High-Early Strength Concrete for Rapid Bridge Deck Repair and Rehabilitation

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A thesis

submitted in partial fulfillment of the

requirements for the degree of

Master of Science

University of Washington

2024

Committee:

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Program Authorized to Offer Degree:

Civil and Environmental Engineering

University of Washington

Abstract

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With an ever-increasing demand for bridge deck rehabilitation due to aging infrastructure and increasing traffic demands, bridge deck overlays are used as a viable economic and environmentally cost-effective solution for prolonging the service life of a bridge. These overlays typically share the same characteristic of fast-setting and high-early strength development to minimize traffic disruptions, however, current methods do not typically address rehabilitation at varying levels of deterioration or make use of expensive non-cementitious materials.

This research investigated the use of belitic calcium sulfoaluminate (CSA) cement to determine highest performing mix designs and surface preparations, to aid in the implementation and identification of a cement-based alternative repair material. An extensive experimental testing program resulted in nine slab specimens that were cast, overlayed, bond tested, and evaluated to

identify the best performing BCSA mix designs, surface preparations, and admixtures. Various overlay and substrate laboratory specimens were also tested to identify fresh and hardened concrete properties which were essential in understanding overlay-to-substrate compatibility for long-lasting repairs.

The results of the testing program indicate that BCSA cements show high potential to be successful in accelerated overlay applications. BCSA cements tested in this studied exhibited fast-setting and rapid strength gain, reaching minimum opening strength thresholds from various state agencies within a day. When compared to the conventional portland cement substrate cast in this study, BCSA cements exhibited much lower drying shrinkage, and no cracks were observed in the overlays cast. Polymer modified BCSA cements exhibited exceptional bond strengths higher than performance criteria specified for ultra-high-performance overlays by Caltrans (>400 psi) and comparable to bond strength requirements for polyester polymer concrete (500 psi). Bond testing results indicate that polymer modifying BCSA cements leads to significant increases in bond strength.

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CHAPTER 1 INTRODUCTION

1.1 Project Motivation

Bridge deck preservation programs are essential in protecting critical infrastructure from severe structural deterioration and preventing bridge deck serviceability related issues. Preservation programs throughout the country have long been underfunded [1], which has led to a backlog of structurally deficient bridges in need of repair. As infrastructure continues to age, more bridges will have either met their expected service life or will develop structural deficiencies due to bridge deck durability related issues (e.g. freeze-thaw cracking, chloride induced corrosion, etc.). The Washington State Department of Transportation (WSDOT) projects that the State's cumulative bridge deck areas that are in poor condition will grow to between 8.5% to 12.1% by 2027, potentially exceeding the Federal Transportation Performance Management Act's 10 % threshold [2].

If bridge decks in poor condition are not addressed promptly, the structural integrity of the deck and superstructure could be compromised, leading to bridges being load restricted or permanently closed. Proactive mitigation can be done for a fraction of the economic and environmental cost of complete replacement and can, therefore, reduce the impact of long-term closures for the traveling public. These rehabilitation strategies can range from small patch repairs to full deck overlays, which provide additional protection from deleterious substances, such as deicing salts and can increase load capacities or extend the service life of bridges. Due to increased traffic demands, especially in dense urbanized areas, such preservation efforts often require rapid turnaround to ensure minimal traffic disruptions and sometimes rapid mobilization for emergency repairs. Therefore, the long-term success of such preservation programs is heavily reliant on the availability of reliable repair materials that are characterized by rapid strength gain, excellent substrate-to-overlay bond strengths, and superior durability. High early strength concretes (HESC) are possible materials that meets these criteria and are the focus of this research program.

Figure 1.1 summarizes economic impacts of traffic delays in the United States. Traffic delays have a negative impact on the economy due to inefficient fuel consumption in heavy traffic [3] and heavily congested roads in work zones lead to increased traffic collisions that affect societal crash costs [4]. These associated expenses translate to an annual cost of $8.1 billion and $36 billion for the United States, respectively. Although construction-related activities do not account for all of the associated traffic delay costs previously mentioned, they are responsible for 10% of traffic congestion nationally [4]. HESC materials are desirable to state DOTs for repair work because the process of mixing and placing them is familiar to contractors and the curing and strength gain of the concrete occurs rapidly, hardening to significant levels of strength in a matter of hours. This allows for concrete repair work to be done relatively quickly, when compared to conventional concretes, minimizing disruptions to the traveling public.

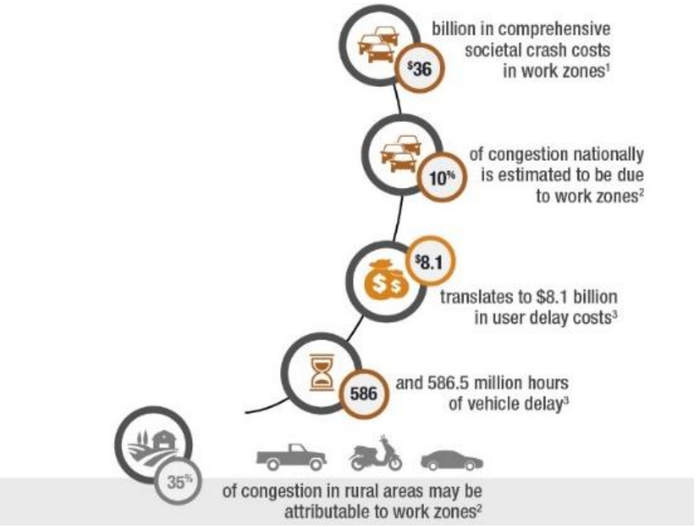


Figure 1.1: Economic Impacts of Traffic Delays from [4]

HESC binders can be broadly categorized into two main types: cementitious binders (e.g., Type III, calcium sulfoaluminate, or magnesium phosphate) and non-cementitious polymer binders (e.g., polyester or poly methyl methacrylate). Cementitious binders that consist of portland cement typically include various additives to achieve high early strengths among various other desirable properties. Examples of concrete materials that have been developed specifically for overlay and repair applications include polyester polymer concrete (PPC), ultra-high performance concrete (UHPC), calcium sulfoaluminate concrete, and latex modified portland cement concrete.

Polymer concrete exhibits rapid set times and high early strength making it a suitable candidate material for overlay and repair applications. Polymer concrete utilizes a composite system of binder, aggregates, and fillers to achieve specific properties based on their relative proportions [5]. The binder used in this system is non-cementitious and is most often polyester or epoxy resin. These polymer resins harden through the use of initiators or catalysts, and accelerators, producing a material similar to traditional concrete made with hydrated cement.

Many state agencies, including WSDOT, have some experience in the implementation of PPC overlays [6]. Although most PPC applications have been limited to thin overlays, due to its shortcomings, they help define its applicability range in rehabilitation strategies. The main limitations of PPC are the safety and handling of polymer-based binders, its susceptibility to temperature, and its associated cost. The cost of PPC is much higher than OPC making projects requiring significant structural rehabilitation and/or improved load capacities unfeasible, due to the high cost in producing a PPC overlay thick enough to provide any additional structural support [5], [6], [7]. PPC overlays are thus more commonly used for wearable surface applications where the primary objective is to extend the lifespan of the superstructure. It is relatively common for new bridges to be overlaid with PPC prior to being opened to traffic.

The set times of PPC can be modified by increasing the quantity of accelerator used. Once polymer resins are polymerized by the decomposition of initiators, accelerators are used to modify set times based on ambient temperatures and working time needed, as they increase the decomposition rate. Since the set times of PPC is sensitive to ambient temperatures, a wide range of accelerators and catalysts are available that, together, perform better under certain temperatures. However, it is important to note that these components that help harden polymer resins can pose a safety concern for those working with these binders [7]. The individual components can be highly flammable and have the potential to emit noxious fumes. Therefore, careful transportation and storage is essential as well as proper ventilation and personal protective equipment.

There is also concern about PPC overlay's performance under low and high heat environments. While low temperatures are primarily a concern prior to hardening, it can affect set times and overall quality of the overlay if not managed properly. Typical ranges for which PPC overlay construction is recommended are 45° F to 90° F [6]. PPC overlays are also highly susceptible to high heat environments once hardened. It was reported that PPC saw a 25% reduction in strength and stiffness when subjected to an increase in temperature ranging from 68° F to 120° F [6].

While PPC provides exceptional protection to the existing substrate, the aforementioned challenges often restrict PPC to thin overlays. The application of PPC overlays is extremely useful where low clearance is a concern and when the existing superstructure does not need extensive rehabilitation. PPC has proven to have a number of benefits including high bond strengths, low shrinkage, good skid resistance, exceptional abrasion resistance, high chemical resistance, provides minimal additional dead load, and has very low permeability [6]. Overall, PPC overlays are useful in mitigating further deterioration but do not directly address bridge deck rehabilitation.

UHPC has garnered attention in overlay applications, in part due to its success as a structural closure joint material between prefabricated bridge elements. UHPC is a highly engineered portland cement-based concrete created to achieve outstanding properties. UHPC’s main constituents are portland cement, fine sand, high range water reducers, supplementary cementitious materials (SCMs), and steel fibers. The FHWA defines UHPC as a cementitious based concrete, with discontinuous fiber reinforcement, achieving compressive and tensile strengths greater than 21.7 ksi and 0.72 ksi respectively, while exhibiting enhanced durability properties [8]. UHPC achieves such high strengths due to its low water-to-cementitious (W/CM), ratios ranging from 0.18 to 0.22 [9], and through the addition of a high volume fraction of steel fibers, greater than 2% by volume. Workability is maintained at these low W/CM ratios through the use of high range water reducers. UHPC also has superior durability properties due to dense particle packing through minimal to no inclusion of coarse aggregates in mixture designs. Dense particle packing through adequate use of fine sand, fibers, and high cement contents produces a low porosity system [10]. As such, it has been reported that UHPC inhibits water and chemical permeation up to two orders of magnitude higher than OPC.

While UHPC exhibits high tensile and compressive strengths that could be useful in many applications, its implementation as an overlay material has been hindered by its high upfront cost, despite some researchers arguing that the long-term savings due to the lower maintenance and greater longevity of UHPC, when compared to conventional repair materials, could offset the higher upfront cost [11]. Additionally, due to extremely low water contents, UHPC may also suffer from plastic shrinkage cracking that can lead to lower quality concrete due to environmental conditions during casting [11]. While UHPC can attain high compressive strengths in the long-term, early strength gain is heavily dependent on ambient conditions and set accelerators do not seem to make significant improvements [11]. As such, final set times have been reported to range from 5 to 20 hours, similar to conventional cementitious concrete [8].

Polymer modified concrete overlays have been the primary overlay type used by most state agencies, although the specifications between state agencies vary considerably and may not necessarily lead to high early strengths. For example, the Washington State Department of Transportation (WSDOT) does not allow for the use of Type III cement in modified concrete overlays [12]. Overlay applications in Washington specify the use of Type I/II cement which leads to a minimum of 42-hour cure times. Strength verification tests are then performed to determine if the overlay has met the minimum threshold of 3000 psi that is required before reopening to traffic. Although some experimental studies have been done on small overlay sections using Type III cement in the state of Washington [13], Type I/II continues to be the preferred cement type. Other state agencies have allowed the use of Type III cement in modified concrete mixture designs and have had success in truncating cure times.

The use of Type III cement in latex modified concrete produces what is known as high early strength latex modified concrete (LMC-HE). LMC-HE has the same benefits of improved overlay-to-substrate bond strengths, improved durability, lower permeability, and enhanced workability that is inherent when modifying concrete with polymers. However, LMC-HE utilizes Type III cement that is rich in alite, albeit at much higher cement contents, to produce concrete that can achieve the 3000-psi minimum threshold within 24 hours of casting [13], [14]. The use of Type III cement is not without challenges; Type III cement can produce high temperatures due to the exothermic reaction that can lead to thermal cracking and poor durability. Previous implementations of LMC-HE overlays have largely assuaged these concerns, presumably because the overlays were relatively thin and the polymer modifiers effectively mitigated durability issues.

It is important to note that the short-term permeability of LMC-HE is higher than latex modified concrete (LMC) but decreases over time to be equivalent at an age of about 26 weeks [14].

While the benefits of LMC and LMC-HE has led to its widespread use, polymer modified concrete continues to be susceptible to plastic shrinkage cracking. Plastic shrinkage cracking occurs when the evaporation rate exceeds the bleeding rate. Polymer modified concrete consists of lower water contents than conventional concrete, leading to less bleed water, and therefore are more susceptible to cracking if conditions are right [10]. Plastic shrinkage cracking mitigation efforts, based on forecasted temperatures and wind conditions, are therefore carefully evaluated but cracking remains prevalent.

Despite the many possible solutions for bridge deck repair and overlays, each is not without its challenges, especially when high early strength is necessary. Consequently, there is an urgent need in identifying, characterizing, and implementing sustainable and advanced high-early strength concrete (HESC) materials to support rapid bridge deck rehabilitation.

1.2 Belitic Calcium Sulfoaluminate (BCSA) Concrete

This research investigated the use of belitic calcium sulfoaluminate cement (BCSA) as a repair material for rapid bridge deck rehabilitation and repairs. BCSA is a standalone hydraulic cementitious material that qualifies as very rapid hardening (VRH) per ASTM C1600 [15], owing to the mineral ye'elimite ($C_4A_3\overline{S}$) in its composition. Ye'elimite in the presence of calcium sulfates rapidly hydrates to form ettringite ($C_6A\overline{S}_3H_{32}$). This rapid ettringite formation leads to early-age expansion resulting in a lower or neutral long-term shrinkage stress development and thus, reduced cracking potential. It also produces rapid set times (15 minutes) and strengths exceeding 3000 psi in 3 hours. In addition, BCSA contains significant amounts of belite (C_2S), which is the compound responsible for long-term strength gain in conventional portland cements. Therefore, BCSA can exhibit high early strength and rapid setting characteristics without significantly compromising long term strength development as well as durability.

While the main incentive of using BCSA cement is its rapid strength gaining properties, it has also been shown to be a more durable and sustainable alternative to OPC. BCSA having lower amounts of tricalcium aluminate (C_3A), is more resistant to sulfate attacks than OPC. Additionally, its much lower porosity leads to improved durability in areas prone to freeze-thaw cycles [16]. The absence of alite (C_3S) in a ye'elimite driven system leads to lower temperatures required for calcination which reduces the amount of fuel needed to produce the cement. Due to BCSA's lower limestone composition, it also emits less carbon during calcination. Together, BCSA production results in a 30-35% reduction in carbon emissions in comparison to traditional portland cement [17]. This reduction is significant when considering that the production of cement is responsible for about 5% of total global anthropogenic carbon emissions [18].

While many states agencies have adopted the use of BCSA in repair applications, the California Department of Transportation (Caltrans) has had success in both large- and small-scale rehabilitation projects. Following the Northridge earthquake in 1994, BCSA was used to repair the approach slab of the La Cienega overpass on the I-10 Santa Monica Freeway [19]. BCSA materials were mixed and transported similarly to conventional concrete with the addition of retarding admixtures to allow for transit. This was the first time that Caltrans had used BCSA concrete, and this project's success led to further widespread use for fast-track repairs. Many of the smaller projects where BCSA was used were due to contract change orders to replace portland cement with BCSA. Contract change orders were approved owing to savings from increased efficiency in concrete production during the same construction windows, even with BCSA's higher upfront cost [20].

Table 1-1 summarizes major projects completed by Caltrans using BCSA [20]. Subsequent projects became even more ambitious with much larger volumes of rapid setting BCSA concrete. Large scale pours however, had some resistance but the Task Force created by the Long Life Pavement Team (a specialized team focused on the research, development, and implementation of long-lasting pavements for Caltrans) facilitated rapid setting cement's acceptance in large rehabilitation projects. In 1997, 600 cubic yards of BCSA were placed under the direction of the Task Force utilizing a central batch plant, mixing trucks for transportation, and a 12-ft wide slip form paver. These efforts to expand the use of BCSA in California culminated in 1999 with the I-10 Freeway in Pomona, an multi-award-winning project, that used BCSA in large scale repairs (over 20,000 cubic yards of BCSA were poured) [20].

Table 1-1 Major Projects Completed by Caltrans Utilizing BCSA [20], [21]

Project Name	**Location**	**Year Completed**	**Scope of Work**	**BCSA Cement (cy)**	**Notes**
I-110 Freeway	Los Angeles, California	1995	Panel Replacements	50	---
I-10 Freeway	Los Angeles, California	1996	Panel Replacements	180	---
I-605 Freeway	Los Angeles, California	1997	HOV Lane Addition	600	Central batch plant was used with 12-ft wide slip form paver.
60/71 Interchange	Los Angeles, California	1998	Large Scale Paving Operation	4,000	Central batch plant was used with 24-ft wide slip form paver. 100° F daytime temperatures.
I-5 Freeway	Burbank, California	1999	Panel Replacements	100 per shift	Central batch plant was used to batch aggregates and water into mixing trucks. Cement was added using supersacks. Nighttime temperatures below 45° F.
I-10 Freeway	Pomona, California	1999	Large Scale Paving Operation	20,000	Work began Friday night and by Monday morning 5,000 cubic yards were placed. Nighttime shifts over the span of multiple days placed the remaining 15,000 cubic yards.
I-280 Freeway	San Fransico, California	2014	Bridge Deck Hinge Replacement	130	Significant structural repairs were completed on a bridge that routes traffic to and from San Fransico. [21]

Figure 1.2 shows an I-208 freeway bridge hinge that was replaced and reopened to traffic during a holiday weekend in 2014 using BCSA cement. While bridge deck overlays are the most widely used application for BCSA, it has been proven that it is also a viable material for significant structural repairs. BCSA can fast-track significant structural rehabilitation as was evident in 2014 on the I-208 freeway where bridge deck hinges were replaced. This project was completed within 100 hours and compressive strengths reached 1200 psi and 3500 psi in three and four hours

respectively. Furthermore, it is reported that the hinges have an estimated service life of 60 years and have not shown any signs of distress as of 2018 [21].

Figure 1.2: Hinge Replacement on I-208 Freeway from [21]

While California has completed the most rehabilitation work with BCSA, there are some other notable instances in which BCSA has been used in the US. For example, runway panel replacements at SeaTac Airport in the state of Washington were completed using BCSA in 1994. The use of BCSA in this project resulted in a 53.5% cost reduction due to lower replacement rates when compared to OPC panels [22]. This application demonstrated that the relatively high upfront cost of BCSA can be offset by long term savings due to lasting repairs and its rapid strength gaining properties. When compared to OPC panel replacements cast at the same time as the BCSA panels, the nearly two times longer service life of BCSA panel replacements leads to an even lower carbon footprint than the reduced carbon emissions from production alone may imply. It was also evident from this application that BCSA shows continual long-term strength development that is typically not characteristic of fast-setting and high-early strength cements. This is evident from BCSA cores that had strengths nearly twice that of the samples tested within 24 hours of pouring [22].

Overall, BCSA has shown promising results in previous studies and applications, but more research is needed to fully understand the characteristics of these materials (including bond), which are needed to develop guidelines and specifications for the use of BCSA as an overlay repair material.

1.3 Mixing and Placement of HESC

High early strength materials, such as BCSA, exhibit rapid set times therefore conventional mixing methods may not be feasible. Contrary to rapid setting cements, OPC mixes are typically produced at batch plants and transported on-site using ready-mix trucks. Delays due to traffic conditions or accelerated set times due to high temperatures are well managed through the replacement of water with ice and/or the addition of retarding admixtures. With BCSA, the time to initial and final set are much lower (on the order of an hour) which can lead to complete loss of concrete and/or equipment due to concrete setting in the truck or extreme slump loss during transit. While the use of ready-mix trucks to place BCSA concrete is certainly possible, precise logistical planning is required to ensure that all variables and potential obstacles are accounted for and addressed. This could lead to batch plants utilizing excessive amounts of citric acid retarders which would be detrimental to the high early strength development and rapid set times that is essential for accelerated construction windows.

