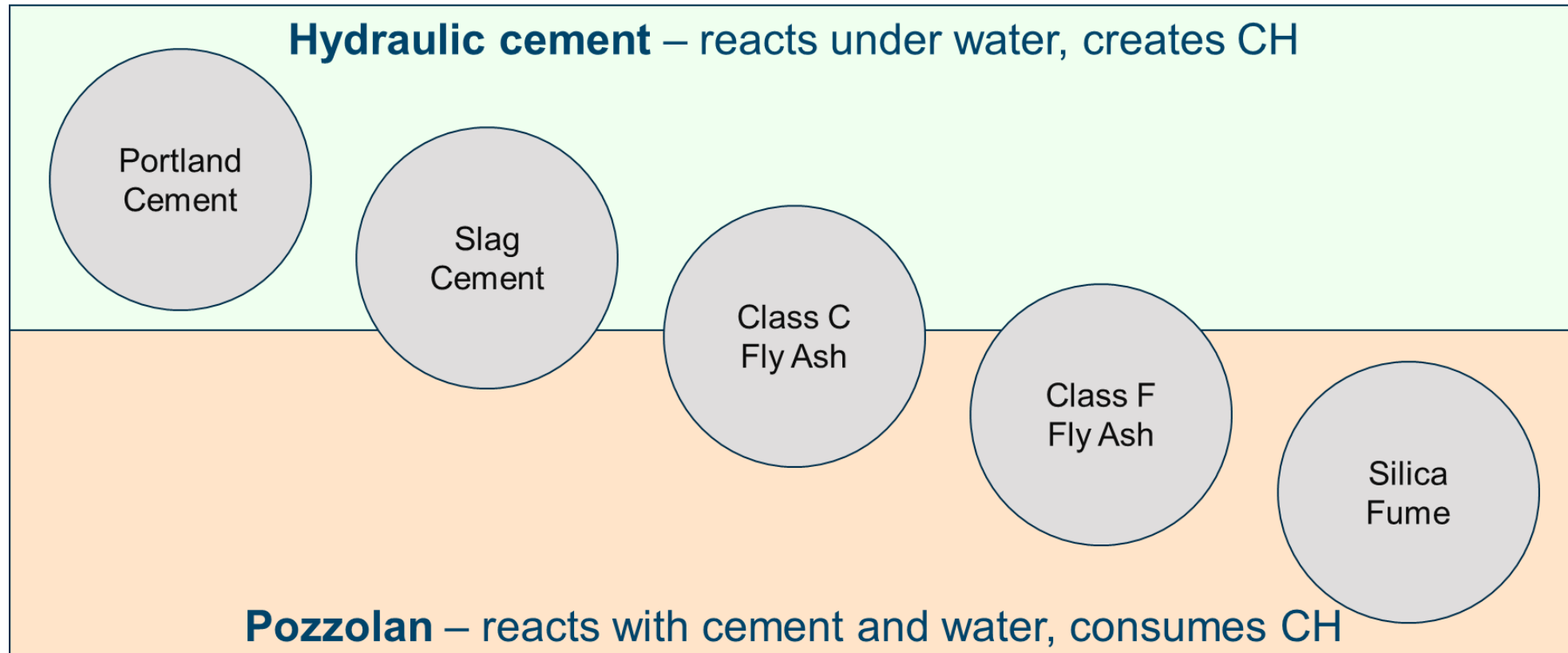
What Make SCMs Distinct from Cement?

- Consist of many of the same chemical compounds as portland cement
- Contribute to the properties of cementitious materials through hydraulic and/or pozzolanic activity
- Can be naturally-occurring minerals, industrial byproducts, or processed from raw or recycled materials

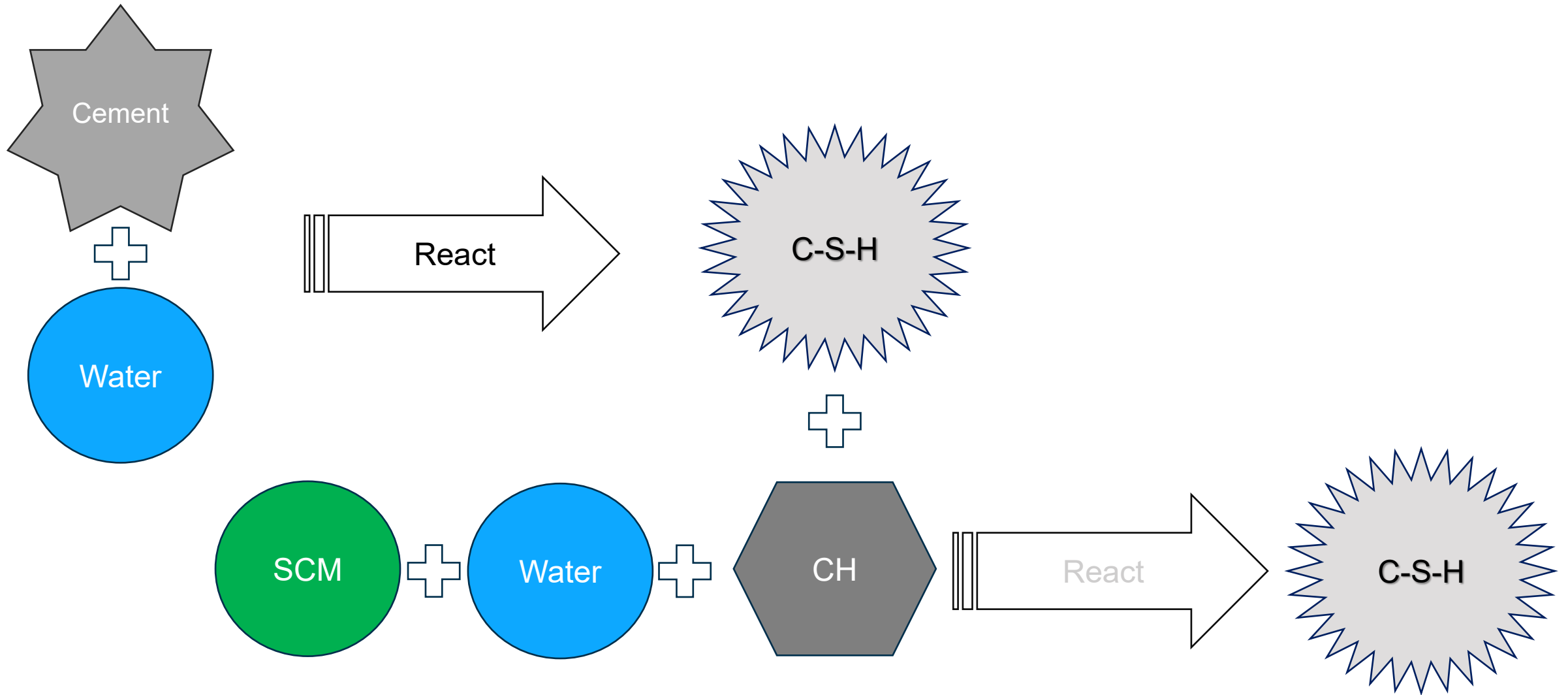


What Make SCMs Distinct from Cement?

