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Fast Setting, Low Carbon Infrastructure Rehabilitation Using Belitic Calcium Sulfoaluminate (BCSA) Concrete

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Abstract. Rapid-setting binders such as Belitic Calcium Sulfoaluminate (BCSA) are increasingly important as the demand for rehabilitation and fast return to service of roads and bridges grows. Speed of construction, low shrinkage, and low carbon footprint are the key features of BCSA concrete. The binder was first developed in the United States in the mid-seventies. It allows pavement, bridge decks or other concrete infrastructure to be replaced and returned to service in a matter of hours. BCSA concrete slabs placed at the Seattle International Airport (SEA) in the 1990s are still in service 20 years later. The binder also allows innovation in pavement design. Taking advantage of the low shrinkage of BCSA concrete, a single 40 ft x 40 ft airport slab without joints was placed at this airport, as an alternative to the placement of four contiguous conventional-size portland slabs. BCSA was also to be the basis for the design of various rapid-setting performance-engineered concretes, such as low-permeability or UHPC concrete. This paper will review recent concrete applications based on BCSA cement, and the opportunities they offer in building a more resilient, lower carbon concrete infrastructure.

1 Introduction

The use of calcium sulfoaluminate (C4A3Ŝ) in cement was first investigated for the ability of its hydrates to expand and compensate the shrinkage of Portland cement [1]. In 1972, U.S. Gypsum developed a rapid-setting binder containing belite as its main component and calcium sulfoaluminate as its second largest by mass. The first industrial production of this cement took place in 1978, based on the Ost patent on VHE (Very High Early) cement. The term “belitic calcium sulfoaluminate” (BCSA) reflects the role of these two main compounds in the strength development of the concrete or mortar: calcium sulfoaluminate provides the early strength, and belite provides the later-age strength [2, 3]. In addition to fast-setting characteristics, this binder is sometimes referred to as a “low-energy” or “low-carbon” cement due to the lower limestone content and lower temperatures used during manufacturing, compared to Portland cement. Such characteristics have been documented in an Environmental Product Declaration [4]. As a non-portland, alternative cementitious binder, the material is also a focus of American Concrete Institute Committee 242 on alternative cements, which will shortly publish a proposed nomenclature for several types of CSA-containing cements. BCSA, as sold in the United States, meets the ASTM C1600 specification for rapid-hardening hydraulic cement, a performance-based specification built around early strength and other important durability characteristics such as low shrinkage, ASR or sulfate expansion. The binder was also recently issued a European Technical Assessment (ETA-19/0458) by the Deutsches Institut für Bautechnik, summarizing some of its key chemical and performance characteristics under European testing protocols.

In this paper, we discuss examples of the use of BCSA concrete in the field and we discuss some examples of performance-engineered mixes based on the binder.

2 Carbon Footprint

Increasing the sustainability of the built concrete environment is a necessity. Alternative binders and addition of SCMs are two of the most investigated avenues in order to lower the carbon footprint of traditional Portland Cement (OPC). Although BCSA cement was developed for its fast strength development, it is now also attracting attention as a low-carbon alternative to OPC. It is shown to be more environmentally friendly while also giving fast setting times, higher early strengths and lower shrinkage, compared to OPC. An EPD-LCA (Environmental Product Declaration – Life Cycle Analysis) was carried out to quantify the carbon emissions during production. BCSA was shown to emit 0.751 tons of CO_2 per ton of cement [5]. This indicates approximately a 25% decrease in carbon emissions compared to the typical 1 ton of CO_2 per ton of OPC cement [4].

It is unlikely that BCSA would, or even could, eventually substitute for OPC in the future, given the large amounts of Portland cement produced and the cost and challenges in procuring alumina-based raw materials. However, it is worth stressing that the manufacture of the binder can take place in Portland cement plants, which is

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an advantage compared to other proposed low-carbon binders currently investigated.

If one restricts the sustainability discussion to the field of rapid-setting binders, a comparison of the carbon dioxide intensity (CI) of different mixes is helpful [6]. It is defined as the amount of carbon dioxide emitted to deliver one unit of performance. The performance indicator for this discussion is chosen to be compressive strength. This concept explores the carbon footprint of a concrete per unit performance in MPa at a given age. Considering the unit performance at an early age, rather than at 28 days, a significant difference emerges between different binder chemistries. Carbon dioxide emissions for several rapid-setting mixes were calculated using the carbon emissions from the EPD and the mass percentages of each component of the concrete. The Carbon Intensity (kg/m^3 MPa) of these materials was then calculated using their compressive strengths and the total carbon emissions for each mix.

OPC, BCSA and other SCMs (LCC: Limestone-Calcined Clay and Calcium Hydroxide) were used to prepare mixes shown in Table 1.

Table 1 : Mixing Proportions for Sample Preparation.

Cement	Cement Content (kg/m^3)	CO_2 per m^3 (kg)	Carbon Intensity (tonnes/m^3 MPa)
BCSA	362	271.86	0.1
CSA-OPC	362	326.74	0.12
Accel OPC	474	492.96	0.18

It is known that a composite binder consisting of OPC and the limestone - calcined clay system (LCC) has shown promising results in lowering cement content and carbon emissions while maintaining mechanical performance [5]. Thus, the LCC system was included in the study to compare the BCSA cement performance against these other composite mixes. The LCC sytem was also tested with BCSA in an attempt to explore a further reduction in its carbon footprint.

early strength applications. Carbon dioxide emission values of 0.30 pounds per pound (0.14 kg per kg) of calcined clay and 0.78 pounds per pound (0.35 kg per kg) of calcium hydroxide produced were used for calculation. The Carbon Intensity and the compressive strengths for these mortars are shown in Figure. 1.

