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ABSTRACT

Accelerated pavement rehabilitation under cold weather conditions is traditionally constrained by the slow early-age strength development of conventional Portland cement systems. This limitation directly impacts the ability of agencies to reopen critical infrastructure within short construction windows.

This paper demonstrates that Belitic Calcium Sulfoaluminate (BCSA) cement-based concrete—a binder system entirely free of Portland cement phases (Alite C_3S and Tricalciumaluminate C_3A)—can reliably achieve compressive strengths on the order of 3,800–4,800 psi (26–33 MPa) within 4 hours across a range of placement temperatures from approximately 30°F to 70°F, enabling rapid return-to-service even under adverse environmental conditions. Results are drawn from three field projects involving airfield pavements, highway reconstruction, and structural bridge elements, executed using both ready-mix and volumetric delivery systems.

Unlike many calcium sulfoaluminate systems that rely on partial replacement or hybridization with Portland cement, the BCSA binder used in this study derives its performance entirely from its intrinsic phase assemblage, dominated by ye'elimite and belite.

Beyond documenting case study performance, this work proposes a performance-based framework for rapid concrete construction centered on strength at time-of-opening as the governing design parameter. The results show that early-age performance is primarily controlled by the interaction of binder chemistry, thermal management, and construction logistics, rather than ambient temperature alone.

The findings challenge conventional assumptions regarding cold-weather concreting limitations and demonstrate that predictable reopening within a 4-hour window is achievable near freezing conditions when appropriate material systems and field controls are implemented. This supports a shift toward performance-based specifications for rapid infrastructure rehabilitation, where time-to-strength—not prescriptive composition—defines success.

KEY WORDS

HIGH EARLY STRENGTH CONCRETE / BELITIC CALCIUM SULFOALUMINATE CEMENT / AIRFIELD PAVEMENTS / HIGHWAY PAVEMENTS / PAVEMENT REHABILITATION.

1. INTRODUCTION

Transportation infrastructures such as airfields, ports, and high-volume roadways operate under continuous or near-continuous traffic demands and typically cannot accommodate extended closures for pavement rehabilitation or reconstruction. For these facilities, prolonged shutdowns can lead to significant economic losses, operational disruptions, and safety concerns. As a result, agencies increasingly rely on overnight or short-duration construction windows, with pavements required to reopen to traffic within hours rather than days (Bescher, 2024),

Conventional Portland-cement-based concrete is often unable to satisfy these constraints due to its relatively slow early-age strength development, particularly under cold-weather conditions. While accelerated mixtures and chemical admixtures can improve early strength, performance becomes increasingly uncertain when placements are conducted at subfreezing temperatures, where hydration kinetics slow and the risk of early-age freezing increases (ACI306, 2016).

Rapid-strength binders have therefore emerged as a key enabling technology for expedient pavement rehabilitation. Among these, Belitic Calcium Sulfoaluminate (BCSA) cement-based concrete has been used for more than two decades in critical infrastructure applications, including airports, highways, and port facilities. BCSA concrete combines fast setting, high early-age strength, and low shrinkage, allowing pavements to be returned to service within hours while maintaining long-term performance and durability (Deo et al., 2023).

This paper presents a practical review of three cold-weather pavement construction projects completed in 2025 using BCSA cement-based concrete under severe operational and environmental constraints. The projects include a high-volume highway, a bridge reconstruction involving link slabs, and a major international airport pavement rehabilitation, all executed during nighttime closures and/or subfreezing ambient conditions. The paper focuses on material innovation, construction logistics, cold-weather mitigation strategies, and early performance outcomes, with the objective of providing transferable lessons for agencies considering rapid concrete pavement rehabilitation in similar conditions.

2. BACKGROUND ON BCSA FOR RAPID PAVEMENT REHABILITATION

Belitic Calcium Sulfoaluminate (BCSA) cement belongs to the family of calcium sulfoaluminate-based binders and was originally developed in the United States in the 1970s as a very-high-early-strength cement. The major oxide contents and phase composition of BCSA are shown in Table 1. In BCSA cement, the early-strength-imparting alite and C_3A phases typical of Portland cement are replaced by ye'elimite ($C_4A_3\hat{S}$), while belite (C_2S) contributes to later-age strength development. This phase assemblage enables rapid strength gain without excessive heat release or long-term shrinkage (Hanein et al., 2023). The rapid hydration kinetics of BCSA compared with Portland cement, together with ettringite formation in the BCSA samples, are shown by calorimetry, TGA, and XRD in Figure 1.

Key characteristics that make BCSA cement particularly well-suited for expedited pavement rehabilitation include (Bescher et al, 2022):

- Very rapid setting and strength gain, enabling opening to traffic in a little as 2-4 hours.
- Low shrinkage, reducing the risk of early cracking.
- Lower heat of hydration compared to accelerated portland cement concrete systems.
- Proven long-term durability in pavement and airfield applications.

Table 1 – Cement chemical composition using XRF and cement content in concrete mixes. Six major oxides normalized to 100%.