- Hydraulic vs. pozzolanic reactions:

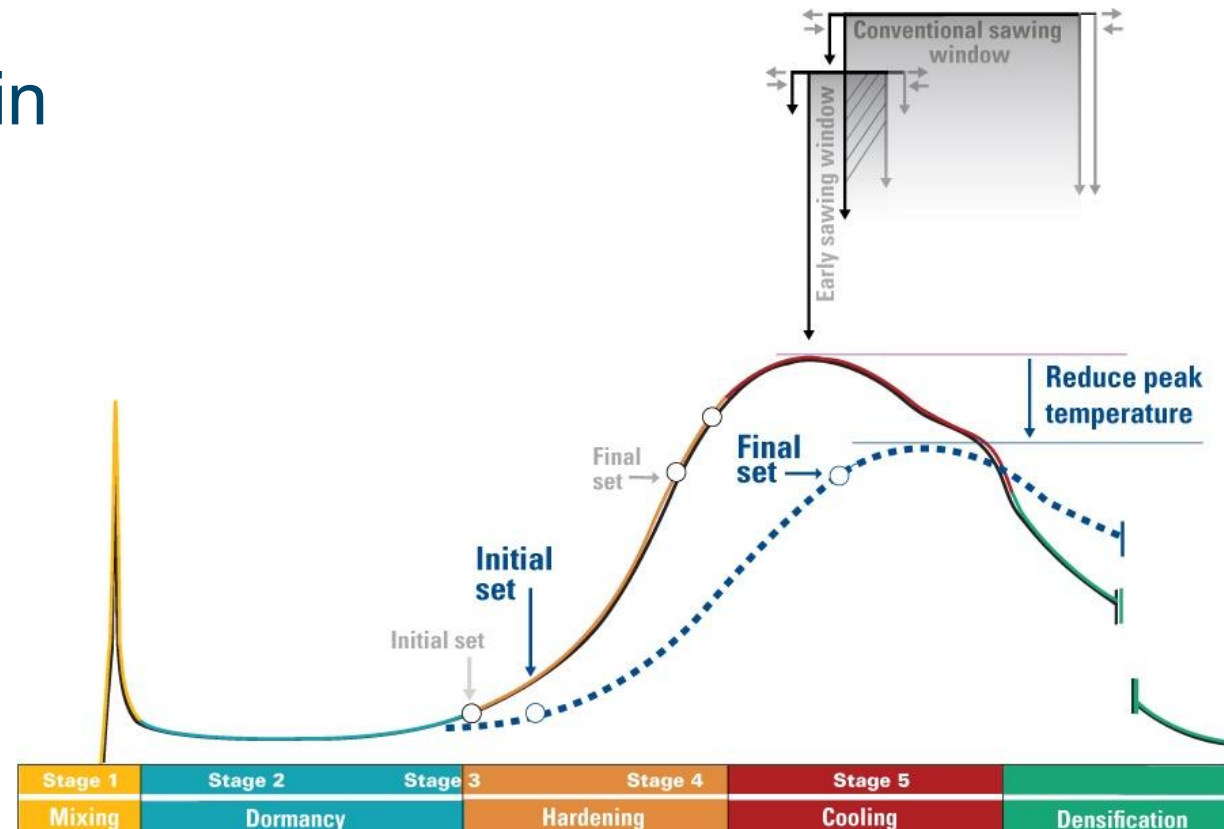


Pozzolanic Reaction



Effects of SCMs on Concrete Properties

- Slowing of the hydration reaction
 - Delayed final set
 - Reduced heat peak
 - Slower early-age strength gain
- Increased long-term strength
- Reduced permeability
- Improved long-term durability, including mitigation of specific issues such as ASR



Other Considerations for SCMs in Pavements

- Extending time to final set may delay or narrow the sawing window
- Decreasing the rate of early-age strength gain may increase time to reach opening strength
- Set time and initial strength gain may be further slowed in colder temperatures
- In late fall construction, there is less time for concrete to gain strength before winter exposure to de-icing chemicals and freeze-thaw cycles

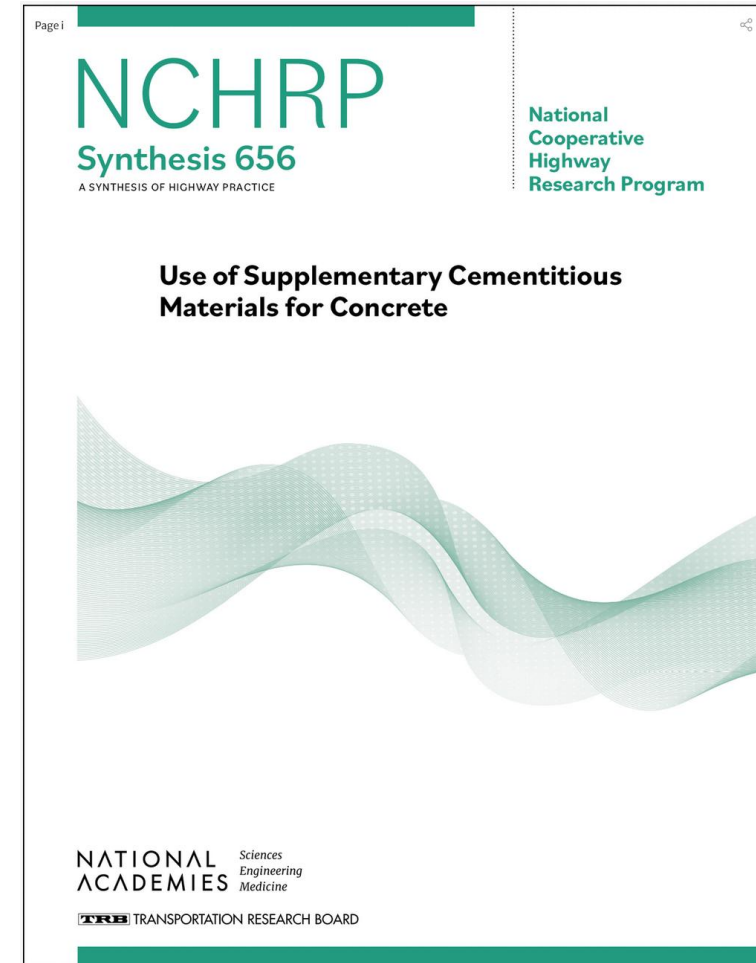
Typical SCM Replacement Rates

- SCMs may be added at the concrete batch plant, or blended or interground at the cement plant (**blended cement**)
- The SCM content of a concrete mix is usually expressed as a rate of replacement of portland cement by weight

| Product | Typical Replacement Rate |
|-----------------|--------------------------|
| Class F fly ash | 15% to 25% |
| Class C fly ash | 15% to 40% |
| Slag cement | 25% to 50% |
| Silica fume | 5% to 15% |