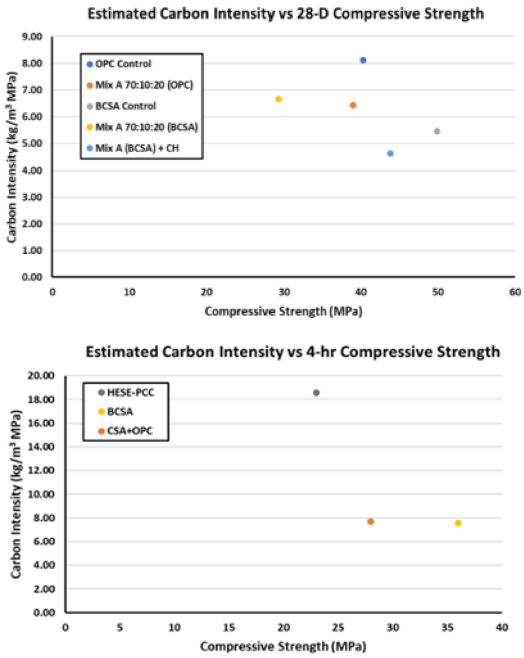

Figure. 1. Carbon Intensity vs compressive strength. (a) CI at 28 days (*top*), (b) CI at 4 hours (*bottom*).

The CI between different rapid-setting concretes giving the same performance (flexural strength of 2.75 MPa) was also calculated. The cement quantity required for BCSA, Accelerated OPC and CSA-OPC concrete mixes to achieve 2.75 MPa flexural strength at 4 hours was calculated [14]. These three rapid-setting concretes are commonly used in the rehabilitation of California concrete highways. The EPD numbers were used to calculate the Carbon Intensity of these mixes. The CI for these mixes is given in Table 2.

Table 2. Carbon Intensity (CI) for rapid-setting concretes of similar flexural strength (2.75 MPa at 4 hours)

Mass %	BCSA	OPC	Mix A BCSA	Mix A OPC	CSA-OPC	Mix A BCSA with CH
BCSA	100	-	70	-	-	70
OPC	-	100	-	70	40	-
Limestone	-	-	10	10	-	3.33
Calcined Clay	-	-	20	20	-	6.66
Calcium Hydroxide	-	-	-	-	-	20
CSA	-	-	-	-	60	-

BCSA binders have typical applications for very early strength concrete. Thus, experimentation for both, the early age (4 hours) and 28-days was done for the calculation of the CI. High early strength Portland (HESE PCC) had to be used for the early calculation as traditional OPC mix has slower set and strength gain. BCSA, and CSA-OPC mixes were also prepared for comparing the

Low carbon intensity and high compressive strength are desirable characteristics for such concretes. From Figure 1 it can be seen that for both, 4-hour and 28-day testing, pure BCSA samples showed the best performance. High early strength Portland cement mortar requires a higher sack content (i.e. more cement) to reach similar strength as BCSA in 4 hours, making the material much less sustainable. The LCC SCM made the OPC mixes more sustainable while maintaining performance but they were still lacking when compared to the pure BCSA mixes.

LCC is known to act like a pozzolanic material when used with OPC ,which maintains the compressive strength of the sample even at a lower cement content [5]. But in the case of BCSA, due to the different chemistry and hydration products, namely lack of lime, the addition of LCC leads to lowered strengths as shown in Figure 1 (a). This indicated that LCC was not as pozzolanic with BCSA as with OPC, but probably acts as more of a filler. Thus, addition of calcium hydroxide was explored when preparing a BCSA-LCC system, to recover the pozzolanic effect. But this addition offset the effective reduction in carbon emissions, which was the primary reason for the incorporation of LCC in the first place.

Looking at the CI values in the concretes from Table 2, similar early strength performance is achieved by the BCSA concrete at lower cement content, compared to CSA-OPC and accelerated OPC. Overall, BCSA gave the lowest CI with the highest compressive strength, compared to standard OPC and OPC - SCM mixes. These results indicate that BCSA is a promising alternative binder for its unique properties and low CI, especially when comparing rapid setting concretes on the basis of early strength gain. Composite binders like OPC-LCC and Portland Limestone Cement (PLC) are becoming more widespread in the industry. A BCSA-OPC mix or a BCSA-OPC-LCC mix make an interesting case for early strength, more sustainable binders. The results in this study show the potential of alternative binders and calls for detailed cost and performance-based studies with these composite binder systems.

3 Full-depth concrete pavement replacement for airports

Airports worldwide face a need for rapid, sometimes overnight, rehabilitation of runways and taxiways. The rapid strength gain of BCSA cement concrete make such rapid pavement rehabilitation strategies feasible [**7**]. In fact, BCSA cement has been used in concrete pavements at airports around the world for nearly 30 years. It is possible to achieve compressive strengths in excess of 30 MPa in 2 hours.

Several major airports across the United States and throughout the world already have experience with full-depth rapid slab repair and replacement using rapid-setting materials. Examples include Atlanta Hartsfield Int'l (ATL), Boston Logan Int'l (BOS), John F. Kennedy Int'l (JFK), Seattle-Tacoma Int'l (SEA), Los Angeles Int'l (LAX), Dubai Int'l (DXB), Amsterdam Schipol (AMS), and Sydney Int'l (SYD).

