TECHNOTE

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Novel Alternative Cementitious Materials for Development of the Next Generation of Sustainable Transportation Infrastructure

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RESEARCH DESCRIPTION

The ubiquity and the necessity of concrete infrastructure prompt innovation to address the global challenge of societal needs in the most economical and sustainable ways possible. Increasing the use of non-portland cements, or "alternative cementitious materials" (ACMs), is of growing interest because of ACMs' potential to reduce the environmental footprint of concrete due to its special properties. The special properties of ACMs vary by material, including: rapid setting, rapid strength development, higher ultimate strength, improved dimensional stability, and increased durability in aggressive environments. The increased strength (and the resulting potential from fewer needed materials) and the increased durability further contribute to enhanced sustainability and can help offset initially higher material costs.

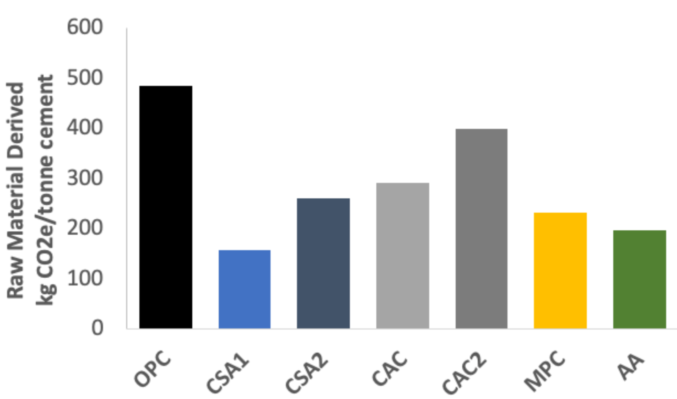
ACMs have primarily been used in specialty applications, such as repairing defects or rapid replacement of damaged pavement sections and creating joints for precast panel road replacements. Of the numerous commercially available ACMs, chemically activated aluminosilicates (AA) (including geopolymer concrete), calcium sulfoaluminate (CSA) cements, calcium aluminate cements (CAC), phosphate-based cements (e.g., magnesium phosphate cements (MPC)), and novel (e.g., high belite, blended with ACMs) portland cement formulations are shown to be feasible in lab-scale studies for the partial or full replacement of ordinary portland cements (OPC) used in concrete. However, little is known about the scalability of construction with these material systems, their long-term performance, their durability in a range of environments, and their structural response when subjected to transportation-relevant loading conditions. The goal of this research is to study early-age and long-term material properties and complete multiscale durability investigations. Guidance for ACM selection and mixture design for use in transportation infrastructure, including highway structures and rigid pavements, will be provided at the end of the TechNote, in the "Summary, Recommendations, and Technology Readiness Assessment" section.

MOTIVATION AND BACKGROUND

Two primary motivations for expanded use of ACMs are potential to contribute to sustainable construction and longer service life in a range of aggressive environments. ACM is a term that includes clinkered, calcined, and un-clinkered binding materials (ACI ITG 10R-18). Often, ACMs can be produced with lower carbon dioxide (CO_2) emissions than portland cement can.[1] The manufacturing of CSA and CAC cement clinkers can result in approximately 30-percent and 15-percent reductions in CO_2 emissions, respectively.[2] The reductions in CO_2 emissions come from the reduced amounts of calcium carbonate feedstock and lower temperatures during thermal processing. When blending with other less energy intensive mineral phases (e.g., calcium sulfates, limestone), such as in CSA or ternary blends of CAC, OPC, and calcium sulfate (CACT), further reductions in embodied CO_2 are realized due to dilution. Other ACM formulations, like geopolymers or other activated AA, do not require calcination. As a result, the embodied CO_2 in these systems can vary, even among ACM classes. Embodied CO_2 for these mixtures is primarily a function of the activating solution used and can vary considerably based on the type and quantity of AA precursor(s).

Figure 1 gives an overview of potential CO_2 reductions for ACM cements, calculated based on the cement compositions (by phase) used in this study, with an earlier FHWA TechBrief comparing material and fuel-derived emissions for each ACM class, based on historical compositions and generalized production methods.[2] Relative uncertainty in production methods for the AA and MPC materials examined (related to their variable feedstocks, processing methods, and composition, all of which can vary by manufacturer), as compared to Portland cements, must be considered when reviewing determined values.

Figure 1. Calculated potential reductions in embodied carbon dioxide in ACMs examined in this study are grounded in phase compositions.



Note: MPC values are based on periclase content of the binder used in this study; AA values are reflected from data in Yang, Song, and Song.[2]

ACMs have also been used in applications where their unique properties—high early-strength development, high later-age strength, low shrinkage, and/or superior durability—are valued. For example, alkali-activated materials are known for their thermal stability and fire resistance, and MPCs exhibit rapid setting and high early strengths.[4] Other unique properties of ACMs include high early strength development, high later age strengths, low shrinkage, and/or superior durability. Some CAC formulations are known for their superior resistance to acid and sulfate attack and mechanical abrasion, and some CSA systems have been associated with improved dimensional stability and resistance to freezing and thawing and sulfate attack.[5,6,7] Despite the potential advantages of ACMs, only about half of the States that responded to a 2014 American Association of State Highway and Transportation Officials survey reported experience with ACMs, citing concerns about the long-term performance of ACM concrete as the most common issue preventing broader use of these materials in transportation infrastructure.[2]

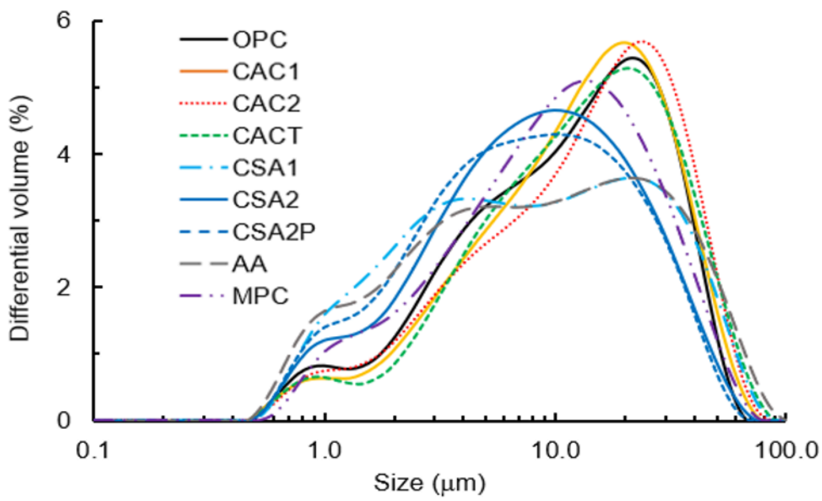
MATERIALS CHARACTERIZATION

Commercial sources of materials remained the focus of this work. The goal was to develop mixtures from broadly available ACM sources that could be batched using conventional equipment. Commercial sources were selected due to their potential for rapid upscaling compared to lab-produced materials and other materials that require specialized batching or production. Initially, more than a dozen commercially produced ACMs were considered in this study. Nine ACMs were selected for further examination, as follows:[8]

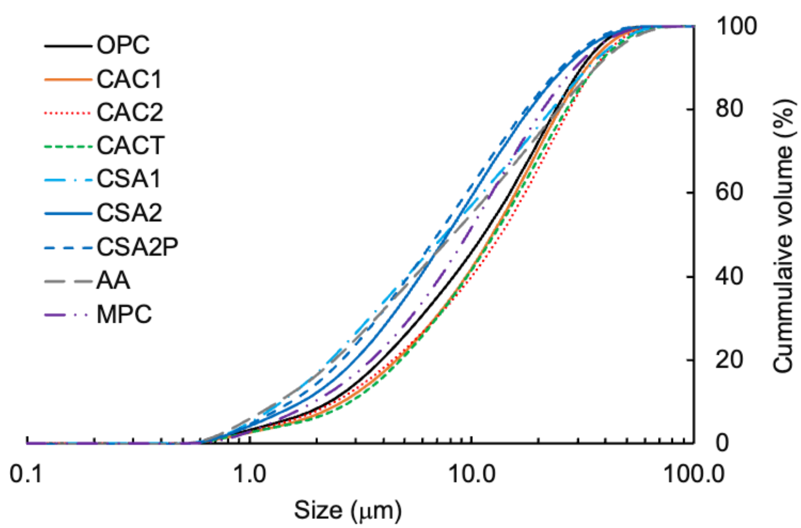
- Two CACs (CAC1 and CAC2).
- One ternary blend of CAC, portland cement, and CACT.
- Three CSA belite cements, including one with polymer (P) modification (CSA1, CSA2, and CSA2P).
- One chemically activated AA binder system, consisting of an ASTM C618 Class C fly ash and a proprietary two-part activator solution.
- One MPC.

For all the candidate cements, particle size and chemical composition are shown in figure 2 and figure 3, respectively. Table 1 summarizes the physical properties.

Figure 2. Particle size for ACM sources compared to OPC.



A. Differential volume.



B. Cumulative volume.

The three CSAs and the AA are significantly finer than the OPC and the other ACMs, and the MPC is slightly finer than the OPC. Each of the ACMs examined has a lower CaO content than OPC, as related to the lower limestone content in their feedstock and the associated savings in carbon dioxide emissions. These cements have different reaction mechanisms, reaction rates, products, and microstructures than OPC. An overview of the ACM reactions with water, or in the case of AA, with chemical activator solution, can be found in a TechBrief published by this team as well as in a YouTube video presentation by a team member.(2,10)

Table 1. Specific gravity (SG), specific surface area (SSA), D-values (D10, D50, D90), and normal consistency (NC) of ACMs compared to OPC.

Cement	OPC	CAC1	CAC2	CACT	CSA1	CSA2	CSA2P	AA	MPC
SG	3.05	3.13	2.97	2.91	2.81	2.81	2.81	2.58	2.77
SSA (m2/kg)	333.3	291.5	306.4	302.7	501.3	453.2	492.6	550.7	398.2
D10[b] (µm)	2.58	2.95	2.77	3.2	1.59	1.93	1.73	1.52	2.23
D50[b] (µm)	12.8	14	15.3	14.3	8.59	8.8	7.96	9.3	10.9
D90[b] (µm)	35.4	37.4	40.6	40.8	37.9	29.7	28.6	41	33.1
NC[a]	0.25	0.325	0.285	0.27	0.31	0.31	0.31	—	0.21

—No data.
[a] W/b ratio determined according to ASTM C187-11.(9)
[b] Based on distribution by volume.

Figure 3. Oxide composition of ACMs and OPC used in this study.

