Use of Supplementary Cementitious Materials for Concrete

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National Concrete Consortium
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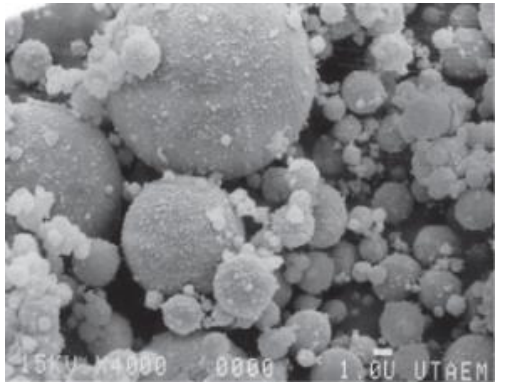
Slag Cement Association

Silica Fume Association

Shubham Mishra (each above)



ACI 323.2R-18

Overview

Objective

- To document state DOT practices for specifying and using SCMs in concrete used in transportation infrastructure applications.

Information Gathering Methodology

1. Review of literature
2. Survey of state DOTs
3. Case examples from select state DOTs

Target audience

- Agencies, practitioners, students, others needing information on SCMs and their uses

Information Gathered

- Types of SCMs allowed by the state DOTs
- Use and applications of different SCMs
- Use of Natural Pozzolans (NPs) and harvested ash
- Percent replacement of portland cement by different SCMs in binary and ternary mixtures
- Challenges associated with the use of SCMs
- Practices of monitoring quality of SCMs
- Availability of fly ash and how the state DOTs are responding to the shortage of fly ash
- Use and availability of Alternative SCMs (ASCMs)
- Types of demonstration projects for ASCMs, and
- Use of ASCMs in conventional DOT concrete specifications

Synthesis Contents

Chapter 1: Introduction

Chapter 2: Literature Review

Chapter 3: State DOT Practices

Responses to Agency Survey Questionnaire

Chapter 4: Case Examples

Caltrans, Colorado DOT, Louisiana DOTD, Minnesota DOT, Utah DOT

Chapter 5: Summary of Findings

Summary

Gaps in the Information on SCMs

Research Needs

Introduction

For the past 4 decades, Conventional SCMs such as fly ash, slag cement and silica fume have been specified and used by state DOTs in concrete mixtures for paving and structural projects.

In Fresh Concrete Mixtures:

- Can enhance workability, reduce bleeding, improve concrete placement and finishability.
- Fly ash and slag reduce the rate of heat development from the cement hydration to control the rise in concrete temperature in mass structures.

In Hardened Concrete:

- SCMs improve the ultimate strength of concrete.
- Reduce concrete permeability to enhance its resistance to chemical attack from sulfates, ASR, and corrosion-inducing chlorides (from seawater and deicing salts).

Sustainability Benefits:

- Replace a percent of the cement content in concrete mixtures – lower clinker content.
- Greenhouse gas emissions, and specifically CO_2, from the manufacturing of portland cement are reduced.

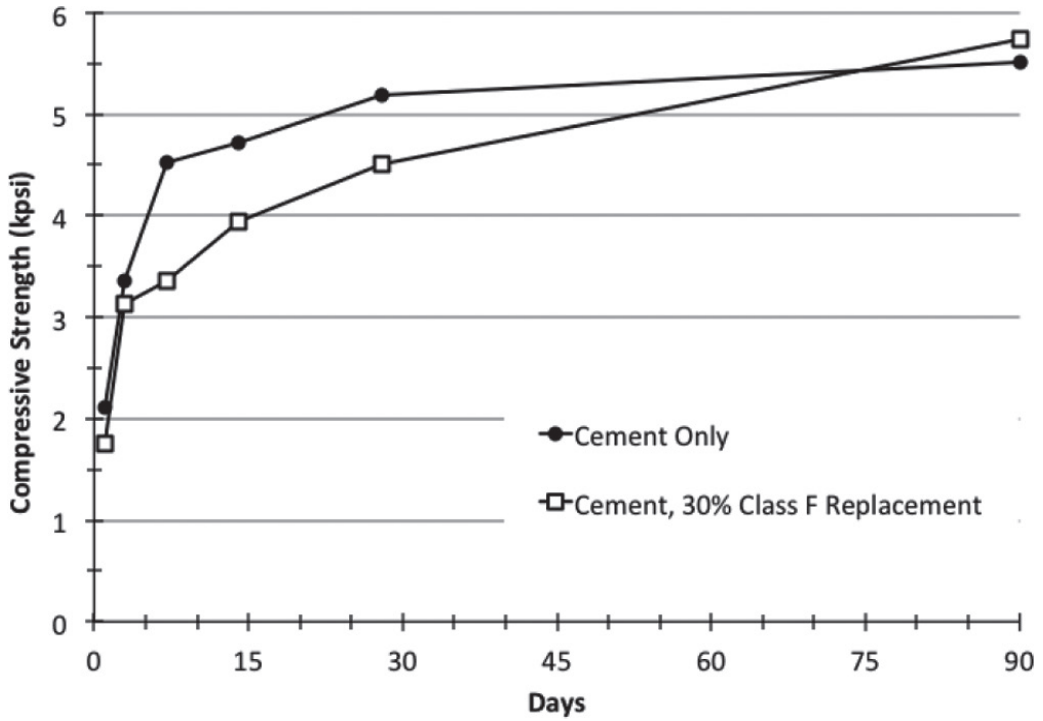
Introduction

- Types of SCMs
- Mechanisms and benefits
  - SCMs possess pozzolanic characteristics that, when added to a concrete mixture, engage in pozzolanic reaction with $Ca(OH)_2$ (CH), a byproduct alkali of the cement-water hydration process.
  - The pozzolanic reaction depletes CH in concrete and produces additional useful (C-S-H) hydration binder gel that fills spaces in the paste capillary pores to ultimately reduce permeability of concrete.
  - The densification of the paste increases concrete strength and improves its durability to resist chemical attack from sulfates, chlorides, other agents. Also mitigates ASR.
- Binary/ternary/quaternary blends
  - SCMs work together to improve properties of concrete, and, in some cases, offset shortcomings of each other's properties.
- Changes in SCM availability
  - Fly ash shortage, harvested/beneficiated ash, changes in ASTM C618, etc.
  - Natural pozzolans
  - Alternative SCMs

Literature Review – Coal Ash

- Changes in ASTM C618-23
  - Uses the term “coal ash” instead of fly ash, and as before, allows NPs.
  - Now allows harvested ash that meets its chemical and physical requirements.
- Typical composition, characteristics
- Performance of concrete containing coal ash
  - Fresh/hardened properties
  - Durability performance

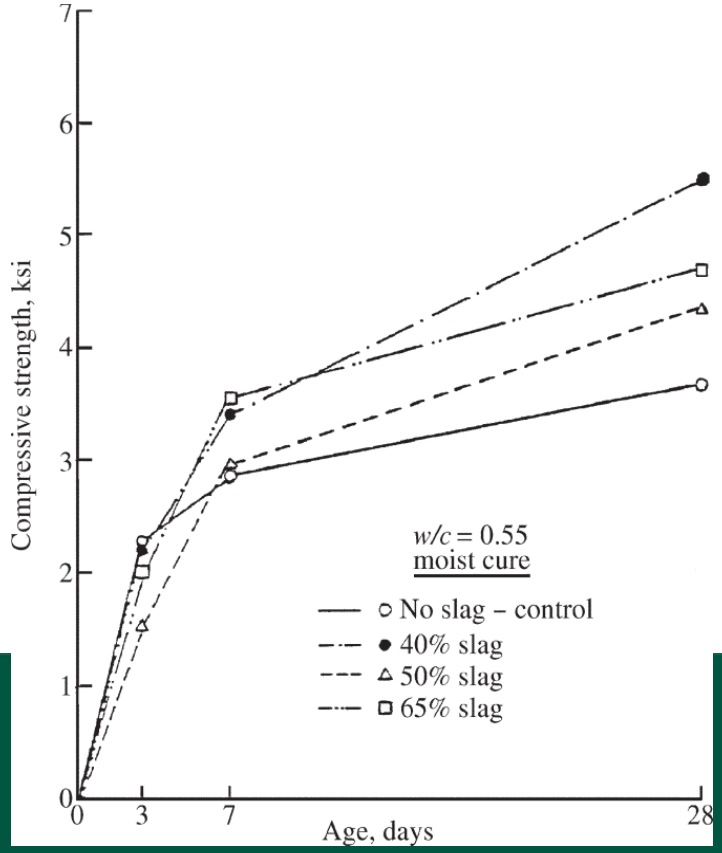
- High-volume fly ash
- Availability of coal ash
- Harvested coal ash
  - Characteristics
  - Beneficiation



Rate of strength gain for a mixture with F fly ash at 30% replacement of cement as compared to a control mixture with cement only (Sutter et al. 2014).