The Seattle-Tacoma International Airport (SEA), has a 25-year history of successfully placing such full-depth concrete slabs using rapid-setting BCSA cement on runways, taxiways, and aprons, and returning such pavements to service overnight [8]. More than 500 runway panels have been placed on SEA's runway 16R/34 over a span of 13 years. Photographs showing the construction and location of these slabs at SEA are shown in Figure 2.

Figure 2. Photographs showing the construction of runway slabs at SEA : preparation of base (*top left*) ; newly placed concrte slab (*top right)* ; extraction of a section of concrete slab for performance evaluation (*bottom left*); Aerial view of the location of runway slabs (*bottom right*).

The process of overnight rehabilitation of concrete runway slabs using BCSA cement usually takes 2 nights of operation, however, at some airports including Sydney (SYD) and Melbourne (MEL), pavement removal and replacement is completed within a single night. At the SEA airport, the 2-night pavement rehabilitation work involves the following steps: (a) on the first night, saw cutting operation or demolition of the existing slab is carried out along with the preparation of the base and installation of dowel bars and temporary precast panels, and (b) on the second night, temporary precast panels are removed, a single mat of rebar is placed over each slab, just above the dowel bars, and fresh concrete is poured and levelled using a conventional roller screed.

This is followed by further finishing steps such as the use of a bull float, a Fresno trowel finisher, and surface tining or grooving. The final step of the second night involves curing the concrete surface using water curing. Other airports often use curing compounds as the final step of this pavement rehabilitation work. The 2-night pavement rehabilitation work is shown in Figure 3 and Figure 4. One BCSA slab was recently removed for performance evaluation after nearly 25 years of service. Figure 5 shows the cutting the concrete slab into beams or bar samples for mechanical testing and evaluation. An example of a concrete bar cut from the SEA airport slab is shown in Figure 6. Concrete cylinders (100 mm x 200 mm) were also cored from this slab.

The average compressive strength of the cored cylinders per ASTM C42 was 9,605 psi or 66.2 MPa, and the average flexural strength of the bar samples per ASTM C78 was 875 psi or 6 MPa (the opening strength was 550 psi or 3.8 MPa). Petrographic evaluation of the cores revealed siliceous coarse and fine aggregates (0.8 in. or 20.3 mm top size) in a hardened BCSA cement paste. No signs of cracking or visible distress were found in the concrete cores.

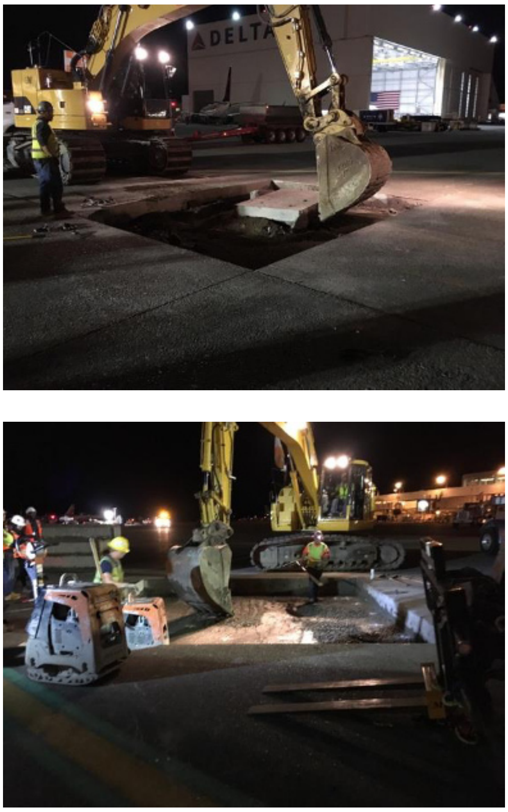

Figure 3. First night of runway slab rehabilitation work at SEA airport : excavation and removal of exisiting panel (*top*) ; preparation of base material and compaction (*bottom*)

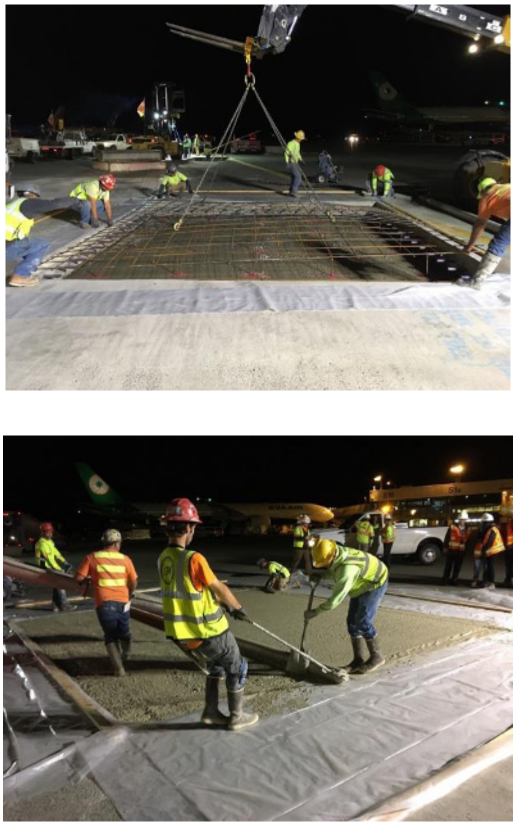

Figure 4. Second night of runway slab rehabilitation work at SEA airport : placement of single mat of rebar after removing the temporary panels (*top*) ; pouring and leveling of mixed concrete (*bottom*).