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	
15.9	15.4	1.5	51.4	0.6	15.2	
Belite (C_2S)	**Yeelimite ($C_4A_3\$$)**	**Anhydrite ($C\$$)**	**Ferrite (C_4AF)**	**Ternesite/spurrite ($C_5S_2\$$)**	**Calcite $CaCO_3$**	**Bassanite ($C\$H_{0.5}$)**
43.4	26.9	12.0	4.3	7.4	2.6	3.4

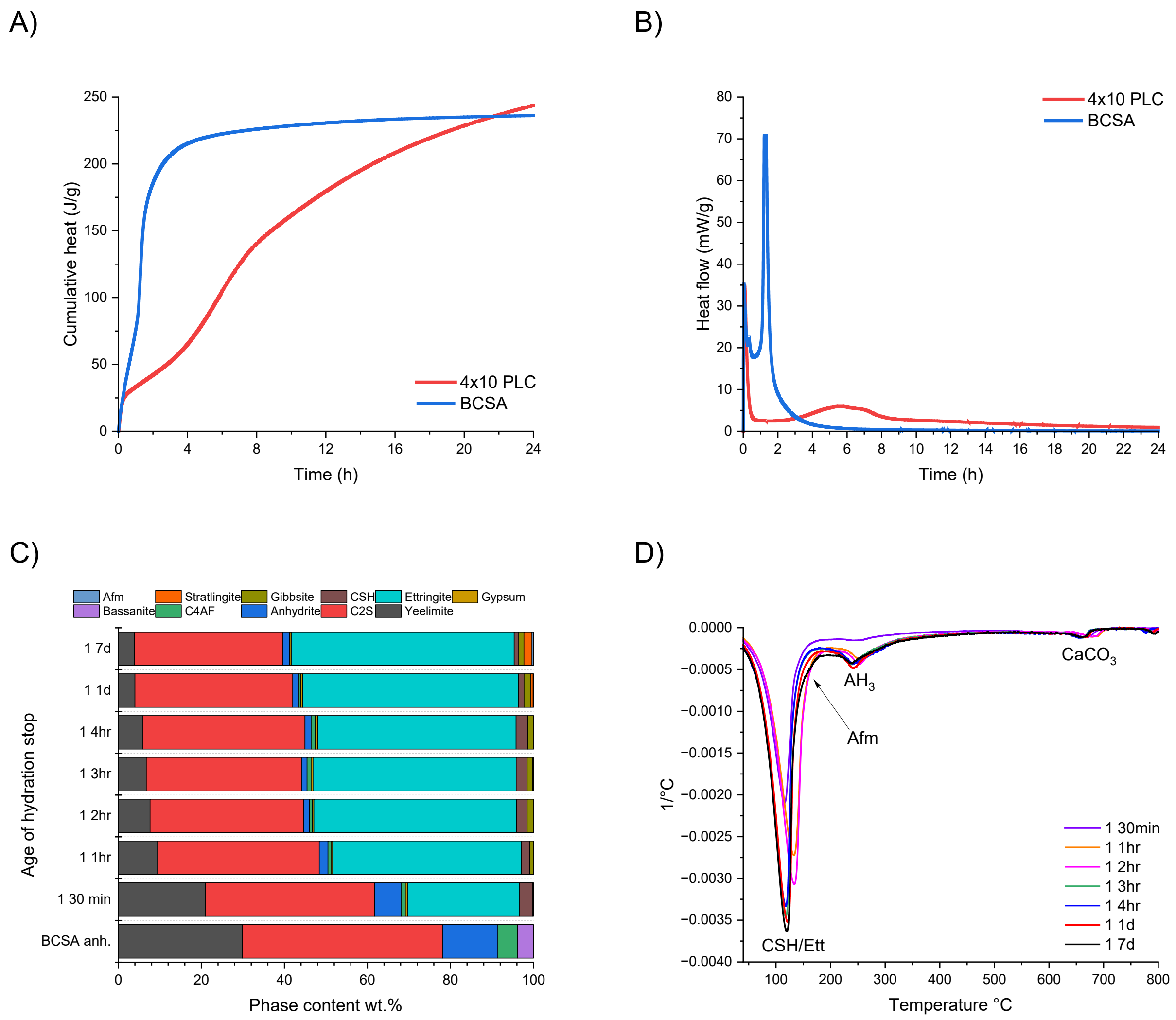

Figure 1 – All cement paste samples are prepared without additives and with water to binder ratio 0.5. (A) Cumulative heat release measured by isothermal calorimetry for BCSA compared with Type IL cement (4×10 PLC). (B) Heat flow of BCSA compared with Type IL cement. (C) Early hydration phase development of BCSA, measured from cement paste samples stopped at selected ages using the solvent-exchange method. (D) DTG curves of hydration-stopped BCSA samples.

BCSA concrete has been extensively used for full-depth pavement repairs, slab replacements, bridge decks, and airfield pavements where closure windows are extremely restricted. Long-term evaluations at major airports, including Seattle-Tacoma International Airport, have demonstrated that BCSA concrete pavements placed during overnight closures have remained in service for more than 20–25 years, often exhibiting continued strength gain over time (Ramseyer and Bescher, 2014).

In the United States, rapid-setting BCSA cements are commonly specified under ASTM C1600, a performance-based specification that allows agencies to define early-age strength requirements without prescribing cement chemistry.