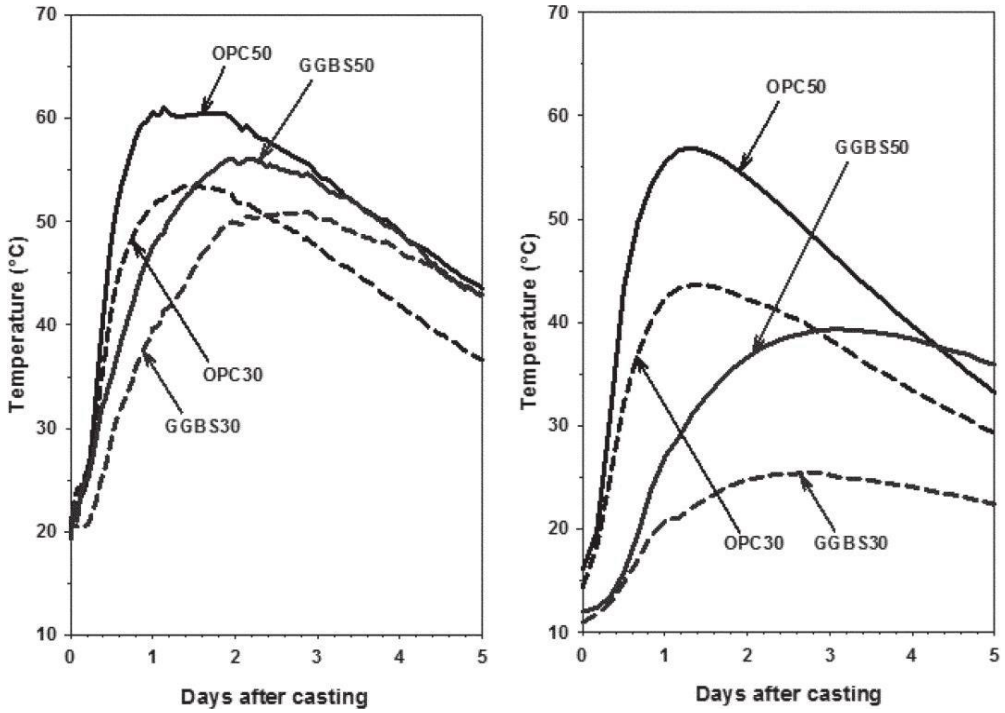
Literature Review – Slag

- Slag cement (ground granulated blast furnace slag)
- Typical composition, characteristics
- Performance of concrete containing slag
  - Fresh/hardened properties
  - Durability performance



Compressive strength of concrete containing various percent slag cement content compared with no-slag concrete (Hogan and Meusel 1981)

- Applications
  - Temperature control of mass concrete



Temperature rise of 4.9 ft (1.5 m) concrete blocks cast in warm (left) and cool (right) weather with 0 and 50 percent slag cement (Soutsos et al. 2016)

Literature Review – Silica Fume

- Typical composition, characteristics
- Product forms
- Performance of concrete containing coal ash
  - Fresh/hardened properties
  - Durability performance

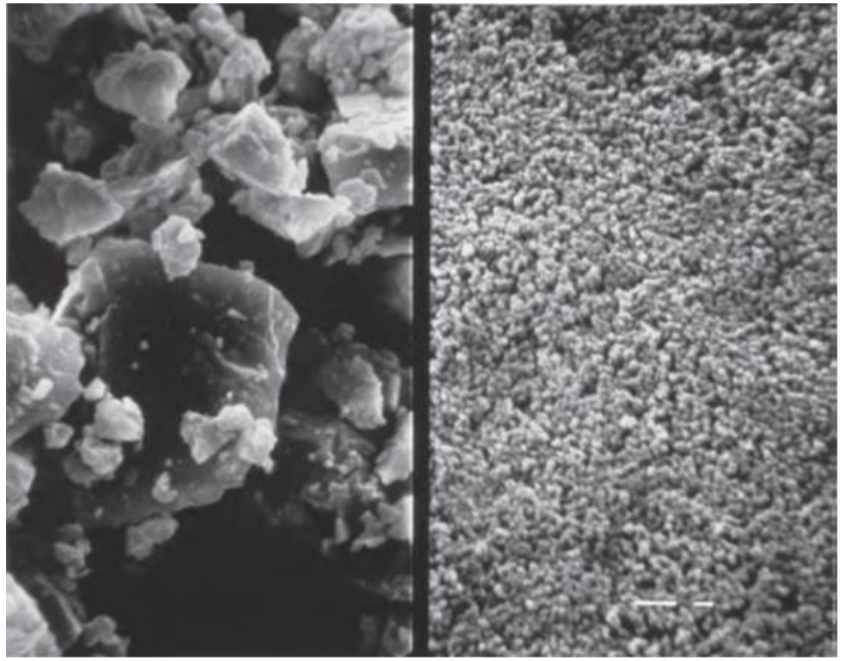
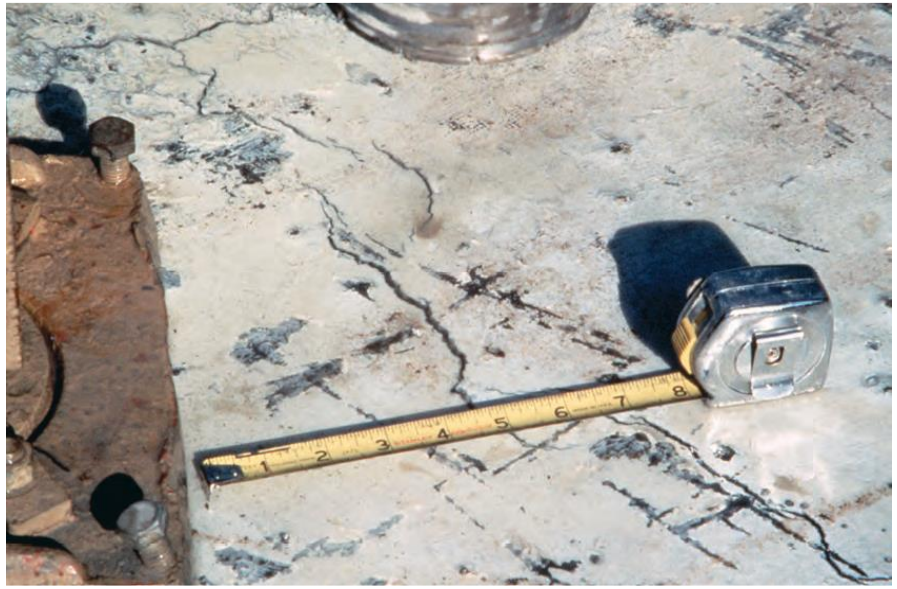


Illustration of difference in fineness between cement and silica fume (SFA 2022).

- Applications
  - Primarily structures
  - Discussion on site conditions and cautions

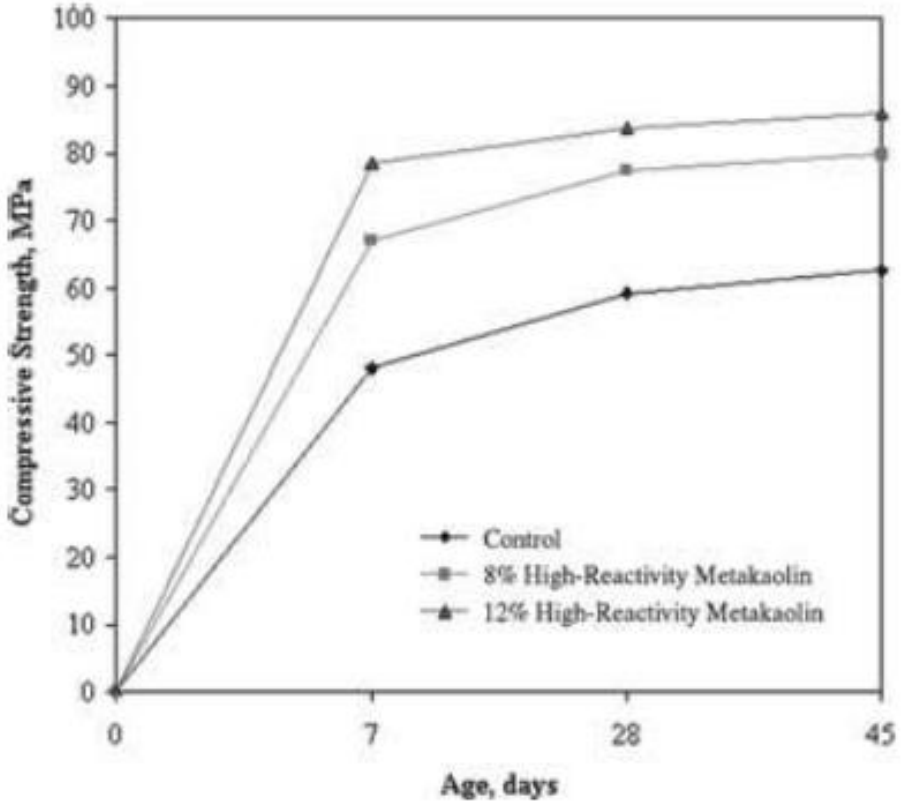


Plastic shrinkage cracks (SFA 2022).