SCMs in Concrete Pavements Today

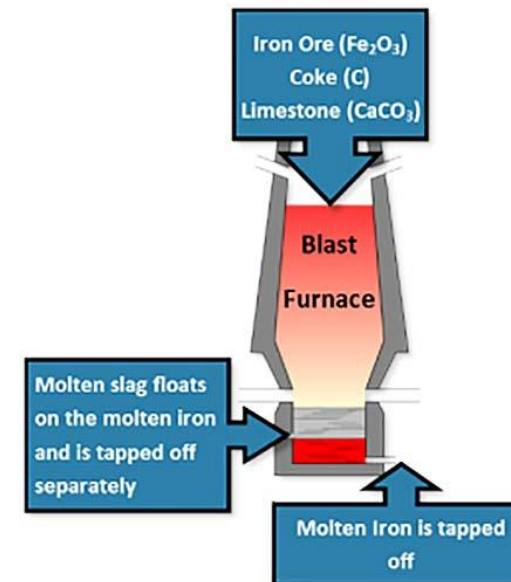
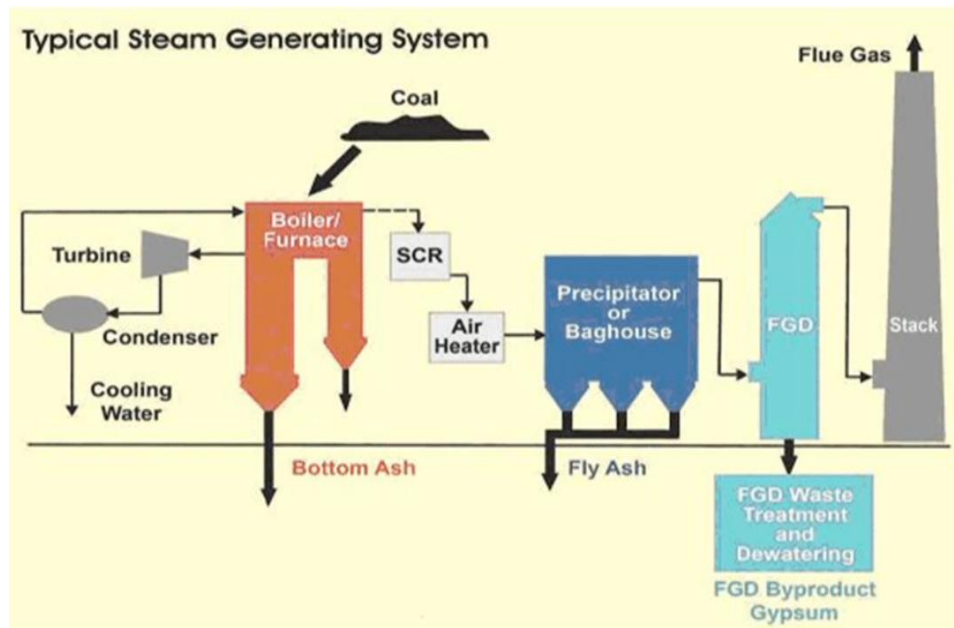
- Nearly every state DOT allows the use of SCMs in concrete pavements and in other transportation applications
- Concrete produced with SCMs has met or exceeded state DOT requirements for strength and durability
- SCMs have also been very successful in mitigating materials-related distresses, such as ASR



Future of SCMs

Future of SCMs

- The most-used SCMs today, like fly ash and slag cement, are industrial byproducts with a very low carbon footprint
- As a result, replacing portland cement with SCMs is an excellent way to **reduce CO₂ emissions** of a concrete mixture



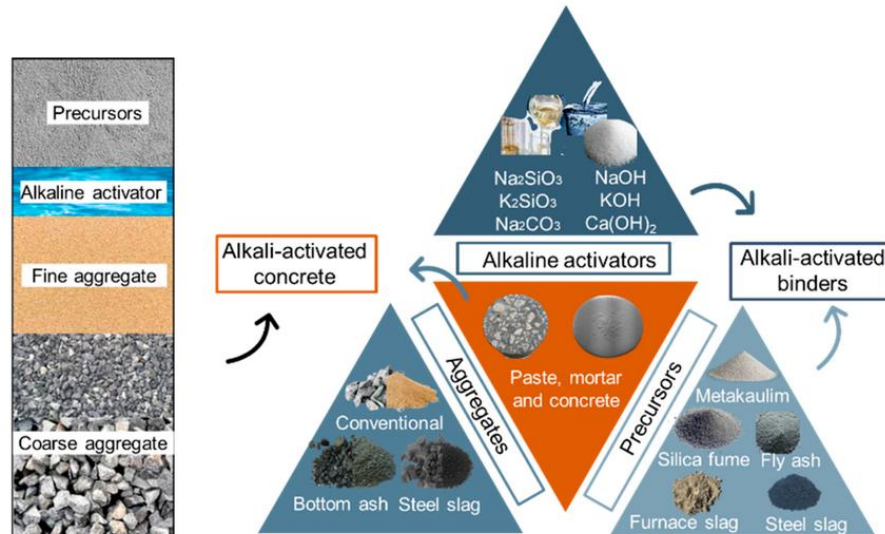
Future of SCMs

- Greater interest in sustainable concrete construction is likely to **increase** demand for SCMs and use of SCMs
 - Use of SCMs across a wider range of applications
 - Use of higher SCM replacement rates where appropriate



Alkali-Activated Binders

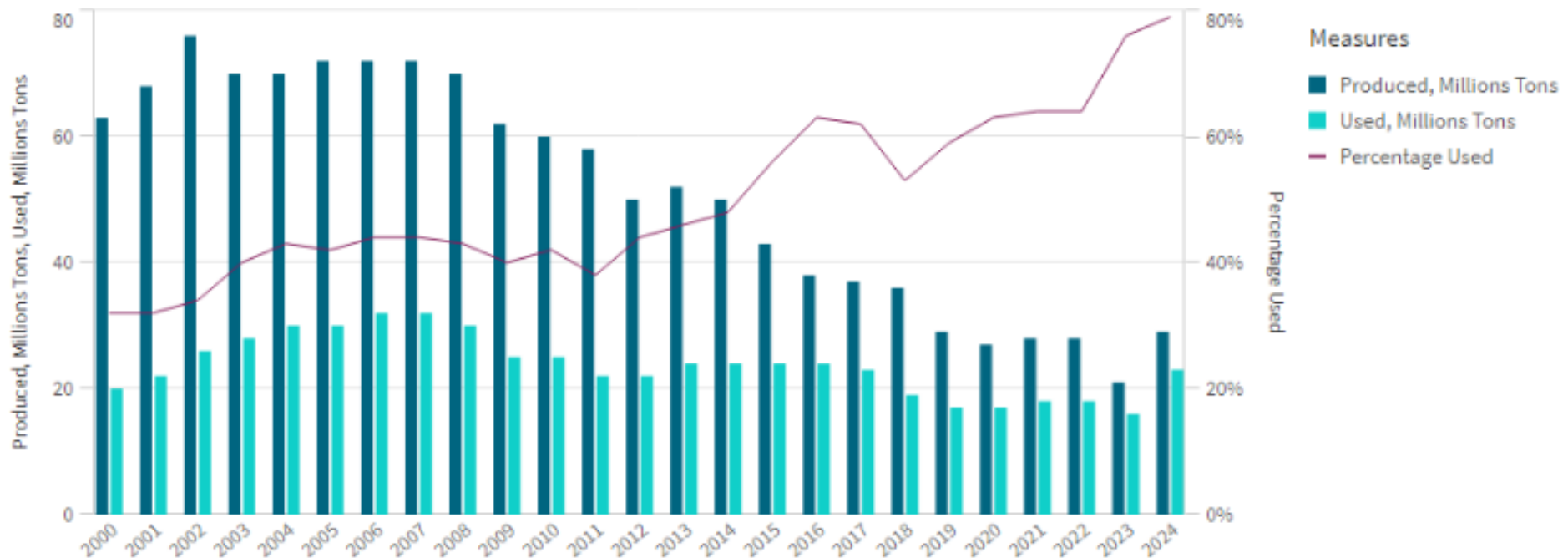
- Alkali-activated binders (AABs) are alternative binder systems that consist of a precursor material and an alkali activator
 - Slag-based AABs react at room temperature to form hydration products similar to conventional concrete mixtures
 - Fresh and hardened properties can vary significantly compared to conventional concrete mixtures