Figure 1.3 summarizes volumetric mixer components and their respective purpose. Volumetric mixing trucks have thus been the primary way of producing BCSA concrete in rehabilitation projects. Volumetric mixing trucks are popular in BCSA applications owing to their ability to mix dry batched materials on-site as needed. While ingredients are dispensed by a batch plant into ready-mix trucks by weight, volumetric trucks measure concrete constituents by volume instead. This requires initial calibration to ensure that the concrete volume produced is as expected, and that fresh concrete properties meet specifications. Improper calibration can lead to performance issues due to incorrect mixture proportions therefore, the success in mixing using volumetric trucks is heavily reliant on the operator’s ability to produce consistent concrete. Homogeneity is also a concern in volumetric truck mixing. This is because the aggregates, binder, water, and admixtures are held in compartmentalized containers and mixed using an auger. While the material passes through the auger, it is continually mixed, however this mixing is short lived and only around 15 seconds of mixing is achieved.

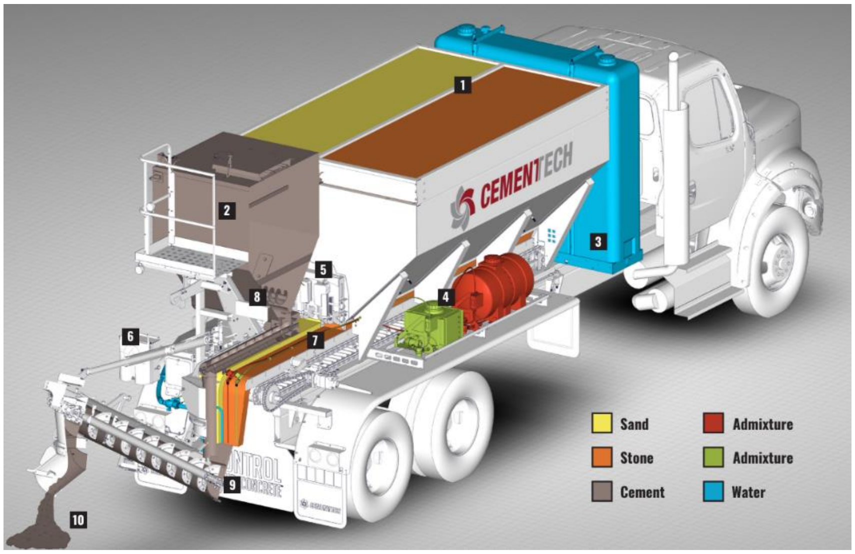


Figure 1.3: Volumetric Mixing Truck Components from [23]

(1) Sand and stone compartments. (2) Cement in sealed and watertight compartment. (3) Water tank compartment. (4) Admixture tanks. (5) Sand and stone gates. (6) Operator controls. (7) Sand and stone transported to auger. (8) Cement bin meters quantity deposited into auger. (9) Auger continuously mixes concrete. (10) Mixture deposited out of discharge chute.

Since concrete mixing is done on-site, little to no citric acid retarder can be used, leading to rapid strength gain and reopening to traffic is possible within hours of mixing. Other advantages include less waste, since concrete is mixed as needed, and mixture designs can be adjusted by changing mixture proportions as needed. Volumetric trucks are also not limited by transit time allowing for concrete to be poured even in remote locations. However, due to the wide use of OPC and ready-mix trucks, volumetric trucks may not be readily available in some areas. This has led to make-shift “volumetric mixing” where aggregate is loaded into a ready-mixture truck at the batch plant, and BCSA is added on-site by pouring super-sacks into the drum prior to mixing.

1.4 Report Organization

BCSAs are gaining the attention of many state agencies, owing to their rapid setting and high-early-age strength gain, which can be leveraged to accelerate project delivery and shorten the duration of on-site concreting activities. These cements have great potential to be successfully used in repair and overlay applications, especially when minimal traffic disruption is crucial. The primary objectives of this research project were to determine high performing BCSA based mixture designs and evaluate their bond properties. These objectives were accomplished by monitoring fresh and hardened concrete properties to quantify each mixes’ workability and working time as well as strength development over time. Optimum mixture designs were then tested in direct tension using the pull-off test method as outlined by ASTM C1583 [24]. These pull-off tests were performed following a robust testing matrix which includes polymer modified BCSA’s as well as various levels of surface preparation to determine whether truncating preparation activities is also possible.

The document is organized as follows:

- **Chapter 2: BCSA Literature Review** presents a comprehensive review of past experimental research involving BCSA material properties and supplemental additives used, that are applicable to this research project.

- **Chapter 3: Experimental Test Program** summarizes the hardened and fresh concrete testing program for the preliminary and selected optimum BCSA mixture designs as well as the conventional concrete substrates cast for pull-off testing,

- **Chapter 4: Mixture Design Optimization** describes the preliminary mixture design optimization including mixing procedures and test results, including variables that affected workability and the strength development of each mixture design.

- **Chapter 5: Properties of Selected BCSA Mixtures** presents the material properties of the selected optimized mixture designs including bond, identifying variables affecting constructability and cost effectiveness of each mixture design and surface preparation methods.

- **Chapter 6: Summary, Conclusions, and Recommendations** summarizes the research project and the conclusions drawn from the analysis of the test. Recommendations for next steps and future work, with emphasis on durability and bridge deck specimens that were cast in conjunction with the specimens from this study, are also presented.

CHAPTER 2 LITERATURE REVIEW

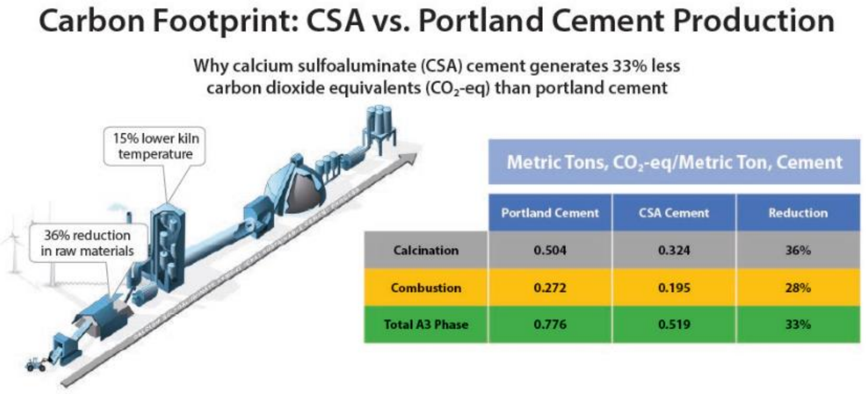
This chapter presents an overview of past experimental studies and applications relevant to this research. The chapter is divided into subsections focusing on areas that reflect the project objectives. These subsections include an overview of BCSA cements, additives used in BCSA concrete mixtures, and a performance evaluation of BCSA cements.

2.1 History and Production of BCSA

Alexander Klein's development of shrinkage compensating Type K cement, utilizing the expansion characteristics of ye'elimite, led way to the development of CSA as a standalone hydraulic cement [25], [26]. While Alexander Klein focused on using ye'elimite ($C_4A_3\overline{S}$) as an additive to OPC, Borje Ost went on to discover and patent belite-rich CSA cement in the 1970's. This cement's major component is dicalcium silicate (C_2S) also known as belite and gave the name to belitic calcium sulfoaluminate cement [19]. Since then, CSA has only grown in production as a standalone cement and many different compositions, with varying levels of belite, ye'elimite, and calcium sulphates have been produced. These different compositions, although having drastically different behaviors, are all advertised as CSA cements.

With the use of ye'elimite as the main source of early hydration products and rapid set times in CSA, it eliminates the need for tricalcium silicate (C_3S) also known as alite. C_3S in OPC is the primary driver for early strength gain and essential in its production. The disadvantage of relying on C_3S for early strength gain in OPC is the high temperature (1450° C) required for the formation of this compound. The temperature required for the formation of ye'elimite is lower (1250° C) leading to a more sustainable cementitious material due to lower fuel consumption needed to reach these temperatures in the kiln [17], [19].

Figure 2.1 summarizes the carbon emissions reduction in the production of CSA reported by CTS Cement Manufacturing Corporation. Raw materials used in the production of CSA are primarily bauxite, limestone, and calcium sulfate which can either be sourced from gypsum or anhydrite. Due to the lower limestone content of raw materials in CSA, this also contributes to the sustainability of the cement since less carbon is emitted during calcination [27]. Additionally, CSA clinker once calcined, exhibits a higher porosity leading to less energy consumption used in grinding the clinker nodules into fine power. The cost of CSA is the primary set back since it is much higher than OPC due to the limited availability of bauxite [27], [28].



	Metric Tons, CO_2-eq/Metric Ton, Cement		
	Portland Cement	CSA Cement	Reduction
Calcination	0.504	0.324	36%
Combustion	0.272	0.195	28%
Total A3 Phase	0.776	0.519	33%

Figure 2.1: Fig. from CTS Cement Manufacturing Corporation EPD Press Release [29]

2.2 Chemical and Mineralogical Composition of BCSA

Table 2-1 summarizes the results of a mineralogical and chemical composition study. As mentioned above, the chemical and mineralogical composition of CSA cements varies by manufacturer however Eric Bescher and John Kim [19] did a hydration study on a BCSA produced specifically by CTS Cement Manufacturing Corporation. The mineralogical and chemical composition of BCSA aided the research team in correlating studies on the compatibility of set controlling and flowability admixtures including the use of water reducing agents and polymer modifiers.

Table 2-1: Table 1 from Bescher and Kim [19] Mineralogical and Chemical Composition of BCSA Cement produced by CTS Cement Manufacturing Corporation (0.487 w/c)

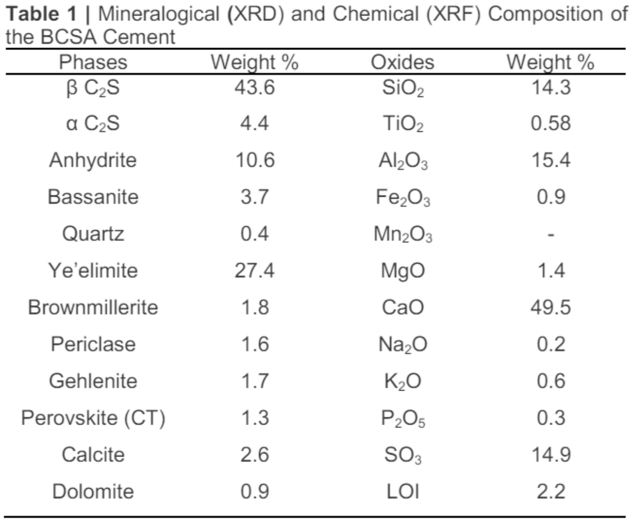


Table 1 | Mineralogical (XRD) and Chemical (XRF) Composition of the BCSA Cement

Phases	Weight %	Oxides	Weight %
β C_2S	43.6	SiO_2	14.3
α C_2S	4.4	TiO_2	0.58
Anhydrite	10.6	Al_2O_3	15.4
Bassanite	3.7	Fe_2O_3	0.9
Quartz	0.4	Mn_2O_3	-
Ye'elimite	27.4	MgO	1.4
Brownmillerite	1.8	CaO	49.5
Periclase	1.6	Na_2O	0.2
Gehlenite	1.7	K_2O	0.6
Perovskite (CT)	1.3	P_2O_5	0.3
Calcite	2.6	SO_3	14.9
Dolomite	0.9	LOI	2.2

2.3 Classification of CSA Cements

Table 2-2 summarizes the proposed nomenclature by Bescher and Kim to aid in the implementation and characterization of CSA cements. CSA cements exhibit different properties, but they can be categorized based on their mineralogical composition. Bescher and Kim proposed implementing a standardized classification such as is used for Type I-IV portland cements [19]. The three main constituents of CSA cements and their relative proportions are what define their behavior therefore it is important to understand their hydration characteristics.

Table 2-2: Table 2 from Bescher and Kim [19] Proposed Types of CSA Cements

CSA Type	CSA [%]	C_2S [%]	$C\bar{S}$ [%]	Other [%]
Type A – Accelerating Additive	35-45	0-20	10-30	5-55
Type B – Belitic CSA	20-30	30-60	5-25	0-35
Type C – Expansive Additive	10-20	10-30	40-60	0-40
Type K – Shrinkage Compensating Cement	1-10	30-50	1-20	20-70

The hydration of ye'elimite ($C_4A_3\bar{S}$) is the primary driver for producing different behaviors in CSA cements as the hydration products are highly dependent on the presence of calcium sulfate and/or calcium hydroxide. Ye'elimite ($C_4A_3\bar{S}$), when hydrated alone or when all calcium sulfates are depleted, will yield hydration products consisting of monosulfate ($C_4A\bar{S}H_{12}$) and aluminum hydroxide (AH_3) as shown in Equation 2.1 [30].

$$C_4A_3\bar{S} + 18H \rightarrow C_4A\bar{S}H_{12} + 2AH_3 \tag{2.1}$$

The raw materials in CSA production also contain calcium sulfates derived from either gypsum ($C\bar{S}H_2$) or anhydrite ($C\bar{S}$). However, anhydrite has a slower dissolution rate than gypsum leading to differences in ettringite formation that could affect mechanical properties [31]. Regardless, blends of ye'elimite ($C_4A_3\bar{S}$) and gypsum ($C\bar{S}H_2$) produce different hydration products. When mixed at a molar ratio of 1:2 respectively, the resulting hydration product is ettringite ($C_6A\bar{S}_3H_{32}$) and aluminum hydroxide (AH_3). If the blend contains lower molar ratios, monosulfate ($C_4A\bar{S}H_{12}$) is also formed [25]. Each reaction product is shown in Equation 2.2 and Equation 2.3 respectively.

(Molar Ratio 1:2)

$$C_4A_3\bar{S} + 2C\bar{S}H_2 + 34H \rightarrow C_6A\bar{S}_3H_{32} + 2AH_3 \qquad 2.2$$

(Molar Ratio 2:2)

$$2C_4A_3\bar{S} + 2C\bar{S}H_2 + 52H \rightarrow C_6A\bar{S}_3H_{32} + C_4A\bar{S}H_{12} + 4AH_3 \qquad 2.3$$

In the absence of lime, also known as calcium hydroxide (CH), the hydration equations previously mentioned are true. However, when sufficient amounts of calcium hydroxide (CH) and gypsum ($C\bar{S}H_2$) are present, ettringite ($C_6A\bar{S}_3H_{32}$) is the sole hydration product [30]. This reaction is shown in Equation 2.4.

$$C_4A_3\bar{S} + 8C\bar{S}H_2 + 6CH + 74H \rightarrow 3C_6A\bar{S}_3H_{32} \qquad 2.4$$

When comparing the molar ratios of ye'elimite, gypsum, and ettringite constituents appearing in Equations 2.2 and 2.4, the molar ratios are 1:2:1 and 1:8:3 respectively. Therefore, the presence of lime in CSA cements leads to rapid ettringite formation, however calcium sulfates are consumed rather quickly. Since only one mole of ye'elimite is consumed to produce three moles of ettringite, CSA cements with lime can exhibit greater expansive properties [32], [33]. It is also evident that different blends consisting of various proportions of ye'elimite and calcium sulfates can lead to either rapid strength gaining properties or highly expansive cements.

In a ternary system consisting of belite, ye'elimite and gypsum, as is the case with BCSA, additional hydration products exist and have been studied. Research by Winnefeld and Lothenbach [34], showed that thermodynamic equilibrium calculations of binary systems can be used to predict hydrate formation of the ternary system with various proportions of the main constituents.

Thermodynamic equilibrium equations predicted that the amount of belite in the system affects the formation of stable hydrate assemblages. For blends that contained belite (C_2S) at a rate of at least 35% by mass, all of the aluminum hydroxide (AH_3) is consumed to form strätlingite (C_2ASH_8) as per Equation 2.5.

$$C_2S + AH_3 + 5H \rightarrow C_2ASH_8 \qquad 2.5$$

It was also predicted that belite in excess of 60% by mass will cause the dissolution of strätlingite (C_2ASH_8) and stabilize both calcium silicate hydrates (CSH) and katoite (C_3AH_6) shown in Equation 2.6.

$$C_2S + C_2ASH_8 \rightarrow CSH_2 + C_3AH_6 \qquad 2.6$$

Excess amounts of belite (C_2S) in replacement of ye'elimite ($C_4A_3\bar{S}$), will trigger the dissolution of ettringite ($C_6A\bar{S}_3H_{32}$) into monosulfate ($C_4A\bar{S}H_{12}$) due to the availability of calcium oxides. This process is shown in Equation 2.7. It was also hypothesized that excess belite in the system can stabilize the formation of lime (CH).

$$6C_2S + 2AH_3 + 10H + C_6A\bar{S}_3H_{32} \rightarrow 6CSH_2 + 3C_4A\bar{S}H_{12} \qquad 2.7$$

The authors reported that the ternary diagrams were produced using the reaction equations mentioned above were verified using available experimental data on CSA cements. These ternary diagrams can be used to determine the assemblage of stable hydrates using the initial composition of belite rich CSA cement blends [32].

2.4 Set Controlling Admixtures

BCSA exhibits rapid set times and strength gaining properties which is beneficial in the context of truncating construction windows and cure times. In terms of constructability, the short working time has proven to be a challenge in upscaling BCSA rehabilitation applications. This has led to various research studies investigating the use of set retarders to improve slump flow retention and extend set times. Among the various set retarders available, most CSA manufacturers continue to recommend the use of citric acid.

Figure 2.2 illustrates the results of how different citric acid dosages affected two CSA cements. Research by Burris and Kurtis [35] sought to quantify how increasing citric acid dosage affected hydration, setting time, and compressive strengths of CSA. In this study, two CSA cements were used; one with a lower belite phase composition referred to as CSA1, and the second with nearly twice as much referred to as CSA2. In this study, the two CSA cements exhibited different levels of retardation for the same dosage of citric acid, where the belite-rich CSA had greater delayed set times.

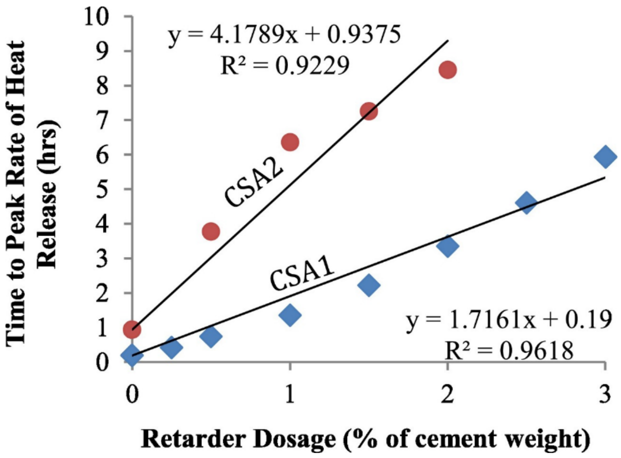


Figure 2.2: Fig. 5 from Burris & Kurtis [35] Time to Peak Heat Evolution vs. Citric Acid Dosage

Figure 2.3 summarizes the cumulative heat evolution of CSA2.The authors attributed these results to the lower soluble-sulfates of the belite-rich cement due to lower phase composition of anhydrites. The isothermal calorimetry recordings from this study also indicate that citric acid can delay hydration reactions without significantly impacting the total hydration of the two CSAs.