Literature Review – Natural Pozzolans

- Types of natural pozzolans
  - Calcined clay
  - Calcined shale
  - Metakaolin
  - Pumice
  - Rice husk ash

- Availability
- Chemical compositions, characteristics
- Processing required to activate
- Reaction mechanisms
- Performance of concrete containing NPs
  - Fresh/hardened properties
  - Durability performance

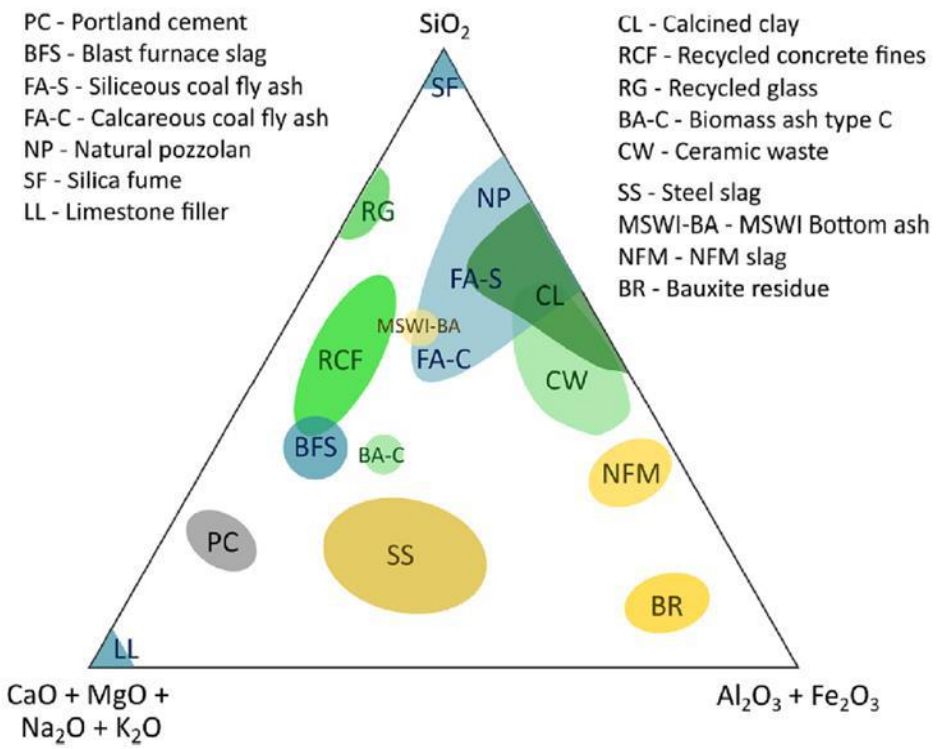


Effect of high reactivity metakaolin at 0.4 w/cm on compressive strength of concrete (Hooton et al. 1997)

Literature Review – Alternative SCMs

- Recycled Materials from Waste and Construction Applications
  - Ground glass pozzolan (GGP)
  - Fines from concrete recycling
  - Ceramic waste
- Ashes from combustion of materials other than coal
  - Municipal solid waste incineration ash (MSWI)
  - Biomass ash
- Wastes from mining and industrial processes
  - Non-ferrous metallurgy (NFM) slags
  - Mining, quarrying, and dredging wastes
  - Bauxite residue

- Availability, chemical compositions, characteristics
- Processing required to activate
- Overview of reactivity tests - existing and emerging

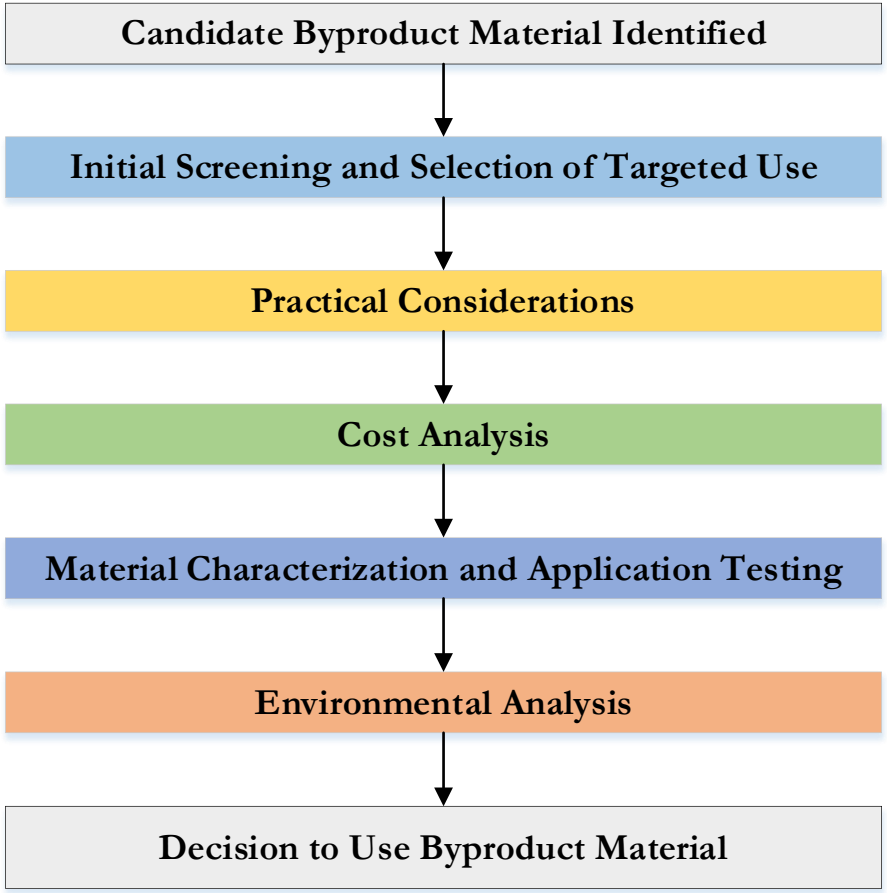


Chemical compositions of conventional SCMs and fillers (green and blue), and ASCMs (yellow) along with portland cement (gray). NFM: "non-ferrous metallurgical" and MSWI: "municipal solid waste incineration." (Snellings et al. 2023)

Literature Review – Alternative SCMs

- Reaction mechanisms
- Performance of concrete containing ASCMs
  - Fresh/hardened properties
  - Durability performance

- Evaluation of ASCMs for use in concrete applications
  - Overview of ASTM C1709
  - Stage I. Characterization of the material
  - Stage II. Determination of suitable fineness
  - Stage III. Testing to specifications such as ASTM C618, ASTM C989, ASTM C1240, or ASTM C1866
  - Stage IV. Concrete performance tests
  - Stage V. Field trials and long-term performance and durability assessment
  - General approach for evaluation



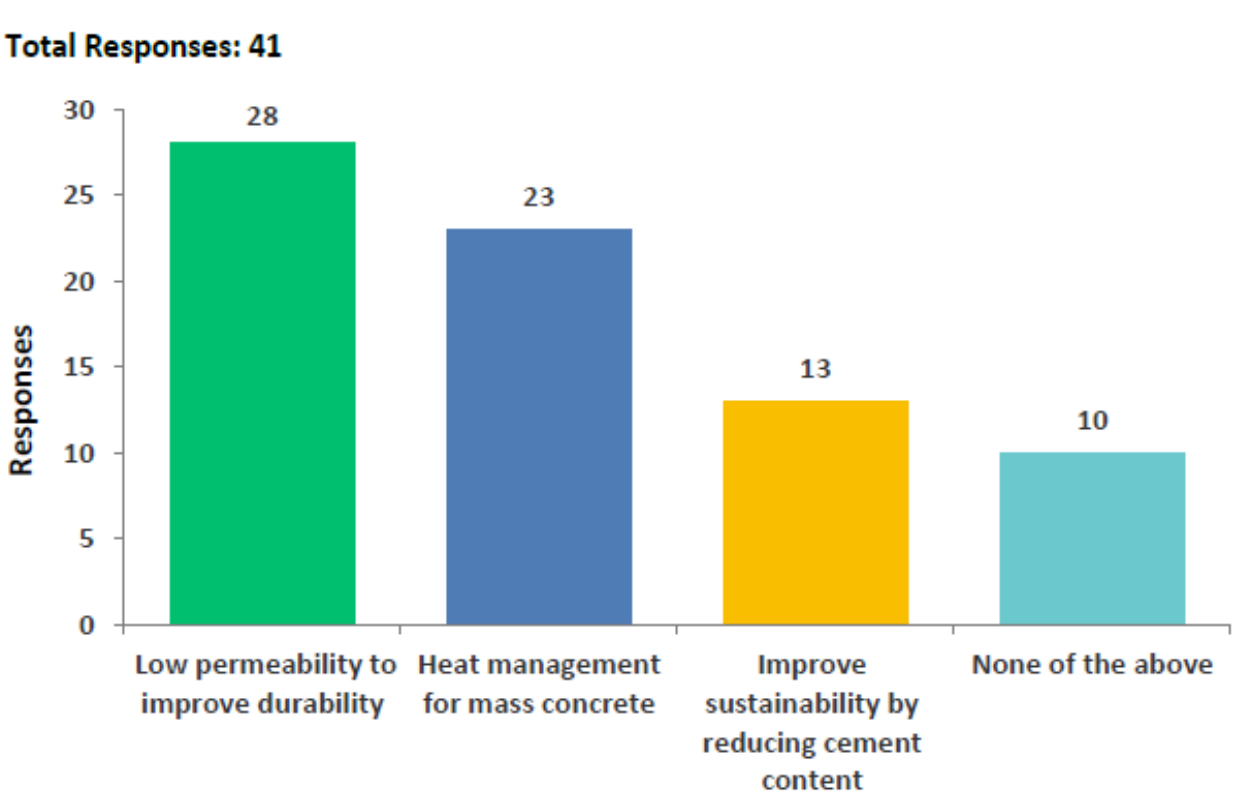
General framework for evaluation of a byproduct material for use in concrete (Cavalline and Sutter 2024).