Adapting to Changing SCM Availability

- At the same time, supplies of conventional SCMs are becoming less abundant and more uncertain
 - The production of fly ash in particular has declined:

Fly Ash Production & Use (2000-2024)



Adapting to Changing SCM Availability

- ASTM C618 is now the “Standard Specification for **Coal Ash** and Raw or Calcined Natural Pozzolan for Use in Concrete”
 - Coal ash encompasses fly ash and bottom ash, and includes materials obtained from current power plant production or harvested from landfills or impoundments

Fly Ash



Bottom Ash



Adapting to Changing SCM Availability

- All coal ash must still meet the standard chemical and physical requirements for fly ash to be used in concrete
- Class C and Class F designations are unchanged in ASTM C618



Adapting to Changing SCM Availability

- Materials like natural pozzolans and calcined clay are classified as **Class N** materials in ASTM C618
 - Natural pozzolans consist of naturally-occurring minerals with pozzolanic properties (e.g. volcanic ashes)
 - Calcined clay is a manufactured natural pozzolan produced by heating clay to 550°C to $1,090^{\circ}\text{C}$



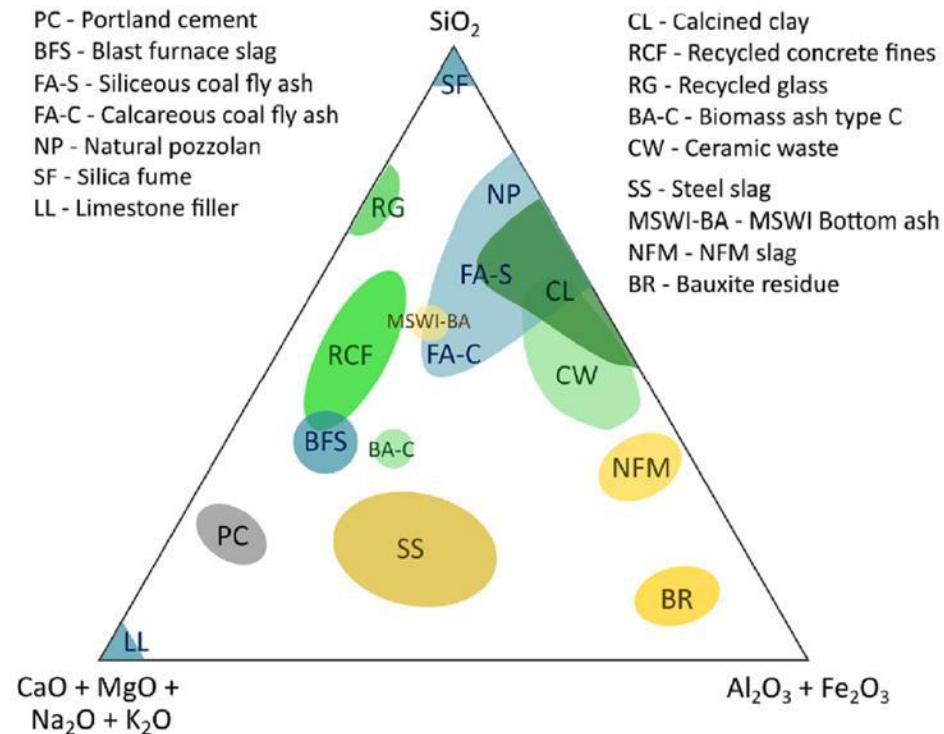
Adapting to Changing SCM Variability

- Researches are exploring a number of other products for potential use as SCMs in the future:
 - Recycled ground glass
 - Recycled concrete fines
 - Ceramic waste
 - Biomass ash
 - Waste from mining and industrial processes
 - Bauxite residue
 - CO₂-treated minerals and waste products



Adapting to Changing SCM Availability

- These newer and alternative SCMs have a similar chemistry to our familiar SCMs, and should have similar long-term effects on long-term strength and durability



Adapting to Changing SCM Availability

- That said, each new SCM has its own unique behavior and properties, and may have differing impacts on concrete
 - Placement (workability, finishing)
 - Setting time
 - Strength development
- Behavior of familiar admixtures may change as new types of blended cements and SCMs are introduced
- It's critically important to study these materials to understand and adapt to changes in concrete behavior

2024 MnROAD Concrete Pavement Test Sections

Overview of 2024 Test Sections

- Five new low carbon concrete test sections (plus a control mixture) were constructed in 2024
- Unique aspects of these test sections included the amount of SCMs used in each mixture (**high**) and the combinations of materials that were used
- The SCMs were added either:
 - At the concrete batch plant
 - As components of a blended cement
 - As the predominant cementitious material in an alkali-activated binder

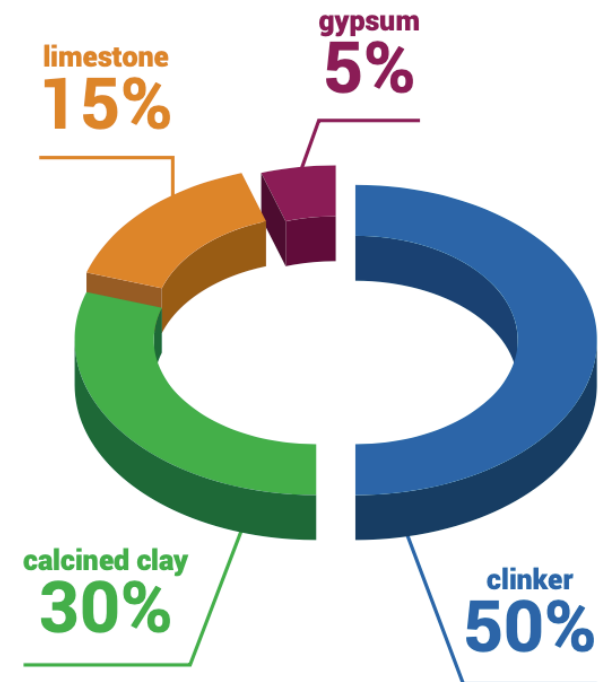
Mixtures & Materials in 2024 Test Sections