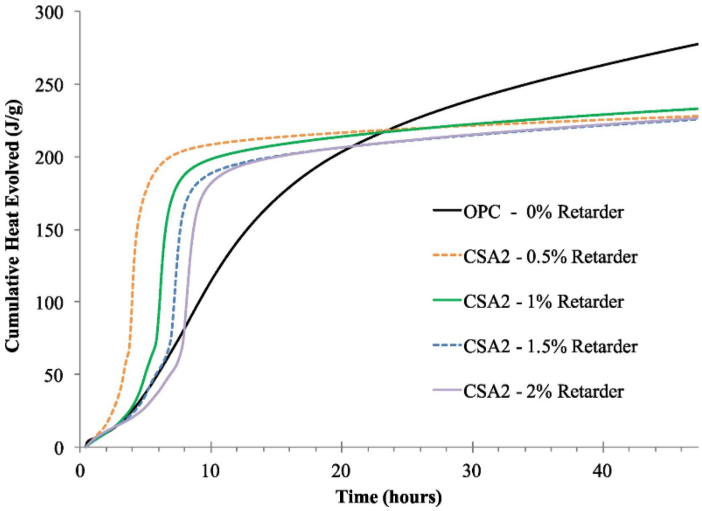


Figure 2.3: Fig. 7 from Burris & Kurtis [35] Cumulative Heat Evolved vs. Time for CSA2

The compressive strengths at ages ranging from 1 to 28 days for both cements, appeared to not be significantly affected up to a citric acid dosage rate of 2% and set times exceeding 120 minutes were achieved. Overall, the results of this study indicate that citric acid is effective at delaying set times of CSAs while not significantly affecting long term mechanical properties.

Figure 2.4 shows the results of how citric acid dosages affected BCSA cements. Another study by Soriano [36] focused on set retarding belite-rich CSA using citric acid. This study confirmed the linear relationship between the initial set and citric acid dosage previously reported by Burris and Kurtis [35]. However, this study that is specific to BCSA cements, shows a general upwards trend in increased compressive strengths after one day curing for mixtures with higher citric acid, albeit at a lower initial compressive strength.

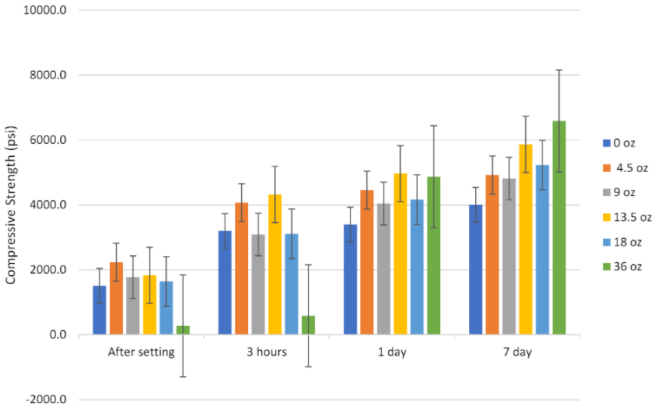


Figure 2.4: Fig. 5 from Soriano [36] Compressive Strengths w.r.t. Citric Acid Dosage for BCSA

The author describes this trend as there being some citric acid dosage between 0.7% and 1.4% by mass, that causes compressive strengths to transition to later ages. According to the author, this later age strength development could be explained by more hydration reactions leading to more ettringite products and lower porosity due to the delay of set.

Overall, citric acid appears to have a well-documented performance at being effective in retarding CSA cements. Literature on citric acid dosages were used to inform the research team on preliminary mixture designs. The major drawback from most research done on retarding CSA using citric acid is that it is based on mortar mixes. The behavior of CSA concrete can thus prove to be significantly different, and care should be taken to fully understand expected material characteristics using trial mixes.

2.5 Flow Controlling Admixtures

Water reducers are widely used in the concrete industry to improve fluidity in concrete mixtures by effectively reducing the amount of water needed to maintain a desired level of workability. Reduced water contents can also lead to improved strengths due to lower water-to-cement ratios and increased durability. High range water reducers (HRWR), also known as superplasticizers, share the same general characteristics but are much more efficient. The use of HRWR in concrete mixtures benefits from water reductions ranging from 12% to 30% leading to ultimate strengths exceeding 70 MPa (10 ksi). HRWR are also used in the production of self-consolidating concrete where typical consolidation methods cannot be used. The use HRWR may lead to reduced drying shrinkage when compared to concrete with higher water contents to achieve the same level of workability [37]. HRWR have evolved over the years leading to a new generation of superplasticizers that use polycarboxylate technology.

Figure 2.5 summarizes how the amount of PC needed to achieve the same fluidity is much lower than other admixtures used in this study, indicating that it is a much more efficient admixture for this purpose. A study by Huang et al [38], focused on quantifying how different HRWR affect fluidity, hydration, and set delay in ferrite aluminate cements. The HRWR included in this study were an aliphatic water reducing agent (AP), a melamine-based water reducing agent (MA), and a polycarboxylate acid-based water reducing agent (PC). The results from this study show that PC HRWR are the most effective in increasing fluidity of ferrite aluminate cements.

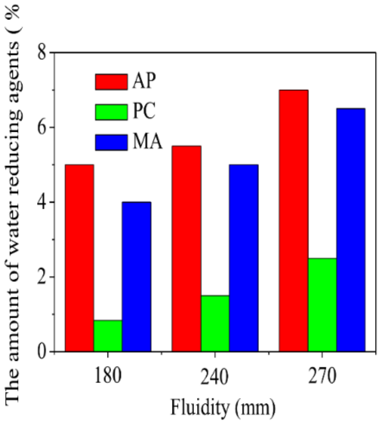


Figure 2.5: Fig. 3 from C. Huang et al [38] Amount of Water Reducing Agents vs. Fluidity

Figure 2.6 summarizes the set delay caused by each water reducing agent with respective dosages needed to achieve the same fluidity. However, it was reported that PC HRWR can drastically increase both initial and final set times of ferrite sulfoaluminate cements. These delayed set times were recorded to be up to 6.08 hours and 7.16 hours respectively, when dosed at 2.5%.

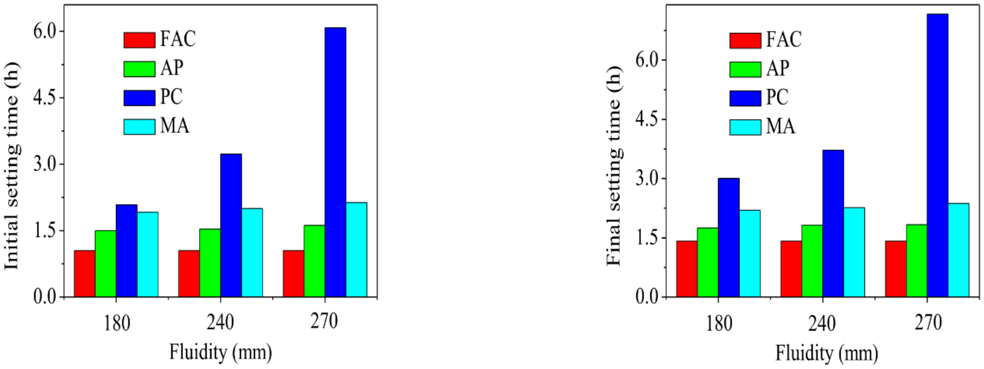


Figure 2.6: Fig. 4 from C. Huang et al [38] Fluidity vs. Initial and Final Set Times

Although PC HRWR produced significant retardation in ferrite sulfoaluminate cements, isothermal calorimetry studies from this research indicated that total hydration was not significantly impacted by PC HRWR and was more so affected by the use of MA.

A different study by Ma e.t. al [39], on the compatibility of PC HRWR and belite rich sulfoaluminate cement had similar results. The authors for this study reported that PC-based HRWR will start to exhibit delayed set times when added in dosages greater than 0.075% by mass. Mixes with dosages higher than this threshold exhibited strength reductions at 1 day as high as 21.5% but with no significant change at three days. More importantly it was observed that a dosage equal to 0.075% was accompanied by a remarkable increase in strength at 28 days of up to 44.5%.

Figure 2.7 and Figure 2.8 shows schematics, produced by the authors, that describe the proposed mechanisms which influence the absorption of each admixture and their combination. A recent study by Belhadi et al [40] focusing on the conjunctive use of citric acid as a set retarder and PC-based HRWR on CSA mixtures sought to determine compatibility issues between admixtures. Due to the high reactivity of CSA, fluidity associated with HRWR is lost quickly and therefore can be mitigated by set retarder admixtures. This study found that citric acid inhibits the dissolution of ye'elimite and anahydrite, and thus the formation of ettringite and other phases. This allows PC HRWR to maintain dispersion efficiency reducing the quick loss of fluidity. However, citric acid and PC HRWR were found to have a competitive absorption where citric acid is absorbed first, obstructing the absorption of the HRWR, and thus reducing initial fluidity

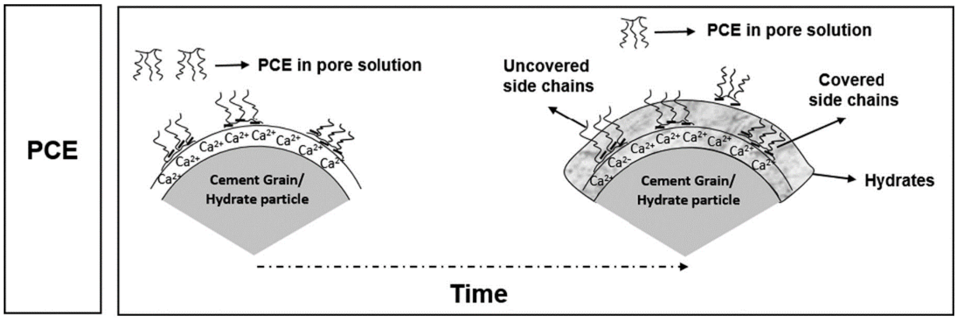


Figure 2.7: Fig. 14 from Belhadi et al [40] Illustration of Mechanism in PC Absorption

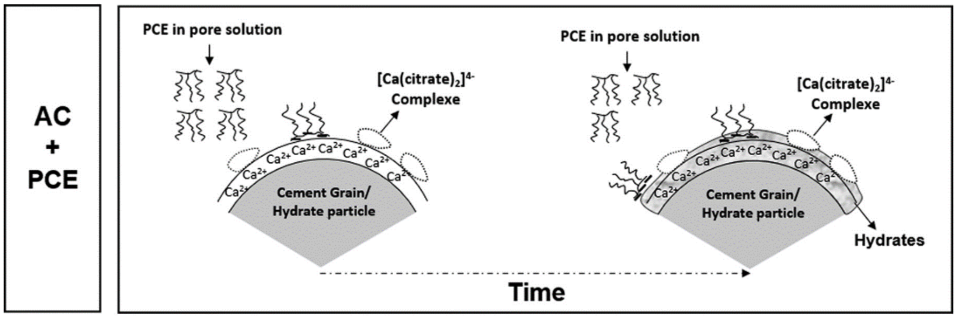


Figure 2.8: Fig. 15 from Belhadi et al [40] Illustration of Mechanism in PC + CA Absorption

Figure 2.9 summarizes the isothermal calorimetry results for this study. Perhaps the most important result from this study is that set delay between citric acid and PC HRWR is not cumulative, it is rather dominated by the citric acid with a much smaller contribution by the PC HRWR. Furthermore, isothermal calorimetry recordings from this study seem to conflict with previously mentioned research articles. Results indicated that total hydration of CSA is decreased by both citric acid and PC HRWR even when used exclusively.

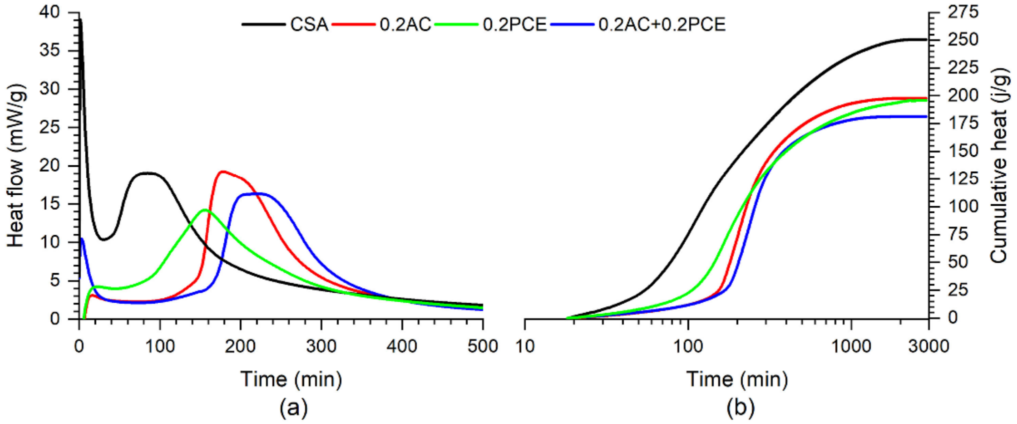


Figure 2.9: Fig. 2 from Belhadi et al [40] Heat Evolution of CSA w/ Citric Acid and PC HRWR

2.6 Polymer Modifiers

Polymer modified concrete has been the preferred choice for bridge deck overlay applications for State Departments of Transportation throughout the country owing to improved durability and improved mechanical properties of conventional hydraulic cement. Improved properties reported include increased freeze-thaw resistance, increased chloride penetration resistance, and improved overlay-to-substrate bond strengths. The inclusion of such polymers in concrete has reportedly resulted in an extended overlay service life of 14 to 50 years [41].

Styrene-butadiene mortar mixes were first developed by the DOW Chemical Company in 1957 and were later used in concrete mixes for rehabilitation projects in the 1970's due to laboratory test results indicating inhibition of chloride ingress [42]. Styrene-butadiene has now grown to be the standard polymer used in the creation of latex modified concrete. Fresh concrete properties unique to latex modified concrete include lower water contents needed to achieve good workability and requires no air entrainment due to air entrapment naturally occurring during the mixing process [43]. The wide use of styrene-butadiene in latex modified concrete and its benefits, has piqued the interest of researchers and studies have been published on the performance of latex modified CSA concrete.

Figure 2.10 summarizes water-reduction rates for each latex polymer. A study published by Lin et al [44], focused on the performance of latex modifying CSA, using different latex polymers and dosages. Performance of each latex polymer was quantified by their effectiveness to increase durability, workability, and mechanical properties of CSA mortar mixes. The three polymer latexes used in the study were styrene-butadiene rubber (SBR), styrene acrylic ester (SAE), and polyacrylic ester (PAE). This study had varying results depending on the polymer latex used and their dosage. For workability improvements in CSA, it was reported that higher dosages of all polymer latexes resulted in water-reduction rates with SBR and PAE latexes performing similarly well.

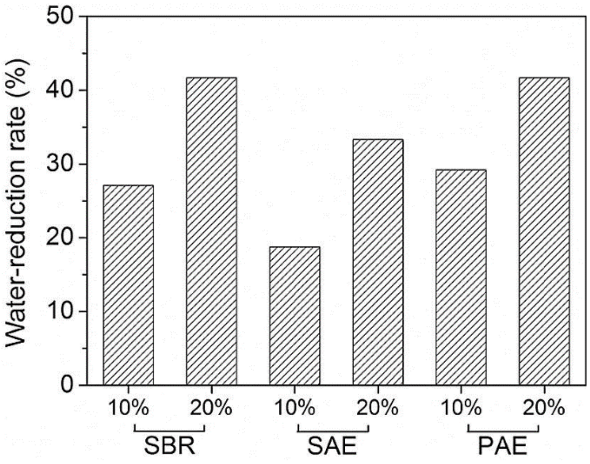


Figure 2.10: Fig. 3 from Lin et al [44] Water Reduction Rate vs. Latex Polymer Dosages

Another finding was SAE latex was found to delay set times the most with PAE latex exhibiting no set delays. CSA mechanical strength properties were also affected resulting in all polymer latexes increasing compressive and flexural strengths with SBR performing the best. The addition of latex polymers also resulted in lower drying shrinking, improved resistance to water capillary absorption, and enhanced durability to sulfate attack and carbonization. However, SBR was the only polymer latex that exhibited improvements to freeze-thaw cycle resistance although having very little influence on drying shrinkage.

2.7 Carbonation Vulnerability of BCSA

While CSA cement is considered more durable than OPC in most aspects, cementitious materials continue to be vulnerable to carbonation. Carbonation can lead to several durability issues affecting embedded reinforcement steel and the mechanical properties of the overlay material. It is generally well reported that CSA is even more susceptible to carbonation than OPC. In CSA specifically, carbonation can affect volumetric stability due to the decomposition of ettringite, an expansive hydration product, leading to shrinkage induced cracking. This may be further exacerbated by uneven shrinkage in material within and outside the carbonation depth, leading to surface degradation and spalling. Decomposition of hydrate phases can also increase porosity further decreasing the durability potential of CSA cements. If carbonation advances to the reinforcement steel, it will begin to corrode and expand causing damage to the overlaying material. Therefore, research studies seeking to mitigate carbonation induced durability issues in CSA cements have been reported.

According to [45] carbonation in CSA cement can be mitigated by lower water to cement ratios and high calcium sulfate molar ratios. In this study, it was reported that compressive strengths saw reductions equal to -14%, -7%, and +5% for a calcium sulfate to ye’elimite molar ratio of 1.4 and water to cement ratios equal to 0.65, 0.525, and 0.40 respectively. This indicates that lower water to cement ratios in CSA cements increases carbonation resistance. It was also reported that higher water to cement ratios (0.65) exhibited an increase in total porosity while lower water to cement ratios (0.525, 0.40) had a decrease in total porosity. When comparing the performance of calcium aluminate (CAC), portland, and calcium sulfoaluminate cements at a water to cement ratio of 0.40, both CAC and portland cements exhibited greater decreases in total porosity and greater increases in strength than CSA when subjected to carbonation. Furthermore, it was found that increasing the calcium sulfate to ye'elimite ratios inhibits carbonation as it can diminish the cement's CO_2 binding capacity if the cement has hydrated 100%.

Another study [46] sought to determine how carbonation is affected when supplementary cementitious materials (SCMs)are used in conjunction with CSA. In this study it was found that SCMs decreased CSA's resistance to carbonation, further increasing degradation potential. It was also found that monosulfate serves as the initial carbonation buffer and destabilizes into monocarbonate in blended and CSA only systems. It should be noted that literature on how SCMs affect blended portland cement mixtures have long had conflicting results between researchers. While in theory SCMs should reduce carbonation by reducing portlandite hydration products in OPC blended systems, it was found that carbonation is highly variable. According to [47] carbonation in portland cement blended systems was found to be affected by curing conditions, environmental exposure, porosity, and permeability. And SCMs have a direct impact on the porosity and permeability of the system based on which SCMs are used and how they are blended.

CHAPTER 3 EXPERIMENTAL TEST PROGRAM

The testing program's primary objectives were to screen potential high performing BSCA mixture designs and evaluate bond characteristics on selected mixtures. Literature review information was used to inform the research team on relative admixture dosages and BCSA behavior for trial batches. The construction of forms, concrete casting, and testing was carried out at the UW Center for Education and Research in Construction (an off-campus research facility) as well as More Hall (Civil and Environmental Engineering building), both in Seattle, WA.

3.1 Materials Testing

3.1.1 Cements

A total of three different cements were used for this project. Two BCSA cements were used for the overlays; one had Low-P™ polymers integral with the cement and the second was an BCSA cement without additives. The BCSA cement without additives was used to produce a Liquid Low-P™ modified BCSA mixture, a latex modified BCSA mixture, and a BCSA mixture without polymer additives. For the substrate, portland cement Type I-L was used alongside fly ash as the only supplementary cementitious material (SCM). The cementitious materials used for the substrate were dictated by the local ready-mix producer that delivered the WSDOT Concrete Class 4000D mixture, used for bridge decks.

3.1.2 Aggregates

Figure 3.1 shows the gradation of the fine aggregate as compared to the ASTM C33 [48] requirements. Aggregates used in this research were sourced from Dupont, Washington and consisted of pea gravel and river sand. Gradation analysis was conducted for both aggregates to verify compliance with ASTM C33.