State DOT Practices – Survey Findings

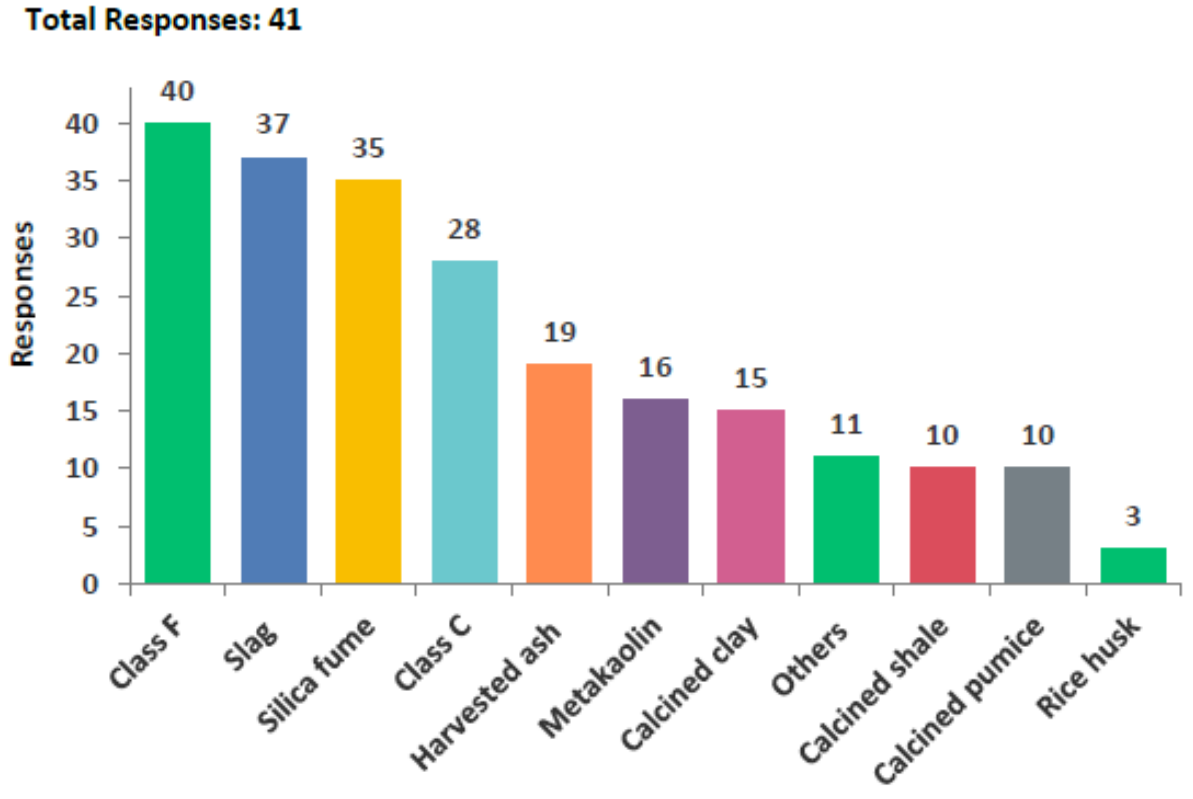
- Survey questionnaire developed and sent to all 50 state DOTs, District of Columbia and Puerto Rico
- February-March 2024
- 25 questions
  - Agency practices related to uses and applications of SCMs
  - Shortages of fly ash and agency responses
  - Use of ASCMs in agency projects
  - Willingness to be interviewed for case examples
- 42 state agencies and Puerto Rico responded
  - Some agencies left some questions blank

Questions asked about:

- State DOTs' use of SCMs in concrete
- Applications where specifications allows the use of SCMs
- Conditions requiring the use of SCMs in concrete.
- Types of SCMs allowed/used in concrete.
- Percent replacement of SCMs used in concrete mixtures
- Natural pozzolans used in concrete mixtures
- Ternary and quaternary SCM mixtures
- Acceptance requirements for concrete with SCMs.
- SCMs in concrete with IL Cement.
- Availability of fly ash
- Alternative SCMs
- Case example interview willingness



Specific applications of SCMs



Agency use/allowance of SCMs

Percent conventional SCMs permitted in pavement concrete by the responding states (41 responses).

State DOT	< 10%	10%-15%	20%	25%	30%	40%	50%	60%	Other %	Not Used
Fly ash F	ND, WI, IL, MS	ND,WI, GA, MO, IL, FL, DE, MS, HI	SD, ND, IA, SC, AZ, KY, CT, WV, NV, IL, TX, FL, OK, MS, VA	TN, SD, NE, MO, OH, IL, TX, FL, MS, VA	MT, ME, OR, RI, NC, AL, TX, FL, MA, UT	MI, PR, PA, TX, FL	CO, TX, FL		WI, WA, MN, CA, NY, MS, LA	VT
Fly ash C	ND, WI, IL, MS	ND,WI, GA, MO, IL, FL, MS	ND, WI, IA, SC, AZ, CT, WV, IL, TX, FL, OK, MS	TN, WI, MO, OH, IL, TX, FL, MS	MT, WI, OR, KY, RI, AL, IL, TX, FL	MI, PA, TX, FL	CO, TX, FL		MN, WA, NC	SD, NE, NV, CA, PR, VT, DE, VA, MA, UT, HI
Slag	ND, Wi, IL, MS	ND, WI, IL, MS	ND,WI, NV, IL, MS	ND, WI, PR, IL, MS	MT, MO, WA, WI, MO, KY, CT, IL, TX, MS, OH	MI, PA, TX, DE, MS, VA	CO, SC, OR, GA, WV, RI, NC, AL, TX, FL, OK, DE, MS, VA, MA	FL	TN, NE, IA, MN, CA, NY, PR, IL, FL, LA	SD, AZ, VT, UT, HI
Silica fume	MT, WI, OR, MO, WV, RI, NC, KY, OH, PR, IL, PA, TX, FL, UT	WI, GA, KY, AL, OK	WI, NV	WI	WI		CO		TN, SC, CT, CA, LA, MA	SD, ME, WA, MI, ND, IA, NE, MN, AZ, NY, VT, DE, MS, VA, HI

Percent conventional SCMs permitted in structural concrete by the responding states (41 responses).

State DOT	< 10%	10%-15%	20%	25%	30%	40%	50%	60%	Other %	Not Used
Fly ash F	ND, WI, IL, MS	SD, ND, WI, GA, MO, IL, FL, DE, MS, HI,	SD, ND, IA, SC, NE, MO, AZ, KY, CT, WV, NV, OH, IL, TX, FL, OK, MS, VA	TN, SD, ND, IA, NE, MO, AZ, KY, CT, NV, OH, IL, TX, FL, MS, VA, WV, OK	MT, ME, MN, OR, RI, NC, AL, TX, FL, MA, UT	MI, PR, PA, TX, FL	CO, TX, FL		WA, WI, MN, CA, NY, VT, IL, MS, LA	
Fly ash C	WI, IL, MS	WI, GA, MO, IL, FL, MS	WI, IA, SC, AZ, CT, WV, OH, IL, FL, OK, MS	TN, WI, IA, AZ, CT, WV, OH, IL, FL, OK, MS	MT, WI, MN, OR, KY, RI, AL, IL, FL	MI, PA, FL	CO, FL		WA, MN, NC, NY, TX, LA	SD, ND, ME, NE, NV, CA, PR, VT, DE, VA, MA, UT, HI
Slag	WI, IL, MS	WI, IL, MS	WI, NV, PR, IL, MS	WI, NV, PR, IL, MS	MT, MO, WI, KY, CT, OH, IL, TX, MS,	MI, PA, TX, DE, MS, VA	CO, ME, WA, SC, OR, GA, WV, RI, NC, AL, TX, FL, OK, DE, MS, VA, MA	FL	TN, NE, MN, CA, NY, VT, IL, FL, LA	SD, ND, AZ, UT, HI
Silica fume	MT, WA, MI, WI, OR, MO, MN, AZ, KY, WV, RI, NC, OH, PR, IL, PA, TX, FL, VA, UT	WI, GA, AZ, KY, AL, OK	WI, NV	WI, NV, PR, IL, MS	WI,		CO		TN, ME CT, CA, NY, VT, LA, MA	SD, ND, IA, SC, NE, DE, MI, HI