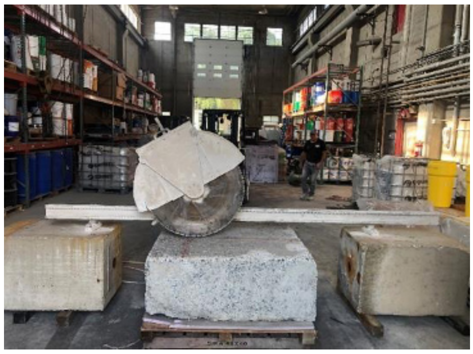

Figure 5. Cutting operation of one of the BCSA concrete slab obtained from SEA airport.

Figure 6. Example of a concrete bar cut from the SEA airport BCSA concrete slab.

Air content was found to be between 7% to 9%. An SEM examination was also conducted, which revealed a uniform and dense microstructure for the paste in the concrete body. No evidence of deleterious chemical reactions such as alkali-silica or alkali-aggregate reaction was observed. The average carbonation depth based on the phenolphthalein method was found to be 0.5 in. (± 0.1 in.) or 12.7 mm (± 2.5 mm). Figure 7 shows a saw-cut cross-sectional surface of a cylindrical core treated with pH indicator (phenolphthalein) solution, which imparts a magenta stain to high pH, non-carbonated paste, but does not stain carbonated paste.

The experience at SEA airport shows that BCSA concrete slabs, which have a very different chemistry from that of Portland cement concrete, exhibit good durability in the field, at least in the Seattle climate.

While BCSA concrete has a demonstrated use in replacing slabs, the low shrinkage of the material can also be used to improve pavement design. Typical U.S. Federal Aviation Administration (FAA), guidance for the construction of concrete slabs is for slabs be constructed 18.75 feet (5.72 m) wide by 18.75 feet (5.72 m) or 20 feet (6.1 m) long. But this guidance applies to Portland cement concrete. The lower shrinkage of BCSA concrete compared to OPC (about 25%), could allow for an increase in joint spacings. A slab quadruple the size of a standard airfield slab was proposed [9]. A schematic of how this quadruple-sized slab would modify the design of a conventional runway is shown in Figure 9.

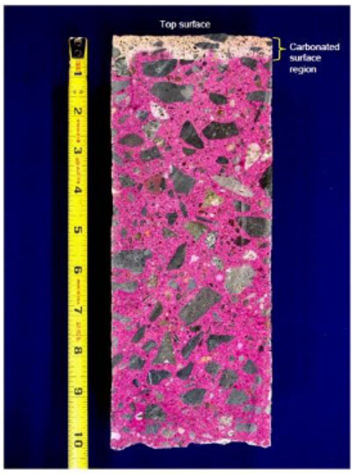

Figure 7. Cross-section of the concrete cylindrical core obtained from SEA airport slab showing the depth of carbonated surface.

The placement of a pilot quadruple-sized 11.3 m^2 (37.5 ft^2) BCSA slab in Anaheim, California in 2015 is shown in Figure 8. The pilot slab was constructed monolithically, in a few hours and without construction joints. This was possible because of the unique chemistry of BCSA, which affords rapid strength gain and low shrinkage.

Figure 8. Placement of the quadruple-sized (11.43 m x 11.43 m or 37.5 ft. x 37.5 ft.) BCSA concrete test slab.

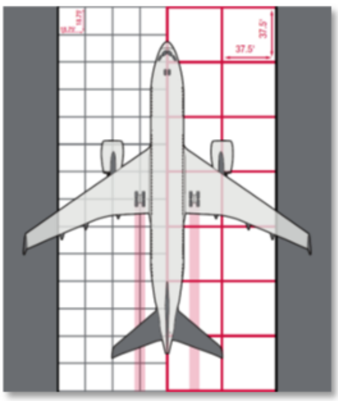

Figure 9. Schematic of a quadruple-sized runway slab compared to conventional runway slabs.

Based on the experience gained from this pilot slab, a similar large slab was placed at the Seattle airport in November 2019. It met the opening strength requirements of the FAA (550 psi or 3.8 MPa flexural strength), in 2 hours. Eight vibrating wire strain gauges (VWSG) were embedded at different depths and orientation to track the slab dimensional changes over the duration of a year. VWSG collect strain data by measuring the frequency of a wire within its structure. The dimensional change of the concrete imparts a strain on the wire which can be "plucked" like a guitar string to measure a frequency. This frequency is then converted into strain units using the LogView datalogging software. The overall expansion and contraction of the slab can be calculated by averaging data from the two sensors. The VWSGs in the longitudinal direction were the Geokon G4210 (0.36 m or 14 in. long) and the VWSGs in the transverse direction were Geokon G4200 (0.15 m or 6 in. long), as seen in Figure 10.

Figure 10. Longitudinal VWSGs Geokon G4210 (left) and Transverse VWSGs Geokon G4200 (right).

In addition, the curling and warping of the airport slab was determined by measuring the difference in sensor readings between the top and the bottom of the slab. The average sensor readings from VWSGs located in the center of the slab fluctuated in the range of +25 $\mu\varepsilon$ to -130 $\mu\varepsilon$, and the average sensor readings in the corner of the slab fluctuated from +40 $\mu\varepsilon$ to -60 $\mu\varepsilon$. This dimensional change is considered very low when compared to Portland concrete slabs. Overall, the data obtained from embedded vibrating wire strain gauges showed very little dimensional change and curling of the slab, and they even show the slab developing a slight convex geometry.