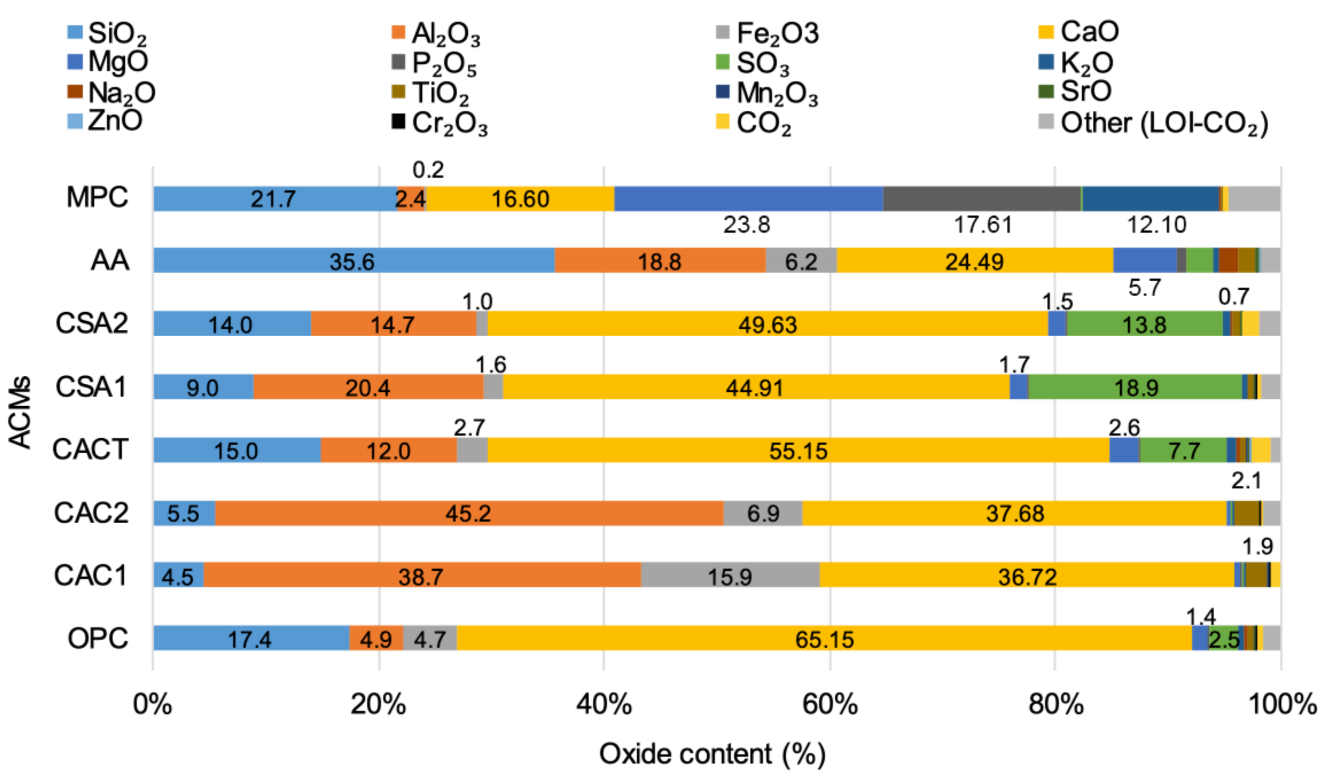
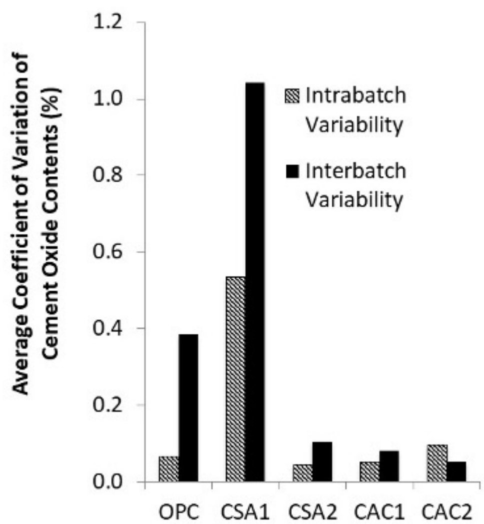


Table 2. Oxide composition of ACMs and OPC used in this study.

Oxide	OPC	CAC1	CAC2	CACT	CSA1	CSA2	CSA2P	CSA3	AA	MPC
SiO_2	17.39	4.54	5.50	14.95	8.96	13.97	14.21	13.20	35.56	21.70
Al_2O_3	4.87	38.70	45.16	12.03	20.44	14.70	15.40	18.10	18.80	2.35
Fe_2O_3	4.71	15.89	6.90	2.66	1.57	1.04	0.92	6.60	6.19	0.21
CaO	65.15	36.72	37.68	55.15	44.91	49.63	49.94	48.30	24.49	16.60
MgO	1.40	0.54	0.22	2.57	1.65	1.54	1.43	1.50	5.66	23.82
P_2O_5	0.13	0.12	0.09	0.14	0.19	0.11	0.10	0.06	0.94	17.61
SO_3	2.51	0.13	0.07	7.72	18.87	13.80	13.92	7.50	2.33	0.15
K_2O	0.48	0.19	0.26	0.83	0.38	0.68	0.62	0.70	0.50	12.10
Na_2O	0.46	0.06	0.00	0.28	0.10	0.13	0.13	0.10	1.77	0.11
TiO_2	0.39	1.87	2.11	0.51	0.47	0.71	0.65	0.93	1.45	0.10
Mn_2O_3	0.11	0.19	0.02	0.16	0.08	0.02	0.02	0.08	0.03	0.02
SrO	0.15	0.02	0.04	0.21	0.08	0.20	0.16	0.10	0.41	0.00
ZnO	0.03	0.01	0.00	0.11	0.05	0.01	0.02	0.00	0.01	0.00
Cr_2O_3	0.09	0.13	0.09	0.07	0.05	0.05	0.05	0.04	0.05	0.03
CO_2	0.57	0.90	0.24	1.61	0.50	1.43	0.49	0.38	0.08	0.45
Other ($LOI–CO_2$)	1.56	0.00	1.62	1.00	1.70	1.99	1.94	2.41	1.73	4.74

Materials received by the research teams were analyzed independently and compared to understand their variability in composition. Figure 4 shows the variability of five considered cements, quantifying variability for materials from the same batch (per manufacturer) shipped to different partners (i.e., intrabatch variability) and the materials produced from different batches by the same manufacturer at different times (i.e., interbatch variability). Based on the high variability of the CSA1 composition, and with early reports of variability in performance, CSA1 was excluded from much of the ensuing evaluation.

Figure 4. Variability in cement oxide contents for five of the cements examined.



APPROACH

To minimize capital investment, use of conventional concrete proportioning, mixing methods, and construction techniques for ACM concretes were preferred by the research team, with a vision for facilitating translation and broadening use in practice. To compare among ACMs and to benchmark against OPC performance, the research team used a combination of prescriptive and performance metrics. The metrics were based on input from an advisory board composed of transportation and construction professionals. The prescriptive requirements for the ACM concrete included a water-to-cement (w/c) (or solids) ratio of 0.40 or less, at least 765 lb of cement per cubic yard (454 kg/m^3) of concrete, and the use of a three-quarter inch (19 mm) maximum size coarse aggregate meeting ASTM C33 Number 67 gradation.[11] The performance requirements included a set time of 1 h or more, at least a 3-inch (76-mm) slump 60 min after mixing, a 7-d compressive strength of at least 3,500 psi (24 MPa), and a 28-d modulus of rupture of at least 700 psi (4.8 MPa).

Performance was benchmarked against OPC concrete meeting these criteria. ACM concrete that did not achieve these prescriptive and/or performance requirements was not included in further investigation. The research was conducted in two phases. First, an initial screening phase that included mixture proportioning, early age and hardened properties, and the assessment of basic transport properties for all ACMs took place. Second, a more detailed investigation of down selected ACMs ensued to assess the ACMs' durability, dimensional stability, and other performance characteristics.

EARLY AGE PROPERTIES AND MIX DESIGN DEVELOPMENT

Many ACMs experience rapid hydration and early set; thus, it was necessary to identify suitable retarding admixtures and dosages, particularly for CACT and CSA mixes. For ACM concretes, high-range water-reducing admixtures were needed to achieve necessary workability. The successful concrete mixtures were developed by adopting a combination of isothermal calorimetry, x-ray diffraction, set time assessments, and mini-slump tests. The goal was to link cement characteristics, admixture type, and dose to early age behavior. For all ACMs except CAC1 and MPC, concretes were designed to meet the early age requirements for set time and slump, at w/c ratios of 0.40 or less. Despite investigations of admixture type and dosing rate, a workable CAC1 mix was not produced. For MPC, an increase in w/c ratio was necessary to achieve an adequate slump; however, this increase produced a concrete that failed to meet strength criteria. Table 3 summarizes the resulting mix designs for cements that met the target performance.

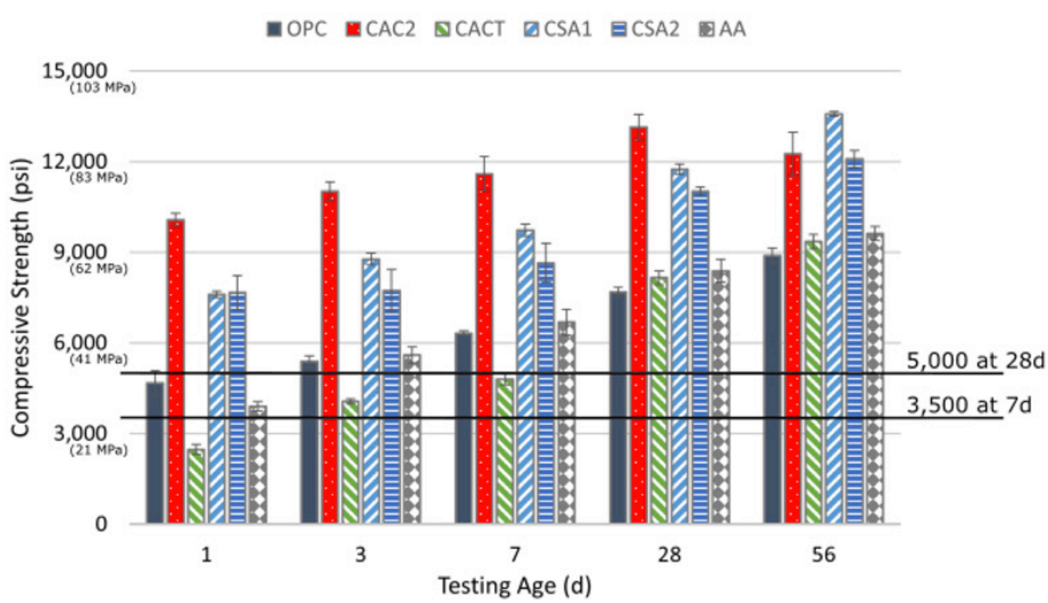
MECHANICAL PROPERTIES

The following mechanical properties—concrete compressive strength development over 56 d, flexural strength (modulus of rupture) development over 28 d, 28-d elastic modulus and Poisson's ratio, and flexural fatigue performance—were assessed. Figure 5 through figure 7 present the collected results. The ACMs examined—CAC2, CACT, CSA1, CSA2, and AA—met the set performance requirements (i.e., 7-d strength of 3,500 psi; 7-d modulus of rupture of 700 psi). The rates of strength development and the ultimate strength, both in compression and flexure, varied considerably among the ACMs, including CAC2 achieving the highest strengths. Caution should be taken with CACs due to their significant strength loss, related to conversion, which was made evident by the increase in bulk conductivity observed after 50 d (figure 8) and the slight reduction in strength from 28 d to 56 d in figure 5-A. ACMs generally showed more variability in fatigue performance than OPC, but AA performance and variations suggest longer fatigue lives may be possible in some ACM concrete.