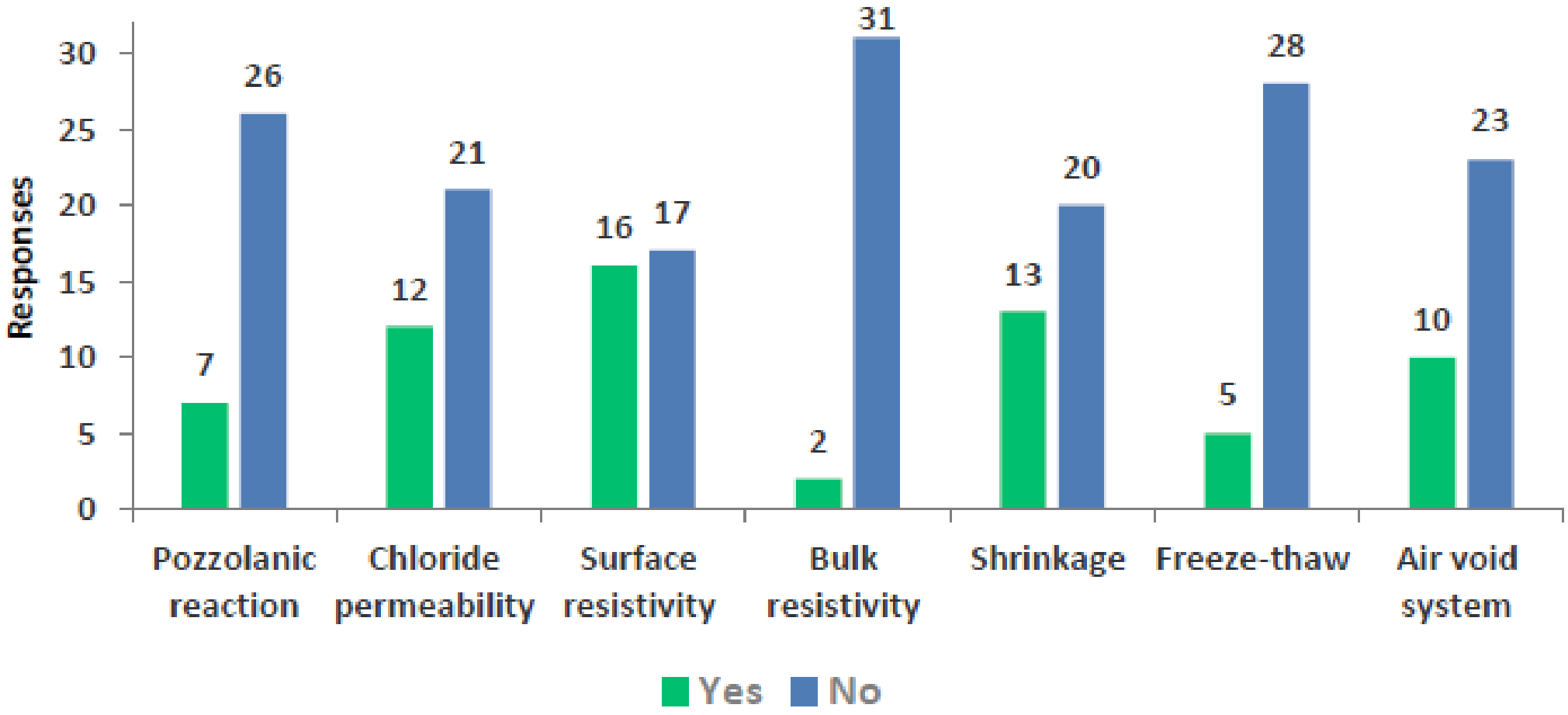
State DOTs that reported percent natural pozzolans permitted in their specifications (41 responses).

State DOT	% Calcined clay	% Calcined shale	% Calcined pumice	% Metakaolin	% Rice husk	% Natural pozzolans not in specification
Arizona	20	20	0	0	0	0
California	Note Below					
Colorado	50	50	50	50	50	0
Florida	15-50	15-50	15-50	8-12	0	0
Georgia	0	0	0	≤ 15	0	0
Iowa	20	20	20	20	0	0
Louisiana	0	0	0	50	0	0
Massachusetts	0	0	0	0	0	30
Missouri	0	0	0	15	0	0
Montana	0	0	0	0	20	0
Nebraska	25	0	0	25	0	25
Nevada	20	20	20	20	20	0
New York	Note Below					
North Carolina	30	30	30	30	30	0
Oregon	30	30	30	30	0	0
Puerto Rico	40	0	0	0	0	0
Texas	20	20	20	20	0	0
Utah	30	30	30	0	0	0
Virginia	0	0	0	7-10	0	0
Washington	0	0	35	0	0	0

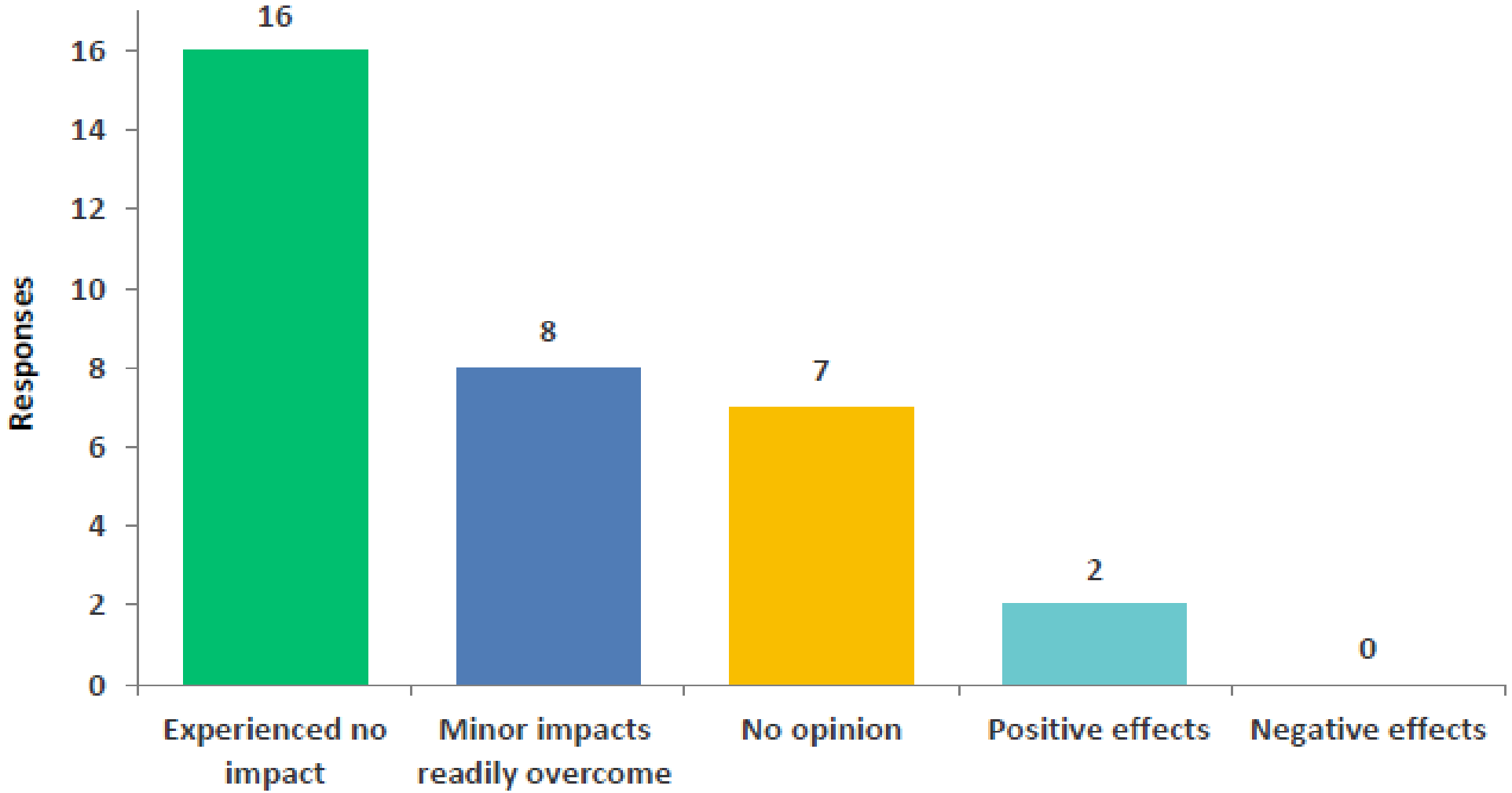
Percent SCMs allowed in ternary mixtures (33 responses).