Despite concerns that a concrete slab of such large dimensions would crack into quarters, neither the 2015 Anaheim proof-of-concept slab, nor the 2019 SEA large test slab at two years have exhibited cracking to date. These field reports and collected data demonstrate an innovative use of BCSA cement in concrete pavement, and can potentially improve construction productivity and protocols, refine slab designs, and allow overnight placement of four contiguous, conventional-sized portland concrete slabs with a single concrete slab on an active taxiway.

Regarding cement specifications for airfield pavement, under the FAA AC 150/5370-10 specification, item P-501 lacks a provision for accelerated construction or pavement rehabilitation using rapid-setting materials like BCSA cement. The P-501 section specifies Portland cement per ASTM C150 as well as cements meeting ASTM C1157. However, most cements used for rapid concrete rehabilitation do not meet the C150 specification for initial setting time due to their rapid-setting characteristics. Also, the P-501 does not provide sufficient details on accelerated construction methods, testing protocols, and/or material section to help airport engineers with construction under very short closure times. In most instances, *ad hoc* materials and construction specifications must be developed for airport concrete pavement. However, a recently published Airfield Cooperative Research Program or ACRP Research Report 234 [10] titled "Rapid Slab Repair and Replacement of Airfield Concrete Pavement", which is sponsored by FAA, suggests that ASTM C1600 cements can be used as rapid setting materials.

4 Full-depth concrete pavement replacement for highways

In the late 1990s, the Department of Transportation in California (Caltrans) initiated a project on the fast rehabilitation of the aging freeway constructed between the 1950s and 1970s. With the ever-increasing traffic, not only were freeways subjected to higher ADTs (average undesirable as they would adversely impact the travelling public. Thus, Caltrans collaborated with contractors and suppliers to develop new methods, materials, and skills for fast-track concrete placement. The Interstate I-10 Pomona Freeway in Los Angeles, California with an ADT of 240,000 was chosen as the demonstration project to rebuild 2 lane miles of pavement for a 40-year design life. Specifications were developed to utilize what was then known as Fast Setting Hydraulic Cement Concrete (FSHCC), calling for minimal flexural strengths of 2.75 MPa to open to traffic and 4.2 MPa at 28 days to resist fatigue loads. Though there were a few initial setbacks with concrete delivery and equipment malfunction, this project was completed successfully within the allotted one weekend of night closures and it is still in service to this day [11].

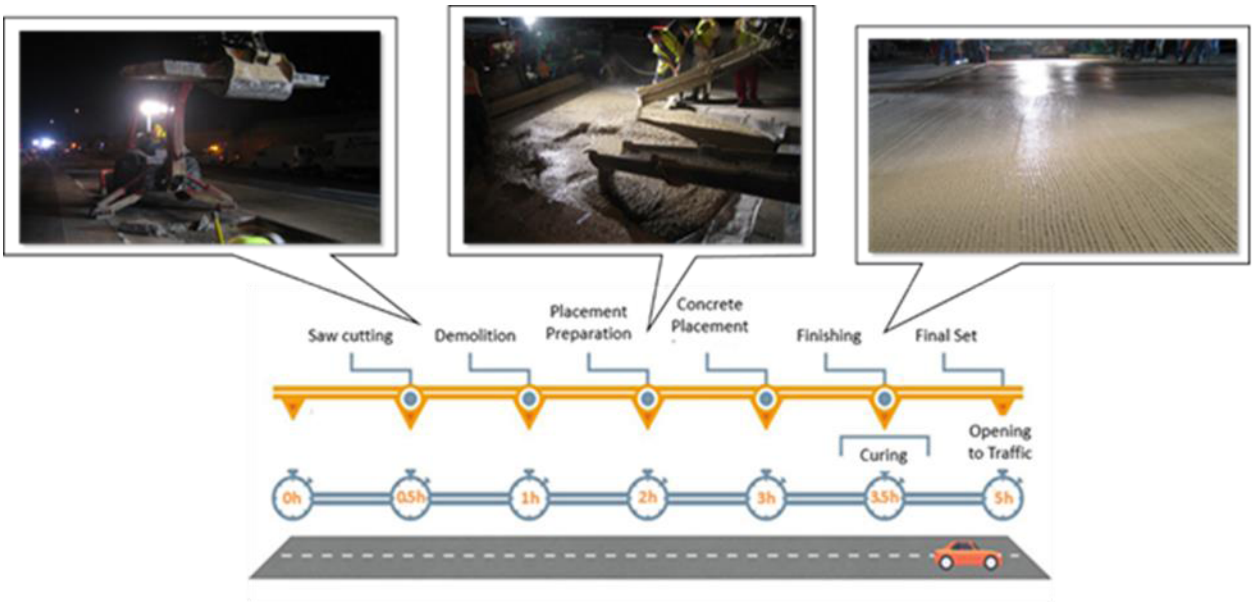

Figure 11. Timeline of a fast-track rehabilitation for a highway concrete pavement using BCSA cement.

daily traffic) but long construction closures were Caltrans' initative with fast-track construction using FSHCC made its way into other applications - namely, the overnight full-depth individual slab replacement program using rapid-setting concrete as specified in Section 41-9 of the Caltrans specification [12]. This minimizes traffic disruptions by closing just one or two lanes of the freeway for no more than 5-8 hours, usually late at night when traffic is the lightest. During this time, the damaged slabs are removed, the subgrade and any steel/dowel bars prepared, and the rapid setting concrete such as BCSA is placed and finished (Figure 11). The concrete achieves 2.75 MPa in 1 ½ - 2 hours (4.5 MPa in 3 days) and the pavement is open to traffic by early morningFrom a safety perspective, it is important to note that a rapid repair strategy using BCSA cement concrete substantially reduces the amount of time a construction worker is at risk onsite.