Table 3. Concrete mixture proportions.

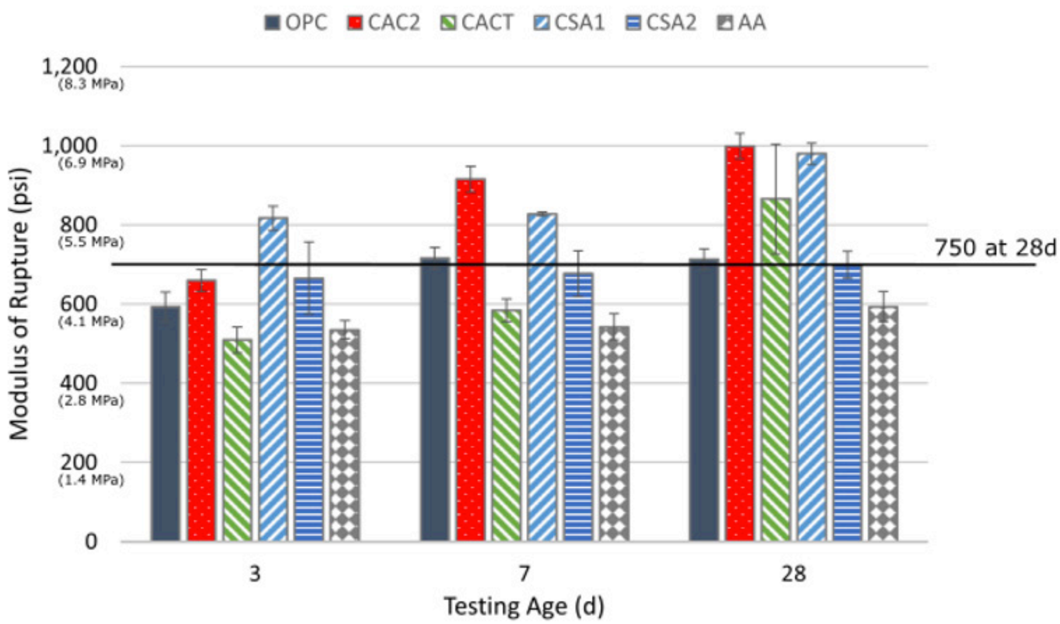
Cement	W/c Ratio	Admixtures/activators (by weight of cement or fly ash)	Cement kg/m³ (lb/yd³)	Water kg/m³ (lb/yd³)	Sand kg/m³ (lb/yd³)	Number 67 aggregate kg/m³ (lb/yd³)
OPC	0.40	HRWR1—3.5 ml/kg (0.054 fl oz/lb)	454 (765)	189 (319)	703 (1,185)	1,056 (1,780)
CAC2	0.40	HRWR2—1.6 ml/kg (0.025 fl oz/lb)	454 (765)	189 (319)	693 (1,168)	1,056 (1,780)
CACT	0.40	Citric acid—1.5 percent, HRWR1—3.5 ml/kg (0.054 fl oz/lb)	454 (765)	189 (319)	674 (1,136)	1,056 (1,780)
CSA1	0.40	Citric acid—2 percent, HRWR1—3.0 ml/kg (0.046 fl oz/lb)	454 (765)	189 (319)	656 (1,106)	1,056 (1,780)
CSA2	0.40	Citric acid—0.5 percent, HRWR1—0.5 ml/kg (0.008 fl oz/lb)	454 (765)	189 (319)	656 (1,106)	1,056 (1,780)
AA	0.205	Activator 1—2.27 percent, activator 2—1.78 percent	488 (765)	109 (184)	811 (1,367)	1,056 (1,780)

Figure 5. Development of ACMs relative to OPC. Testing performed according to procedures in ASTM C39 and C78 (1,000 psi = 6.9 MPa).[12,13]



A. Concrete compressive strength.

Figure 5. Development of ACMs relative to OPC. Testing performed according to procedures in ASTM C39 and C78 (1,000 psi = 6.9 MPa).[12,13] (Continued)



B. Flexural strength.

Figure 6. Elastic modulus and Poisson's ratio of ACM concretes relative to OPC concrete. Testing performed according to procedures in ASTM C469 (1 GPa = 145 ksi).

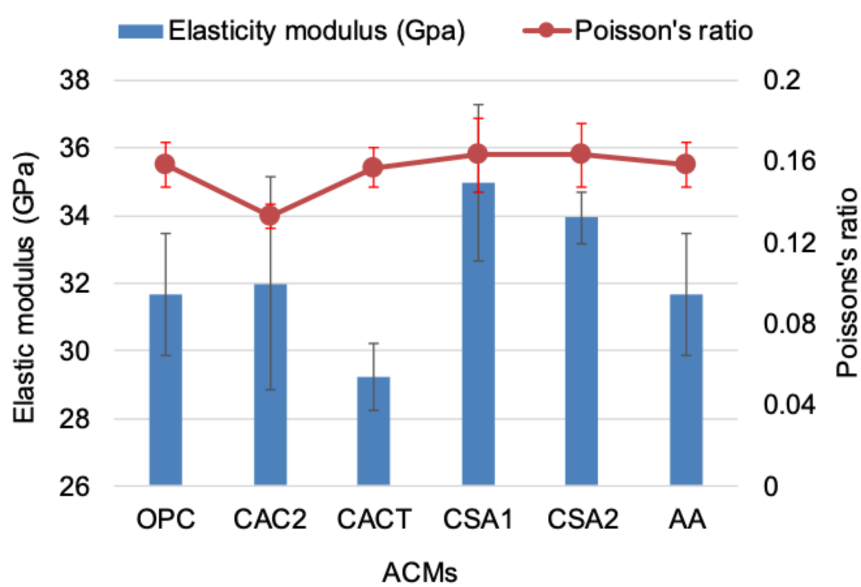


Figure 7. Flexural fatigue of unreinforced ACM concretes relative to OPC concrete.

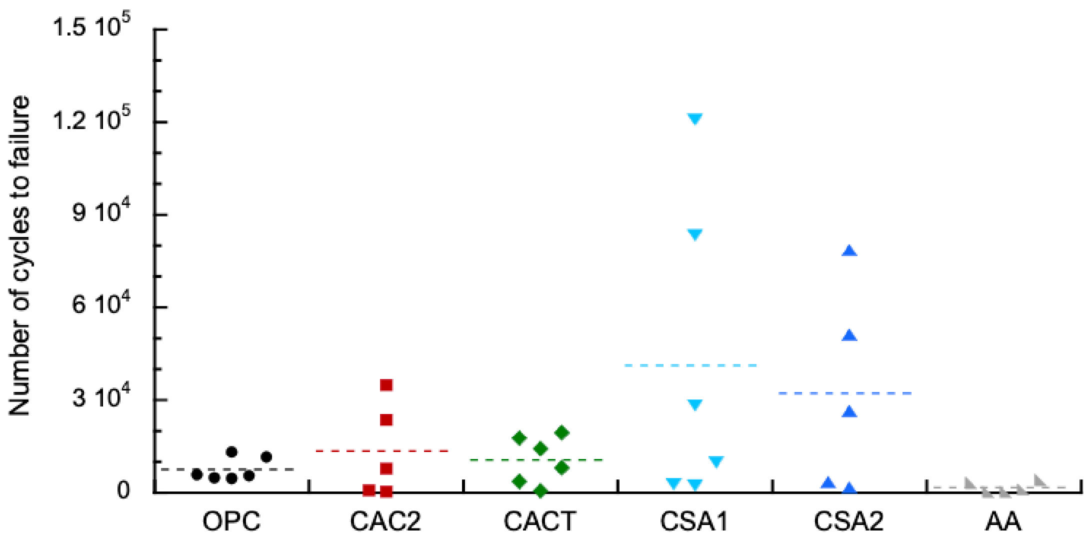
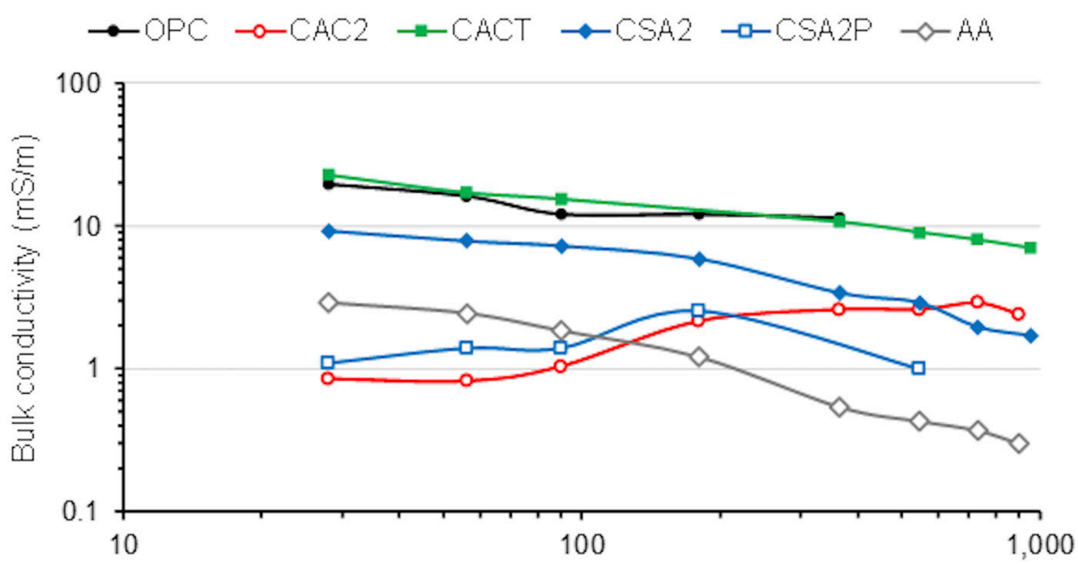


Figure 8. Change in bulk conductivity of ACM and OPC concrete mixtures over hydration time.