3. TECHNICAL CHALLENGES OF COLD-WEATHER CONCRETE CONSTRUCTION

Executing concrete pavement construction during overnight closures in cold weather presents a combination of technical, logistical, and operational challenges. Cold temperatures reduce the rate of cement hydration, delay strength development, and increase the vulnerability of concrete to early-age freezing, which can irreversibly damage microstructure and durability if adequate strength has not been achieved (ACI306, 2016)

From a construction standpoint, overnight work windows typically range from 6 to 8 hours, including demolition, subgrade preparation, placing, curing, and verification of strength prior to reopening. Any delays in material delivery, batching, or placement can directly jeopardize reopening deadlines. These constraints are further intensified during winter, when ambient and substrate temperatures may be below freezing but also, wind and precipitation increase heat loss from fresh concrete. Conventional wet curing methods may be impractical or detrimental during cold weather scenarios (Mahmood et al., 2025)

Cold-weather concreting guidelines such as ACI 306R emphasize the need to control concrete temperature at placement, prevent early-age freezing, limit thermal gradients, and ensure sufficient early strength development. However, applying these principles within short nighttime closures requires careful coordination of material selection, mix design, construction sequencing, and curing strategies, particularly when rapid reopening is mandatory.

Prior field experience indicates that BCSA cement-based concrete can reliably achieve the required early-age strength and durability under cold conditions when Mix designs are optimized for temperature and workability and then, logistics are tightly coordinated, including ready-mix supply. Thermal protection and curing protocols have to be rigorously implemented (Darter et al., 2020)

The following sections present three case studies that illustrate how these challenges were addressed in practice across different infrastructure types and climatic conditions.

4. COLD WEATHER CASE STUDIES USING BCSA CONCRETE

This section presents three case studies illustrating the use of BCSA cement-based rapid-strength concrete for expedited construction under cold or operationally constrained conditions. The projects were executed between Winter 2024–2025 and Spring 2025 and include an airfield pavement rehabilitation, a highway reconstruction, and structural bridge link slabs. While the infrastructure types and environmental conditions varied, all projects required rapid strength development, strict reopening schedules, and robust performance under challenging placement conditions.

4.1. Summary of projects and construction context.

The three projects shared common constraints related to short construction windows, limited closures, and the need for early-age performance, yet differed in geometry, logistics, and performance targets. These differences provide a valuable basis for assessing the flexibility of BCSA cement-based concrete across applications.

4.2. Case Study 1 – Seattle International Airport (SEATAC) Pavement Rehabilitation

The first case study involved the overnight replacement of airfield concrete pavement slabs at Seattle International Airport during Spring 2025. The project was conducted under typical Pacific Northwest Spring conditions, with nighttime temperatures in the 50s °F (10 °C), and required strict adherence to operational constraints to ensure reopening before morning aircraft operations.

The pavement geometry consisted of jointed concrete slabs measuring 20 ft × 20 ft × 18 in. (6 m. x 6 m. x 18 cm.). Rehabilitation activities within each nightly closure included saw cutting, slab demolition, base preparation, installation of dowels and steel reinforcement mats, concrete placement, and curing. Due to the tight work window, all construction activities had to be carefully sequenced and executed within a single nighttime shift.

The concrete material used was a BCSA cement-based rapid-set concrete, incorporating lithium sulfate as an ASR-mitigating admixture. Unlike many expedited airfield projects that rely on on-site batching, this project utilized conventional ready-mix trucks, which required additional attention to mix stability, delivery timing, and consistency under rapid-setting conditions.

The primary performance requirement was achieving a flexural strength of 550 psi before reopening, typically before 5:00 a.m. each morning. The project demonstrated that with appropriate mix design engineering, logistics coordination, and curing practices, ready-mix-delivered BCSA concrete can reliably meet rapid reopening criteria for large-scale airfield pavement rehabilitation (Figure 2).

Figure 2 – Ready-mix concrete delivery on SEATAC slab replacement project.

4.3. Case Study 2 – Minnesota DOT (MnROAD) cold-weather highway reconstruction

The second case study focused on a highway pavement reconstruction project completed for the Minnesota Department of Transportation on November 26th, 2024, under freezing temperature conditions. Ambient air temperatures were approximately 30 °F (-1 °C) at the time of placement, increasing to 34 °F (1 °C) by the end of the day.

The scope of work consisted of constructing a 60 ft × 12 ft (18 m. x 3.65 m.) pavement section with a thickness of 6 inches (15 cm.), intended to replace a gap in construction that could not be completed with alternative materials due to adverse weather. Leaving the section incomplete posed a significant safety hazard during the winter season, necessitating an expedited permanent solution (Figure 3).

BCSA cement-based concrete was selected to address challenges related to cold base temperatures, low ambient air temperatures, and accelerated strength requirements. Concrete was produced and placed using a volumetric truck, allowing on-site control of mix proportions and fresh concrete temperature.

The project performance target was achieving 4,000 psi (27.5 MPa) compressive strength within 4 hours, enabling the pavement section to be safely completed despite freezing conditions. This case study highlights the effectiveness of BCSA concrete for emergency or late-season highway construction, where conventional solutions may no longer be viable.

Figure 3 – Highway pavement placement under freezing conditions using a volumetric truck.