A construction site has numerous safety concerns for both the construction workers and passing vehicles or pedestrians. The Associated General Contractors of America (AGC) reported work zone crashes and fatalities have increased by 42% since 2013 [9], and despite the lower traffic volumes during the COVID-19 pandemic, the number of incidents still rose in 2020 [12].

To date, over 1300 lane-kilometres of BCSA cement concrete pavement have been placed in California alone [13]. Many state DOTs such as New York, Washington, Virginia, Colorado, Massachusetts, and Ohio have developed their own specification for fast-track construction. These specifications can be descriptive (e.g., opening flexural strengths, drying shrinkage limits) or, more rarely, prescriptive (e.g., cement composition, cement manufacturer), but when defining the rapid setting binder to use for Rapid Setting Concretes of RSCs, ASTM C1600 is typically used.

There are many types of concrete systems that fall under the definition of RSC. This simple nomenclature, can hide important differences between all these types of RSC in terms of mineralogies, binder compositions, and respective characteristics. The market for RSCs can be broadly categorized into three binder systems: 1) single, standalone cement such as BCSA, 2) binary or ternary cement with BCSA and OPC, and 3) portland cement accelerated with additives. All three can achieve the necessary strength in mere hours but may differ in other characteristics such as cement content, w/c, type and amounts of additives and drying shrinkage. In fact the three systems exhibit significant differences in shrinkage. BCSA cement concrete is a single, standalone cement system and because of its mineralogical composition and hydration kinetics, it develops strength rapidly and exhibits very low shrinkage [14].

The RSC system was once viewed as a temporary repair material until a more permanent solution could be implemented. However, an investigation in the long-term performance of RSC slabs on the California freeways reports that after approximately 13 years of service carrying 1 to 34 million trucks in their respective lanes, a large majority of the slabs exhibited no significant distress and were expected to last several more years. Less than 10% of the surveyed slabs experienced transverse (fatigue) cracking, which was the most prevalent stress type due to repeated truck loadings and upward curling slabs. Other distresses such as corner cracking, spalling along joints, and other longitudinal cracking totaled to less than 2% of the slabs [15]. The notion that RSC slabs have more durability problems than conventional concrete is outdated as emerging cement technologies, such as BCSA cement concrete, and improved pavement design, show that fast rehabilitation and durability are not mutually exclusive concepts. It should be noted that the use of BCSA cement was to some extent built on the growing use of volumetric (or mobile) mixers. Volumetric mixing is the preferred delivery method of BCSA cement concrete because of the material's fast-setting properties. It provides the contractors with the flexibility to adjust concrete rheology, workability, or setting time in real-time to accommodate work conditions. The delivery of the concrete takes place on-site and no significant retardation is needed. Examples of the use of volumetric mixing and placement of concrete are shown in Figure 12 and Figure 13.

Figure 12. RSC application in Massachusetts over one weekend to avoid disruption to weekday traffic.

Figure 13. RSC pour by Wagman Concrete Group in Virginia.

BCSA concrete can also be delivered using ready-mix trucks if the concrete mix is sufficiently retarded to allow transit time. A large 20 km project on the Mexico-Queretaro highway, the most heavily trafficked highway in Mexico, was rehabilitated using BCSA concrete retarded with citric acid and shaved ice during warm weather conditions.

5 Fast-setting, low-permeability concrete repair (bridge decks)

Since the 1950s, styrene butadiene has been used with hydraulic cements to produce latex-modified concrete (LMC), which is now used by Department of Transportation (DOTs) across the nation as a method to extend the service life of bridge decks. Compared to traditional concrete, the properties of LMC are: higher resistance to chloride-ion ingress, better freeze-thaw resistance, and greater bond strength to substrates [16]. A survey of transportation agencies reports that LMC can extend the overlay service life by about 14 to 50 years, depending on environmental conditions and construction quality [17]. ACI Committee 548 wrote the specifications for LMC (ACI 548.4-11) to detail mix proportions, performance guidelines, and construction procedure. To keep up with the demand for fast return-to-service projects, Rapid Setting Latex-Modified Concrete (RSLMC) based on BCSA was developed and first utilized by the Virginia Department of Transportation in the 1990s, and then quickly found its way through the Mid-West and South-East regions of the United States.

ACI 548 Section 3.3 specifies BCSA cement to be used for RSLMC projects that need to reopen to traffic in 3 hours. For projects in which liquid latex cannot be used due to equipment or logistical issues, BCSA cement can be also be preblended with functional powder additives. The prepackaged cement can be mixed with aggregates by conventional methods to produce fast-setting, low-permeability concrete (marketed as "Low-P" BCSA). A key property of these overlay materials is the ability to reduce water and chloride ion ingress. This is tested using ASTM C1202 – Rapid Chloride-Ion Permeability Test (RCPT, unit: Coulombs) and, more recently, correlated with AASHTO T358 – Surface Resistivity (SR, unit:

kΩ·cm). Figure 14 shows the increase in SR and the decrease of chloride ion permeability with the alternative BCSA cement systems compared to a conventional portland mix [18].