- Two portland cement-based mixtures containing combinations of different SCMs: ternary (T) and quaternary (Q)

| Cell Number | Construction Date | Mixture Name | Description |
|-------------|-------------------|--------------------|----------------------------------------------------------------------------------------------------------------|
| 2405 | 9/11/2024 | Study Control (SC) | Mixture with Type IL cement and 30% Class F coal ash replacement |
| 2407 | 9/12/2024 | Ternary (T) | Mixture with Type IL cement and SCM replacements of 30% Class F coal ash and 20% slag cement |
| 2403 | 9/10/2024 | Quaternary (Q) | (Final Quaternary proportions: 48% Type IL cement, 24% slag cement, 20% Class F coal ash, 8% natural pozzolan) |

Mixtures & Materials in 2024 Test Sections

- One mixture contained **limestone calcined clay cement (LC³)**
 - Benefits from pozzolanic reactions between calcined clay and CH
 - Carbonate ions present in limestone react with aluminate phases in the calcined clay to produce a refined microstructure with less connected pores



Mixtures & Materials in 2024 Test Sections

- Two mixtures containing alkali-activated binders: **activated slag cement (AS)** and **slag blended cement (SB)**
 - The binder in the AS mixture consisted entirely of a slag-based AAB
 - The SB mixture primarily consisted of a slag-based AAB, but also contained some Type IL cement

| Cell Number | Construction Date | Mixture Name | Description |
|-------------|-------------------|-----------------------|--------------------------------------------------------------------------------------------------------------------|
| 2406 | 9/11/2024 | Activated Slag Cement | Mixture with an alkali-activated binder containing slag cement and an activator |
| 2408 | 9/12/2024 | Slag Blended Cement | Mixture with an alkali-activated binder containing slag cement (74%), portland cement (24%), and an activator (2%) |

Mixtures & Materials in 2024 Test Sections

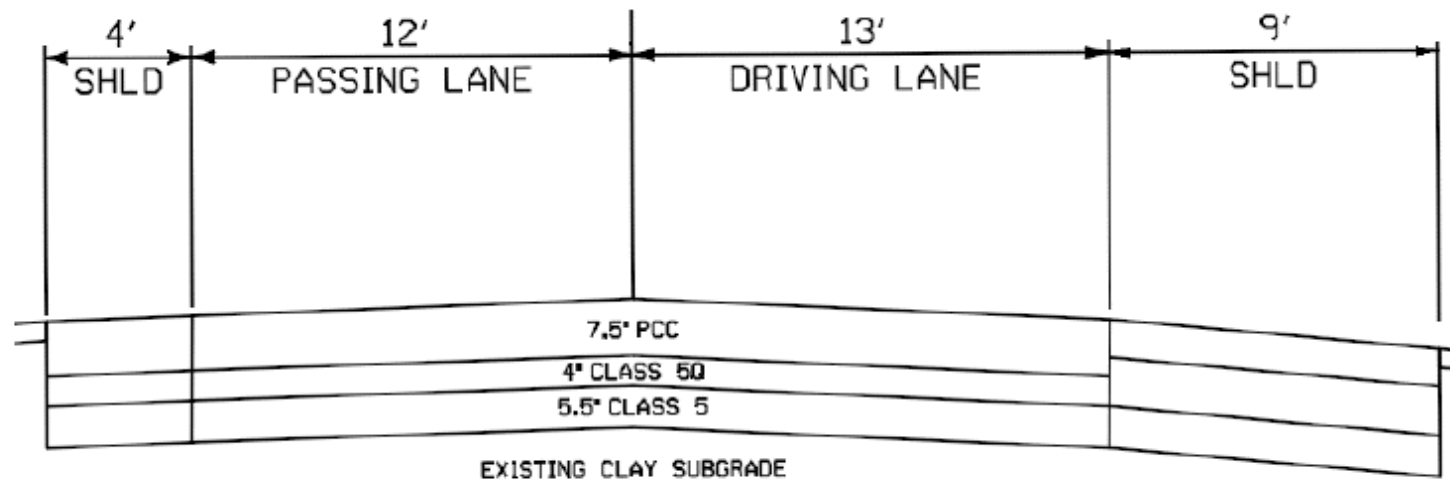
- Mixtures were prepared at different total cementitious material contents and water-to-cementitious material (w/cm) ratios
- Aggregates were proportioned consistent with typical practices for MnDOT concrete pavement mixtures

| | SC | T | Q | LC³ | AS | SB |
|--------------------------------------------------|-----------|----------|----------|-----------------------|-----------|-----------|
| Total Cementitious Content (lb/yd ³) | 570 | 570 | 540 | 570 | 700 | 540 |
| w/cm | 0.40 | 0.40 | 0.38 | 0.42 | 0.32 | 0.41 |

Constructability Evaluation

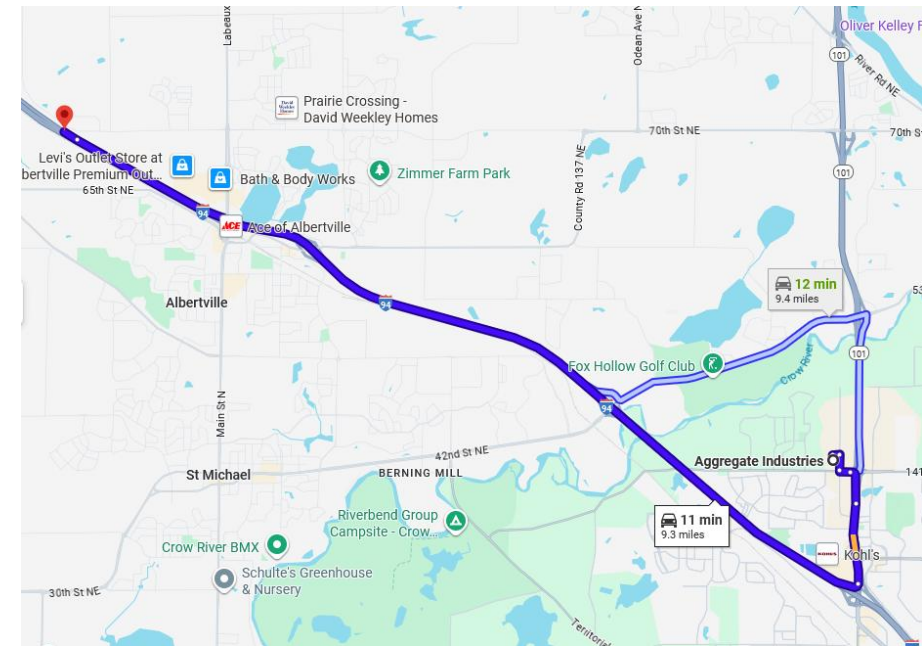
Test Section Pavement Design

- Each test section was 180 to 227 ft in length
 - 4 ft integral concrete shoulder on inside of cross-section
 - Outside shoulder was HMA
 - 145 to 188 cy of concrete in each test section



Batching, Delivery, and Placement

- Concrete was produced at Amrize's Rogers ready mix plant
 - Typical 10 yd³ batch
- Concrete delivered in ready mix trucks
- Water and admixture dosages were adjusted both at the batch plant and at the grade
- Pavement was placed with a Wirtgen SP-94i slipform paving machine