4.4. Case Study 3 – Maryland Bay bridge link slabs

The third case study involved the construction of structural link slabs connecting consecutive bridge spans on the Maryland Bay Bridge between November 2024 and March 2025. Link slabs are structurally critical elements designed to accommodate movement while maintaining continuity between spans, and in this case featured very dense steel reinforcement (Figure 4).

Construction was conducted under night-only closures and strict reopening deadlines. Environmental conditions included ambient temperatures of approximately 50 °F (10 °C), combined with wind speeds reaching up to 10 mph (16 km/h), which increased the risk of heat loss during placement and early curing.

The concrete material used was a BCSA cement-based rapid-strength concrete, incorporating a liquid-lowP admixture to reduce permeability and enhance corrosion resistance—an important consideration for bridge applications in aggressive environments. Concrete was produced using a volumetric truck, enabling precise control during placement around congested reinforcement.

Performance requirements for the link slabs included:

- Low shrinkage, less than 0.04% at 28 days.
- 4,000 psi (27.5 MPa) compressive strength at 3 hours.
- Electrical resistivity values exceeding 21 kΩ-cm, indicating enhanced durability and reduced permeability.

This project demonstrates the applicability of BCSA concrete beyond pavement slabs, showing its suitability for structural bridge elements constructed under cold, windy, and highly constrained conditions.

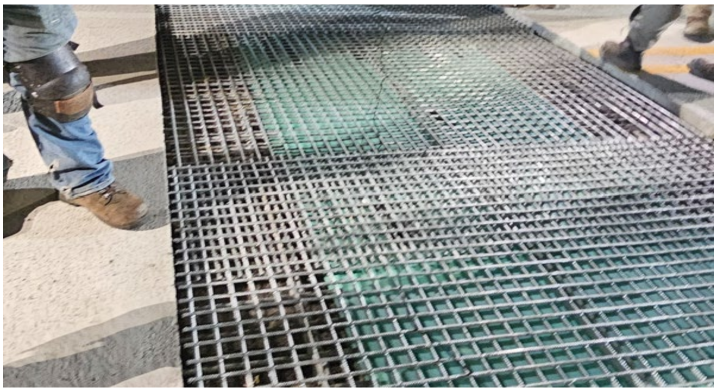

Figure 4 – Link slab reinforcement prior to concrete placement using BCSA concrete.

5. DISCUSSION

5.1 Toward a Performance-Based Framework for Rapid Concrete Construction

The results from the three case studies demonstrate that the governing parameter for accelerated pavement construction is not compressive strength at 28 days, but achievable strength at the time of reopening. Across all projects, compressive strengths in the range of 3,800–4,800 psi (26.2 - 33 MPa) were consistently achieved within 4 hours, regardless of infrastructure type or delivery method.

This suggests that rapid construction should be framed in terms of a performance index defined by strength-to-time. In practical terms, the relevant question is not whether a system meets conventional specifications, but whether it can reliably deliver sufficient structural capacity within the available construction window. The data indicate that BCSA cement-based systems provide a robust and predictable response in this context, enabling reopening timelines that are largely decoupled from the constraints typically associated with conventional concrete.

5.2 Temperature Is Not the Limiting Variable—Thermal Control Is

A key insight from the case studies is that ambient temperature alone does not govern early-age performance. While placements were conducted under conditions ranging from near freezing ~30°F (-1 °C) to moderate temperatures ~70°F (21 °C), early strength targets were achieved in all cases. Instead, performance was controlled by:

- Initial concrete temperature at placement
- Heat retention during early hydration
- Protection from convective and radiative heat loss

This distinction is critical. Cold weather does not inherently prevent rapid strength gain; rather, insufficient thermal management does. When appropriate measures—such as heated materials, insulated curing, and controlled logistics—are implemented, the hydration kinetics of BCSA systems remain sufficiently rapid, and the internal heat development is high enough to meet reopening requirements.

This challenges the conventional paradigm in which cold weather is treated as a limiting boundary condition, and instead reframes it as a controllable variable within the construction process. BCSA systems have also been successfully deployed in permafrost environments, further demonstrating that early-age performance can be maintained under extreme thermal conditions when appropriate thermal control strategies are implemented (Feng et al.).

5.3 Delivery Method as a Function of Risk and Temperature

Both ready-mix and volumetric delivery systems were shown to be viable; however, their suitability depends on environmental conditions and operational risk tolerance.

Volumetric mixing provides a distinct advantage under cold or highly constrained conditions by allowing real-time adjustment of water content, mixture temperature, amount and type of admixture and discharge rate. This flexibility becomes increasingly important as temperatures approach freezing, where small deviations in timing or temperature can significantly impact setting behavior.

Conversely, ready-mix delivery is effective for large-scale, repetitive operations when logistics are tightly controlled, as demonstrated in the airfield pavement project. However, its success depends on minimizing transport time variability and maintaining mixture stability during delivery. A practical interpretation is that ready-mix is efficient under controlled conditions and moderate temperatures. Volumetric systems become essential as environmental and logistical uncertainty increases.