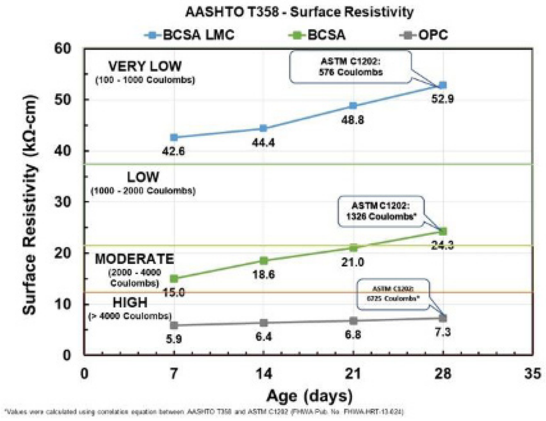

Figure 14. Surface Resistivity vs. Time for alternate BCSA systems compared with OPC.

Low permeability can also be evaluated by measuring the chloride diffusion coefficient. This is generally considered to be a better indicator than surface resistivity as it directly measures the ion penetration in a mixture. Other publications have mentioned a lack of correlation between electrical methods (i.e. surface resistivity) and actual measurement of the concrete pore structure [19]. A technical report from the National Concrete Pavement Technology Center (NCPT) investigated the chloride diffusion coefficient for different alternative cement systems (i.e. BCSA cement, calcium aluminate cement, alkali-activated cement, etc.). The diffusion coefficient for OPC remains largely unchanged after 35 days of hydration, but for BCSA, significant improvement could be seen after 90 days. Furthermore, diffusion coefficient in Low-P BCSA was 10 times lower than that of OPC, after 35 days of hydration. This can probably be ascribed to interaction between the organic-inorganic additive and the developing microstructure of BCSA. It is speculated that the polymer reduces pore connectivity and lowers the permeability [20]. The report also examines other durability aspects of alternative cement systems such as alkali-silica reactivity, sulfate attack, freeze-thaw resistance, etc. of which low-permeability BCSA cement concrete performs as well as, if not better, than conventional OPC concrete.

It is also possible to use a liquid admixture compatible with BCSA cement to produce low-permeability concrete at 1/100th by weight of the dosage of the latex in RSLMC. This can be appealing to contractors or projects that are unable to accommodate the use of large amounts of latex and it allows concrete mobile mixers to conveniently alternate between production of standard pavement concrete to low-permeability concrete, with minimal interruptions in mixing operations. Preliminary results indicate that concrete produced with the liquid admixture are comparable to other rapid setting, low-permeability concrete overlay systems.

With inherently low shrinkage, rapid strength gain, low permeability properties, and lower carbon footprint, these performance-engineered BCSA-concretes are interesting materials for rapid bridge rehabilitation projects.

6 Ultra-High Performance Concrete

Ultra-high performance concrete (UHPC) is attracting attention due to its use in accelerated bridge construction and other high-performance applications in infrastructure rehabilitation. The Federal Highway Administration (FHWA) characterizes UHPC as a cementitious composite material that requires a lower water-to-cementitious materials ratio, and a proportionate amount of discontinuous internal fiber reinforcement [21]. There are other definitions. Currently, the FHWA is working with the American Association of State Highway and Transportation Officials (AASHTO) to develop a guide specification for UHPC. This guide plans to refine the definition of UHPC and to supplement existing design specifications. However, the UHPC material must exhibit key attributes: high compressive strength, tensile strength, and durability [22]. Other organizations, such as ASTM International (formally known as American Standard of Testing and Materials), cite that UHPC is a cementitious material with a compressive strength of at least 120 MPa, generally containing fibers having properties that comply with specified durability, ductility, and toughness requirements [23].

Although there is no consistent definition of UHPC, well-known key features include high tensile strength, excellent bonding to other concrete substrates, low permeability, and a compressive strength that is typically greater than 96 MPa. These traits have garnered much attention as they are greatly compatible for projects that require high durability in highway infrastructure, compared to normal strength concrete. This section describes how the rapid setting characteristics of BCSA, can yield a Rapid-setting UHPC (RS-UHPC).

The past decades have shown significant improvements in UHPC formulations. The typically dense microstructure allows for the material to achieve high tensile strength and low permeability, due to a combination of low water demand and a composition of fine materials [24]. Adding fibers to UHPC improves the mechanical properties of the concrete. The fibers can be steel, mineral or synthetic, and have a variety in size and shapes. Fiber-reinforced UHPC has been used to repair structural components, build bridge closure joints and stay-in-place formwork. Furthermore, fibers can extend the service life of UHPC by improving tensile and flexural strengths [25]. However, early strength is not a typical feature of UHPC, which typically requires long curing time. In many instances, such as a bridge closure, this is a drawback. It is often desirable to re-open to traffic overnight. BCSA can be used as a base binder to achieve this goal. Further, the low energy characteristics of BCSA afford RS-UHPC a lower carbon footprint.

Figure 15 shows an example of compressive strength development in a steel fiber-reinforced RS-UHPC exhibiting 55 MPa at 4 hours and 121 MPa at 28 days. While the addition of steel fibers enhances the characteristics, RS-UHPC adds the additional desirable quality of fast strength gain in addition to the high 28 day-strength.

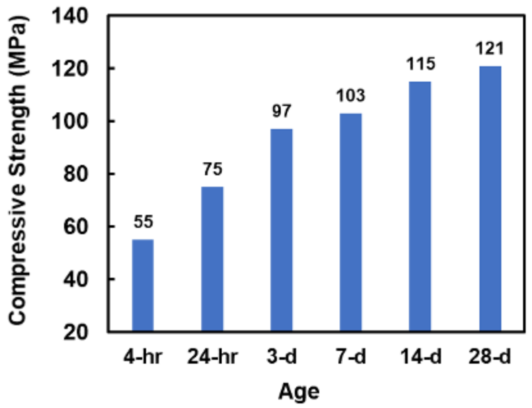

Figure 15. Compressive strength vs. Age for BCSA cement-based UHPC.