DIMENSIONAL STABILITY

The chemical, autogenous, and drying shrinkage potential of four commercially available alternative binder formulations was compared to a typical OPC (figure 9 through figure 11). Although the CSA2, CAC2, and AA binders showed two-to-three times more chemical shrinkage than the OPC mixture, the chemical shrinkage did not lead to significant increases in autogenous shrinkage. Similarly, the CSA2, CAC2, and AA binders performed significantly better than the OPC mixture over 10 mo of drying, generating between 45 and 55 percent less drying shrinkage than their OPC counterpart. Conversely, the CACT binder generated slightly lower amounts of chemical shrinkage relative to OPC but the same or greater quantities of autogenous shrinkage, and quantities of drying shrinkage were approximately 25 percent greater for CACT than OPC. Based on these results, the CSA2, CAC2, and AA binders investigated in this study may be good choices in situations where shrinkage is of concern; meanwhile, blended CACT binders, such as OPC binders, should be used with caution.

Figure 9. Chemical shrinkage (mL/g cement) of ACMs compared to OPC, all at 7 d of age, as assessed by the ASTM C1608 dilatometry method.[14]

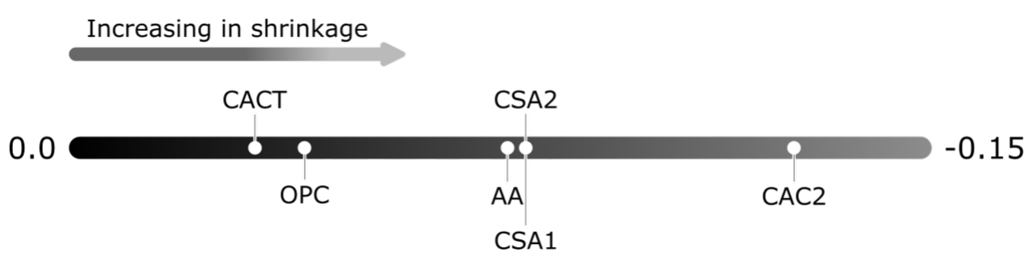


Figure 10. Autogenous shrinkage (mm/m) of ACMs compared to OPC, all at 28 d of age, as assessed by ASTM C1698.[15]

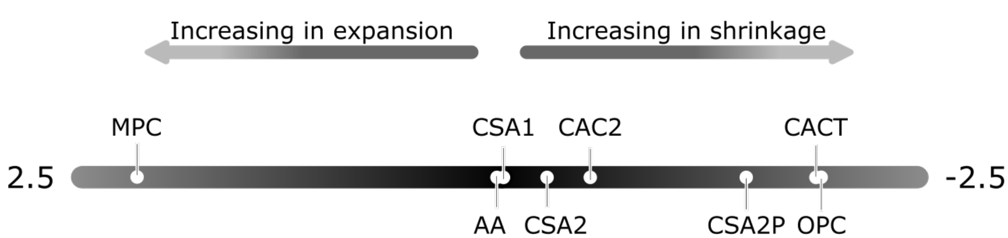
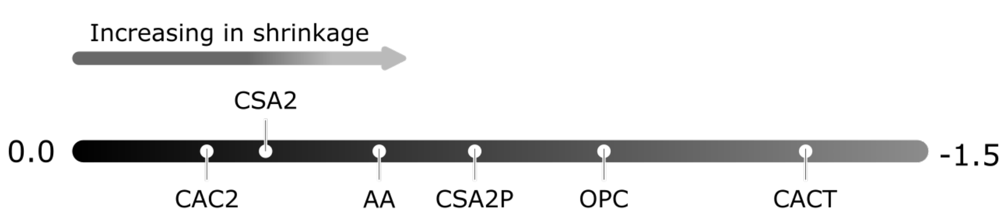


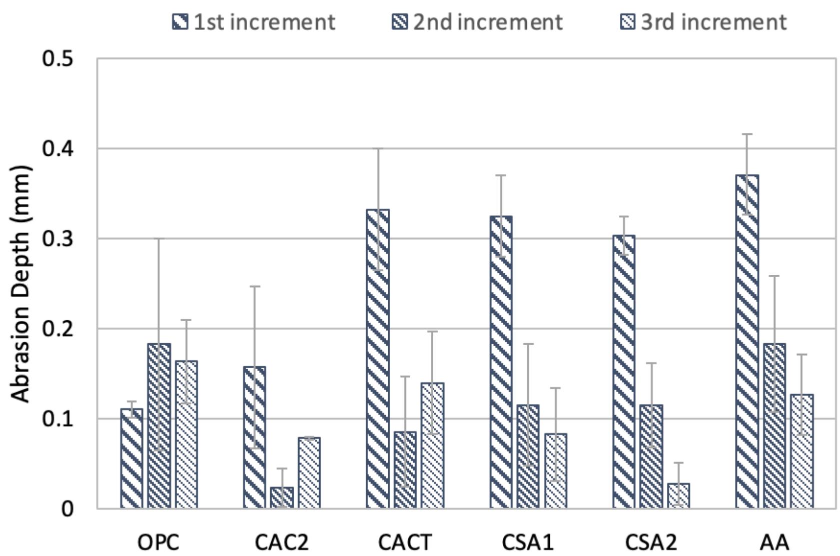
Figure 11. Drying shrinkage (mm/m) of ACMs relative to OPC at 300 d of drying. Testing performed according to procedures in ASTM C157, initiating after 7 d of curing.[16]



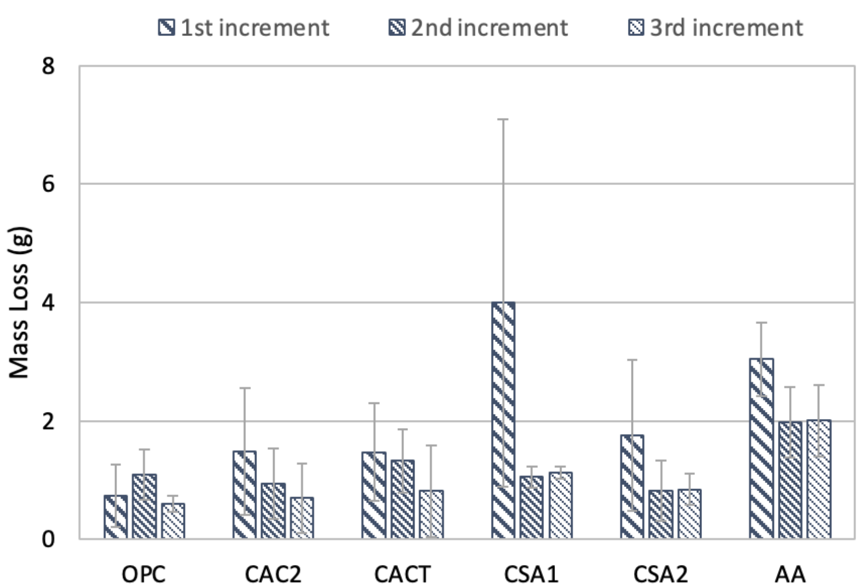
DURABILITY TESTING

Researchers performed a comprehensive evaluation of durability and assessed the resistance to physical forms of degradation, including abrasion, freeze/thaw cycling, and salt scaling (figure 13 and table 4).

Figure 12. Mass loss and abrasion depth with mechanical abrasion assessed by ASTM C944 *Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method*.[17]

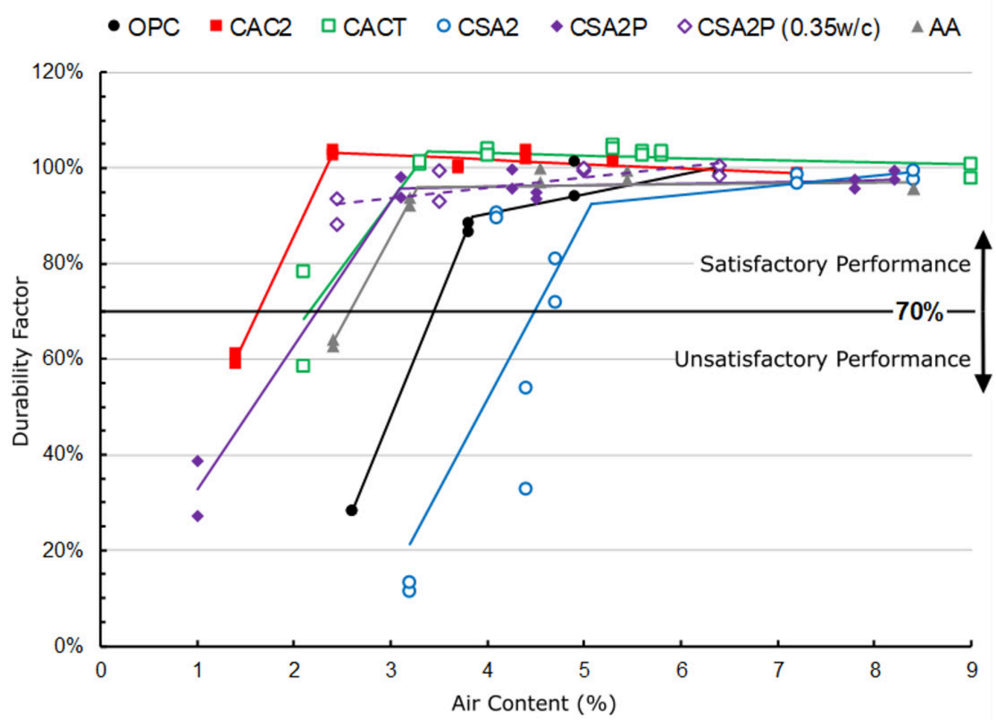


A. Mass loss.



B. Abrasion depth with mechanical abrasion.

Figure 13. Freeze/thaw performance, as measured by durability factor (DF) according to ASTM C666 Procedure A, for ACM concrete produced with varying air contents using commercial air entraining admixtures, with air content (percent) required to meet 70 percent DF.[18]



Note: All concretes were produced at a w/c ratio of 0.42, with CSA2P also produced at an additional (lower) w/c ratio for comparison.