2405: Study Control (SC)

- Construction date: 9/11/24
 - Paving start: 7:25 a.m. (concrete arrived at 7:00 a.m.)
 - Paving finish: 9:00 a.m.
- Production notes
 - Consistent delivery timing initially, slowed as paving continued
 - 3 to 4 gallons of water added to each truck at the grade beginning about halfway through paving
 - Production rate of approx. 84 cy/hr

2405: Study Control (SC)

- Placement went well
- No concerns with finishing or surface texture
- Sawing went well and cuts looked clean



2407: Ternary (T)

- Construction date: 9/12/24
 - Paving start: 7:20 a.m. (concrete arrived at 7:00 a.m.)
 - Paving finish: 9:00 a.m.
- Production notes
 - Consistent delivery timing initially, slowed as paving continued
 - No mixture adjustments were required at the grade
 - Production rate of 79 cy/hr

2407: Ternary (T)

- Placement went well
- No concerns with finishing or surface texture
- Sawing went well



2403: Quaternary (Q)

- Construction date: 9/10/24
 - Paving start: 7:30 a.m. (concrete arrived at 7:00 a.m.)
 - Paving finish: 9:10 a.m.
- Production notes
 - Consistent delivery times throughout
 - 3 to 4 gallons of water added to each truck at the grade throughout
 - Water reducer added beginning around truck 10-12
 - Production rate of 68 cy/hr

2403: Quaternary (Q)

- Additional finishing work needed early on, adding material to fully close up the surface
- Finishing became easier by the end of paving
- Texture was a little light early on, improved after cleaning turf
- Sawing went well, some minor raveling and chipping in later portions



2401: LC³

- Construction date: 9/9/24
 - Paving start: 7:48 a.m. (concrete arrived at 7:20 a.m.)
 - Paving finish: 9:45 a.m.
- Production notes
 - 4 to 5 gallons of water added to each truck at the grade beginning with truck 3
 - Water reducer dosage rate had to be increased from 5.5 oz./cwt to 7.5 oz./cwt between truck 7 and truck 9
 - Production rate of 61 cy/hr

2401: LC³

- Mix initially dry, not as creamy as other mixes when finishing, but responded to float to fill holes
- Some edge slump that required re-forming on south edge
- Good texture noted during construction
- Started sawing at 3 p.m. and then stopped for an hour, typ. 1/4" raveling and chipping observed in some saw cuts

2401: LC³



2406: Activated Slag Cement (AS)

- Construction date: 9/11/24
 - Paving start: 9:12 a.m.
 - Paving finish: 10:55 a.m.
- Production notes
 - Mix initially very stiff and difficult to get out of the chute
 - Immediate need for 5 gallons of water at the grade on truck 1
 - Paver was working very hard to consolidate the concrete



2406: Activated Slag Cement (AS)

- Production notes (cont.)
 - Water addition increased to 10 gallons at truck 7
 - Water addition increased to 15 gallons at truck 9
 - Workability proved very sensitive to this water addition
 - Production rate of 86 cy/hr



2406: Activated Slag Cement (AS)

- Lots of work required to finish the surface (all hands on deck)
- Virtually no surface texture early on, some improvement with water addition on north side (not on south side)
- Lots of voids left at the surface
- Initially the edge held, but needed to re-form the edges after the increases in water addition
- Sawing looked like it mostly went well until the last 2 to 3 slabs, which had significant raveling

2406: Activated Slag Cement (AS)



2408: Slag Blended Cement (SB)

- Construction date: 9/12/24
 - Paving start: 9:20 a.m. (concrete arrived at 9:07 a.m.)
 - Paving finish: 11:45 a.m.
- Production notes
 - Consistent delivery and good batch-to-batch consistency early on
 - Delivery slowed down (paver had to stop a few times) and the mixture became less consistent during placement
 - 5 gallons of water was immediately added to the first truck, as the mixture was dry coming out of the chute

2408: Slag Blended Cement (SB)

- Production notes (cont.)
 - Water addition increased to 8 to 9 gallons from truck 4 onward
 - Water reducer dosage rate increased beginning with truck 11
 - Production rate of 62 cy/hr
- Consistent issues with edge slump and re-forming the edge



2408: Slag Blended Cement (SB)

- Finishing and surface texture
 - Good overall, especially at the beginning
 - Became more difficult to finish and texture got lighter towards the end, especially after the paving machine had to stop a few times



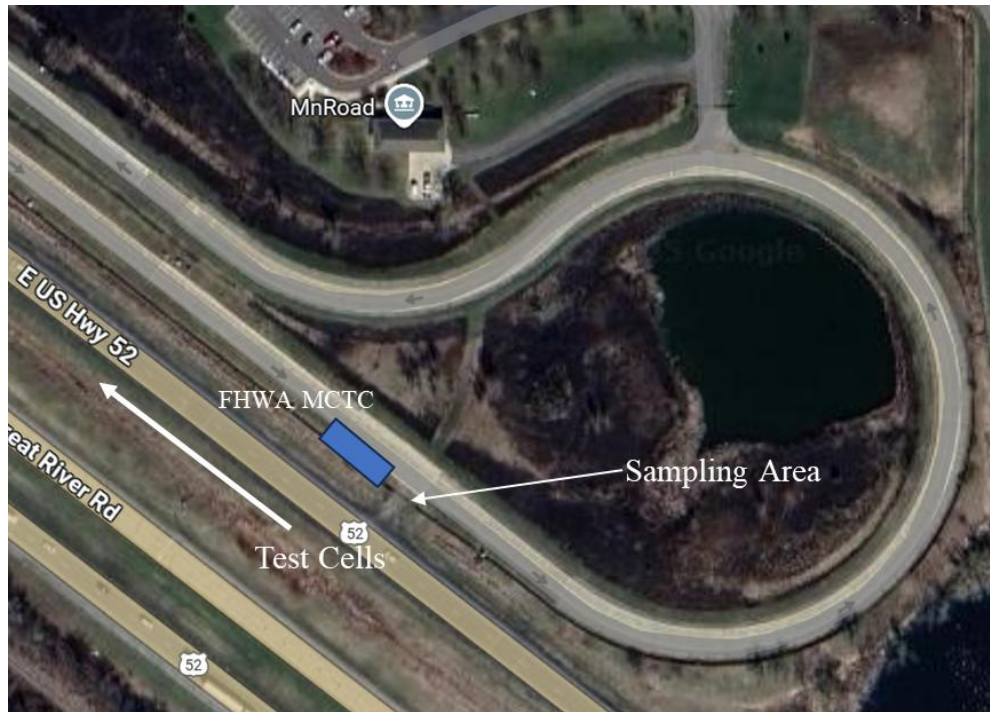
Summary of Findings

- The SC, T, and Q mixtures placed and finished well and required very few adjustments
- More adjustments were needed for the LC³ mixture, but it ultimately placed and finished well
- The AS and SB mixtures were more difficult to dial in and had more issues (especially surface texture of the AS mixture), but both were able to be placed!