State DOT	10% + ≤ 10%	20% + ≤ 10%	50% + ≤ 10%	20% + 20%	20% + 30%	30% + 30%	40% + 20%	10% + 50%	15% + 50%	Other %	Not Used
Fly ash F + Fly ash C	OR, FL	MI, OR, TX, FL	FL	RI, TX, FL	TX, FL				WA	CO, MI, WI, NY, OH, IL, PA, OK, LA	TN, SD, ME, IA, AZ, WV, NC, CA, PR, VT, MS, VA, UT
Fly ash + Slag	OR, FL	OR, PR, TX		MI, OR, TX	IA, OR, RI, TX, VA				WA, FL	TN, MT, MI, WI, MN, NC, CA, NY, OH, VT, IL, PA, LA	SD, ME, AZ, WV, OK, MS, UT
Fly Ash + Silica fume	OR	OR, WV, RI, TX, FL, VA, UT								WA, WI, NC, CA, NY, OH, IL, PA, FL, OK, LA	ME, MI, IA, AZ, PR, MS
Slag + Silica fume	OR, AZ	OR, WV, VT, VA	ME, OR, RI, FL							WA, MI, WI, NC, CA, NY, OH, VT, IL, PA, TX, OK, LA	TN, SD, IA, PR, MS, UT
Ntural Pozzolan + Slag	OR,	OR, TX		OR, TX	IA, OR, TX			FL	FL	WI, MN, NC, CA, NY, OH	TN, SD, ME, MI, AZ, RI, PR, VT, IL, PA, OK, MS, LA, VA, UT

Tests required by agency specifications (24 responses).



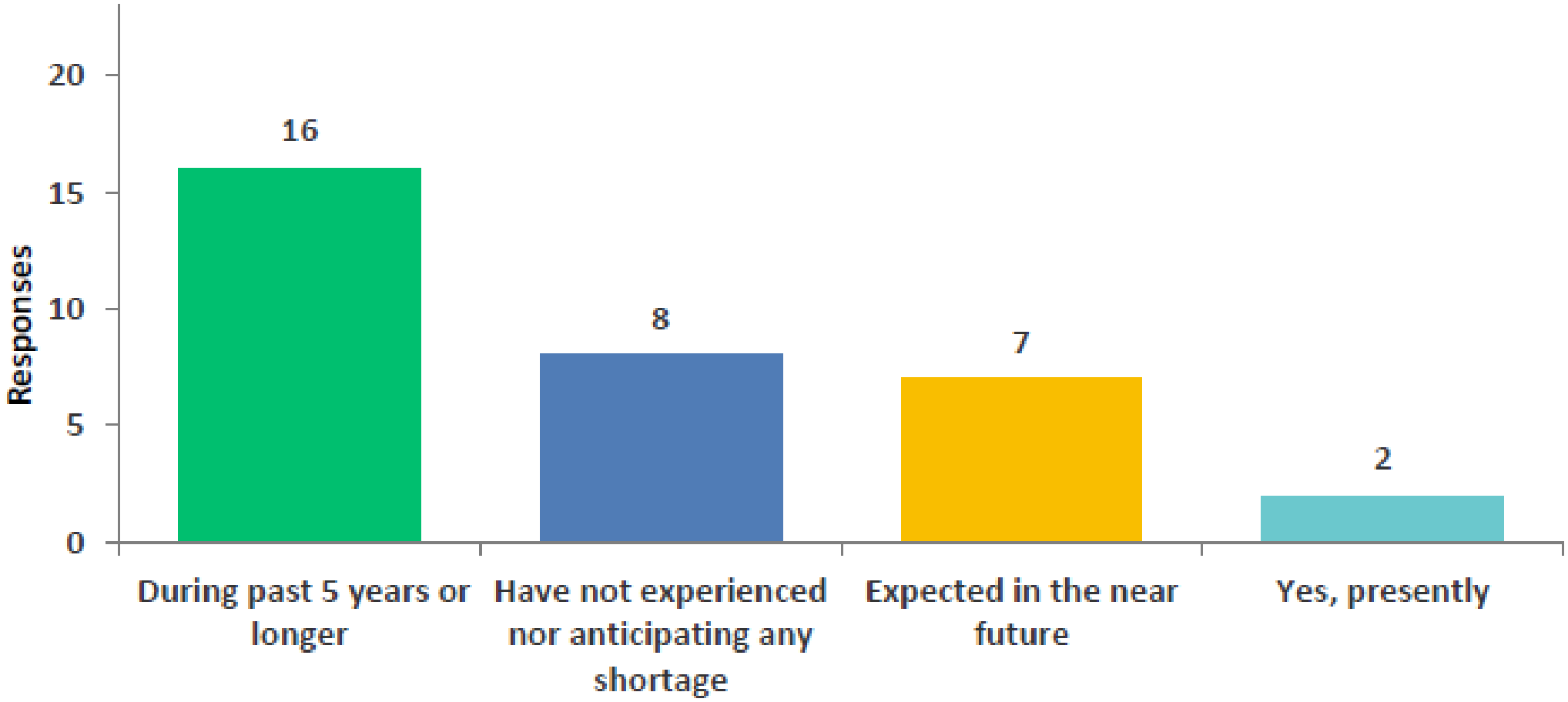
Effect of SCMs on performance of concrete when Type IL cement used (33 responses).



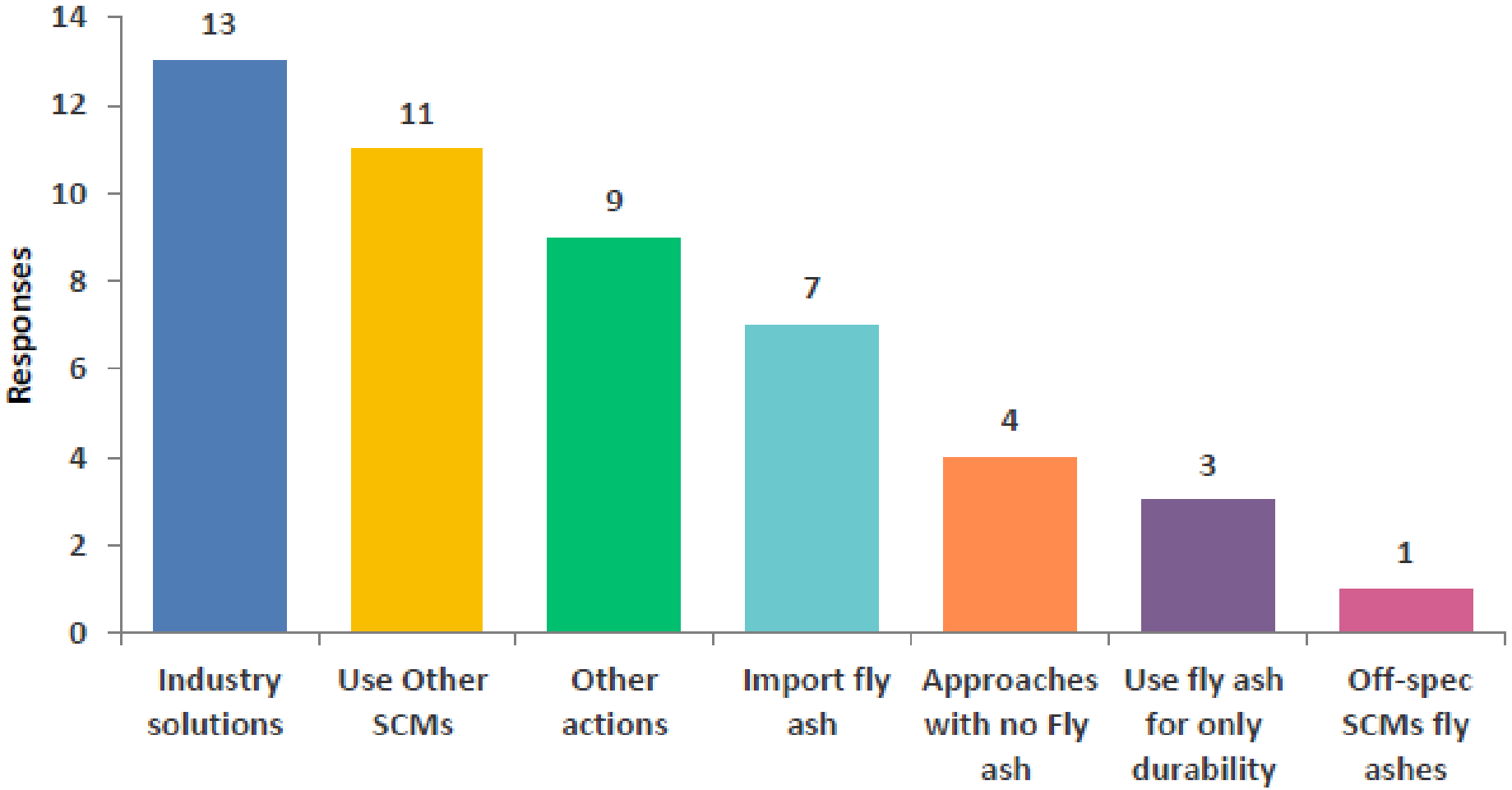
Impact of SCMs on performance of concrete with Type IL cement (15 responses).