Table 4. Summary of results from freeze/thaw testing (ASTM C666) and salt scaling testing (ASTM C672) for ACM oncrete produced at varying fresh air contents.[18,19]

Binder	Fresh Air (%)	Cycles	Scaled Mass (%)	Visual Inspection Rating	C666 DF (%)	C666 Mass Change (%)	C666 and C672 Status	Pass Air Content Range (%)
OPC	2.6	10	0.0400[f]	4[f]	27[f]	0.95	Fail	≥3.8
	3.8	50	0.0132	3	87	−0.51	Pass	
	4.9	50	0.0136	3	98	−0.21	Pass	
	6.4	50	0.0045	2	99	−0.50	Pass	
	11.5	50	0.0018	1	98	−0.76	Pass	
CACT	2.1	50	0.0018	2	69[f]	−5.23*	Fail	None
	3.3	25	0.0354[f]	4[f]	101	−0.40	Fail	
	4.0	35	0.0450[f]	4[f]	103	−0.19	Fail	
	5.8	50	0.0310[f]	4[f]	103	−0.06	Fail	
	9.0	25	0.1141[f]	5[f]	99	−1.27	Fail	

Table 4. Summary of results from freeze/thaw testing (ASTM C666) and salt scaling testing (ASTM C672) for ACM oncrete produced at varying fresh air contents.[18,19] (Continued)

Binder	Frsh Air (%)	Cycles	Scaled Mass (%)	Visual Inspection Rating	C666 DF (%)	C666 Mass Change (%)	C666 and C672 Status	Pass Air Content Range (%)
CAC2	1.4	50	0.0013	1	60[f]	−0.88	Fail	2.4 to 5.3
	2.4	50	0.0039	1	103	−0.21	Pass	
	3.7	50	0.0113	1	100	−0.04	Pass	
	5.3	50	0.0110	3	102	−0.85	Pass	
	7.2	50	0.0313[f]	5[f]	98	−0.33	Fail	
CSA2	4.7	20	0.0634[f]	5[f]	76	−0.56	Fail	None
	7.2	20	0.1458[f]	5[f]	98	−1.43	Fail	
	8.4	25	0.1019[f]	5[f]	98	−0.14	Fail	
CSA2P	1.0	25	0.0417[f]	5[f]	33[f]	−3.83[c]	Fail	3.1
	3.1	50	0.0137	3	96	−2.93[c]	Concern	
	4.3	20	0.0302[f]	4[f]	98	−3.38[c]	Fail	
	4.5	50	0.0185[f]	4[f]	94	−2.58[c]	Fail	
	8.2	20	0.0256[f]	5[f]	98	−2.59[c]	Fail	
CSA2P 0.35 w/c ratio	2.5	50	0.0019	1	91	−1.12	Pass	2.5 to 6.4
	3.5	50	0.0018	2	96	−0.41	Pass	
	5.0	50	0.0024	2	100	−0.75	Pass	
	6.4	50	0.0022	1	100	−2.21[c]	Concern	
AA	2.4	40	0.0260[f]	3	63[f]	−0.52	Fail	None
	3.2	25	0.0324[f]	4[f]	93	−0.14	Fail	
	4.6	50	0.0197[f]	4[f]	99	−0.17	Fail	
	5.5	25	0.0243[f]	4[f]	98	−0.16	Fail	
	8.4	25	0.0327[f]	4[f]	96	−0.19	Fail	

[c] Exceeds concern threshold.
[f] Exceeds failure threshold.
* ICP-OES = inductively coupled plasma-optical emission spectrometry.

In addition, researchers measured the resistance to alkali-silica reaction (using a known reactive aggregate), sulfate attack (measuring both expansion and strength loss), and carbonation (figure 14 through figure 17).

Figure 14. Expansion of ACM concrete prisms, relative to OPC concrete, produced with reactive aggregate and subject to ASTM C1293 exposure conditions.[20]

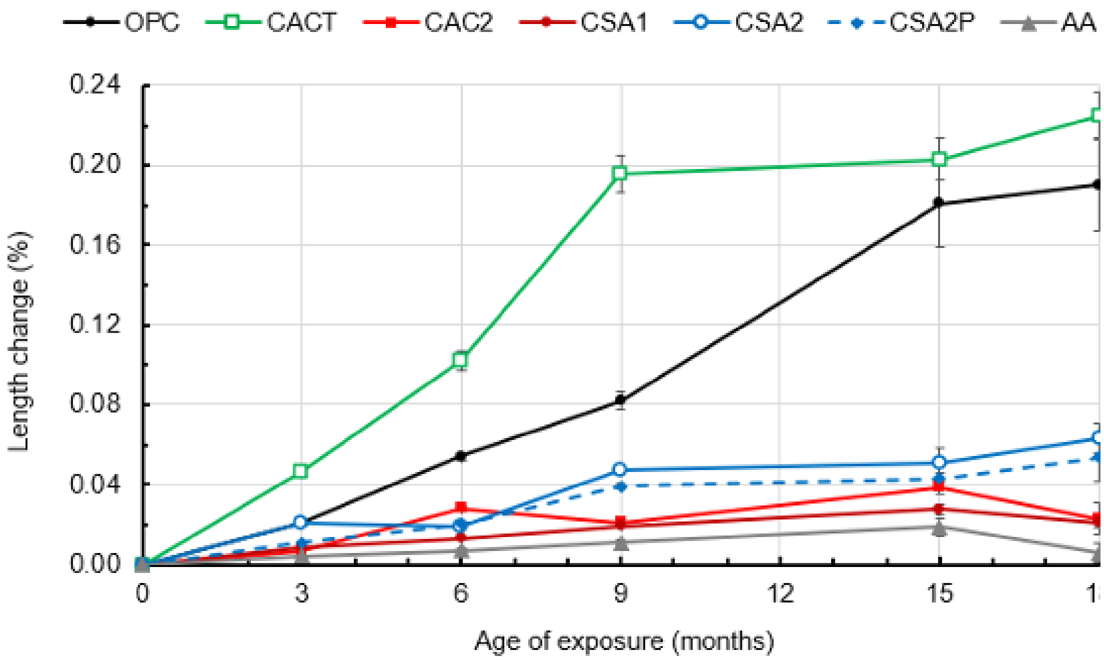


Figure 15. Average expansion of ACM and OPC mortar bars subjected to ASTM C1012 sulfate testing.[21]

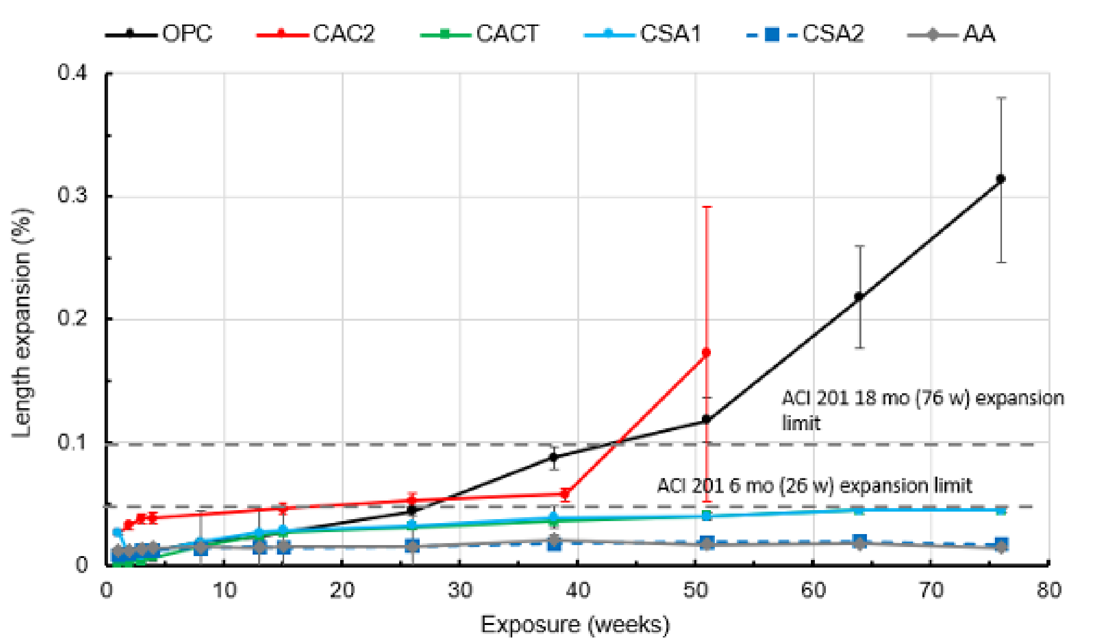
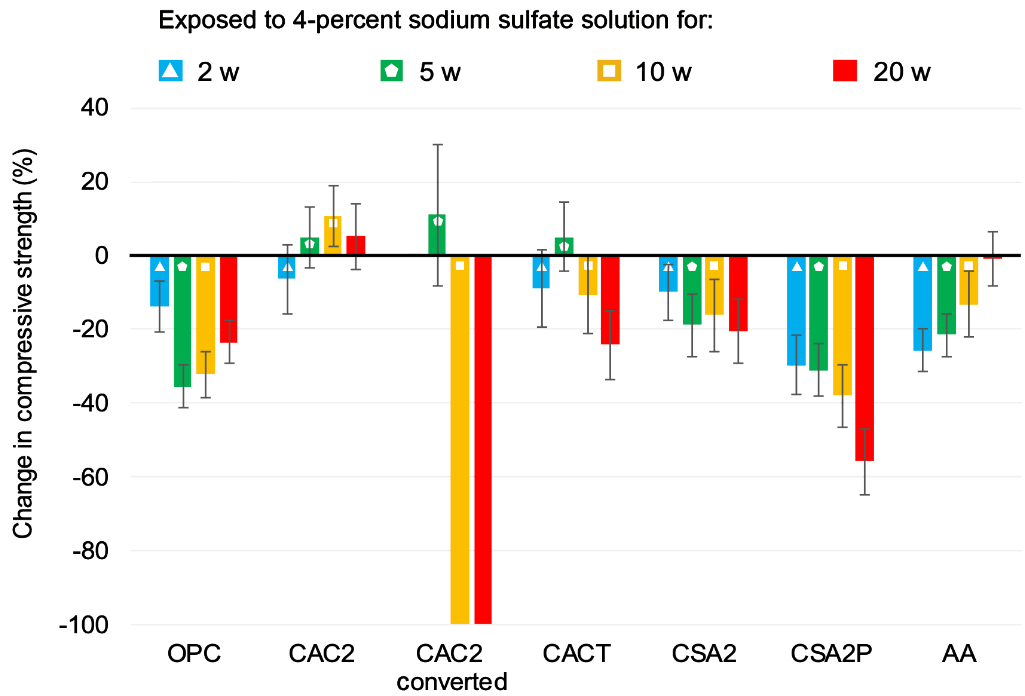
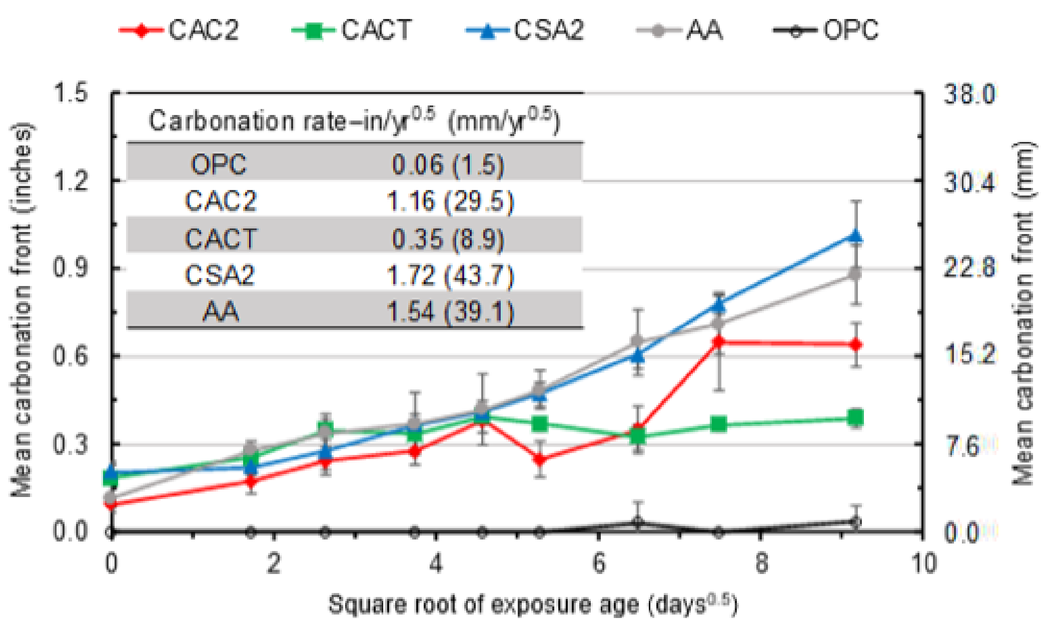


Figure 16. Average change in compressive strength of cement paste cubes exposed to sodium sulfate solution.