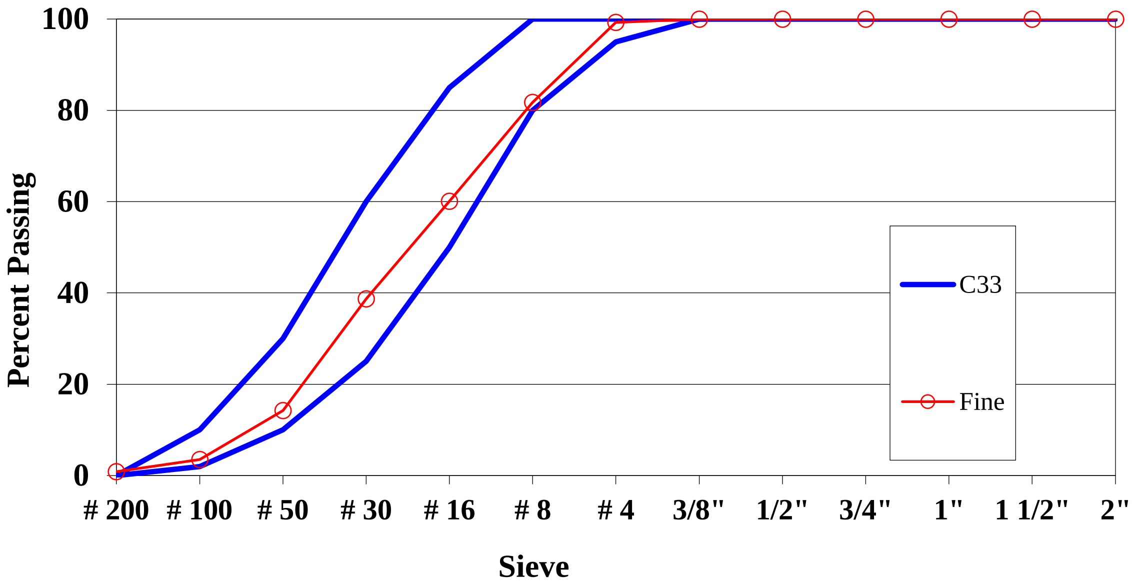


Figure 3.1: Fine Aggregate Gradation as compared to ASTM C33

Figure 3.2 shows the coarse aggregate gradation as compared to the ASTM C33 requirements for Size 7 and Size 8 aggregate classifications. This figure shows that the aggregate tested is slightly out of bounds of each aggregate classification previously mentioned. This deviation may be attributed to material loss during sieving as well as potential non-representative sampling from laboratory supersacks that may have occurred.

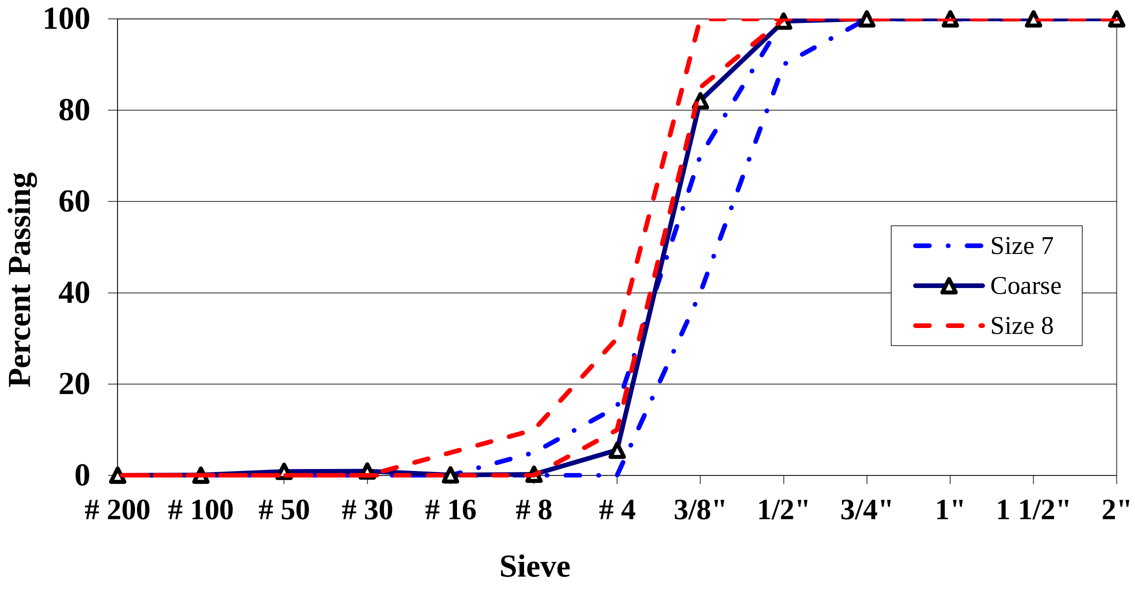


Figure 3.2: Coarse Aggregate Gradation

Table 3-1 summarizes the material properties of the aggregates used to produce concrete mixtures. Since these aggregates have been used for previous research projects at the University of Washington, absorption capacities as well as specific gravities have been extensively tested and the respective values previously recorded were used when determining mixture proportions and moisture corrections.

Table 3-1: Aggregate Properties

Aggregate	Specific Gravity	Absorption Capacity (%)
River Sand	2.65	2.10
Pea Gravel	2.68	1.12

3.1.3 Mineral and Chemical Admixtures

Various admixtures were used for achieving specific concrete properties. This included air entrainers and high-range water reducers. The air entrainers used consisted of a variety of formulations due to particular challenges with air entraining Low-P™ polymer modified mixtures. When concrete was made that consisted of Low-P™ polymers, a vinsol-resin based air entrainer called MasterAir® VR 10 was used. MasterAir® AE 200 was used for BCSA cement mixtures without polymers to achieve the target air content. Other air entrainers that were tested for preliminary mixture designs included Daravair® 1000 and MasterAir® AE 90.

All of the high-range water reducers (HRWR) used to produce the desired workability were polycarboxylate-based admixtures. However, there were differences in performance based on chemical composition therefore a few different HRWR were used for preliminary mixtures. These included MasterGlenium® 7920 and ADVA® 195 with the former being used for optimized mixtures and further testing. Both HRWR conform to ASTM C494 [49] requirements for Type A – water reducing, and Type F – high range water reducing admixtures.

Citric acid was used to control set times of BCSA concrete mixtures for both preliminary and optimized mixtures. The citric acid was incorporated by dissolving into the batch water after bringing the aggregate to saturated surface dry conditions. The dosage rates varied per preliminary mixture designs however all optimized mixtures used a 0.25 lbs/cwt dosage rate. The citric acid used was an anhydrous fine granular powder.

Two different polymer admixtures were used. Liquid Low-P® is a proprietary polymer made to produce low permeability concrete to inhibit corrosion of reinforcement steel. The polymer is reported to be 50% solids by mass, with recommended addition rates being as low as 10.0 fl-oz/cwt. STYROFAN® 1186 is a styrene-butadiene emulsion polymer which was used to produce latex modified BCSA concrete. The latex polymer is reported to be 48% solids by mass with current WSDOT Standard Specifications recommending addition rates almost 50 times that of Liquid® Low-P. Since the dosage rates for the two polymers were significantly different, water adjustments to account for the water content in the polymer was done for mixes incorporating STYROFAN® 1186 to preserve the targeted W/CM ratio.

3.2 Substrate Selection, Casting, Surface Preparation, and Laboratory Testing

3.2.1 Substrate Selection

The substrate concrete mixture design was selected to be representative of current bridges that may be in need of repairs and/or rehabilitation. For this purpose, a 2004 WSDOT bridge deck mixture design, “Concrete Class 4000D,” was selected. This historical, prescriptive concrete specification was selected to maintain the project focus on bridge deck rehabilitation, since bridges where protective overlays are considered are typically at least 20 years old.

Figure 3.3 shows the dimensions of for the cast “paver-sized” substrates (16”x16”x3.5”) that were used for this research project to test overlay-to substrate bond strength of the “optimized” mixture designs developed.

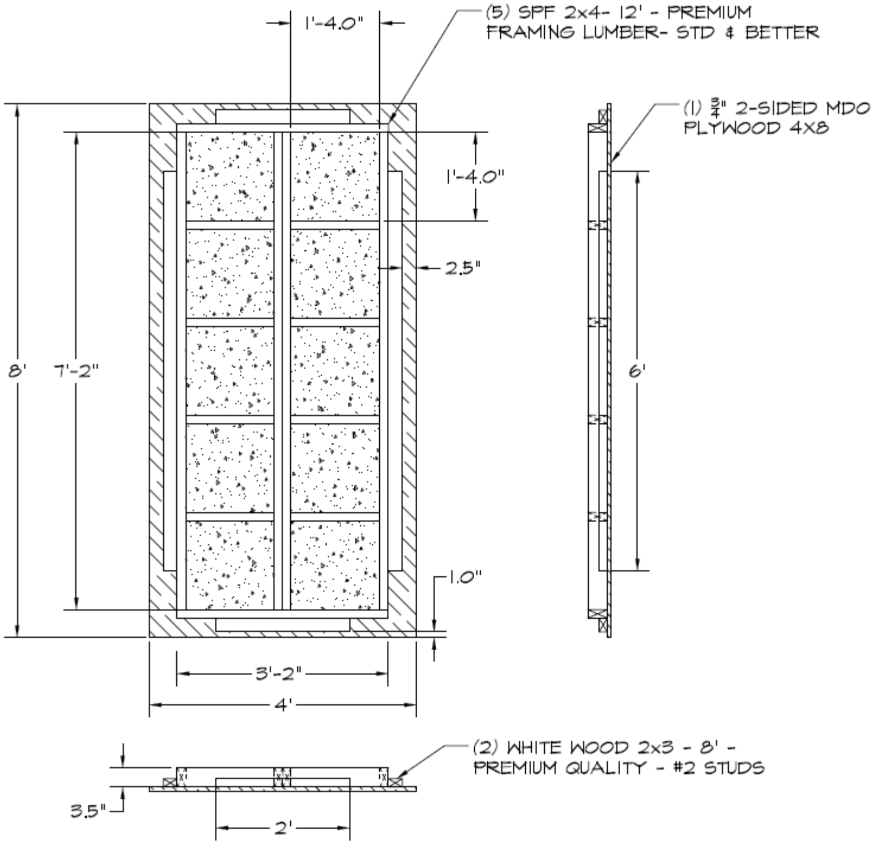


Figure 3.3: Formwork and dimensions of “paver-sized” specimens (16 in×16 in×3.5 in).

Figure 3.4 shows a completed formwork that was used for the paver-sized substrates. The paver-sized substrates did not contain any deformed bar reinforcement, since their sole purpose was overlay-to-substrate bond strength tests using small overlay thicknesses. In total, formwork for 30 paver-sized substrates were constructed for concrete casting.

Figure 3.4: Paver-Sized Substrate Formwork.

3.2.2 Substrate Casting

Figure 3.5 – Figure 3.7 shows multiple stages during the substrate casting operation. In addition to the paver-sized substrates, larger reinforced substrates intended for a separate, follow-on investigation were also cast at the same time. More details about the design of the larger substrates can be found in Appendix A. Once the formwork for the specimens was constructed, the substrate mixture design was chosen, and the total concrete volume required was calculated, a local ready-mix producer was contacted to schedule concrete delivery using one of their ready-mix trucks. The ready-mix producer delivered a total of 3.5 cubic yards of a Concrete Class 4000D mixture meeting the 2004 WSDOT Standard Specification [50]. The concrete was poured at 1 pm on September 19th, 2023, with partly cloudy skies, an ambient temperature of 65° F, and 0 mph wind gusts.

The concrete was cast in a single lift and consolidated using interval vibration. Excess concrete was struck off using a 2x6 screed and smoothed using magnesium hand floats. Once the concrete was firm to the touch, surface retarders were sprayed on the substrate specimens using a pump sprayer and the concrete was allowed to cure until the following day. Further information on the surface retarders used will be discussed in the following section. In addition to the paver-sized substrates, material property samples (4 in×8 in cylinders) were cast according to the ASTM C31 standard [51].

Figure 3.5: Paver-Sized Substrate Formwork Placed Outside Awaiting Ready-Mix Truck

Figure 3.6: Concrete Cast in Progress

Figure 3.7: Concrete Pour Finished

3.2.3 Substrate Surface Preparation

To simulate different surface preparation conditions, the top surface of the slabs were treated with two different spray-on surface retarders to obtain different surface textures. The two spray-on surface retarders used were Top-Cast® 05 (sandblast finish) and Top-Cast® 150 (exposed aggregate finish ⅜" to ⅝" etch). Specimens were stored outdoors to ensure they had gone through most of their shrinkage before the overlays were placed. The sandblast finish (SB) surface retarder had a blue-tinged color were as the exposed aggregate (EA) finish surface retarder had a green-tinged color.

Figure 3.8 shows the surface retarder application after the concrete cast. Thirteen (13) paver-sized substrates were treated with the EA surface retarder, twelve (12) paver-sized substrates were treated with the SB surface retarder, and the remaining five (5) paver-sized substrates were not treated with any surface retarders, hereafter referred to as the "as-is" surface condition. These "as-is" paver-sized substrates served as the controls when bond testing to quantify how surface preparation affects bond strength. In Figure 3.8, the five paver-sized specimens that were left without surface retarders can be seen.

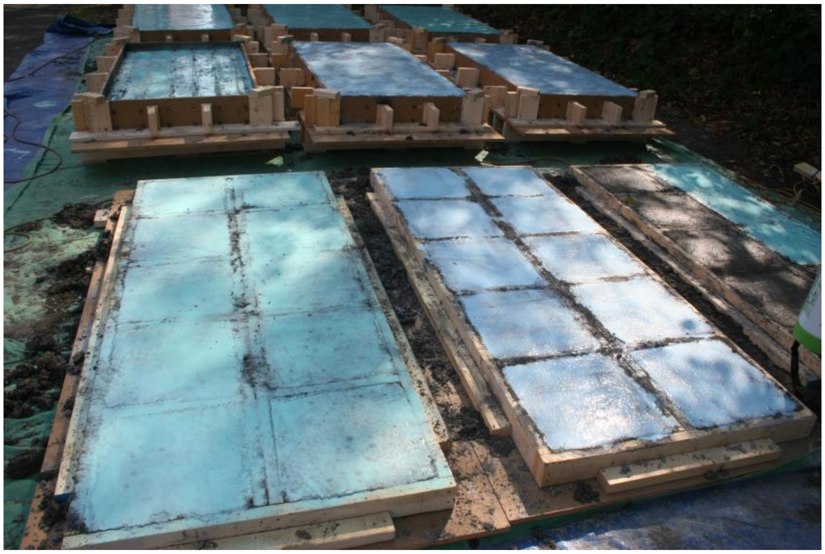


Figure 3.8: Close-Up of Surface Retarders and the 5 As-is Paver-Sized Substrates

Figure 3.9 – Figure 3.11 show the surface etching left behind by each of the surface retarders. The following day, the top surface was cleaned using a pressure washer and a metal wire brush to remove unhardened cement paste and expose the surface etching. Specimens were covered with tarp and wet burlap following final set and when pressure washing was finished.

Figure 3.9: Exposed Aggregate Etching

Figure 3.10: Sandblast Etching

Figure 3.11: Surface Etching of Paver-Sized Specimens

3.2.4 Fresh Concrete Testing

Table 3-2 summarizes the fresh concrete properties that were sampled during substrate cast day. These tests were done to verify compliance with the Concrete Class 4000D (2004) WSDOT specifications regarding slump and air contents.

Table 3-2: Substrate Fresh Concrete Testing Program

Substrate Cast Day	
Test	**ASTM Standard**
Slump	ASTM C143 [52]
Air Content (Pressure Method)	ASTM C231 [53]

3.2.5 Hardened Concrete Testing

Table 3-3 summarizes the material properties of the substrate concrete that were measured using companion cylinder, beam, and prism specimens cast alongside substrates. These specimens aimed to gauge strength development of the substrate over time to guide strength targets for BCSA overlays. Compressive strengths were measured to as far as 181 days. Shrinkage properties were also monitored.

Table 3-3: Substrate Hardened Concrete Testing Program

Test	Specimen Size (in x in)	Curing Age	ASTM Standard
Compressive Strength	4x8	(3) per 7D, 28D, 91D, 181D	ASTM C39 [54]
Split Tensile Strength	4x8	(3) 28D	ASTM C496 [55]
Flexural Strength	4x4x16	(2) 28D	ASTM C78 [56]
Drying Shrinkage Beams	3x3x11.25	(3) up to 24 weeks	ASTM C157 [57]

3.3 Laboratory Testing Program to Optimize BCSA Mixtures for Concrete Overlays

3.3.1 Aggregate and Paste Selection using Modified Void Ratio

Preliminary mixture designs were developed utilizing compressive strength data of the OPC substrate as a baseline for target strengths. The target strength of OPC substrate was relatively high, therefore BCSA mixture designs were created with low water to cement ratios. Target strengths were also purposely set high as compressive strengths were used as an indicator of potential bond performance. Additionally, the mixture proportions as well as paste contents were optimized utilizing performance-based mixture proportioning to produce concrete that efficiently utilizes materials to produce concrete that meets specifications [58].

The performance-based mixture proportioning is an iterative procedure involving both aggregates and paste quantities. First, a sieve analysis was performed to obtain aggregate gradations for both the fine and coarse aggregates. For this step, ASTM C136 [59] was followed utilizing the existing inventory of pea gravel and sand super sacks in the laboratory. Following the sieve analysis, aggregate gradations were inputted into the spreadsheet and aggregate proportions were iterated to minimize error in both the Tarantula and Power 45 curves. Once aggregate proportions were known, void percentage was determined using a modified ASTM C29 [60] procedure, where coarse and fine aggregates were blended and tested, matching the proportions found in the previous step.

Cement paste properties, as required per specifications, as well as binder properties were then input which included water to cement ratios and air contents. An additional input was also required which is referred to as the volume-of-paste to volume-of-voids (V_p/V_v) ratio. This variable determines the volume of paste necessary to fill voids left by the aggregate proportions used, while providing sufficient lubrication to achieve desired workability. Batch quantities were the main output of the spread sheet and trial mixes were made to quantify the effectiveness of the mixture design. The V_p/V_v ratio is a variable that was iterated depending on results from trial mixtures. When new aggregate proportions were chosen, percent voids in aggregate blends were recalculated and a new mixture was developed. Therefore, the V_p/V_v ratios and aggregate proportions and their different combinations were iterated until satisfactory results were produced.

It should be noted that this spreadsheet was created for nominal maximum aggregate sizes (NMAS) greater than or equal to ¾”. Since pea gravel was used, the spread sheet had to be modified to work with the material used. The respective Tarantula curves were also developed for such NMAS, therefore the research team placed further emphasis on minimizing the Power 45 curve to get a densely packed aggregate structure that would have a positive influence on strength and durability. Deviation from recommended V_p/V_v ratios presented by the study was also necessary since the binder used in the development of the spread sheet was portland cement. BCSA exhibits different workability properties owing in part to its fast setting and thus rapid slump loss.

3.3.2 Preliminary Mixture Matrix and Proportions

Table 3-4 and 3-5 summarize the preliminary mixture designs that were developed for strength testing and comparison. Further iteration of individual preliminary mixtures was required; however, only fresh concrete properties were recorded as the primary objectives of these iterations was to determine admixture dosages required to achieve targeted air contents and workability. Whenever the V_p/V_v ratios and aggregate proportions were changed, a new analysis using Peter Talyor's concrete mixture design worksheet was completed.