The mix designs used across the three projects, summarized in Table 2, reflect the differing production methods, placement conditions, and performance objectives. Despite these differences, all mixes fell within the typical water-to-cement ratio range of 0.38 to 0.43, consistent with commonly reported values for BCSA cement-based concrete intended for rapid strength gain.

Table 2 – Concrete mix design of three case study projects.

Mix Design	units/m^3	SEATAC	MNROAD	BAY BRIDGE
Rapid Set Cement	kg.	386	390	390
Fine Agg.	kg.	702	699	756
Coarse Agg. 1	kg.	311	1151	1011
Coarse Agg. 2	kg.	565	0	0
Coarse Agg. 3	kg.	217	0	0
Water	liters	153	149	168
Air	%	5	6	5
Water Reducer	Liters/m^3	7.54	2.80	1.53
Air Entrainment	Liters/m^3	5.03	0.51	0.18
Retarder	Liters/m^3	4.95	0.00	1.02
Liquid LowP	Liters/m^3	0.00	0.00	2.55
water-to-cement	ratio	0.4	0.38	0.43
Unit weight	kg/m^3	2333	2392	2328

A key distinction between the mixes is the aggregate gradation of each project. The Seattle Airport mix incorporated four aggregate fractions, including #4, #8, and #57 coarse aggregates, enabling improved gradation and reduced paste demand. In contrast, the Minnesota DOT and Bay Bridge mixes used single coarse aggregate sizes (#67 and #57, respectively), consistent with volumetric production constraints.

Notable differences were also observed in admixture dosages, particularly air entrainment and retarders. Higher air-entraining admixture dosages were required for the airport pavement application to meet airfield durability requirements, while lower dosages were used for the structural link slabs. Retarder usage was minimal or eliminated in volumetric applications, reflecting the sensitivity of BCSA systems to overdosing—especially under cold conditions—which can significantly delay or suppress strength development.

The Bay Bridge mix incorporated a proprietary liquid low-permeability (“LowP”) admixture, intentionally selected to enhance durability, reduce chloride diffusion and increase resistivity in an aggressive environment. These mix design variations highlight the importance of tailoring BCSA concrete systems to the specific construction method, environment, and performance objectives

5.4 Strength Development and Microstructural Implications

The observed strength development across all projects follows a characteristic BCSA profile: rapid early gain followed by a reduced rate of increase at later ages. Fresh concrete properties (Table 3), measured in accordance with ASTM standards for slump, air content, unit weight, and temperature, demonstrate that all three mixes achieved high workability suitable for rapid placement and consolidation. Slump values ranged from 6.5 to 9 inches, reflecting the need for ease of placement during night operations and around congested reinforcement, particularly for the bridge link slabs.

Table 3 – Fresh concrete properties summary table.

Fresh Properties	Units	SEATTLE	MNROAD	BAY BRIDGE
Slump	cm.	16.5	17.8	22.9
Air (Pressure Meter)	%	4	5.8	3.6
Unit Weight	kg/m^3	2321.1	2261.8	2239.4
Concrete Temp.	°C	22.8	17.8	22.2

Measured air contents were consistent with project requirements and admixture dosages, while unit weights reflected aggregate gradation differences and air content variations. Concrete temperatures at placement ranged from 64 °F to 73 °F (17.7 °C to 22.7 °C) , confirming that temperature management strategies were effective even when ambient conditions were near or below freezing.

Compressive strength

Compressive strength testing (Figure 5) conducted in accordance with ASTM C39, confirmed that all mixes met or exceeded their early-age performance targets. Strengths at 4 hours (first data point) ranged from approximately 3,800 to 4,800 psi (26.2 to 33 MPa), supporting reopening requirements for both pavement and structural applications.

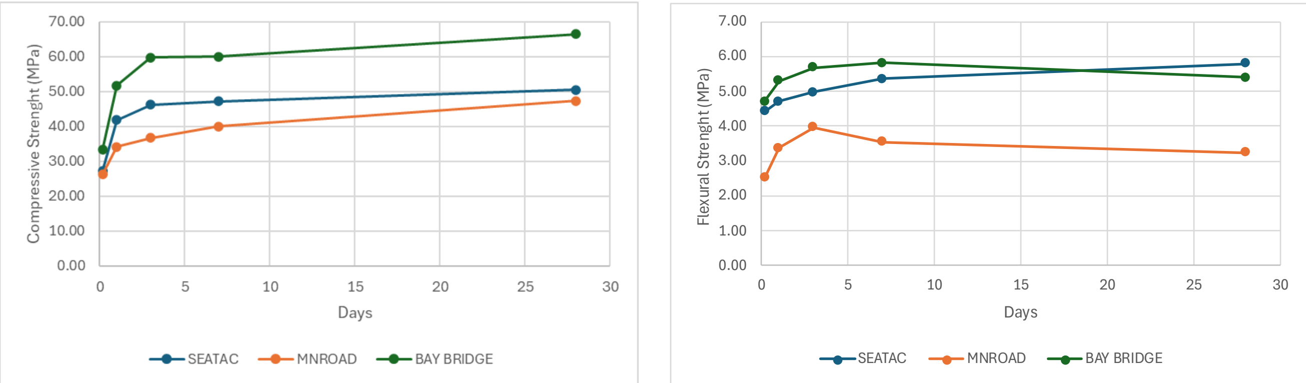

Figure 5 – Strength development (compressive and flexural) of BCSA concrete for all three projects

Flexural strength results (Figure 5), obtained in accordance with ASTM C78, showed that early-age flexural performance closely tracked compressive strength trends and was sufficient to meet opening criteria for all projects. Flexural strengths exceeded 550 psi at early ages where required, particularly for the airport pavement application. A slight reduction in 28-day flexural strength was observed in two of the three projects. Similar behavior has been documented in prior BCSA applications and is generally attributed to specimen preparation, curing variability, or testing sensitivity, rather than inherent material degradation. This conclusion is supported by the continued increase in compressive strength over the same period.