Note: "CAC2 converted" is CAC2 subjected to conditions to induce conversion prior to sulfate exposure.

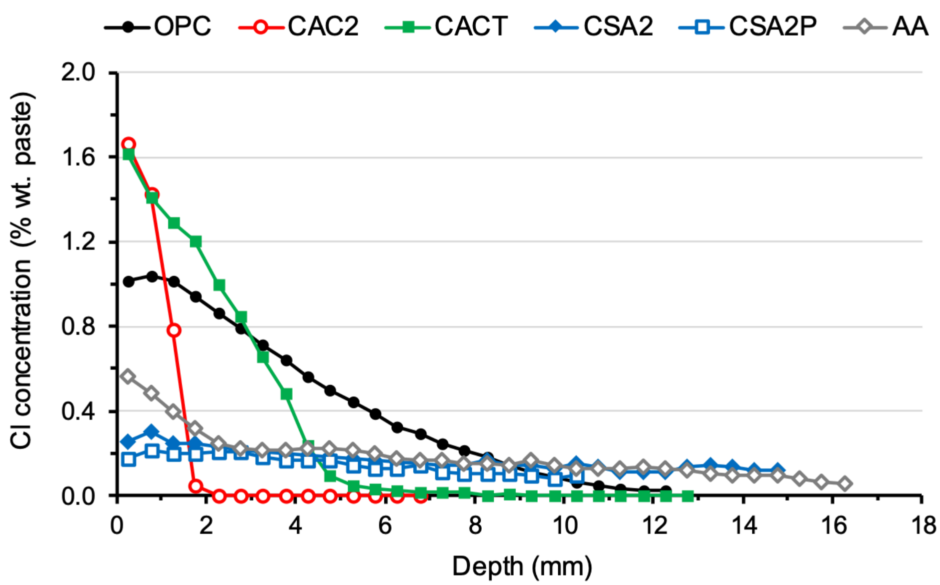
Figure 17. Mean carbonation front of concrete samples made with OPC and ACMs, as well as carbonation rates, determined from 7-percent CO_2 exposure initiated after 56 d of curing.



Note: Results for AA likely reflect changes induced by accelerated carbonation conditions, which are not representative of long-term field performance.[9]

Corrosion resistance was assessed in the lab by chloride penetration, conductivity, measurements of macrocell current, the corrosion potential in saltwater ponding experiments (figure 18 through figure 19), and the calculations of apparent chloride diffusivity coefficients (table 5). The research team also performed additional alkali-silica reaction (ASR), carbonation, transport, and corrosion testing; those findings are not included in this TechNote but can be found in the Novel Alternative Cement Binders for Highway Structures and Pavements Dataset.[22]

Figure 18. Mass transport in ACM paste mixes compared to that of OPC for 28 d of ponding with 0.6 mol/L NaCl solution.



Wt. = weight

Figure 19. Integrated macrocell current between the top and bottom bars of ACM and OPC concrete mixtures exposed to 3-percent NaCl solution over exposure time.

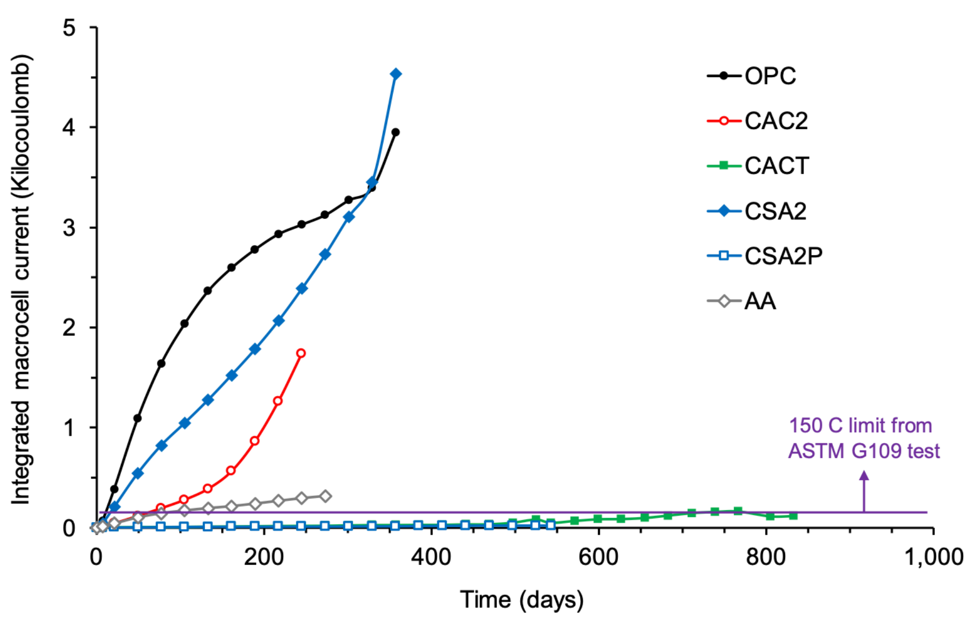


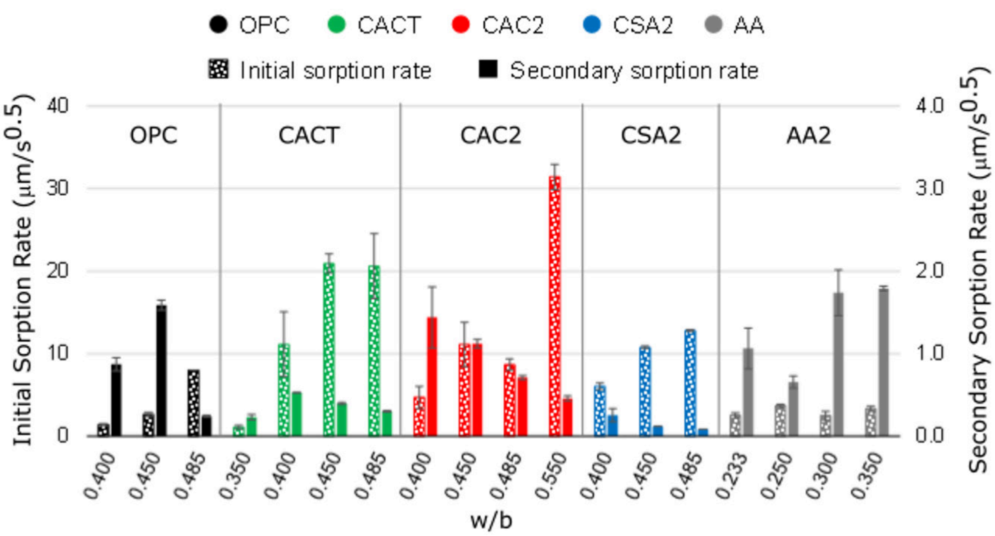
Table 5. Apparent diffusivity coefficients.

Cement	Days of Testing	Apparent Diffusion Coefficient (10^{-12} m^2/s)		Crack to Uncrack Ratio	Diffusion Coefficient Relative to OPC	
		Away From Crack	At Crack		Away From Crack	At Crack
OPC	357	2.83	22.3	7.9	1.0	1.0
CAC2	245	1.87	187	100.0	0.7	8.4
CACT	767	1.48	18.3	12.4	0.5	0.8
CSA1	357	11.1	16,700	1,504.5	3.9	748.9
CSA2	357	57.8	212	3.7	20.4	9.5
CSA2P	441	1.02	3.5	3.4	0.4	0.2
AA	273	5.69	741	130.2	2.0	33.2

Accelerated durability testing relied as much as possible on standardized test methods to facilitate comparison with OPC performance. In some cases, however, standardized test methods were adjusted to account for the differences between ACMs and OPC, which may possibly introduce unintended effects or result in a lack of replication of the distress expected in practice. For example, alkali boosting was not used in the concrete prism test for ASR (ASTM C1293) because predicting the influence of additional alkalis on ACM reactions, products formed, and microstructure is difficult.[20] Instead, the test duration was extended to 2 yr, and the relative performance of ACM mixtures compared to that of OPC mixtures was used as an indicator.[21] ACI-ITG-10R-18 recommends using relative performance (compared to OPC) for assessing ACM durability.[1] The introduction of flexural cracks into reinforced concrete samples that are then subjected to saltwater ponding during corrosion monitoring is another example of test adaptation. With the low permeability of these systems, controlled cracking provides a more rapid assessment of corrosion performance while addressing the influence of common cracking found in the field. In other cases where standardized test methods are not available (e.g., compressive strength loss due to sulfate attack and accelerated carbonation), tests were performed that relied on guidance from peer-reviewed sources.[7]

In all durability assessment cases, the w/c ratio was kept constant for all ACMs and OPCs to best facilitate comparison, except for AA and MPC, which both required a lower water content to meet the strength, setting, and workability requirements. When a w/c ratio was specified in a standard (e.g., ASTM C1012, ASTM C1260, or other established test methods),[7,21,24] that proportion was used to produce samples (except for AA and MPC) that required significantly lower water-to-solid ratios. Otherwise, w/c ratios of 0.40–0.42 were used. Recognizing the influence of w/c on test outcomes, additional studies were performed to compare sorptivity among the ACMs, prepared at different w/c ratios (figure 20). This type of assessment helps to establish “functional equivalence” among ACMs and OPC, facilitating performance comparisons with matched transport properties.

Figure 20. Initial and secondary water sorption of ACM mixes at varied w/b compared to OPC mix at w/b of 0.485.