IMPACT / SCM	Fly ash F	Fly ash C	Slag cement	Silica fume	Natural Pozzolans	Unsure
Has same positive impact on IL concrete as on concrete with other traditional cements.	MT, IA, FL, MS, LA, UT	IA, FL, MS, LA	MT, IA, FL, LA	MT, FL, LA	IA, FL, UT	OH, VT, PA
Impacts workability	IA, FL, MS, LA, UT	IA, FL, MS, LA	MT, IA, FL, LA	IA, VT, FL, LA	IA, FL, UT	WA, OH, PA
Further delays concrete set time	IA, UT	IA	MT, IA, FL	IA	IA, UT	WA, OH, VT, PA, MS, LA
Further delays early strength development	IA, VT	IA, VT	MT, IA, VT, FL	IA, VT	IA	WA, OH, PA, MS, LA
Increases shrinkage	FL	FL	MT, FL	FL	FL	WA, IA, OH, VT, PA, MS, LA
Requires further adjustments in IL concrete mixture designs	IA, VT, FL, MS, UT	IA, VT, FL, MS	MT, IA, VT, FL	MT, IA, VT, FL	IA, FL, UT	WA,OH, LA
Impacts on surface finishing quality	LA, UT	LA	LA	LA	LA, UT	MT, WA, IA, OH, VT, PA, FL, MS

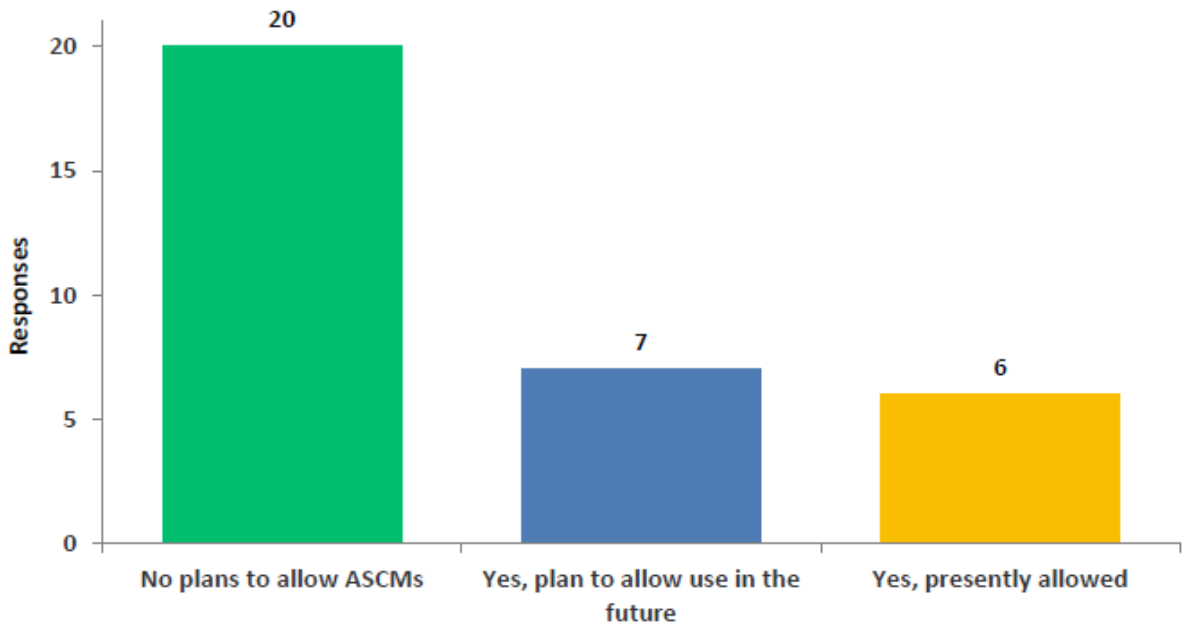
Agency experiences with shortages of fly ash (33 responses).



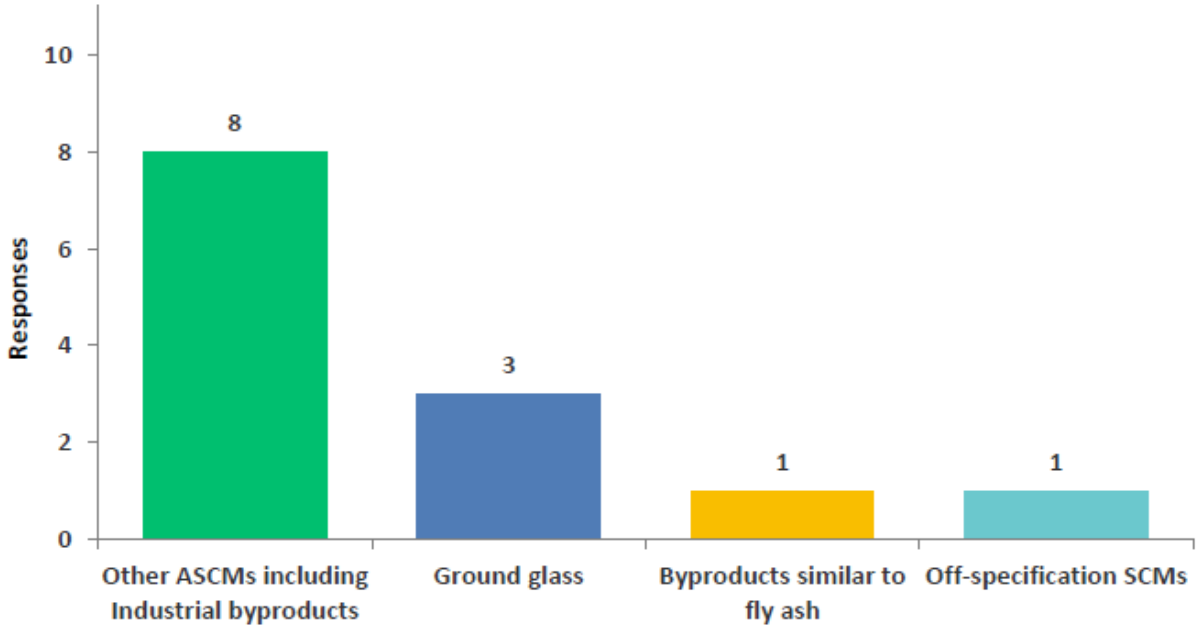
Agency actions to address shortages of fly ash (29 responses).



Agency allowance of ASCMs (33 responses)



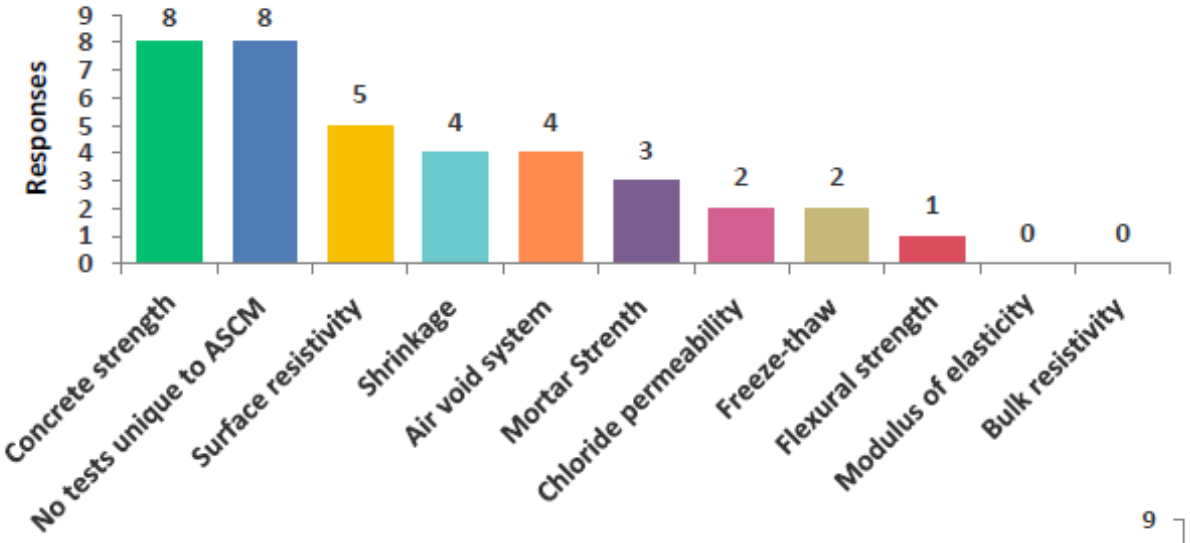
ASCMs permitted by some agencies (13 responses)



Ground glass	Industrial secondary or byproducts similar to fly ash or other ASCMs	Off-specification (not meeting AASHTO M 295 / ASTM C618-23) fly ash
NY, VT, FL	CO, WA, MI, WI, SC, AZ, CA, OH, UT	MN
3	9	1