Strength gain between 1 and 7 days was rapid, followed by a more gradual increase through 28 days. This trend is characteristic of BCSA cement-based concrete and contrasts with the parabolic strength development commonly observed in Portland cement concrete. The early plateau in later-age strength does not indicate poor performance but rather reflects the rapid hydration kinetics of ye'elimite-based systems. This behavior reflects the underlying hydration mechanism, where early strength is dominated by rapid ettringite formation, while belite contributes to longer-term microstructural development. Importantly, the apparent plateau in later-age strength should not be interpreted as a limitation, but rather as a consequence of front-loaded performance. From an engineering perspective, this aligns with the functional requirements of rapid rehabilitation: structural capacity is needed within hours, not weeks.

Shrinkage

Drying shrinkage (Figure 6) was evaluated in accordance with ASTM C157. Results confirmed the low-shrinkage characteristics of the BCSA cement-based concrete across all projects. The Seattle

International Airport specimens exhibited the highest shrinkage magnitude, which is attributed to a modified curing protocol where drying commenced immediately after demolding at approximately 8 hours. In contrast, the Minnesota DOT and Bay Bridge mixes showed minimal net shrinkage, with some early-age expansion, a behavior consistent with ettringite formation in CSA-based systems. These findings support the suitability of BCSA concrete for large slabs and heavily restrained structural elements where shrinkage-related cracking is a concern.

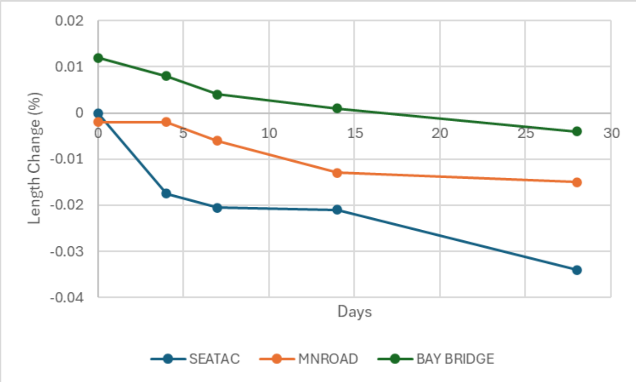

Figure 6 – Drying shrinkage / length change of BCSA concrete mixtures.

All mixtures exhibit low net shrinkage, with the Bay Bridge mixture showing early expansion followed by near-zero net dimensional change. MnROAD remains below 0.02% shrinkage at 28 days, while SEATAC shows higher shrinkage due to early drying conditions. These results confirm the low-shrinkage behavior of BCSA systems in both pavement and structural applications.

5.5 Rethinking Durability Metrics for Rapid Systems

Durability results, including high freeze–thaw resistance and a wide range of electrical resistivity values, confirm that rapid strength does not come at the expense of long-term performance. Selected durability indicators (Table 4) were measured, such as electrical resistivity (ASTM C1876) and freeze-thaw resistance (ASTM C666). Resistivity values varied significantly among the mixes, with the Bay Bridge concrete showing exceptionally high resistivity at 28 days. This performance is directly related to the use of the LowP admixture, which reduced permeability and enhanced resistance to ionic transport.

Table 4 – Durability performance of all three concrete mixes.

Durability	Units	SEATAC	MNROAD	BAY BRIDGE
Resistivity 28D	kΩ•cm	60	33.6	276
Freeze Thaw 300 cycles	DF (%)	97	99	98.5

All mixes demonstrated excellent freeze-thaw durability, with durability factors exceeding 97% after 300 cycles. These results confirm that BCSA cement-based concrete can achieve robust durability performance even when placed under cold-weather conditions, provided that curing and air-void systems are properly controlled.

However, the variability in resistivity—particularly the very high values observed in the LowP-modified system—highlights the need for caution when interpreting traditional durability indicators. In BCSA systems, pore structure evolution, self-desiccation, and admixture interactions can decouple resistivity from conventional permeability assumptions.
This suggests that durability in rapid-setting systems should be evaluated using performance-based criteria specific to the binder chemistry, rather than relying solely on metrics developed for Portland cement systems.