Table 3-4: Preliminary Mixture Designs

Variable: Citric Acid and HRWR				
Preliminary Mixture ID	**Aggregate Proportions (% of Total Mass | % of Total Mass)**	**Binder (V_p/V_v %)**	**Citric Acid (% By Mass of BCSA)**	**HRWR (% By Mass of BCSA)**
PM1	48.9 CA | 51.1 FA	200	1.50	2.29 GCP
PM2	48.9 CA | 51.1 FA	200	1.00	0.62 GCP
PM3	48.9 CA | 51.1 FA	200	0.25	2.48 GCP
PM4	48.9 CA | 51.1 FA	200	0.25	1.61 GCP
Variable: Aggregate Proportions and HRWR				
PM5	55 CA | 45 FA	200	0.25	1.35 GCP
PM6	45 CA | 55 FA	200	0.25	1.35 GCP
Variable: Volume of Paste/Volume of Voids Ratio				
PM7	48.9 CA | 51.1 FA	250	0.25	1.35 GCP

Table 3-5: Preliminary Mixture Designs Focusing on Admixtures and Polymers

<table>
<tr><th colspan="5">Variable: Master® Builders Admixtures (MB)</th></tr>
<tr><th>Preliminary Mixture ID</th><th>Aggregate Proportions (% of Total Mass | % of Total Mass)</th><th>Binder (V_P/V_V %)</th><th>Citric Acid (% By Mass of BCSA)</th><th>HRWR (% By Mass of BCSA)</th></tr>
<tr><td>PM8</td><td>48.9 CA | 51.1 FA</td><td>200</td><td>0.25</td><td>0.82 MB</td></tr>
<tr><th colspan="5">Variable: Liquid Low-P Modified</th></tr>
<tr><td>PM9</td><td>48.9 CA | 51.1 FA</td><td>200</td><td>0.25</td><td>1.15 MB</td></tr>
<tr><th colspan="5">Variable: Low-P Integral with Cement</th></tr>
<tr><td>PM10</td><td>48.9 CA | 51.1 FA</td><td>200</td><td>0.25</td><td>1.02 MB</td></tr>
</table>

3.3.3 Batching and Mixing Procedure

The mixing procedure for preliminary mixtures developed was first completed following the typical procedure for concrete mixing and casting in a laboratory setting outlined by ASTM C192 [61]. However, this procedure did not allow for sufficient time to cast the complete set of compression strength specimens for specific concrete ages of interest. Therefore, a new mixing procedure was developed which expedited the mixing process while still creating a consistent and homogeneous mixture. This mixing process was also used for optimized mixtures that were used to overlay substrates in large-scale pours that is explained in the next section. However, due to much smaller volumes used for preliminary mixtures, mixing time was further minimized.

First, the drum was wetted, and excess moisture was allowed to dissipate. Then the coarse and fine aggregates were added as the drum was spinning in alternating approximate half quantities of the material over the span of 1 minute. Once the aggregates mixed for approximately 2 minutes, the air entrainer was dribbled over the aggregates and then the mixer was turned on for an additional minute. The aggregates were then brought to a saturated surface dry condition through the addition of a quarter of the total batch water and allowed to mix for another minute. While the material was mixing, the HRWR and citric acid were simultaneously added to the remaining ¾ of the batch water and thoroughly mixed to dissolve the citric acid. The cement was then added all at once and the mixer was turned on, occasionally stopping and starting the mixer to incorporate un-hydrated cement from the back of the drum with a trowel. The mixer was then allowed to spin for approximately 2 minutes. The remaining ¾ of the batch water with admixtures was added to the mixer and allowed to continuously mix for 3 minutes. When Liquid Low-P™ was used, it was dribbled onto the concrete mixture during the last 2 minutes of mixing. The total mixing time for preliminary mixtures was 10 minutes.

3.3.4 Fresh Concrete Testing

Fresh concrete testing for preliminary mixtures was limited to air content testing. This was due to the relatively small volumes produced for preliminary mixtures to minimize waste during initial testing. Achieving the target air entrainment (5-7 %) for the BCSA polymer modified mixtures was found to be challenging. Therefore, the research team investigated various different air entrainers from different suppliers and chemical compositions to determine which were best suited to achieve the targeted 6% air content. This often led to mixtures being produced solely for air content testing. The procedure for air content testing followed ASTM C231 [53] using the pressure method.

3.3.5 Hardened Concrete Testing

Figure 3.12 shows a PM4 3x6 cylinder being compression tested. Compression testing was conducted in accordance with ASTM C39 [54] to determine compressive strengths at varying curing ages. In general, preliminary testing consisted primarily of compressive strength tests for concrete ages of 2-4 hours, 1, 7, and 28 days. The age of the specimen was determined as time elapsed from the addition of all the batch water. Three cylinders were cast per curing age and the average was reported. For preliminary testing, 3x6 cylinders were cast to reduce waste. When excessive citric acid dosages in conjunction with high dosages of HRWR retarded set times, the tested ages were modified, and early strength testing was removed and replaced with intermediate ages past one day cures. The cylinders were fitted with neoprene pads and steel capping rings as shown in Figure 3.12.

Figure 3.12: Typical Compression Test Setup

3.4 Laboratory Testing Program for Optimized BCSA Mixtures Design

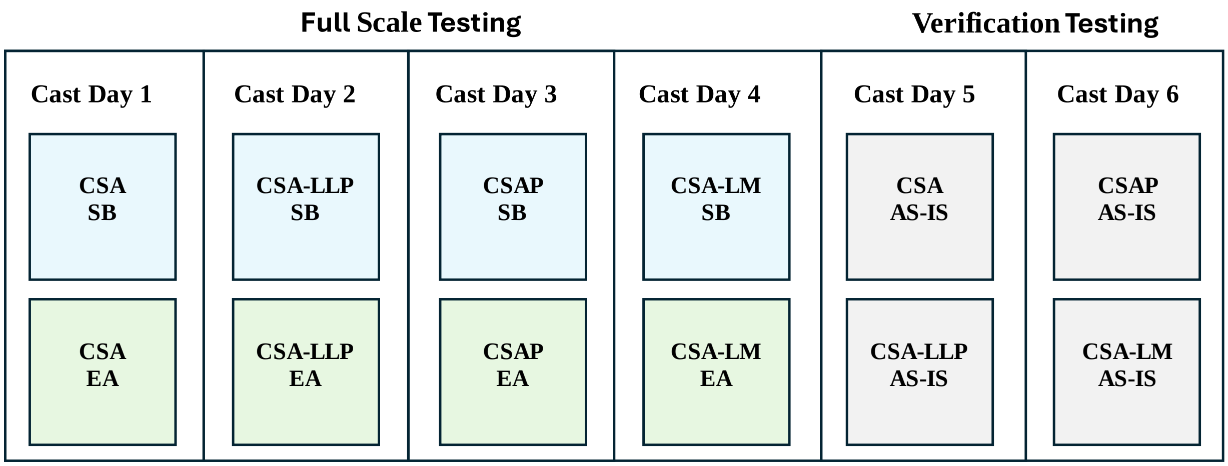
3.4.1 Identification of BCSA Mixture Designs

The main selection of concrete mixtures resulting from preliminary mixture designs and their abbreviations are as shown in Table 3-6.

Table 3-6: Optimum Mixture Designs Developed for Large-Scale Testing

Abbreviation	**Mixture Qualities**
CSA	Rapid Set® BCSA-only using optimum mixture proportions found in preliminary testing.
CSA-LLP	Rapid Set® BCSA modified using Liquid Low-P™ admixture
CSAP	Rapid Set® Low-P™ BCSA (polymer integral with the cement)
CSA-LM	Rapid Set® BCSA latex modified using STYROFAN® 1186. Optimum mixture design adjusted to account for solids and water content of latex.

Figure 3.13 summarizes the casting schedule for each mixture design. The optimized mixture designs were used to overlay substrates each with three surface finishes that include sand blast, exposed aggregate, and as-is. Since concrete coring for bond testing was a time-consuming process, only two paver sized substrates were able to be overlaid at once. Therefore, the as-is substrates were cast separately, and the testing program was limited to strength verification and fresh concrete inspections to ensure quality control. Full scale testing included the complete suite of tests to characterize the material which will be further discussed in the following sections.



SB -Sand Blast Finish
EA - Exposed Aggregate Finish
AS-IS - No Surface Finish

Figure 3.13: Optimum Mixture Design Overlay Casting Schedule

3.4.2 Batching, Mixing, and Curing Procedures for Concrete Overlays

The general mixing procedure for BCSA varied slightly from conventional concrete. In this mixing procedure, further emphasis was placed on getting a homogeneous mixture prior to introducing batch water to the cement. This ensured that the mixture had uniformity, since mixing durations were minimized as much as possible to allow for sufficient working time to consolidate and finish the resulting concrete. First, the drum was wetted, and excess moisture was allowed to dissipate. Then the coarse and fine aggregates were added as the drum was spinning in alternating approximate quarter quantities of the material over the span of 1-2 minutes. This ensured that neither the fine nor coarse aggregates were segregated. Once the aggregates were allowed to mix for approximately 3 minutes, the air entrainer was dribbled over the aggregates. The mixer was then turned on and allowed to spin for an additional 2 minutes. The aggregates were brought close to a saturated surface dry condition through the addition of a quarter of the total batch water and allowed to mix for another 2 minutes. While the material was mixing, the HRWR and citric acid were simultaneously added to the remaining ¾ of the batch water and thoroughly mixed to dissolve the citric acid. The cement was then gradually added in small quantities, occasionally stopping and starting the mixer for dust control and to reincorporate excess cement from the back of the mixer. The mixer was then allowed to spin for approximately 2 minutes. Finally, the remaining ¾ of the batch water with admixtures was added to the mixer and allowed to continuously mix for 5-6 minutes while very briefly stopping the mixer to reincorporate excess cement paste from the back of the mixer. When Liquid Low-P™ was used, it was dribbled unto the concrete mixture during the last 3 minutes of mixing. When STYROFAN® 1186 was used, the procedure was done similarly however, water and latex was added by alternating quarter quantities during the final addition of the remaining ¾ water sequence. The total mixing procedure took no longer than 15 minutes.

The timely addition of admixtures was found to be the most critical aspect during the mixing procedure. It was important to add all the required admixtures at once to ensure there was sufficient time for the effects of the HRWR and air entrainers to take place. This meant there was very little room for adjustments in workability once the final batch of water has been added. Further adjustments yielded diminishing returns since each addition required time for its effects to manifest, reducing the available working time. Additionally, rapid slump loss of the concrete as the elapsed time neared initial set rendered further adjustments futile.

Figure 3.14 shows an exposed aggregate substrate prior to overlay placement. Since the paver-sized substrates were cast using 2x4 (1.5” x 3.5”) studs, overlay forms were created using 2x6’s (1.5” x 5.5”) to achieve a two-inch overlay. Prior to placing the BCSA overlay, the substrates were cleaned using a pressurized air hose to remove any dust and residual surface retarders that would inhibit adhesion. Then the substrates were washed with water remove any lingering substances and to prewet the surface. The forms were then oiled and clamped together around the substrate with caulking used to seal the edges to prevent paste seepage. The mixing process was then started to allow for the aggregate to dry to near SSD level. If the aggregate had dried excessively by the time the concrete was ready for consolidation, water was sprayed over the surface of the substrate and wiped with a clean damp towel.

Figure 3.14: Overlay Formwork Setup

Figures 3.15-3.16 show a trial substrate where surface priming of the substrate was attempted using a thin layer of BCSA grout just prior to overlay placement. A small amount of the BCSA concrete was evenly spread over the surface of the substrate using a stiff brush, forming a thin layer of paste at the bond line. Coarse aggregate was brushed into one corner or the form and removed prior to the overlay placement. It was found that because the BCSA material sets very quickly, especially for thin grout layers, this surface priming acted as a bond breaker. In the hardened state (Figure 3.16), the layer of grout can be visibly differentiated from the rest of the overlay. This practice was abandoned for the remaining overlays, however the substrate surface was still pre-wetted prior to overlay placement.

Figure 3.15: Trial Substrate with Grout Layer Applied

Figure 3.16: Hardened Overlaid Paver Profile View

The procedure for overlay consolidation was simple due to the flowability of the BCSA concrete mixtures. All of the concrete overlays were placed in one lift. Care was taken to ensure that the concrete was evenly distributed throughout the surface by alternating between where concrete was placed. Once the concrete was placed to the top of the formwork, the sides of the forms were tapped with a mallet until the concrete settled evenly. Then a small diameter wire was used to consolidate the corners of the forms, which were then again hit with a mallet to close the resulting pockets that formed. After consolidation, the top surface of the overlay was struck off using a 2x4 and float finished using a magnesium float. This was different than for conventional portland cement concrete as finishing was necessary immediately following casting. The concrete overlays then received minimum curing to simulate overnight closures. This meant that wet burlap was not placed until penetrometer tests indicated that the concrete had reached final set, and they were cured under wet burlap for 3 hours thereafter. The following day, the forms were stripped, and samples were prepared for bond testing.

Figure 3.17 shows the etching observed on the surface of cylinders cured in an oversaturated lime bath compared to a cylinder cured in a lime bath reestablished to meet the ASTM C511 [62] standard. Concrete specimen curing was conducted following ASTM C511 [62], using a temperature-controlled curing tank saturated with lime. It should be noted that during preliminary testing, differences in the long-term strength of samples were observed, which were found to be dependent on the saturation level of the curing tank. When preliminary concrete casting was done, a curing tank oversaturated with lime, used previously for classroom instruction, was utilized. This oversaturation led to visible etching on the cured cylinders and significant strength reductions.

Figure 3.17: Etching Observed on Cylinders Cured in Normal vs Oversaturated Lime Bath

This led the research team to set up a new tank and conduct minor experimentation on how curing conditions may affect strength. During the optimized mixture overlay casting, three extra (3x6) cylinders of the CSA optimum mixture were cast and cured in a water bath without any lime. The strength for these cylinders were on average 10,140 psi at an age of 7 days. For cylinders that were cured in accordance with ASTM C511 (i.e. in a saturated lime solution), the (4x8) cylinders averaged 8,910 psi at the same age. These results, while very preliminary, suggests a potential reduction in strength associated with lime curing for CSA cements on the order of 10%, although further research is needed to quantify this value for a range of mixture designs and cement chemistries.

This is consistent with the observations of [63] who found that for CSA concretes, different curing regimes yielded significantly different compressive strengths, with curing at 100% relative humidity exhibiting the greatest long-term strength development. The study recommended curing in deionized water over a lime bath due to an approximate 18% increase in long-term strength. However, curing in deionized water resulted in about an 18% reduction in long-term strength compared to samples cured at 100% relative humidity. Consequently, there was a 33% reduction in strength, when comparing lime bath curing to 100% relative humidity. This strength reduction was attributed to ettringite instability caused by the higher alkalinity of the lime water solution . Since both curing conditions (100% RH and lime bath) are outlined in ASTM C511, laboratory results could vary drastically depending on which curing methods the laboratory can accommodate. This variability poses challenges in determining mixture conformance, suggesting that further research is needed. Standards originally designed for portland cement may not represent the best practices for HESC binders.

3.4.3 Fresh Concrete Testing

Table 3-7 summarizes the fresh concrete tests completed for each optimized mixture overlay cast. The fresh concrete properties were measured soon after the concrete was discharged into wheelbarrows. These tests were those that are performed regularly on the field, including slump, air content, and unit weight. The time of set for each mixture was also recorded to determine how each polymer and admixture combination affected initial and final sets.

Table 3-7: Optimum Mixture Design Fresh Concrete Testing Program

Full Scale Testing Cast Day	
Test	**ASTM Standard**
Slump	ASTM C143 [52]
Air Content (Pressure Method)	ASTM C231 [53]
Penetrometer Time of Set	ASTM C403 [64]
Verification Testing Cast Day (per optimum mixture)	
Slump	ASTM C143 [52]
Unit Weight	ASTM C138 [65]
Air Content (Pressure Method)	ASTM C231 [53]

Figures 3.18 and Figure 3.19 show sampled test results for CSA as-is paver mixture design properties. Since the procedures for filling and consolidating concrete for both the unit weight and air content tests are the same, both tests were done concurrently.

Figure 3.18: Unit Weight Testing of CSA As-Is Concrete Mixture

Figure 3.19: Air Content Testing of CSA As-Is Concrete Mixture

Figure 3.20 shows the testing equipment used to perform the penetrometer time of set tests. The time of set procedure was slightly modified to allow the research team to complete all of the other sample casting and testing outlined in the testing program. The main modification to the procedure was due to the rapid setting nature of BCSA cements limiting the amount of time that can be allocated to wet sieving the concrete and then quickly cleaning the sieve before the concrete reached initial set. Therefore, the concrete was not wet sieved through a No. 4 sieve, but care was taken so that penetrometer testing did not occur over the coarse aggregate. In the cases where it did occur, the test was repeated following the spacing requirements set forth in the standard. The penetrometer was equipped with five different needle diameters that had areas of 1, ½, ¼, $\frac{1}{10}$, $\frac{1}{20}$, and $\frac{1}{40}$ in^2.

Figure 3.20: Penetrometer Time of Set Equipment

3.4.4 Hardened Concrete Testing

Table 3-8 summarizes the total samples that were cast for each respective cast day. Alongside overlay casting, twenty-seven (27) 4x8 cylinders were cast for strength testing and three (3) 3x3x11.25 beams were cast for drying shrinkage for each full-scale testing cast day. When only as-is pavers were cast for verification testing cast days, the quantity of strength testing was reduced to nine (9) 4x8 cylinders per mixture design.

Table 3-8: Optimum Mixture Design Hardened Concrete Testing Program

Full Scale Testing Cast Day			
Test	**Specimen Size (in x in)**	**Curing Age**	**ASTM Standard**
Compressive Strength	4x8	(3) per 3H, 6H, 1D, 3D, 7D, 28D	ASTM C39 [54]
Split Tensile Strength	4x8	(3) per 6H, 1D, 7D	ASTM C496 [55]
Elastic Modulus*	4x8	(2) tested at 6H, 1D, 7D, 28D	ASTM C469 [66]
Drying Shrinkage	3x3x11.25	(3) up to 8 weeks	ASTM C157 [57]
Substrate w/ BCSA Overlay**	16x16x2	(2) tested at 1D, 7D, 28D	ASTM C1583 [24]
Verification Testing Cast Day (per optimum mixture)			
Compressive Strength	4x8	(3) per 3H, 1D, 7D	ASTM C39 [54]
Substrate w/ BCSA Overlay**	16x16x2	(1) tested at 1D, 7D, 28D	ASTM C1583 [24]

*** Elastic modulus test used the same two cylinders throughout tested ages. These cylinders were then used for 28D compression tests after obtaining 28D elastic modulus results.**
**** Three bond tests were completed per tested age.**

Compressive strengths of optimum mixture designs were sampled at 3H, 6H, 1D, 3D, 7D, and 28D. This was done according to ASTM C39 [54] and 4x8 cylinders were used. For early age testing (3H and 6H), the maximum loading rate allowed by the standard was used to ensure testing was done quickly and to reduce variability in results due to cylinders gaining strength as they were tested. The remaining cylinders stayed in their molds until the following day when the cylinders were stripped and placed in the curing tank.

Figure 3.21 shows the elastic modulus testing rig used for testing. The modulus of elasticity for the optimal mixture designs was measured using the same two cylinders at various ages: 6H, 1D, 3D, 7D, and 28D, following ASTM C469 [66] guidelines. This approach minimized variability arising from inconsistencies in consolidation and casting procedures, ensuring more reliable elastic modulus results. Following the tests conducted for 6 hours, the cylinders were placed in the curing tank. After the final test at 28 days, the cylinders were used for compressive strength tests. During the elastic modulus test, the cylinders were carefully centered on a rig equipped with linear variable differential transformers (LVDTs) to measure displacement as the cylinders were loaded. Raw data was collected ranging from zero load until it reached 40% of the compressive strength at each tested age. Stress and strain values were then computed, and the elastic modulus was recorded, averaged across the two cylinders, with two valid tests per cylinder.

Figure 3.21: Elastic Modulus Testing Rig

Figure 3.22 shows the split tensile strength rig used for testing. The split tensile strength of each optimum mixture design was tested according to ASTM C496 [55]. The tested ages included 6H, 1D, and 7D. The split tensile strength was tested in the same machine used for compression testing. However, a special rig was used to distribute the load evenly along the length of the cylinder. Similarly to compression testing for early ages, the maximum load rate allowed by the standard was used for consistent results.