Another desirable characteristic of UHPC is its high tensile strength. The inclusion of fibers in a BCSA UHPC mixture increases the tensile strength at very early ages. Fiber-reinforced UHPC can effectively inhibit the initiation and expansion of cracks and provide further crack-bridging effects under tensile stress [26]. Splitting tensile strength is RS-UHPC based on BCSA reached 9 MPa at 2 hour, and 13 MPa at 4 hours (Figure 16).

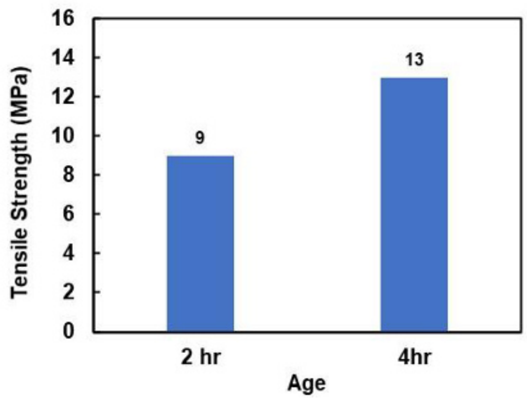

Figure 16. Early-age splitting-tensile strengths of fiber-reinforced RS- UHPC based on BCSA.

While high compressive and tensile strengths are key performance characteristics, UHPC must also exhibit excellent bonding capabilities to substrates. Figure 17 shows the bond strength to the concrete substrate, with a value reaching 26 MPa in 2 hours and 31 MPa in 24 hours making it a suitable candidate for rut repairs and other specialty applications. The bond strength was measured using ASTM C882, a slant shear bonding test, where freshly-mixed concrete is cast to a bonding area of a 30° vertical angle mortar cylinder that ultimately determines the compressive strength. Evaluating the strength that has been developed by a bonding system that joins two regions of concrete is the primary significance of this test [27].

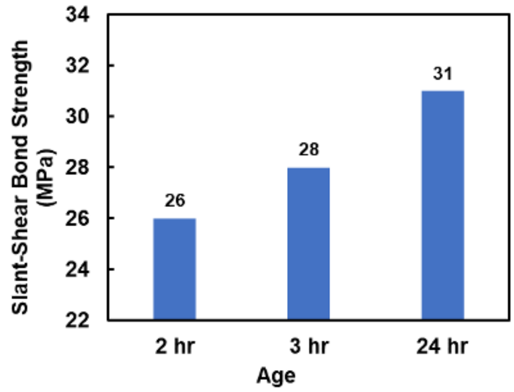

Figure 17. Compressive strength vs. Age for BCSA cement-based UHPC.

RS-UHPC was recently placed as a rut repair application in Washington State, as shown in Figure 18. In some parts of the US, extensive concrete wheeltrack damage can occur in the winter due to the use of studded tires or chains. RS-UHPC material can be a suitable solution to repair this damage when closure times are very short.

Figure 18. BCSA UHPC placed 2 inch-deep and to a featheredge on a concrete substrate and cured (*left*). It was subsequently diamond-ground (*right*). The material bonded well with the concrete

A high bond strength to the substrate is key to maintain a smooth profile after grinding. If UHPC exhibits low strength or does not bond very well to the substrate, the grinding process can cause removal or de-bonding of the UHPC material; and therefore, surface profiling can become an issue. With RS-UHPC, the diamond grinding can be done the day of placement. High bond strengths and exceptional grindability were achieved near the featheredge as well. This is probably due to the very high strength of the material.

BCSA-UHPC offers substantial sustainability benefits due to both the intrinsic low carbon fotoprint of the binder and the relatively low cement content of the concrete. BCSA-UHPC can provide a unique combination of characteristics: high compressive strength, high bond strength, high tensile strength at early ages without compromising its key performance such as freeze-thaw resisitance. With many bridge repairs and designs in need to repair under short closure times, RS-UHPC is an additional tool for the civil engineer interesting in rapid concrete infrastructure rehabilitation.

7 Conclusions

Belitic calcium sulfoaluminate cement is a low-carbon, single binder successfully manufactured and marketed in the United States for more than 40 years. The core characteristics of the binder are fast strength gain, low shrinkage and low carbon footprint.

The binder meets the ASTM C1600 spefication for raid-setting cements. BCSA concrete pavement has been in service in the United States for over 40 years in various climates. Concrete specifications have evolved over time, and many US Departments of Transportation have developed their own. Contractors have also developed their own construction practice around the rapid setting characteristics of the mix. The binder offers opportunities in rapid concrete pavement rehabilitation and also in improving design, for example in taking advantage of the low shrinkage to allow increasing the joint spacing in concrete pavement. The durability of BCSA concrete pavement in the field has been demonstrated, at the Seattle Airport, where slabs placed in 1997 are still in service and performing well and showing a continuing increase in strength over 25 years.

The basic properties of the binder can be enhanced with the use of conventional admixtures such as retarders or superplasticizers. Innovative admixtures allow the design of performance-engineered rapid-setting concretes, such as rapid-setting ultra-high performance concrete (RS-UHPC), low permability mixes, or dowel bar replacement mixes.

Finally, the carbon intensity of BCSA concrete (carbon footprint per unit strength performance) is appealing especially when compared to rapid-setting portland-based concrete mixes requiring high cement contents to achieve early strength.

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