5.6 From Case Studies to Predictability

Several limitations were encountered across the projects, primarily related to weather sensitivity and reduced working time. Cold temperatures, wind, and exposed placement conditions reduced the available finishing window and increased the importance of precise sequencing. Mitigation strategies included:

- Use of heated mixing water.
- Preheating of substrate and keeping aggregates inside a controlled-temperature warehouse.
- Storing volumetric trucks indoors in a temperature-controlled environment prior to placements.
- Extensive use of insulated curing blankets

Retarder usage was carefully limited due to the sensitivity of BCSA cement systems—particularly at low temperatures—where overdosing can significantly delay or suppress strength development. Proper curing was identified as a critical success factor across all projects, reinforcing the need for disciplined curing practices in rapid-strength applications. However, taken together, the results demonstrate that rapid concrete construction can be treated as a predictable engineering system, governed by the interaction of:

- Binder chemistry
- Thermal boundary conditions
- Construction logistics

Rather than viewing each project as a unique challenge, the data support the development of generalized frameworks linking temperature, time, and strength.
This shift—from empirical case studies to predictive performance—represents a necessary step toward broader adoption of rapid-strength materials in critical infrastructure applications.

5.7 Binder Identity and Implications for Performance

An important distinction of the material system evaluated in this study is that the BCSA cement is entirely free of Portland cement phases, particularly alite (C_3S), which is the primary source of early strength in conventional concrete. In this sense, this also differentiates BCSA from traditional CSA cement, which typically requires mixing with Portland cement. This is illustrated graphically in Figure 7.

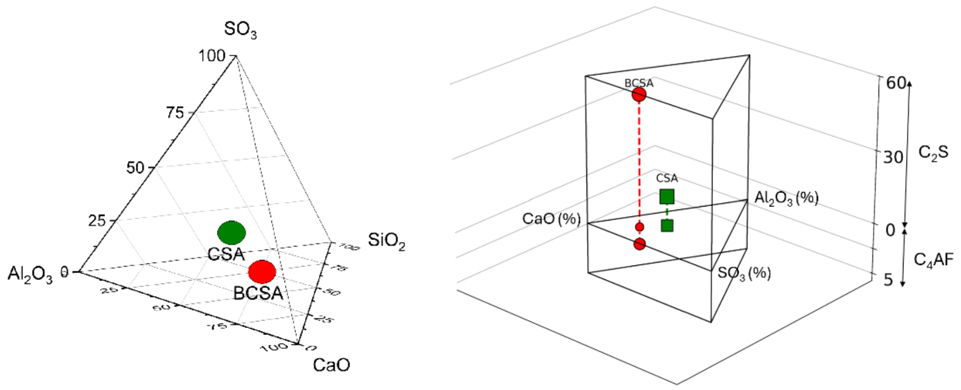

Figure 7 – A new illustration of BCSA & CSA cement systems, showing the use of SiO_2 in belite.

In many calcium sulfoaluminate-based systems reported in the literature, CSA clinker is used as a partial replacement within a Portland cement matrix, resulting in hybrid binders whose performance remains significantly governed by Portland cement hydration kinetics. In contrast, the system evaluated here derives its early strength exclusively from the rapid hydration of ye'elimite and the formation of ettringite, with belite contributing to later-age development. The prism on the right in Figure 7 shows the silicates present only in the C_2S phase, which is the cause of the low carbon footprint of the cement.

This distinction has two important implications. First, it explains the ability of the material to achieve rapid and consistent early strength development even under low-temperature conditions, as the governing hydration reactions differ fundamentally from those of Portland cement. Second, it reinforces the need for performance-based specifications that are independent of Portland cement assumptions, particularly with respect to strength development profiles and durability indicators.

Recognizing the binder as a non-Portland system is therefore essential not only for accurate technical interpretation but also for the broader adoption of alternative cement technologies in infrastructure applications.

Traditional assessments of concrete sustainability are typically expressed in terms of global warming potential (GWP) per unit volume of material (e.g., kg CO_2e/m^3). However, for rapid construction applications, this metric is incomplete, as it does not account for the functional performance required to reopen infrastructure. In accelerated pavement rehabilitation, the relevant performance parameter is strength at time of opening, not 28-day strength. Accordingly, a more meaningful metric is the performance-normalized carbon intensity (Bescher, 2025), defined as:

GWP / MPa at time of opening

Figure 8 compares the BCSA mixtures evaluated in this study with a representative accelerated Portland cement concrete designed to achieve comparable early-age strength. In practice, such Portland cement systems typically require cement contents on the order of 800 lb/yd³ (≈475 kg/m³) to approach 4-hour strength targets. In this comparison, the assumed GWP (per industry published values) for each of the BCSA and OPC binders was 673 and 919 kg CO_2eq/ton, respectively. Also, 475 kg/m³ of cement was assumed for the equivalent OPC concrete mixes.

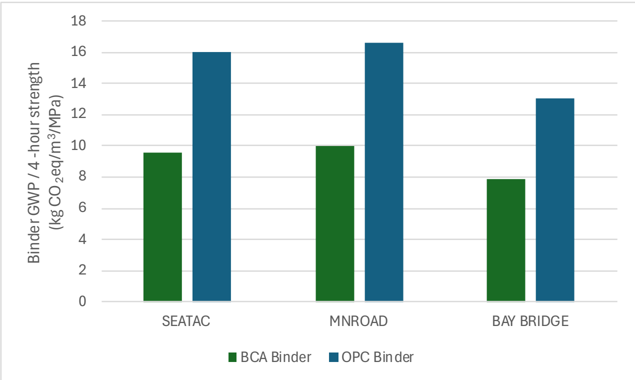

Figure 8 – Carbon Intensity of case study mix designs compared to portland cement-based mixes.