Key outcomes of the durability assessments include the following:

- Abrasion resistance: Mass loss results for ACM concretes were up to three times higher than for the OPC control concrete. However, much of the mass loss in the ACMs, particularly the high mass loss in CSA1 and AA1, appeared to be in the first increment of testing due to rapid abrasion of surface laitance. Once this weaker upper layer was removed, the rate of abrasion appeared to be similar for all materials. Abrasion depth measurements for all ACMs appeared to be very similar to the OPC control, with depths of abrasion less than 1 mm after three increments of abrasion testing. The results indicate the physical abrasion resistance of concretes produced using ACMs is very similar to OPC concretes.
- Freeze/thaw resistance: From the ASTM C666 testing, most cements investigated required less than 4-percent air content to pass the ASTM C666 tests with a durability factor limit of 70 percent.(18) CSA2 was the only cement that required 5-percent air content to achieve a satisfactory durability factor, and samples with CSA2P with a w/c of 0.35 showed satisfactory performance even with 2-percent air in the mixture.
- Scaling resistance: CAC3 and the polymer-modified CSA2P with w/c of 0.35 were the only two ACMs to pass this test. CAC3 showed a decrease in performance at air contents above 6.4 percent. This decline in performance may be caused by the air decreasing the strength of the surface of these samples. CSA2P with w/c of 0.35 showed satisfactory performance even with 2-percent air in the mixture.
- ASR resistance: When cast with a reactive aggregate, AA concrete prisms experienced the least expansion. CAC2, CSA2, and CSA2P also performed well over a 15-mo period with only about one-third of the expansion of the OPC concrete. CACT experienced greater expansion than the OPC, perhaps because of its higher equivalent alkali content of 0.83 percent, compared to the 0.77 percent of OPC. This test remains ongoing.
- Sulfate resistance: In mortar bar expansion testing, all cements examined met the ACI 201 6-mo criteria, but OPC and CAC2 expanded to just under the limit. AA, CSA2, and CACT showed the best resistance to expansion, with lower expansion at 6 mo and substantially lower expansion at 18 mo. Assessments of change in compressive strength during sulfate attack under constant pH and sulfate concentrations showed that CAC2 (unconverted), CSA2, CACT, and AA all showed behavior similar to, or better than, OPC. Converted CAC2, however, showed greater strength loss than OPC, with complete loss of adhesion. CACT, CSA2, and AA exhibited the best overall sulfate resistance.
- Carbonation resistance: Under accelerated conditions, the carbonation rate for all ACMs examined was substantially higher than OPC. This rate, coupled with the initially lower pH and lack

of buffering capacity in many ACMs, may require additional measures to prevent corrosion in the field.

- Chloride penetration: The chloride ion binding capacity was highest in OPC and CACT, followed by CAC2. CSA2 and AA had the lowest binding capacity compared to the others, which could lead to higher penetration of Cl ions, thereby lowering resistance to corrosion. However, the stability of the chloride-containing phases, as well as the potential influence of pore-blocking with polymer additives, deserves more study.
- Bulk conductivity: Although the performance of OPC in this test was essentially constant over the test period, bulk conductivity in most ACMs decreased over time, demonstrating continued reaction or densification of the matrix. In contrast, the bulk conductivity of CAC2 increased over time, indicating increased permeability due to conversion. The CSA2P and AA mixtures had significantly lower bulk conductivity compared to other ACMs and OPC.
- Corrosion resistance: The integrated macrocell corrosion currents were significantly lower in CACT mixtures compared to other ACMs and OPC, likely because of the lower Cl ion penetration depths and higher binding capacity in CACT mixtures and lower conductivity and lower penetration depths in CSA2P mixtures. The CACT showed the best corrosion resistance among the materials (including OPC) with the w/c ratios considered. CSA2P had the second-best performance.
- Sorptivity: The influence of w/b on sorptivity (as influenced by porosity and pore structure) varied with different binder systems; CACT was the most sensitive. The total sorption is significantly higher in CAC2, CACT, and CSA2 mixtures. The AA mixtures had significantly lower sorption compared to other ACMs and OPC but were also produced at lower water (activator) content, per manufacturer recommendations and different reaction chemistry. To design ACM mixes with similar or lower total sorption compared to OPC at 0.485, the w/b in CAC2, CACT, CSA2, and AA mixes should be less than 0.45, 0.40, 0.45, and 0.35, respectively. In other words, for all ACM systems considered, reductions in the w/b ratio are necessary to achieve equivalent or similar sorptivity performance to OPC.

FIELD PERFORMANCE HISTORY

In related research, a team held discussions with the advisory board and other transportation professionals to identify several large-scale applications of ACM concrete throughout the United States. The team visited and photographed sites, created and reviewed inspection reports, and gained additional insights through petrography performed on cores obtained from some long performing ACM sites. Following are highlights from the team's observations and details, many of which are published in full in the resulting FHWA TechBrief, *Novel Alternative Cementitious Materials for Development of the Next Generation of Sustainable Transportation Infrastructure*:[(2)]

- Alkali-activated concrete: AA slabs on I–16 in Dublin, GA, a small inland city south of Atlanta, GA, appeared to be in excellent condition after 5 yr, with only a few cracks present in a slab that had been removed. Researchers believe the cracks may have been induced and/or grew during deconstruction, and took cores from the structure for laboratory testing to examine resistance to chloride penetration. The resistance was evaluated by measuring the existing chloride content in the sample and then ponding the cores with additional chlorides so that a comparison could be made between field samples. The samples did not show high amounts of binding but instead showed high rates of chloride penetration. These findings closely matched the laboratory findings.
- CAC concrete: An evaluated section of CAC pavement on I–90 and I–94 in Chicago, IL was performing well after 5 yr. CAC allowed for rapid replacement after a catastrophic failure, allowing this busy section of roadway to be opened within five hours. Cores were taken from a test pour made in preparation for this repair and investigated for resistance to chloride penetration. The cores showed high amounts of surface binding and a low effective diffusion coefficient. The results closely matched the laboratory test results.
- CSA concrete: A CSA concrete pavement on the California SR 60 East and SR 71 North interchange near Pomona, CA, was performing well after 17 yr, despite heavy traffic loading. Rapid setting caused the pavement to require grinding after placement. Another 42-mi placement of this CSA on CA Route 60 also showed evidence of grinding to compensate for poor compaction. In this section of pavement, spalling at joints and extensive longitudinal and corner cracking were observed despite improvements in pavement design at the time of construction. In another placement, at I–10 near Los Angeles, a 15-yr-old section of CSA concrete showed significant damage, including joint deficiencies and spalls. This CSA is believed to be a different cement than the cement located at CA SR 60E. Adjacent OPC pavements also experienced

similar distress, suggesting that design deficiencies (e.g., poor subgrade, inadequate pavement thickness) contributed to distress.

- The Missouri Department of Transportation (DOT) overlaid several bridge decks in St. Louis, MO, with CSA containing a polymer additive. These overlays were approximately 7 yr old when they were sampled. Some surface scaling was observed on the shoulders of the bridge decks, where ice and brine accumulated during winter. Cores from the overlays were also tested for chloride penetration. A small amount of chloride binding and a high effective diffusion coefficient were observed. The results were akin to the laboratory test results.
- A pavement patch of CSA with polymer additive was used on a major highway near Seattle, WA. After 5 yr of service, the Washington DOT took several cores. These cores showed small amounts of chloride binding, and researchers observed a high effective diffusion coefficient. These results closely matched the laboratory test results.
- To facilitate rapid bridge deck replacement, MPC concrete was combined with precast concrete panels in 18 bridges along the Dalton Highway, between Livengood and Prudhoe, AK. Despite heavy truck traffic and weather exposure, researchers observed that MPC performed well after 20 yr in this application, although some cracking was observed.

EXPOSURE SITES

As a complement to the laboratory durability studies performed on ACM concretes, a series of field studies were performed at two locations in marine environments. One location was in a cold-weather environment and the other in a warm weather environment. The U.S. Army Corps of Engineers Treat Island Natural Weather Station, located off the coast of Eastport, ME, provided the cold-weather site shown in figure 21. All samples were cycled twice per day by rising and falling tides and received 120 to 150 freeze/thaw cycles in winter. This severe combination of wet/dry and freeze/thaw cycles makes the site an ideal location to perform field durability testing in a real-world environment. This location allowed for studying corrosion, freeze/thaw, and other deterioration mechanisms, providing important data for the development of service life models. Located off the coast of Miami, FL, the warm-weather site was developed by the University of Miami (figure 22). Samples there are also cycled twice per day through tidal exposure, but the samples were cycled in water temperatures ranging from 74 °F in the winter to 87 °F in the summer.

In 2015, air-entrained ACM and OPC concrete prism samples—some reinforced, some unreinforced for each ACM type—were placed at Treat Island. The samples were visually inspected and photographed (figure 23) annually. Using ultrasonic pulse velocity (UPV), damage was assessed nondestructively. After 2 yr of field

Figure 21. Location and key features of the exposure site located on Treat Island, ME.

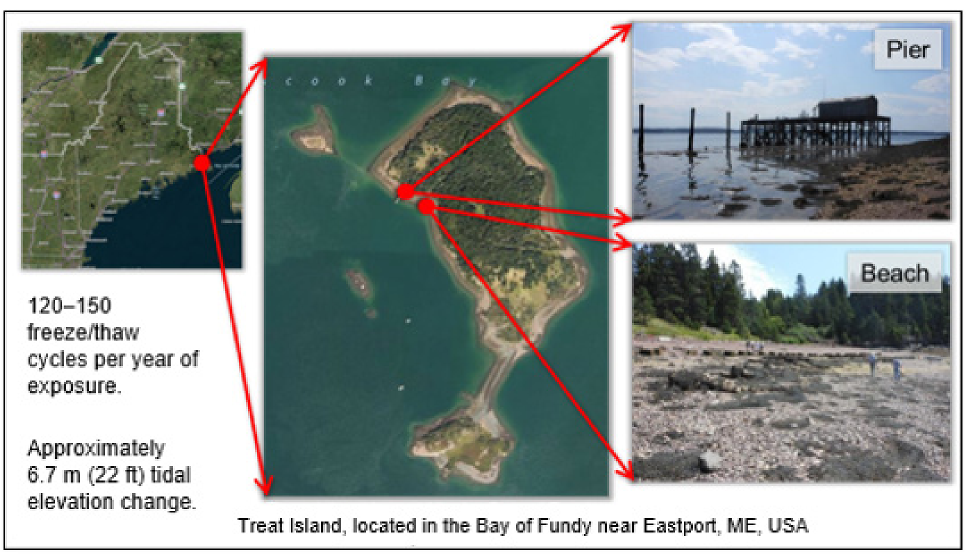


Figure 22. Location and key features of the exposure site located in Miami, FL.

exposure, 1 prism for each ACM was removed and petrographically examined to identify any internal damage, discoloration, freeze/thaw action, or other modes of deterioration. No significant damage was observed in the ACMs. In addition, chloride diffusion into concrete samples was assessed, according to ASTM C1152 *Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete*, using ICP OES* for ion concentration assessment.[25]

The ACM mixtures used at the cold-weather field site have performed remarkably well after 3 yr of severe exposure. All ACM concretes performed as well as or better than the OPC control when studied for evidence of any surface damage from freeze/thaw cycles. After 3 yr of exposure, with approximately 400 freeze/thaw cycles, the concrete surfaces were found to be in good condition. The edges of prisms were retained, and damage appeared minimal, when visually assessed during inspection. UPV data for all ACMs and OPC also showed little to no change over the 3-yr period. For comparison, a lab-produced fly ash (FA) geopolymer (GP), also placed in 2015, experienced significant surface scaling, corner spalling, and cracking during this period. However, the surface of the FA GP was too degraded to allow for UPV measurements.