Early-Age Properties

Sampling and Testing

- Sampling and testing efforts were led by teams from AET and FHWA's Mobile Concrete Technology Center (MCTC)



Fresh Concrete Property Testing

| Test Name | Test Method | AET | FHWA MCTC |
|-----------------|--------------|---------------|---------------|
| Air Content | ASTM C231 | 3 per mixture | 1 per mixture |
| Super Air Meter | AASHTO T 395 | 2 per mixture | 1 per mixture |
| Unit Weight | ASTM C138 | 3 per mixture | 1 per mixture |
| Slump | AASHTO T 119 | 3 per mixture | 1 per mixture |
| Temperature | ASTM C1064 | 3 per mixture | 1 per mixture |
| Box Test | AASHTO T 396 | 2 per mixture | 1 per mixture |
| Phoenix Test | MnDOT 2201 | — | 1 per mixture |
| Microwave test | AASHTO T 318 | — | 1 per mixture |
| VKelly Test | AASHTO T 403 | — | 2 per mixture |

Hardened Concrete Property Testing

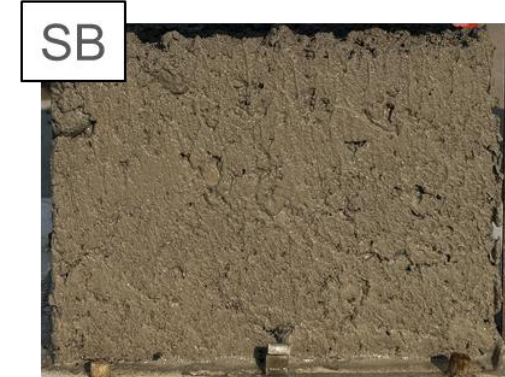
| Test Name | Test Method | AET | FHWA MCTC |
|--------------------------------------------|--------------|---------------------------------------------------------------|--------------------------------------------------------------|
| Compressive Strength | ASTM C39 | 3 sets of two 6"x12" cylinders for each test time per mixture | 1 set of two 6"x12" cylinders for each test time per mixture |
| Flexural Strength | ASTM C78 | 3 sets of two beams for each test time per mixture | 1 set of two beams for each test time per mixture |
| Surface Resistivity | AASHTO T 358 | 3 sets of two 6"x12" cylinders for each test time per mixture | 1 set of two 6"x12" cylinders for each test time per mixture |
| Bulk Resistivity | ASTM C1876 | — | 1 set of three 4"x8" cylinders per mixture |
| Freeze-Thaw | ASTM C666 | 1 set for each mixture | |
| Poisson's Ratio and Elastic Modulus | ASTM C469 | — | 1 per mixture |
| Hardened Air Content | ASTM C457 | 3 per mixture | — |

Hardened Concrete Property Testing

| Test Name | Test Method | AET | FHWA MCTC |
|--------------------------------------------|--------------|----------------------------------|------------------------|
| Compressive Strength | ASTM C39 | 1, 3, 7, 14, 28, 42, and 56 days | 7, 28, and 56 days |
| Flexural Strength | ASTM C78 | 1, 3, 7, 14, 28, and 56 days | 28 days |
| Surface Resistivity | AASHTO T 358 | 1, 3, 7, 14, 28, 42, and 56 days | 7, 28, and 56 days |
| Bulk Resistivity | ASTM C1876 | — | 7, 28, 56, and 91 days |
| Freeze-Thaw | ASTM C666 | 14 days | — |
| Poisson's Ratio and Elastic Modulus | ASTM C469 | — | 28 days |
| Hardened Air Content | ASTM C457 | Various | — |

Summary of Key Findings

- Most of the box test results indicated good workability
 - Only the AS mixture had an unfavorable result, though the LC³ and SB mixtures also had challenges in practice



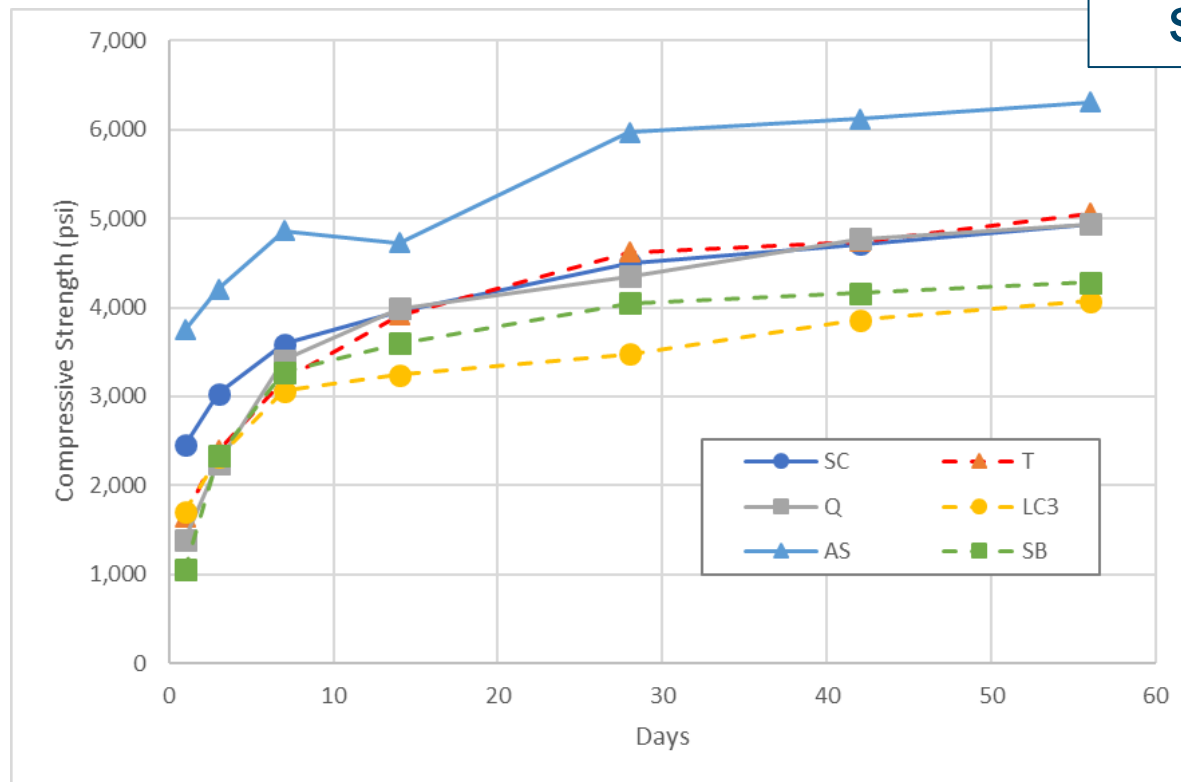
Summary of Key Findings

- The results of the box test weren't ultimately able to predict or compare the relative workability of these mixtures
- Other test(s) might be needed to help assess the ease of placing and finishing mixtures with novel materials and SCMs

Summary of Key Findings

- Compressive strength development was slower for the first 14 to 28 days for many lower clinker mixtures
 - AET's results over time:

- The AS mixture was a significant outlier



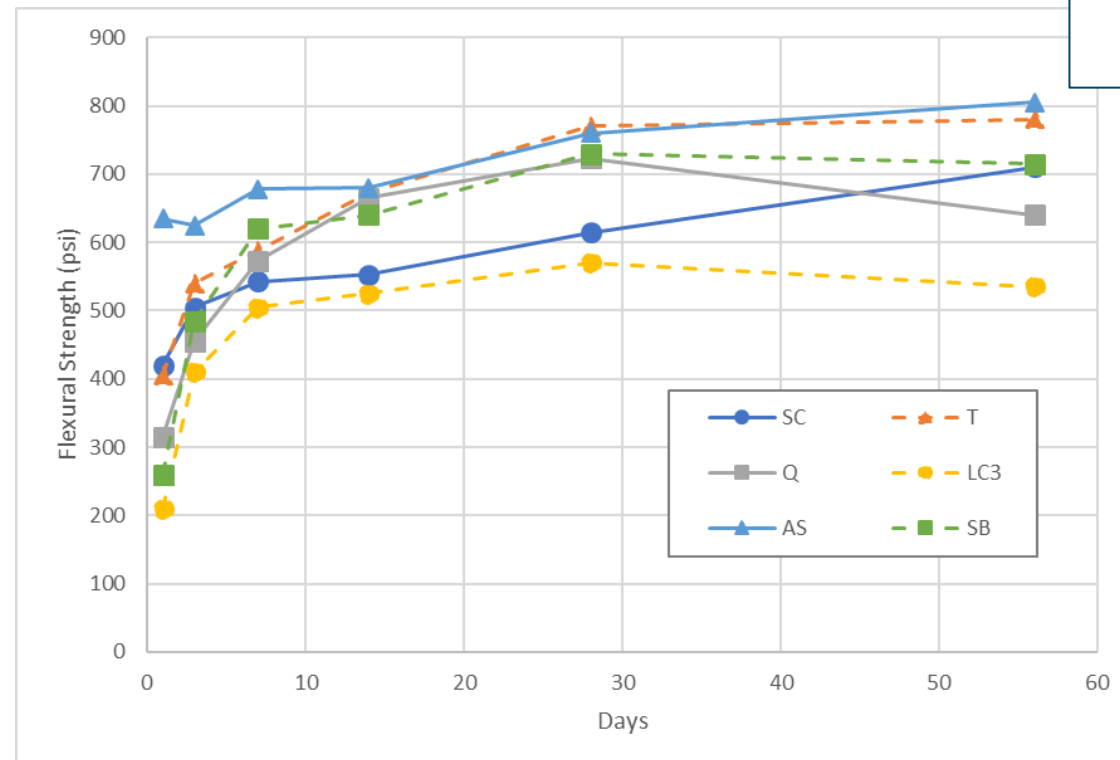
Summary of Key Findings

- Some of the lower clinker mixtures “caught up” to the SC mixture by 28 days, but others remained lower out to 56 days
- Implications:
 - Will acceptance testing times require adjustment?
 - Is more than 56 days needed to fully understand strength development of mixtures that remained lower? (LC³, SB)
 - What adjustments might be needed in late season/colder weather construction?

Summary of Key Findings

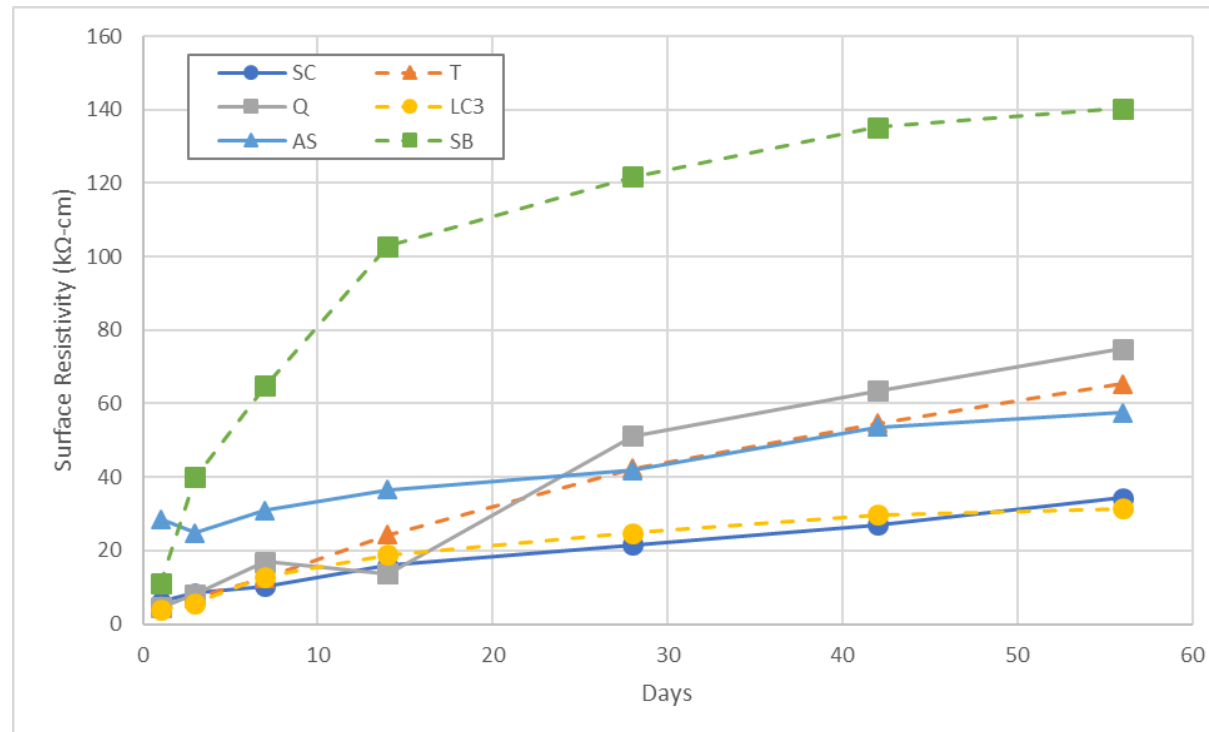
- Flexural strength development for many of the lower carbon mixtures was actually more rapid than the SC
 - AET's results over time:

- The AS mixture was again an outlier



Summary of Key Findings

- Bulk and surface resistivity results were good for all mixtures, but some the AS and SB mixture results were major outliers
 - AET's results over time:



Summary of Key Findings

- The resistivity results indicate that the T, Q, and LC³ mixtures should be capable of achieving similar long-term performance in terms of durability as the study control
- Alternative approaches may be needed to characterize the permeability of alkali-activated binder systems
 - Leaching of alkali ions from the pore solution is known to increase the measured resistivity of concrete

Summary of Key Findings

- The remainder of the testing for early-age fresh and hardened properties indicated similar performance for lower carbon mixtures vs study control
- Some samples failed in freeze-thaw, but it was not immediately obvious why or how these failures occurred
 - Some samples had low air contents, but that didn't clearly correlate with failure in freeze-thaw
 - Possible that 14 days of curing is insufficient for systems with slower early rates of hydration?
 - Re-testing is currently underway