Figure 3.22: Split Tensile Strength Rig

Figures 3.23 – Figure 3.25 show the prism mold used for casting, the comparator, and the drying rack that was used during shrinkage testing. The drying shrinkage prisms were cast in steel molds with gauge studs fitted to the ends. The beams were covered with wet burlap after reaching final set until they were demolded the following day. Immediately following demolding, the first reading was taken using a standard comparator. In total, there were 12 shrinkage beams cast, 3 per optimized mixture design, and their respective average shrinkage was reported.

.

Figure 3.23: Drying Shrinkage Beam Mold (3x3x11.25)

Figure 3.24: Drying Shrinkage Beam Sitting on Comparator

Figure 3.25: Drying Rack

3.4.5 Bond Testing

Figure 3.26 shows the coring process in preparation for pull-off bond testing. Bond testing was performed to measure the overlay-to-substrate bond strengths following ASTM C1583 (pull-off method) [24]. Initially, bond testing as early as 6 hours was considered however, preparation for bond testing required concrete coring to occur well before the concrete had reached sufficient strength to withstand the shear stresses induced by torsional friction and resulted in core debonding prior to testing. Therefore, 6-hour bond testing was omitted and only 1 day, 7 day and 28-day bond testing was conducted. Due to spacing restrictions between individual tests and slab edges, as dictated by ASTM C1583, 16 tests were available to be tested based on the size of the paver-sized substrate. However, preliminary testing indicated high variability in results when testing occurred along slab edges and corners therefore testing remained centralized and only 9 tests were conducted per paver-sized substrate. Testing was done using a 2-inch diameter steel disk and 3 different tests were done per curing age. The age at which the sample was tested was determined as time elapsed from final set and time tolerances, considering setup and testing the three samples, were 1 hour, 6 hours, and 20 hours for the 1 day, 7 day and 28-day tests, respectively. Coring was done following the procedure recommended by the manufacturer of the testing equipment, coring to at least half the diameter of the steel disk used or 1", whichever is greater, into the substrate.

Bond testing using the pull-off method has had various levels of success among other researchers due to variability in break types and strengths within the substrate and overlay [67], [68]. Since ASTM C1583 requires 3 tests to break at the same interface to be averaged and reported, testing requires larger or a much higher quantity of smaller specimens to achieve this. Often data is unreported as results are also highly affected by eccentricities due to un-plane surfaces leading to shear stresses that are developed in the epoxy causing failure in the epoxy-to-overlay interface, an invalid test result according to ASTM C1583. Concrete is also a non-uniform material leading to various strengths developed within both the substrate and overlay.

Figure 3.26: Concrete Coring for Bond Testing

CHAPTER 4 MIXTURE DESIGN OPTIMIZATION

4.1 Preliminary Mixture Design Testing

Preliminary mixture design performance was quantified by ease of consolidation as well as its ability to achieve high early- and long-term strengths. To reduce waste, 3x6 cylinders were cast for preliminary testing and rodded following ASTM C31 [53]. Through the rodding and handling of the fresh concrete, it was determined that the optimum aggregate proportions leading to the most ease in consolidation was that produced initially using performance-based mixture proportioning (48.9 CA | 51.1 FA). Concrete mixtures that had higher fine aggregate proportions led to a very sticky mixture that was hard to finish due to high cohesion. As the concrete began to set rapidly this was further exacerbated and consolidation became very difficult. Concrete mixtures with higher coarse aggregate proportions were visibly rocky and hard to handle. Proper consolidation was difficult due to insufficient paste to fully coat all of the aggregate leading to non-homogeneity.

Multiple iterations of preliminary mixture designs summarized in Table 4-1 were also cast to determine admixture dosages required for durability and flowability holding all else equal. Initially, ADVA 195 and Daravair® 1000 admixtures were used for HRWR and air entrainment, respectively. However, dosages needed to achieve the targeted 5-7% air entrainment as well as produce a decently workable concrete mixture were in excess of the maximum dosages recommended by the manufacturer. The research team consulted with the manufacturer of the BCSA cements used in this research, who recommended the use of two different products: MasterGlenium® 7920 and MasterAir® AE 200. With these two admixtures, the workability and air entrainment were achieved with lower dosages of the admixtures however, reductions in mechanical strength were also observed.

For the CSA mixture design without any polymer modifiers, air entraining using the dosage and admixture reported consistently resulted in an air content between 6-7%. When the same mixture design was used with the addition of Liquid Low-P™ or one-to-one replacements of Rapid Set® cement with Rapid Set® Low-P™ cement, air contents dropped to 2.1-2.5%. As a result, various trial batches with different air entrainers including MasterAir® AE 200, MasterAir® AE 90, and Daravair® 1000 were tested, however none of these trials were successful at producing the 6% air entrainment that was observed in the mixtures without the Low-P polymers. Since the Low-P™ line of polymers is proprietary, it was difficult to find any literature on compatible air entrainers. The manufacturer of the BCSA cements recommended the use of vinsol-resin based air entraining agents. Daravair® 1000 is reported to be chemically similar to vinsol-based products by its data sheet, and the trial batch that included Daravair® 1000 produced an air content of 2.9% with similar dosage rates. When MasterAir® VR 10, a vinsol-resin based air entrainer, was used in subsequent trial batches, it yielded similar results. The highest attainable air content produced using MasterAir® VR 10 was 3.5% at a dosage rate of 24 fl-oz/cwt. The mixtures containing the Low-P polymer were, therefore, produced with the same air entrainer dosage rate as was used for the CSA mixture design without the Low-P polymer using MasterAir® AE 200, after adjusting for differences in specific gravities of admixtures. In addition to changes in air content properties, the Low-P polymers also produced differences in the rheology of the concrete, leading to increased viscosity and therefore HRWR dosages were increased to maintain fluidity.

4.2 Preliminary Mixture Design Test Results

Figure 4.1 shows compressive strength results for preliminary mixtures tested using 3x6 cylinders. For HESC overlay applications, early strength is important to reopen the bridge to traffic. Additionally, it was desirable to produce an overlay material with a compressive strength similar to the bridge deck, which was roughly 11,000 psi for the OPC paver-sized substrates cast for this project. Since compressive strength was used as an indicator of potential performance, highest performing mixtures in compression were selected for further testing. From the data, it can be observed that PM1 and PM2 were excessively dosed with citric acid (0.25 lbs/cwt) leading to no compressive strength data being reported for 2-4 hours and to some extent also affecting long-term compressive strength gain when compared to other preliminary mixtures. Since the objective of this research project was to develop an overlay material that would expedite the delivery of construction for bridge deck overlays (i.e., high early strength), a citric acid dosage of 0.25 lbs/cwt (PM3-PM10) was selected for subsequent mixtures , which allowed for sufficient working time while still providing adequate early strength gain.

The primary variable between PM3 and PM4 was the quantity of HRWR. The data seemed to indicate that compressive strengths were not significantly affected when reducing the dosage of HRWR. Consequently, PM4 and PM5 saw further reductions in HRWR however the primary variable was aggregate proportions. The data indicated that aggregate proportions differing from that obtained by the performance-based aggregate proportioning procedure to minimize error in the Power 45 curve (PM4), saw minor reductions in strength. However, the workability of these mixtures seemed to decrease. Therefore, optimum aggregate proportions were identified as being 48.9 CA|51.1 FA. PM6 increased the volume of cement paste holding all else equal from PM4 however the data seemed to indicate that compressive strengths were not significantly affected.

Therefore, to minimize cement content, the optimum mixture cement content was found to be 648 lbs/cy (PM4).

PM8, which used a different HRWR at lower dosages from PM7 saw significant strength reductions when compared to PM7. However, it should be noted that PM1-PM7 were cast in the winter in an unheated portion of the laboratory, with temperatures dropping as low as 50° F. This could lead to early strength regression and long-term strength increases which is supported by literature when retarding CSA cements [36]. Furthermore, literature suggests that polycarboxylate-based admixtures tend to retard CSA cements and with lower dosages required for workability, it may indicate differences in concentrations used by each supplier [39]. Regardless, the cost benefit of further reduced HRWR dosages led to the identification of PM8 as the optimum mixture for CSA only mixture designs. PM9-PM10 utilized the same optimized mixture after adjusting for the use of different air entrainers and dosages of HRWR due to use of proprietary Low-P™ polymers. Results seem to indicate that Low-P™ integral with the BCSA cement tended to produce the highest early strengths out of all the preliminary mixtures. This may be attributed to the sequence of addition of admixtures where the citric acid may have a similar mechanism that competes with the absorption of other admixtures, which has been observed by others [40], leading to differences in strength.

4.3 Preliminary Mixture Design Results

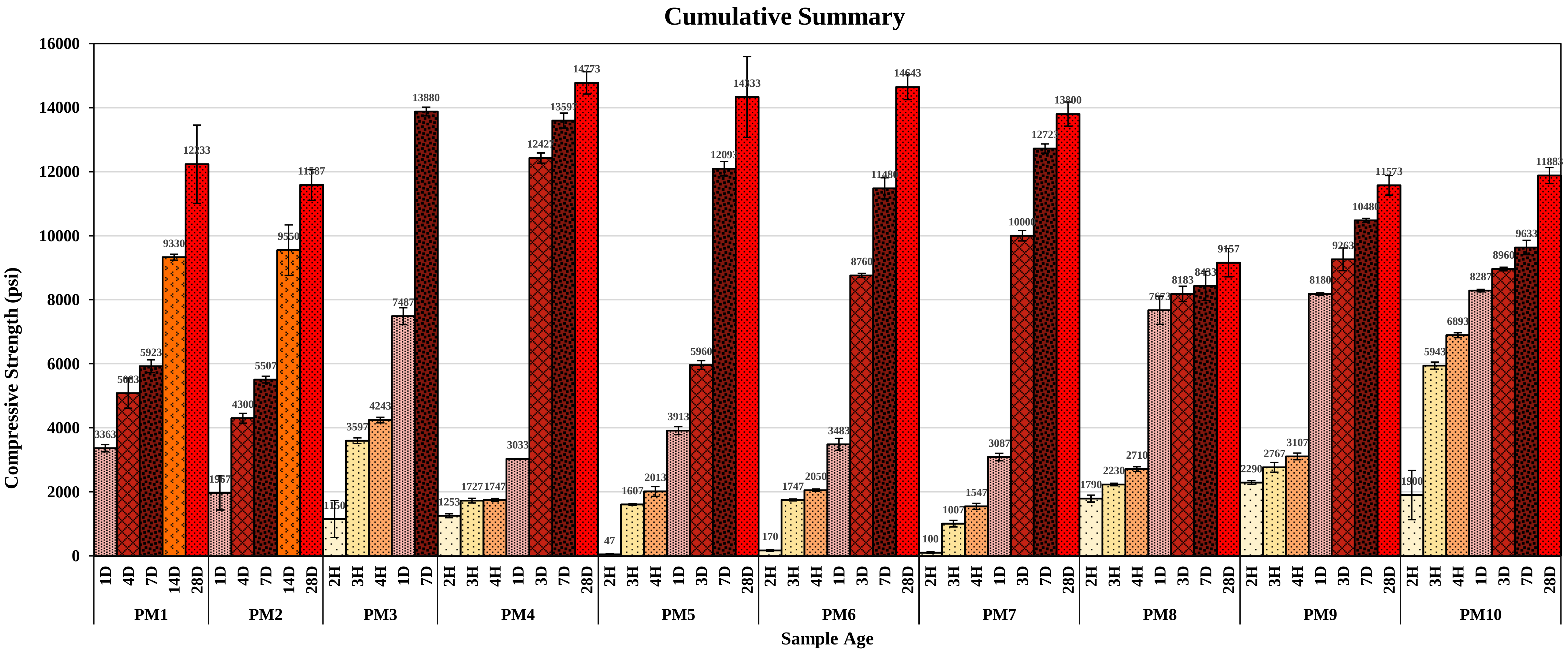
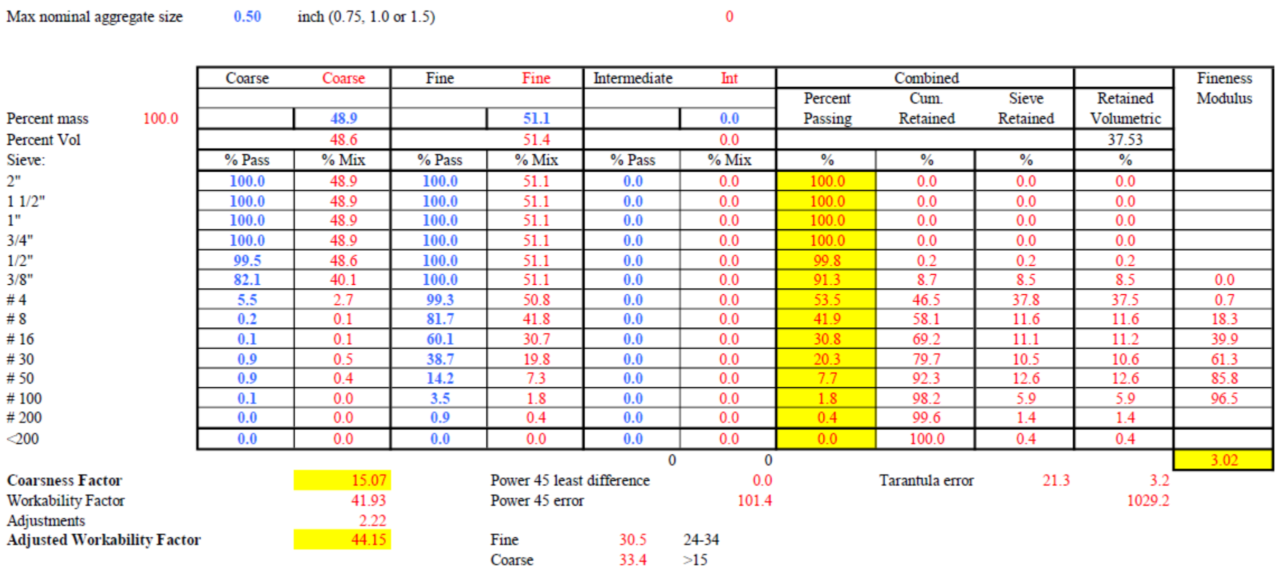


Figure 4.1: Cumulative Summary of Preliminary Mixture Compressive Strength Results

CHAPTER 5 PROPERTIES OF SELECTED BCSA MIXTURES

5.1 Aggregate Proportions

Figure 5.1 – Figure 5.3 summarizes the optimum aggregate proportions and their respective combined gradations. From preliminary testing, an optimized mixture design was developed and used for further characterization including interface bond strength. The same optimized aggregate proportions (48.9 CA | 51.1 FA) were used for the four mixture designs developed. However, the inclusion of latex polymers required modification to total volume of constituents and were adjusted based on solid and water contents. For CSAP, the polymer was integral with the cement therefore no change in specific gravity of the cement was necessary according to the manufacturer data sheet recommendations. Similarly for CSA-LLP, the additions rates were relatively low. Therefore, mixture designs were not adjusted beyond water reductions to account for the water content of the polymer.



Max nominal aggregate size 0.50 inch (0.75, 1.0 or 1.5) 0

		Coarse	Coarse	Fine	Fine	Intermediate	Int	Combined				Fineness Modulus
								Percent Passing	Cum. Retained	Sieve Retained	Retained Volumetric	
Percent mass	100.0		48.9		51.1		0.0					
Percent Vol			48.6		51.4		0.0				37.53	
Sieve:		% Pass	% Mix	% Pass	% Mix	% Pass	% Mix	%	%	%	%	
2"		100.0	48.9	100.0	51.1	0.0	0.0	100.0	0.0	0.0	0.0	
1 1/2"		100.0	48.9	100.0	51.1	0.0	0.0	100.0	0.0	0.0	0.0	
1"		100.0	48.9	100.0	51.1	0.0	0.0	100.0	0.0	0.0	0.0	
3/4"		100.0	48.9	100.0	51.1	0.0	0.0	100.0	0.0	0.0	0.0	
1/2"		99.5	48.6	100.0	51.1	0.0	0.0	99.8	0.2	0.2	0.2	
3/8"		82.1	40.1	100.0	51.1	0.0	0.0	91.3	8.7	8.5	8.5	0.0
# 4		5.5	2.7	99.3	50.8	0.0	0.0	53.5	46.5	37.8	37.5	0.7
# 8		0.2	0.1	81.7	41.8	0.0	0.0	41.9	58.1	11.6	11.6	18.3
# 16		0.1	0.1	60.1	30.7	0.0	0.0	30.8	69.2	11.1	11.2	39.9
# 30		0.9	0.5	38.7	19.8	0.0	0.0	20.3	79.7	10.5	10.6	61.3
# 50		0.9	0.4	14.2	7.3	0.0	0.0	7.7	92.3	12.6	12.6	85.8
# 100		0.1	0.0	3.5	1.8	0.0	0.0	1.8	98.2	5.9	5.9	96.5
# 200		0.0	0.0	0.9	0.4	0.0	0.0	0.4	99.6	1.4	1.4	
<200		0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.4	0.4	
						0	0					3.02

Coarsness Factor 15.07 Power 45 least difference 0.0 Tarantula error 21.3 3.2
Workability Factor 41.93 Power 45 error 101.4 1029.2
Adjustments 2.22
Adjusted Workability Factor 44.15 Fine 30.5 24-34
Coarse 33.4 >15

Figure 5.1: Aggregate System Gradation

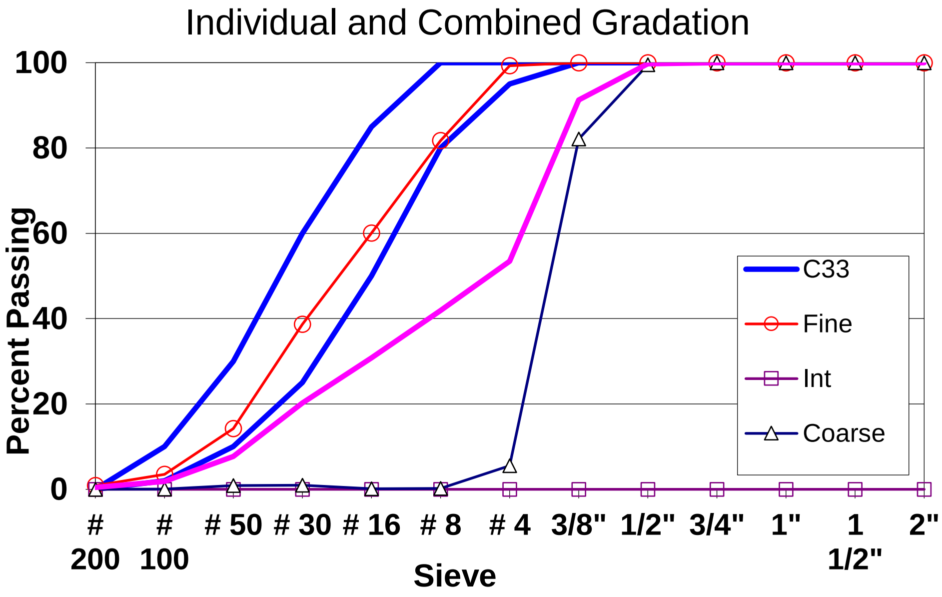


Figure 5.2: Individual and Combined Gradation Plot

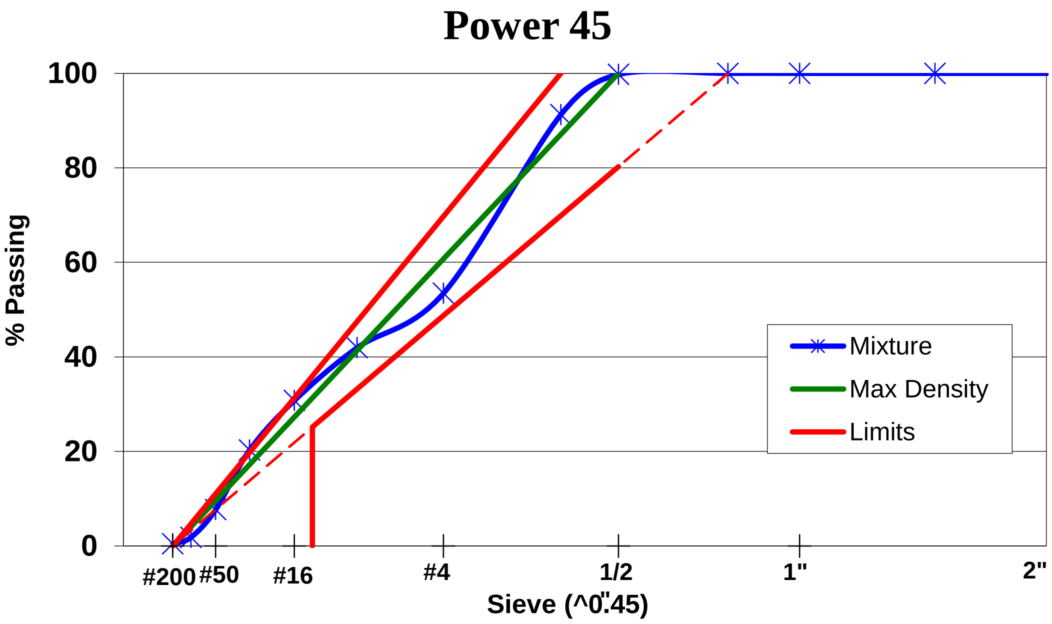


Figure 5.3: Power 45 Plot with Combined Gradation

5.2 Mixture Design Summary

The four mixture designs that were developed for further material characterization are summarized in Table 5-1 to Table 5-4. It is important to note that dosages of admixtures were determined by percentages by mass of cement but are herein reported in fl-oz/cwt as is commonly practiced. These mixture designs used the same optimum aggregate proportions. However, admixtures and admixture dosages varied due to polymer modifiers causing interactions that led to reductions in admixture effectiveness.