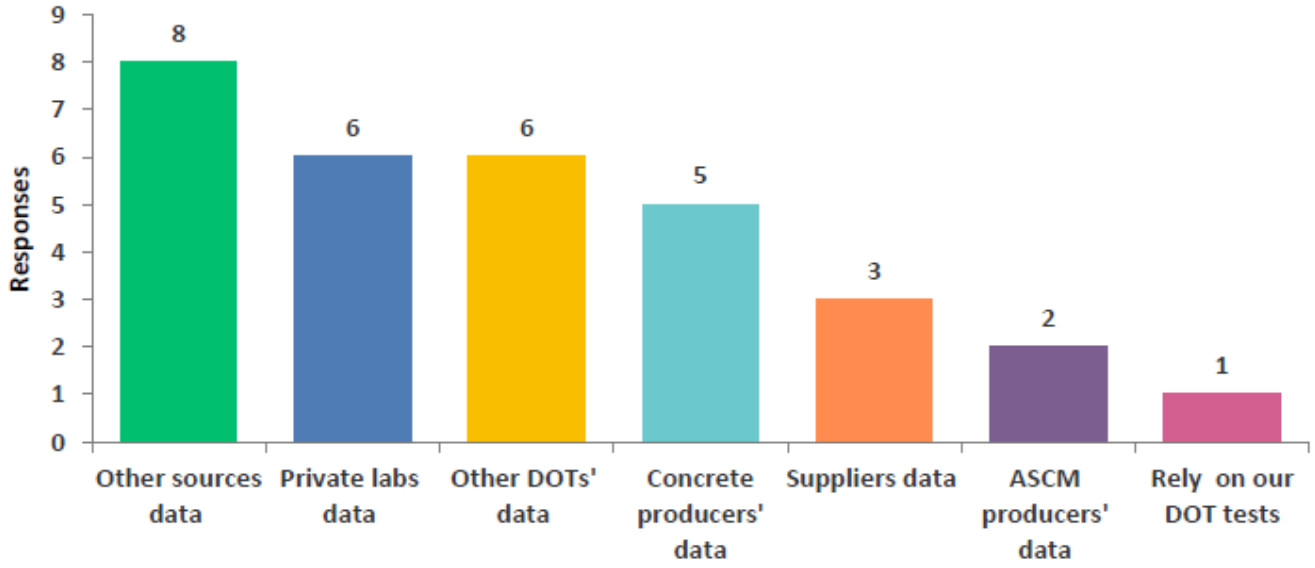
State DOT	Percent ground glass in concrete	Industrial or byproducts similar to fly ash	Percent off-specification (not meeting AASHTO M 295 / ASTM C618-23) fly ash	Other ASCMs	Not sure at present time pending further evaluations
California					x
Colorado					x
Florida	18% - 50%				
Minnesota					x
New York	20%				
Utah				30%	
Vermont	Perfromance Based				
Washington				Ground Pumice	
Wisconsin				30%	

Tests required to approve ASCMs (10 responses)



State DOT	Type of Field Trial
Minnesota	Pavement: https://www.dot.state.mn.us/mnroad/mra/structure-teams/rigid/sustainable-concrete-mix-selection.html
Arizona	Pavement and bridge structure
California	Pavement, bridge structure, mass concrete & parking area. Location to be determined
NEW York	Ground Glass is planned to be used in a project with sidewalks in the 2024 construction season.
OHIO	Pavement bridge structure, mass concrete & parking area. No tials yet.
Vermont	Bridge structure
Utah	Bridge structure

Sources of test data accepted for ASCMs (13 responses)



Case Examples

- History of SCM specification and use
- Current SCM specifications and use
- Quality assurance approaches
- Benefits and challenges associated with SCMs and ASCMs
- Opportunities associated with SCMs and ASCMs
- References
  - Specifications
  - Research/case study reports
  - Other publications

Agencies volunteered/selected:

- Caltrans
- Colorado DOT
- Louisiana DOTD
- Minnesota DOT
- Utah DOT

Caltrans

- Sustainability initiatives drive SCM/ASCM use
- Caltrans's Product Evaluation Program (PEP) guides approval process
- As materials/products are successful in PEP, appropriate tests and targets are added to Authorized Materials List Requirements
- Has facilitated efficient qualification and selection of SCMs and ASCMs
- Caltrans specifications provide equations that:
  - Use characteristics of the SCMs to compute allowable combinations of SCMs and replacement levels
  - Guide mixture design development by contractors and producers (then submitted to Caltrans for approval).
- This approach has been found to support:
  - Construction of infrastructure with desired performance
  - Flexibility to stakeholders to help buffer against supply shortages or other issues
- Extended test ages (42 or 56-day) allowed for some mixtures to accommodate SCMs

Colorado DOT

- SCM use driven by ASR-related distress in 1990s, loss of a prominent low-alkali cement
- Has experienced fly ash shortages, also has sustainability initiatives
- Has funded research on ASCMs, how to qualify them
- CDOT specifications allow concrete suppliers/producers to select the SCMs they'd like to use
  - Must demonstrate the SCM and replacement rate are capable of mitigating ASR through ASSTM C1567 tests
  - Mixtures containing SCMs must meet same requirements as straight cement mixtures
- Extensive use of SCMs in Colorado has resulted in challenges for stakeholders to reduce GWP (already low)
- Paving contractors are outperforming ready-mixed concrete suppliers in terms of using lower reducing cement contents.
  - Likely due to the economics associated with use of SCMs, which are often viewed as "smart business sense."
- Seeing ground pumice used on projects in the I-25 corridor, ASCMs are now emerging for increased use

Louisiana DOTD

- Concrete typically used in structural applications (a few pavements)
- SCMs extensively used, many ternary blends – driven by move to surface resistivity specifications
- LaDOTD has funded research with successful SCM use up to 90% replacement
  - Implemented cap of 70% for structures, 50% for pavements

- Estimate that 80% to 90% of concrete structures and 100% of mass concrete elements are now constructed using ternary blends
- DOTD has experience in supporting suppliers in meeting resistivity targets
  - Moisture control of aggregates found to be a bigger problem than other QC issues
- Appreciates the sustainability benefits that are likely associated with their high SCM replacement rates.
  - Studies show that the GHG associated with shipping aggregates to Louisiana (often from Central America/Caribbean) is very high compared to the much lower GHG emissions associated with transport of SCMs.

Minnesota DOT

- Long history of use of fly ash, beginning in 1970s
- 1990s – materials-related distresses in pavements drove move to w/cm-controlled specification with maximum cementitious content and 25% ash replacement allowed (increased).
- Today, allows SCMs in all pavements and structures
  - Contractor typically selects the SCM to be used and replacement rate
- Currently developing a performance-based specification that should allow use of marginal and off-specification ashes.
- Certification process for evaluation of coal combustion ash not approved by ASTM C618 for use in concrete is provided as an Appendix to case example.
- Currently expanding allowable SCM materials to include natural pozzolans (NPs), including calcined clay, calcined shale, calcined pumice, and metakaolin
- Exploring several ASCMs including industrial byproducts, alternative materials, and other low-carbon transportation materials, at the Minnesota Test Road (MnROAD)

Utah DOT

- Began allowing fly ash, silica fume, and natural pozzolans sometime in the 1990s. Worked to incorporate additional use of SCMs into the UDOT specifications during the 2010s.
- Utah market is proximal to several natural pozzolan producers, and UDOT has several natural pozzolans that are used by suppliers and contractors.
  - Volcanic ash
  - Pumice
  - Expanded shale
- Acceptance of NPs tended to be led by precast concrete companies
- Most impacted by ash supply issues since they were buying in smaller quantities. (Use of Type IP = the fix).
- ASCMs are presently allowed at replacement rates up to 30%.
  - Similar to conventional SCMs, concrete with ASCMs must be qualified through tests including compressive strength of concrete, surface resistivity, shrinkage, freeze/thaw durability and air void system parameters.
  - ASCMs currently of interest within the state include ground glass and an industrial mining slag.

Research Gaps and Future Study Needed

- Laboratory evaluation and field performance trials of NPs lags other conventional SCMs
  - Properties vary based on type and origin – leads to reluctance to allow/use
- Laboratory and field trials with ternary blends, quaternary blends, NPs, harvested coal ash, and ASCMs

- Approaches to evaluate and/or predict the reactivity (and any negative impacts on hydration, performance, or durability) of SCMs, NPs, harvested ash and ASCMs given their composition and characteristics.
- Practical guidance for agency specifications - approving existing SCMs and emerging ASCMs
- An improved understanding of the economic feasibility, variability, and environmental impacts and benefits of SCMs and ASCMs, along with companion tools to assist agencies in developing specification expand their use.

Thank you!

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- Jo Allen Gause – TRB Senior Program Officer
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  - Maria Masten
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- Everyone that answered the survey!

- Case study interviewees
  - Ashkan Bozorgzad and David Carlin - Caltrans
  - Eric Prieve – Colorado DOT
  - Tyson Rupnow – Louisiana DOTD
  - Maria Masten – Minnesota DOT
  - Jason Ritchins – Utah DOT