When normalized by early-age strength, the BCSA mixtures exhibit substantially lower carbon intensity. This is due to two combined effects: Lower binder carbon footprint associated with the absence of alite (C_3S) and reduced limestone demand, and higher early-age strength efficiency, allowing more structural capacity to be delivered per unit of CO_2 emitted.

This comparison highlights a critical point: carbon efficiency is not a material property alone, but a function of performance delivered at the relevant time at which the system is economically desirable. A system that achieves the required strength earlier inherently reduces the carbon intensity of the construction process when evaluated at the point and time of use.

6. PRACTICAL RECOMMENDATIONS FOR AGENCIES AND CONTRACTORS

The case studies presented in this paper demonstrate that BCSA cement-based concrete can be an effective solution for accelerated construction where conventional concrete systems are impractical. However, successful implementation depends on aligning material behavior, construction planning, and cold-weather practices. The following recommendations are derived from field experience and established guidance. BCSA cement-based concrete is particularly well suited for projects with highly constrained closure windows, early strength reopening requirements, and for those situations where user disruption, safety risk, or operational penalties justify accelerated construction. These conditions are typical of airfield and highway pavement rehabilitation and bridge reconstructions and other critical transportation infrastructure applications documented in past BCSA deployments (McNerney et al., 2020)

Agencies are encouraged to use performance-based specifications that define acceptance criteria such as early-age compressive or flexural strength, allowable shrinkage from time of return to service, or durability indicators, rather than prescriptive cement chemistry or mix proportions. This approach is consistent with ASTM C1600 requirements for rapid-hardening hydraulic cements and allows flexibility while maintaining accountability (CP Tech Center, 2025)

6.1. Key considerations for cold-weather use.

Cold-weather construction introduces additional risk for any cementitious system and must be explicitly addressed when using rapid-strength materials.

<u>Mix Design</u>

BCSA concrete mixtures should be proportioned to balance workability, setting time, and early strength development, accounting for ambient air, substrate, and material temperatures. Admixtures may be used to enhance durability performance or mitigate specific risks such as alkali–silica reaction or permeability, depending on project requirements (Isteri et al., 2024).

<u>Delivery methods and constructability</u>

Both conventional ready-mix delivery and volumetric mixing systems can be successfully used with BCSA cement-based concrete. Selection of the delivery method should consider project scale and nightly production demands, sensitivity of the mixture to transport time and site access and space constraints. Volumetric systems may be advantageous for cold-weather work or congested sites, while ready-mix systems can be practical for larger, repetitive slab replacements when logistics are well coordinated.

<u>Placement timing</u>

Because BCSA systems develop strength rapidly, placement operations must be tightly coordinated. Production, delivery, placement, finishing, and curing activities should be sequenced to avoid interruptions that could affect surface quality or early-age performance. This is particularly critical during nighttime or short-window construction.

<u>Curing methods</u>

Early-age curing should prioritize protection from freezing and excessive heat loss, especially in windy or exposed environments. Guidance from cold-weather concreting standards, such as ACI 306R, remains applicable and should be integrated with rapid-strength construction practices (Mateos et al., 2017)

<u>Quality control and workforce</u>

Rapid-setting concrete systems require heightened awareness from construction crews and inspectors. Agencies and contractors should provide project-specific training focused on sequencing and timing, conduct mock-ups or trial placements and establish clear communication protocols during placement and curing. Consistent quality control and disciplined execution are critical success factors for meeting reopening targets in rapid concrete construction (Tingle et al., 2024).

7. CONCLUSIONS

The case studies presented in this paper demonstrate that BCSA cement-based rapid-strength concrete is a practical and reliable solution for expedited pavement and structural concrete construction under cold-weather and operationally constrained conditions. Across three distinct infrastructure types—airport pavements, highway reconstruction, and bridge link slabs—BCSA concrete enabled construction to be completed within short nighttime or cold-weather windows, while meeting strict reopening and performance requirements. The projects confirm that early reopening of concrete infrastructure is achievable when rapid-strength materials are combined with appropriate planning, logistics coordination, and construction sequencing. The flexibility of BCSA systems was illustrated through successful use with both ready-mix and volumetric delivery methods, accommodating a range of geometries, reinforcement conditions, and environmental exposures.

In addition to rapid strength development, the applications highlighted the importance of low shrinkage and durability-oriented performance characteristics, particularly for structurally demanding elements such as bridge link slabs and airfield pavements subjected to heavy traffic loading. The ability to tailor BCSA concrete systems through admixture selection further supports their suitability for diverse project needs, including ASR mitigation and reduced permeability.

These projects reinforce the role of BCSA cement-based concrete as an effective tool for agencies seeking to minimize user disruption, extend construction seasons, and rehabilitate critical infrastructure under challenging conditions.. This is in addition to the low-carbon properties of the binder. In fact, performance historically preceded the interest in the binder’s low-carbon features. Importantly, the adoption of BCSA systems has historically been driven by performance requirements, particularly rapid strength development and dimensional stability, with reduced carbon footprint emerging as a consequential benefit. In this sense, performance comes first, and carbon follows.

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