For the CSA-LM mixture design, no additional admixtures were used besides the citric acid set retarder. The quantity of latex modifier in the mixture was consistent with WSDOT Standard Specifications for latex modified concrete overlays. The reasoning for following WSDOT guidelines for the use of latex for portland modified concrete, is to allow for direct comparison in performance between the two cementitious binders. The addition of latex produced adequate air entrainment and no additional HRWR was needed to improve workability. Further optimization to reduce latex additions could be beneficial for lowering costs.

Table 5-1: Mixture Design for Rapid Set® BCSA Cement

CSA (0.32 w/c ratio)		
Material	**Quantity per Cubic Yard**	**Unit**
Rapid Set® BCSA Cement	648	lbs
Pea Gravel (SSD)	1508	lbs
Sand (SSD)	1579	lbs
MasterGlenium® 7920 (HRWR)	11.70	fl-oz/cwt
MasterAir® AE 200 (Air Entrainer)	4.71	fl-oz/cwt
Citric Acid (Retarder)	0.25	lbs/cwt
Water	208	lbs

Table 5-2: Mixture Design for Rapid Set® BCSA w/ Liquid Low-P™ Polymer

CSA-LLP (0.32 w/c ratio)		
Material	**Quantity per Cubic Yard**	**Unit**
Rapid Set® BCSA Cement	648	lbs
Pea Gravel (SSD)	1508	lbs
Sand (SSD)	1579	lbs
MasterGlenium® 7920 (HRWR)	16.40	fl-oz/cwt
MasterAir® VR 10 (Air Entrainer)	4.66	fl-oz/cwt
Liquid Low-P™	10.0	fl-oz/cwt
Citric Acid (Retarder)	0.25	lbs/cwt
Water	208	lbs

Table 5-3: Mixture Design for Rapid Set® Low-P™ BCSA

CSAP (0.32 w/c ratio)		
Material	**Quantity per Cubic Yard**	**Unit**
Rapid Set® Low-P™ BCSA Cement	648	lbs
Pea Gravel (SSD)	1508	lbs
Sand (SSD)	1579	lbs
MasterGlenium® 7920 (HRWR)	14.55	fl-oz/cwt
MasterAir® VR 10 (Air Entrainer)	4.66	fl-oz/cwt
Citric Acid (Retarder)	0.25	lbs/cwt
Water	208	lbs

Table 5-4: Mixture Design for Rapid Set® BCSA w/ STYROFAN® 1186 Latex Polymer

CSA-LM (0.32 w/c ratio)		
Material	**Quantity per Cubic Yard**	**Unit**
Rapid Set® BCSA Cement	648	lbs
Pea Gravel (SSD)	1350	lbs
Sand (SSD)	1405	lbs
STYROFAN® 1186	3.50	gals/sack
Citric Acid (Retarder)	0.25	lbs/cwt
Water	118	lbs

5.3 Fresh Concrete Properties

Table 5-5 summarizes the fresh properties for all the optimum mixture designs. The fresh concrete properties varied per polymer modifier used. This was especially true for air content, as only two of the four optimum mixture designs were able to achieve the target air entrainment of 6.0%. The CSA-LM concrete seemed to deviate most per mixture produced which was as expected since air entrainment for latex modified concrete is heavily dependent on mixing procedure and slight deviations may yield different results.

Table 5-5: Summary of Fresh Concrete Properties

Exposed Aggregate/Sand Blast Finish Cast Day			
Specimen	Air Content (%)	Slump (in)	Unit Weight (pcf)
CSA	5.9	3	----
CSA-LLP	2.8	9	----
CSAP	2.2	> 10	----
CSA-LM	6.4	9.5	----
As-Is Cast Day			
CSA	7.0	8.75	147.2
CSA-LLP	2.8	9.25	153.3
CSAP	3.4	> 10	150.4
CSA-LM	3.9	9.5	148.0

5.4 Compressive Strength

Figure 5.4 shows the compressive strength results for the optimized mixture designs as a function of time. The compressive strength of the OPC substrate as a function of time is also shown for reference. The horizontal lines in the figure denote compressive strengths required for concrete pavements from two surveys of state agency’s standard specifications [69], [70]. Typically, states differentiated between opening strengths for construction equipment and regular traffic, while others required strengths to be achieved at specified concrete ages [69], [70]. The data indicates that all of the optimized mixture designs can achieve opening strengths within one day of concrete casting. Furthermore, mixtures not using latex or Liquid Low-P™ polymers achieved these opening strengths within 6 hours. The data suggests that expedited project delivery is possible within a 6-hour timeframe for at least half of the optimized mixtures. As was stated previously, the latex modified BCSA utilized the latex polymer quantity dictated by WSDOT Standard Specifications for modified portland concrete. From compressive strength results, it is evident that further optimization of latex quantities or citric acid dosages can be conducted as literature supports BCSA exhibiting retarded set times when it is latex modified [44]. Cold weather concreting procedures utilizing heated batch water was also difficult when such large quantities of latex were used, which may have led to further delayed set times and lower compressive strength gain due to temperature effects.

Figure 5.5 shows the split tensile strengths of the optimized mixtures and the portland cement concrete substrate. The horizontal lines in the figure denote modulus of rupture requirements from several state DOTs before high-early strength concrete overlays can be reopened to traffic [69], [70]. Both test methods (split cylinder and modulus of rupture) measure the tensile strength of concrete, however split tensile strengths for portland cement concrete are typically 67-75% of the modulus of rupture values for a given compressive strength [71]. Therefore, the comparison in the figure is conservative. The data suggests that all of the optimum mixture designs can exceed 28-day split tensile strengths of portland cement substrates within a day. The results indicate that all optimum mixtures achieve the modulus of rupture opening requirements within one day of casting with two optimum mixtures reaching the necessary strength in 6 hours.

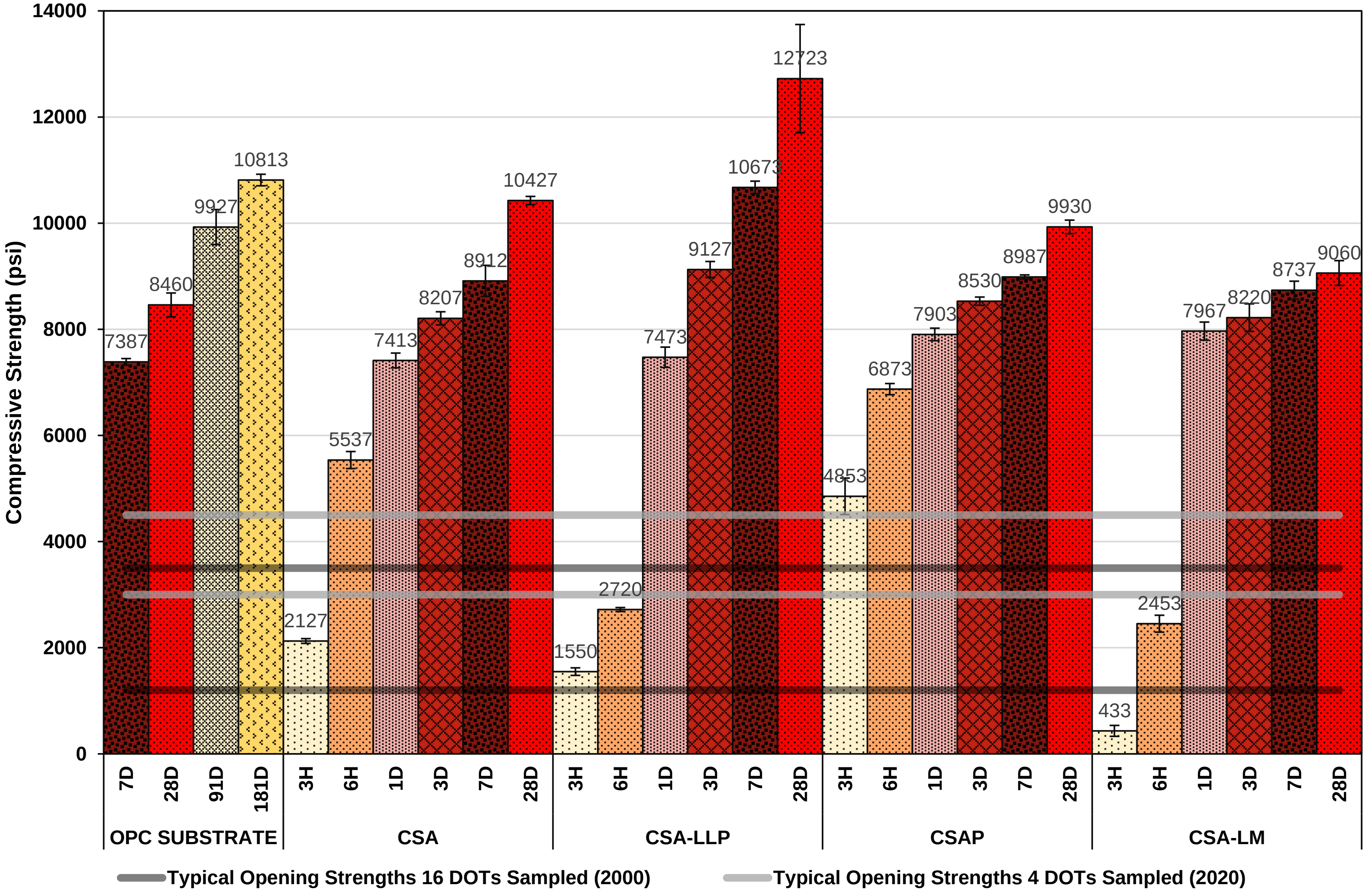


Figure 5.4: Cumulative Compressive Strength Summary

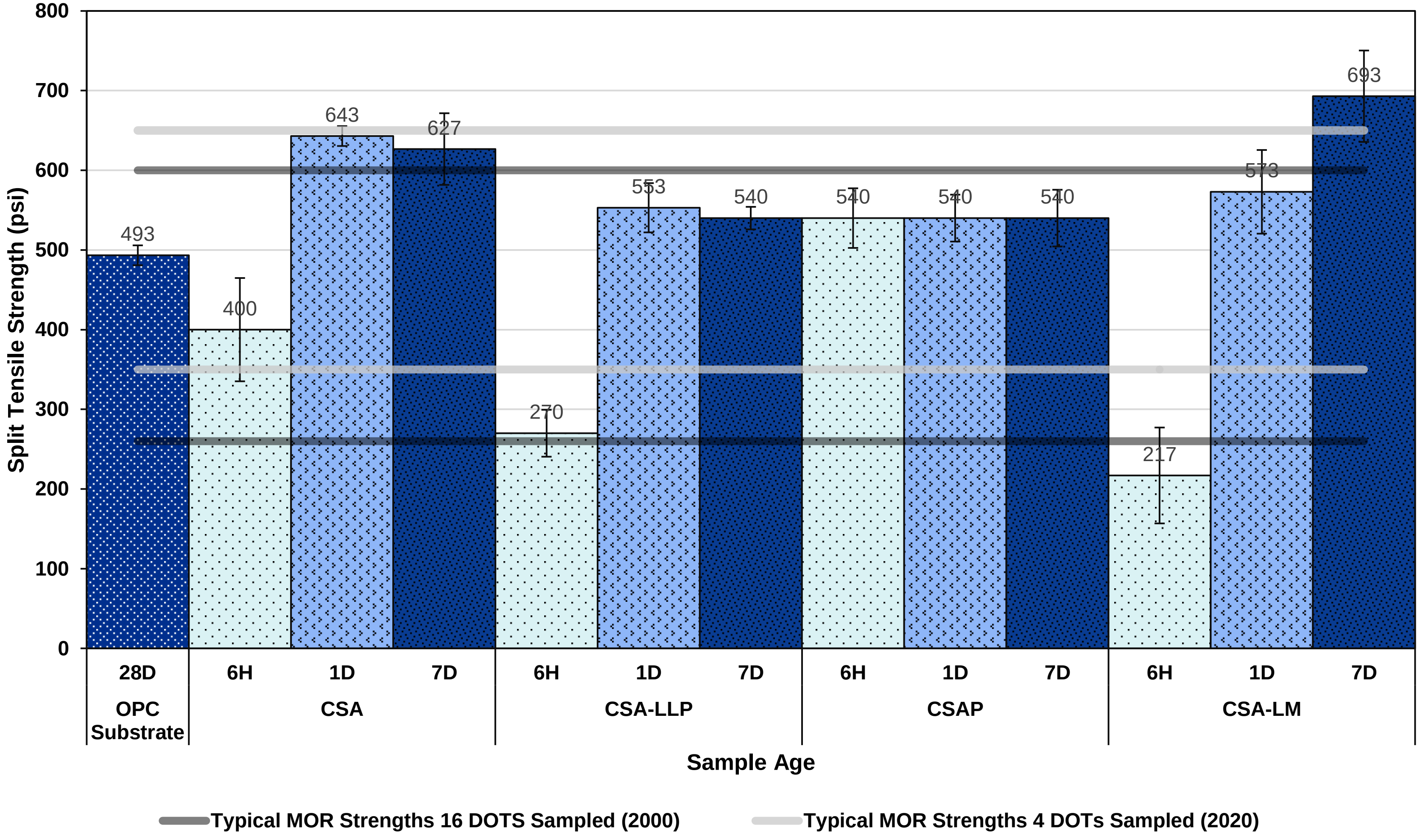


Figure 5.5: Cumulative Split Tensile Strength Summary

5.5 Drying Shrinkage

Figure 5.6 shows the drying shrinkage of all the optimized BCSA mixture designs alongside the portland cement substrate shrinkage results. The drying shrinkage for the optimized mixtures, regardless of whether polymer additives were used, was less than 0.05% within 8-weeks of demolding. Furthermore, drying shrinkage was reduced (less than 0.03% at 8-weeks) when the proprietary Low-P™ polymer was included in the mixture. Previous studies in the literature have shown that different polymers can reduce drying shrinkage characteristics of BCSA cements and that styrene butadiene has little influence on the long-term shrinkage results [44]. This is consistent with the results in Figure 5.6, where the optimized mixture with styrene butadiene polymers (CSA-LM) led to higher early shrinkage values, in excess of that recorded for the portland cement substrates, and 8-week drying shrinkage equal to that of the BCSA mixture without polymer additives (CSA). This is consistent with previous research on latex-modified concrete, which exhibited drying shrinkage cracking, especially when used for high-early strength materials [72]. This was attributed to rapid development of stiffness in conjunction with shrinkage induced strain. For the BCSA paver-sized overlay specimens that were cast as part of this research, no shrinkage cracking was observed.

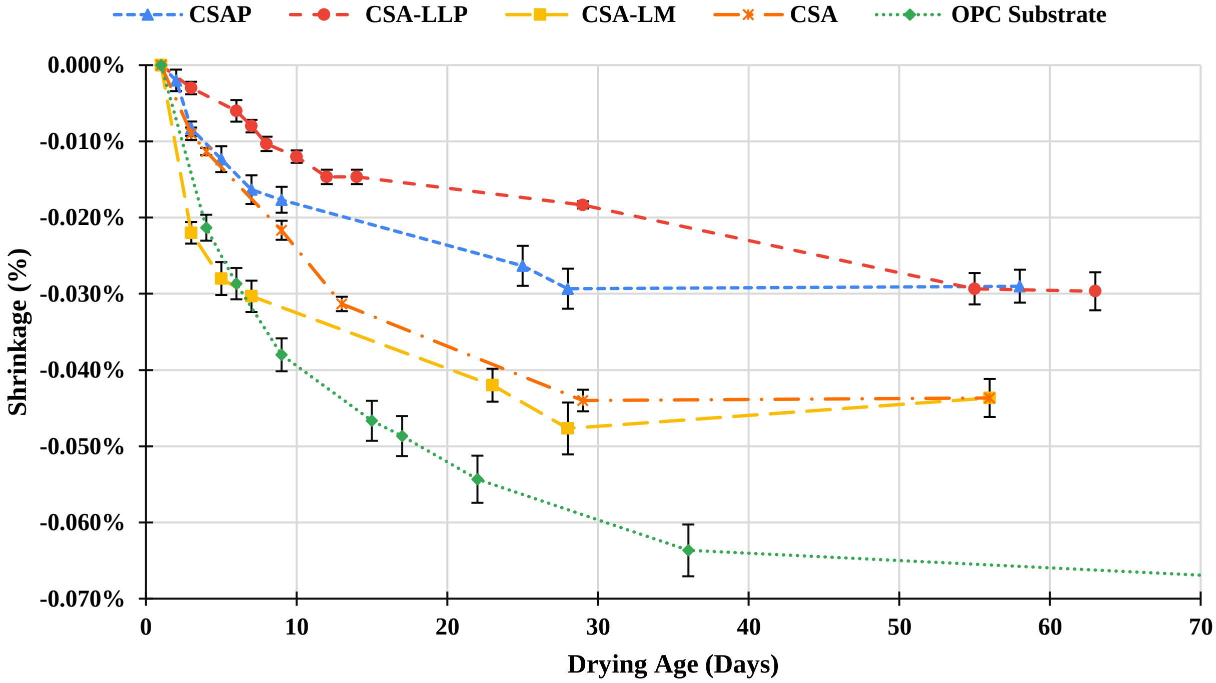


Figure 5.6: Cumulative Split Tensile Strength Summary

5.6 Time of Set

Figure 5.7 shows the penetrometer time of set for optimized mixture designs. The horizontal lines in the figure show the thresholds for initial and final set as specified in the ASTM C403 standard [64]. The optimized mixture design without polymer addition (CSA) exhibited the fastest setting time, followed by the two Low-P™ modified optimum mixtures. The data also suggests that although CSA-LLP reached final set before CSAP, it had lower compressive strengths at early ages. It should be noted that CSA mixture was cast in a laboratory temperature-controlled environment which may have led to faster setting than the other cements. This may also explain conflicting results for compressive strengths and set times since temperature fluctuations were more prevalent and varied between the remaining three mixtures.