After 2 yr of exposure, chloride content versus depth measurements (figure 24) show that all but one of the ACMs exhibited similar or less chloride diffusion than the OPC. The exception was CSA2, which had a very high

Figure 23. Photographs of test specimens taken during placement at the Treat Island, ME, site in 2015 and field site visits conducted in 2017 and 2018.

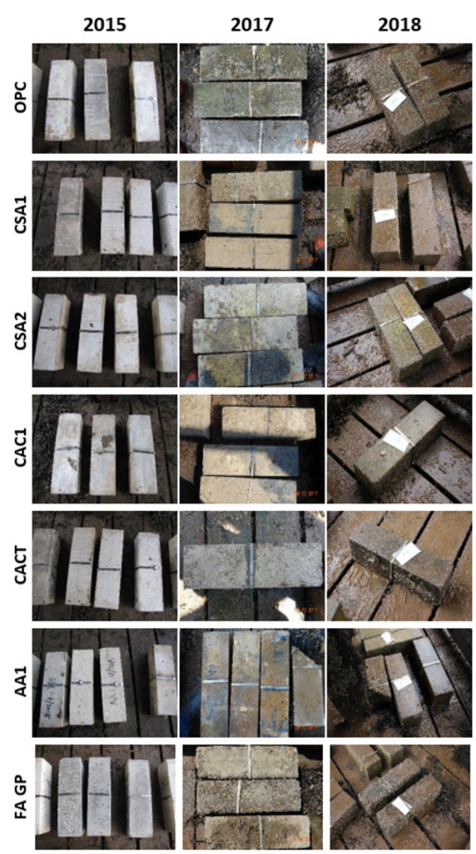
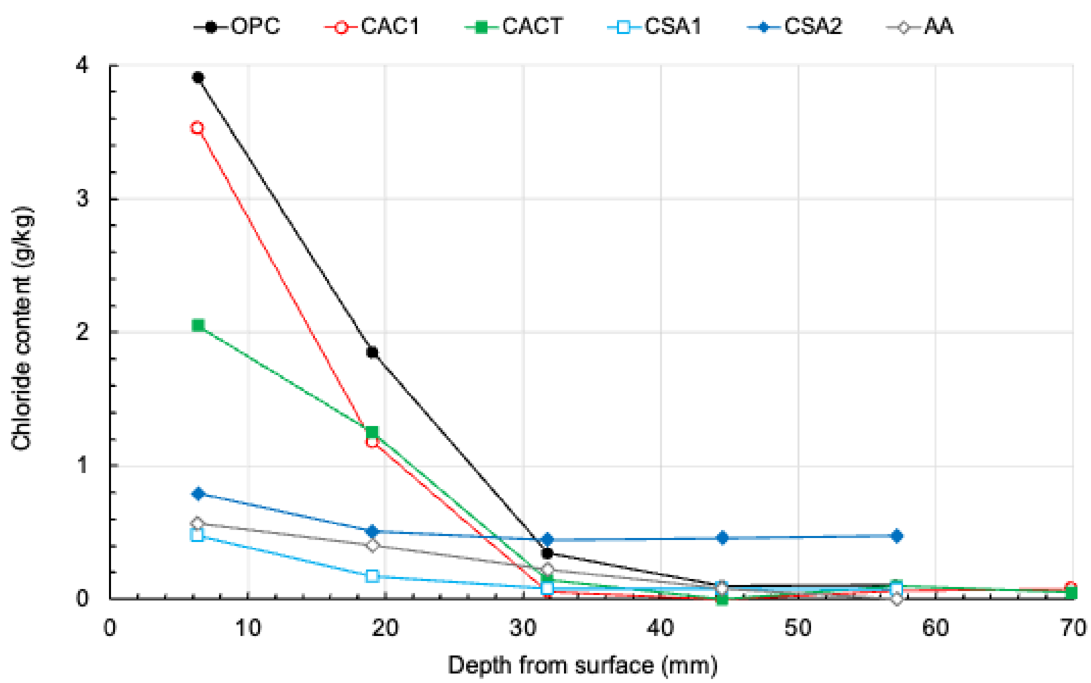


Figure 24. Chloride concentration versus depth curves obtained after 2 yr of field exposure at Treat Island, ME, for ACM and OPC concrete.



diffusion coefficient and showed significant ingress of chlorides to the cover depth after only 2 yr of exposure. CSA and AA1 materials exhibited particularly low chloride diffusion. The pattern of chloride penetration in CAC1, approximate to OPC, suggests that conversion may have contributed to increased permeability.

SUMMARY, RECOMMENDATIONS, AND TECHNOLOGY READINESS ASSESSMENT

In this 4-yr research effort, more than a dozen commercially available ACMs were examined to determine their suitability as alternatives to portland cement in transportation infrastructure. Additional resulting publications and presentations to date, provided at the end of this TechNote, supply a detailed analysis of the results summarized herein.

For this investigation, and for a variety of reasons, the following ACM types and sources were found to be unsuitable for transportation infrastructure construction:

- Magnesium phosphate-based cements, while useful for small-scale repair and to meet specialty durability requirements, could not achieve the extended set time necessary for conventional concrete mixing. In addition, expansion during hydration and leaching can be problematic in some applications. Several MPC formulations from three producers were examined. Despite exploring a range of admixture types and dosages, along with variations in mixture proportions, none of the MPCs examined could achieve the necessary workability, set time, and strength requirements to make them suitable for large-scale pavement or bridge deck construction. It is recommended that additional MPC concrete studies be performed, if extended set in MPC is possible—either through the advent of new admixtures or new cement formulations. MPC concrete could be useful for applications requiring high heat resistance and chemical resistance to oils or acids.
- Of the three CSA cements examined, significant inconsistency was observed in the composition and performance of CSA1. As a result, construction with this material could prove challenging. Variability in key performance criteria, such as set time and strength development, could occur. As a result, the research team did not advance CSA1 for further analysis in this research.

Two CACs showed potential for use in transportation applications, but further technology development is necessary before their implementation:

- CAC1 requires the identification and/or development of appropriate plasticizing admixtures to enhance workability in concrete. While adequate workability could be achieved in pastes and mortars, a workable mix with at least 3 inches of slump at 60 min could not be achieved.
- For CAC2 concrete, depending on application, identification and/or development of appropriate accelerating admixtures may be necessary. A w/c of 0.40, initial and final set was two to three times that of OPC. Also, CAC2, once converted, showed very poor sulfate resistance. The cracking after conversion is also a concern for local chloride ingress and needs to be investigated in greater detail.

An adjustment of design methodology to account for strength loss, increased permeability, and increased propensity for cracking—due to conversion and carbonation—is needed for all CACs. The need for this adjustment is viewed as a critical impediment for broader use of CACs in current transportation infrastructure construction and one that needs more investigation.

Of the remaining ACMs examined, CACT, CSA2, CSA2P, and AA are potentially deployable based on lessons learned from this research effort. These materials showed satisfactory workability, set time, and strength development with a w/c of 0.40 (or w/c = 0.205 for AA).

- AA showed improvements in shrinkage, freeze/thaw performance, sulfate resistance, and ASR resistance relative to OPC but unsatisfactory performance in corrosion, scaling, and ion penetration. AA is recommended for use in dry environments that are not expected to receive freeze/thaw cycles. Care must be taken, however, because AA is a large class of materials that may change due to varied raw materials.
- CACT showed similar shrinkage and ASR performance to OPC and satisfactory performance in freeze/thaw, scaling, and ion penetration. CACT showed better performance in corrosion and resistance to expansion by sulfate attack. These qualities make this material useful in areas where it will be frequently subjected to chlorides or sulfates, such as in coastal structures.
- CSA2 and CSA2P showed significant improvement in shrinkage, sulfate resistance, and ASR performance. CSA2P showed further improved performance in corrosion when compared to OPC and satisfactory performance in freeze/thaw and salt scaling, even with low air volumes when the w/c was decreased to 0.35. This improvement in shrinkage makes these materials apt where dimensional stability is a concern, such as with pavements. Some useful applications of this material include concrete used in dry environments or environments frequently subjected to freeze/thaw conditions, sulfates, and chlorides. The CSA2P material, with the right mixture proportions, is the most versatile material investigated.

An area of concern for all ACMs investigated was carbonation. The rate of carbonation and subsequent corrosion from carbonation must be better understood before ACMs can be recommended for use in structures with low amounts of cover, such as bridge decks or substructure elements. However, these materials can immediately be used in structures with large amounts of cover, such as pavements, and structures that do not contain reinforcing steel, such as overlays or patches. Another option is to combine the use of these materials with corrosion resistant rebar technologies, such as galvanizing, stainless steel, or nonmetallic reinforcing. These combinations of materials could lead to innovative use that could provide long-term durability for infrastructure concrete.

It should be noted that the best-performing materials in this research (CACT and CSA2P) were a blend of different materials. These blends show great promise because a combination of materials can address the weakness of a single component, as with OPC, using fly ash, slag and silica fume. Further experimentation may potentially improve the performance of these ACMs if they can be investigated with a wider array of material combinations.

In view of these outcomes, preliminary Technology Readiness Levels (TRLs) can be assessed. TRLs are assigned considering applications of ACM concrete in transportation infrastructure applications, both reinforced and unreinforced, where conventional concrete mixing and construction practices can be used. ACMs that did not proceed beyond Phase 1 include CAC1, CSA1, and MPC. These ACMs are assigned TRL-3 status and are not deployable without additional technological advancements. Of these ACMs, CSA1 has the greatest potential to advance if quality control issues during production can be addressed.

The ACMs that met initial performance targets and proceeded into Phase 2 durability studies are believed to be at TRL-4 or higher; they include CAC2, CACT, CSA2, CSA2P, and AA. Concerns about conversion require additional investigation, limiting the advancement of CAC2 to higher TRL, despite some promise for applications requiring sulfate resistance, ASR resistance, or low shrinkage. Among the remaining ACMs, AA, CSA2, and CACT performed better than OPC under laboratory sulfate conditions, and AA, CSA2, and CSA2P showed promise for ASR mitigation under long-term laboratory testing. For reinforced concrete structures exposed to chloride environments, CACT and CSA2P showed the best performance. Carbonation may be a concern for all ACMs used in low-cover reinforced concrete, subject to moderate humidity conditions; however, additional studies are needed to assess the influence of carbonation on passivation behavior in reinforced ACM concrete.(26) CSA2P and CACT, when appropriately designed, can exhibit good scaling resistance. AA, CSA1, CSA2, and CSA2P exhibited better dimensional stability than OPC, providing a distinct advantage for some applications. Based on the dimensional stability, laboratory durability studies, and field site exposure data, a TRL of at least six can be assigned to AA, CSA2, CSA2P, and CACT. With their histories of good field performance in transportation structures, the TRL-8 status can be assigned to AA, CSA2, and CSA2P for unreinforced concrete and to CSA2P and CACT for reinforced concrete.

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