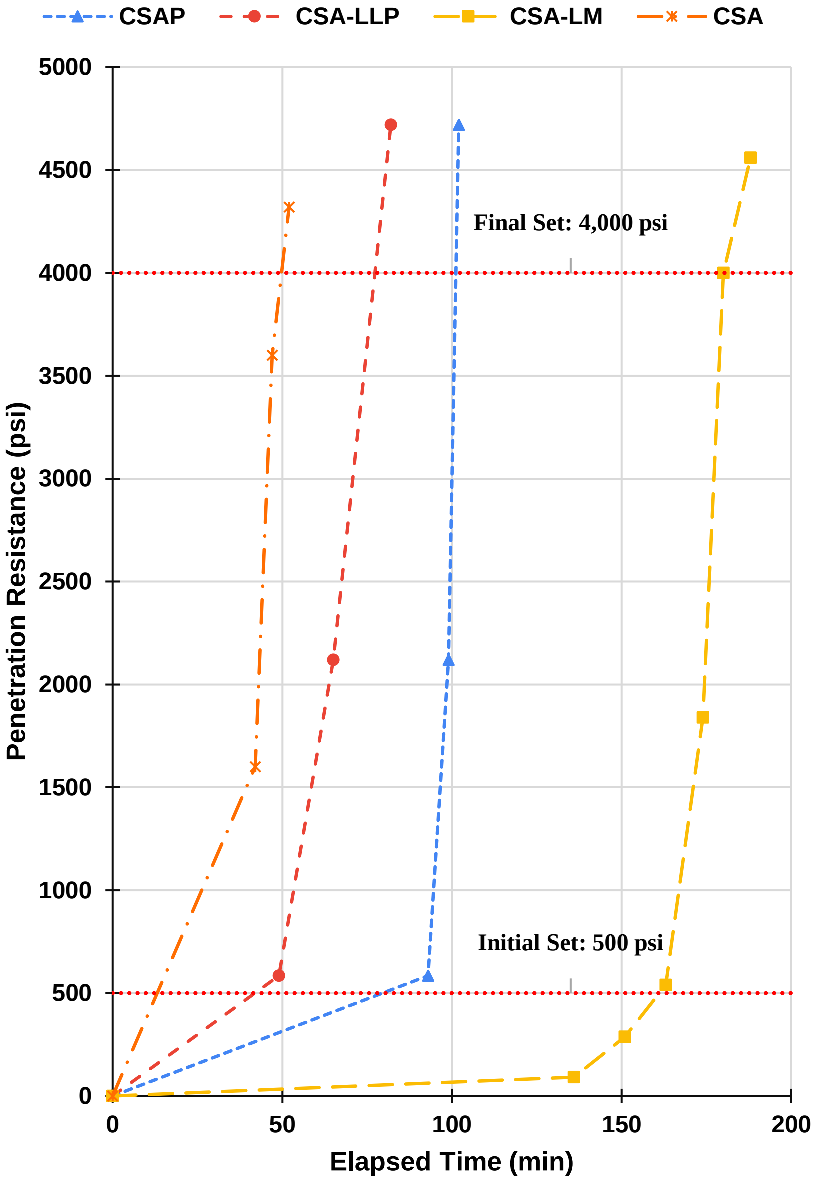


Figure 5.7: Penetrometer Time of Set Cumulative Summary

5.7 Bond Pull-off Strength

Figures 5.8 shows typical failure types that resulted from bond testing. The three main failure types that occurred during testing (from left to right): overlay surface-to-epoxy interface, bond interface, and substrate failure. Despite variation in the failure types observed, bond strength data was averaged across all break types despite the potential for underestimating the bond strength for those tests where failure occurred in the overlay or the substrate materials. Failures that occurred in the substrate or the overlay material indicate a bond strength higher than the recorded value, since overlay-to-substrate adhesion did not control the failure. Typically, most pull-off tests broke at the bond line, however Liquid Low-P™ modified BCSA mixtures had more tests resulting in overlay-to-epoxy interface failures. Therefore, some values reported may not be as representative of actual bond performance. Several plots were developed to compare the results. The first set of plots compared bond strengths of different BCSA optimum mixtures for the same surface finish used. This allowed for a comparative analysis to determine whether polymer modifying BCSA cements enhances bond. The second set of plots developed compared different surface finishes for the same BCSA optimum mixture design. This enabled the comparison of surface preparation methods and whether truncating construction windows utilizing less aggressive surface preparations measures were feasible.

Figure 5.8: Typical Bond Test Failure Types

Figure 5.9 – Figure 5.11 show bond strength results for the optimized mixture designs for the three different surface preparation methods. It can be observed that, typically, BCSA mixtures that were modified with polymers exhibited superior bond strengths. This general trend is consistent for the various surface preparations. The data also suggests that polymer modifying BCSA mixtures with the Low-P™ polymers integral with the BCSA or latex modifying BCSA produced higher bond strengths across the different surface preparations. It should be noted that some data on the CSA optimized mixture without polymer additives (CSA) is missing in Figure 5.10 due to debonding caused by coring, which was first attempted 6 hours after mixing.

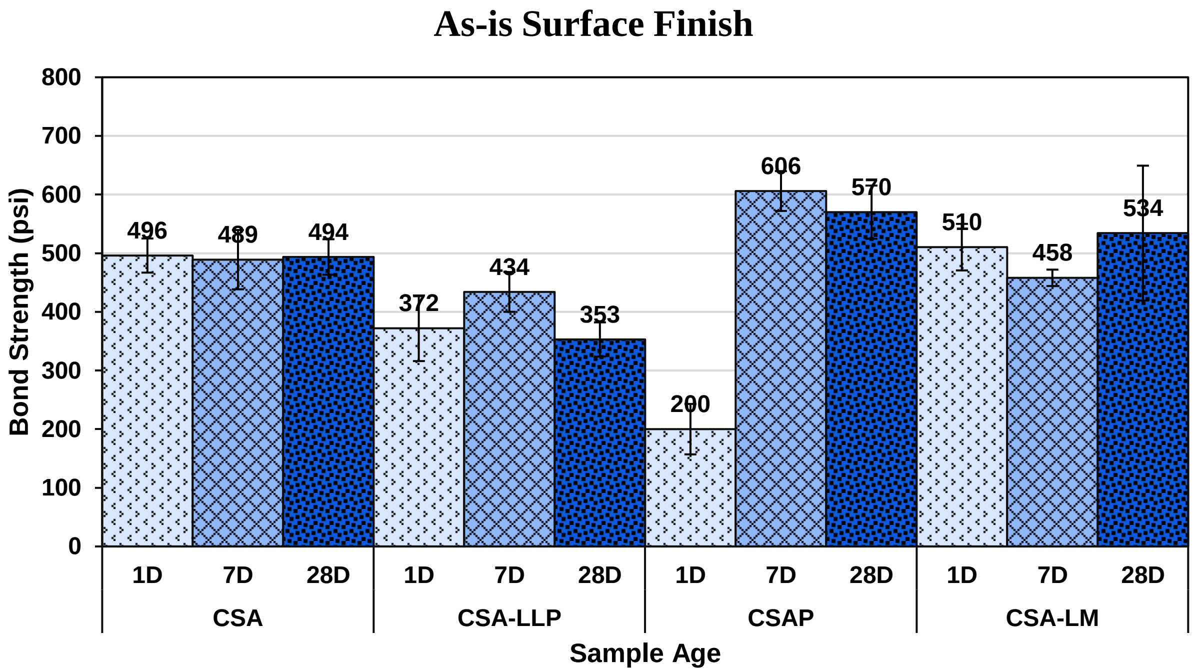


Figure 5.9: As-is Surface Finish Bond Strength Results

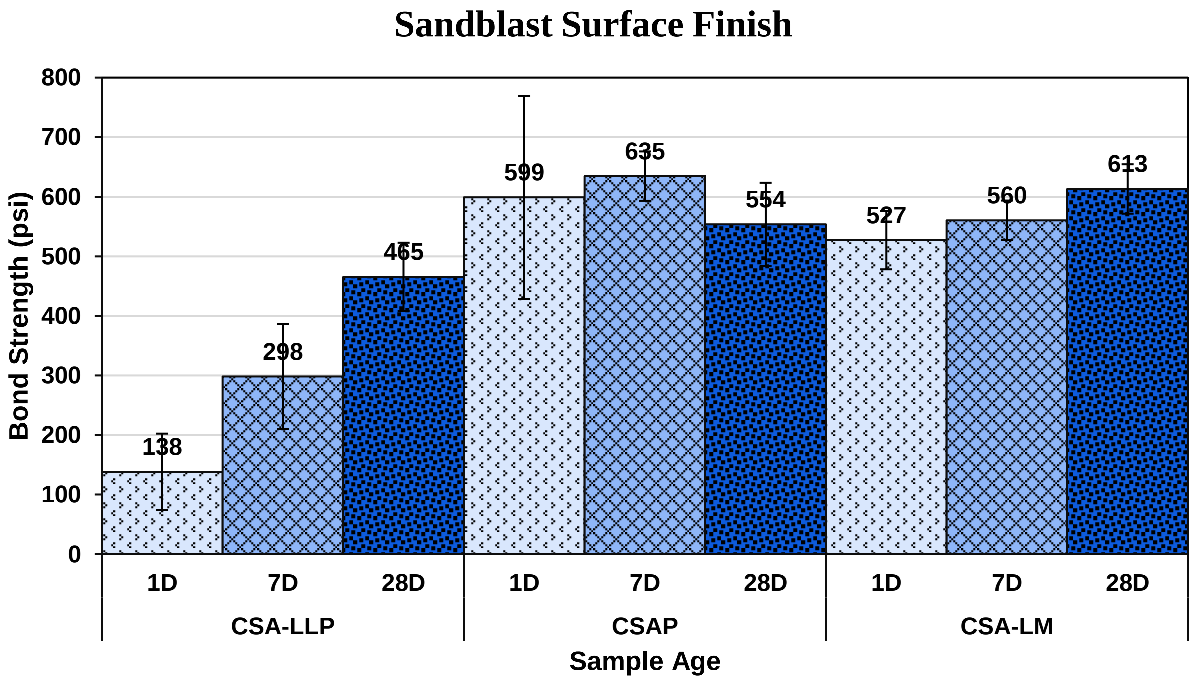


Figure 5.10: Sand Blast Surface Finish Bond Strength Results

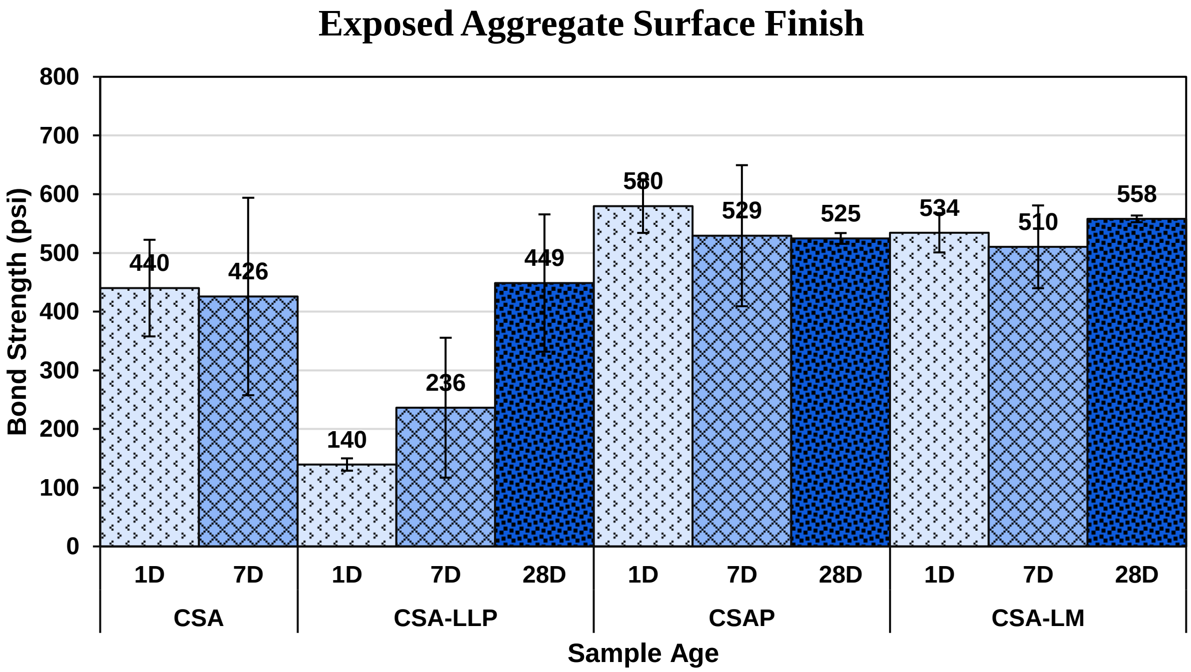


Figure 5.11: Exposed Aggregate Surface Finish Bond Strength Results

Figure 5.12 – Figure 5.14 show the bond strengths of the optimized mixture designs with the polymer additives and the three surface preparation methods used for the different optimized mixtures. From these plots, the surface preparation method, between the three roughness levels achieved in the study, had very little influence on bond strength when the pull-off strength of the same mixture was compared. The 1-day bond strength for the optimized mixture with the integral Low-P™ polymer additive (CSAP) was influenced by the surface preparation method, however the reason for this anomalous behavior is unknown and may be attributable to procedural or environmental factors.

Table 5-6 to Table 5-8 present the measured bond strength values and failure types. Caltrans specifies that fast-setting concretes used for overlays must reach bond strengths of 300 psi within a day and 500 psi for polyester polymer concrete overlays. However, bond strengths to satisfy this requirement utilize a 3-point flexural beam test featuring a composite beam with half spans consisting of a portland cement concrete substrate material and the latter half of the overlay material. Caltrans also has performance criteria for UHPC overlays detailing that bond strengths of at least 400 psi must be achieved following the pull-off test procedure. A study by Sprinkel and Ozyildirim [73] proposed that bond strength results can be quantified by the following performance qualifications:

- Excellent - $\geq$ 300 psi,
- Very Good - 250 psi to 299 psi,
- Good - 200 psi to 249 psi,
- Fair - 100 psi to 199 psi, and
- Poor - $\leq$ 99 psi.

For the measured pull-off data, nearly all of the optimized BCSA mixture designs satisfied the Caltrans criteria and provided “Excellent” bond according to the classification system proposed by Ozyildirim [73]. CSA-LLP primarily had lower measured strengths, often in the “Fair” range, however most of these breaks were not indicative of full bond capacity (because failure occurred in the overlay near the overlay-epoxy interface).

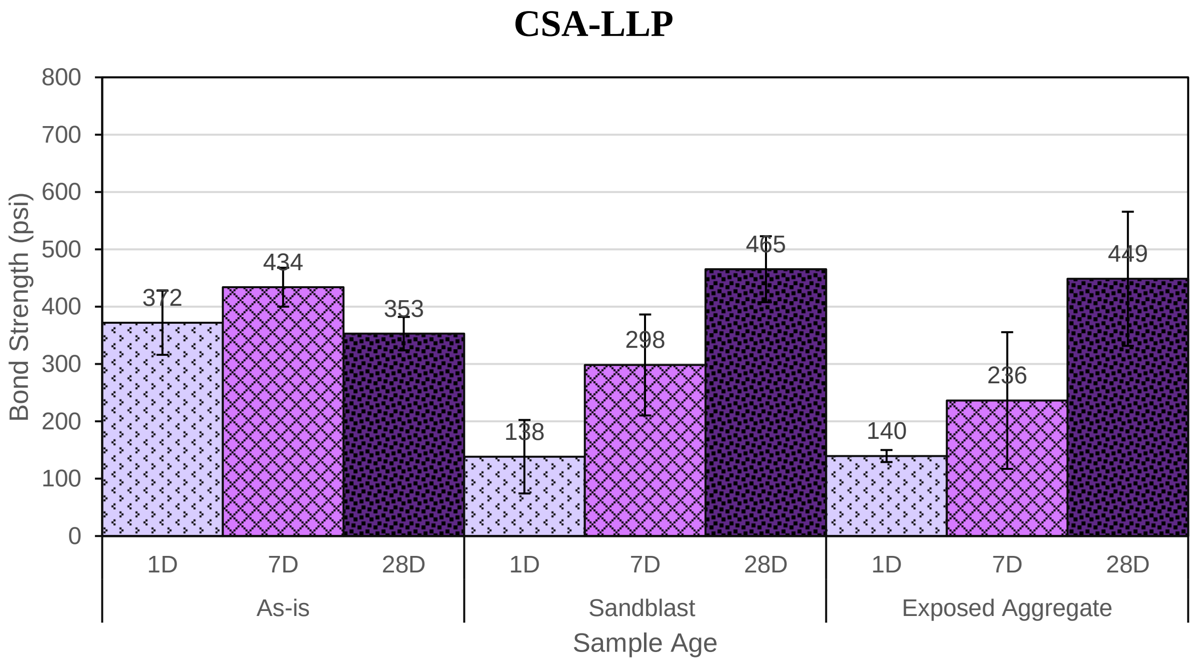


Figure 5.12: CSA-LLP Bond Strength Results

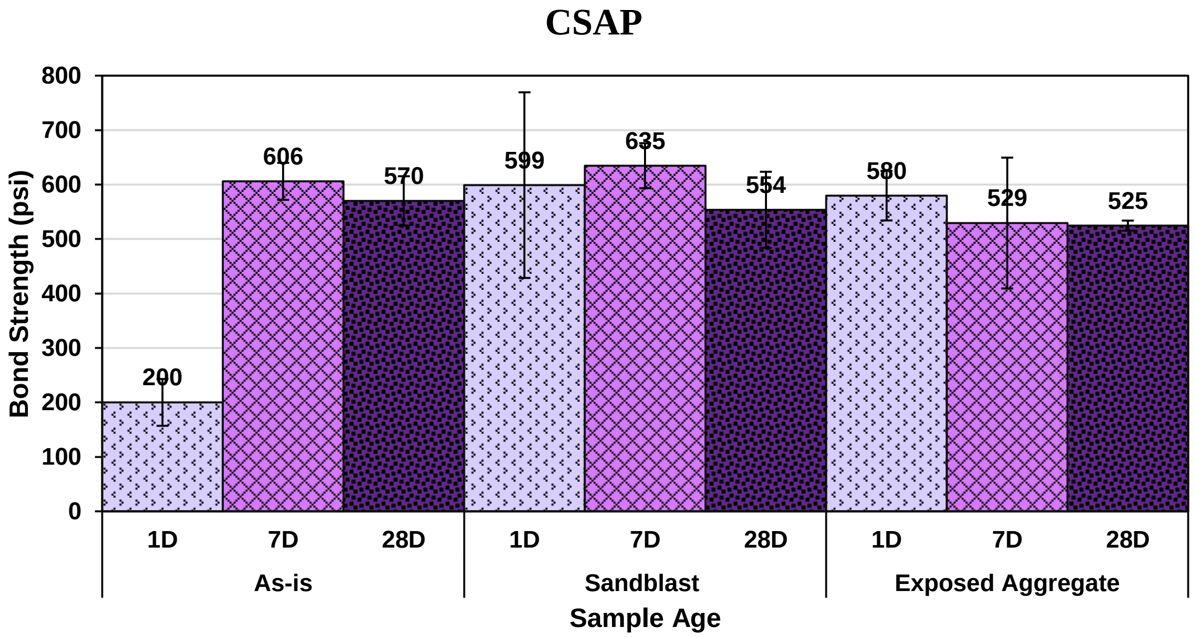


Figure 5.13: CSAP Bond Strength Results

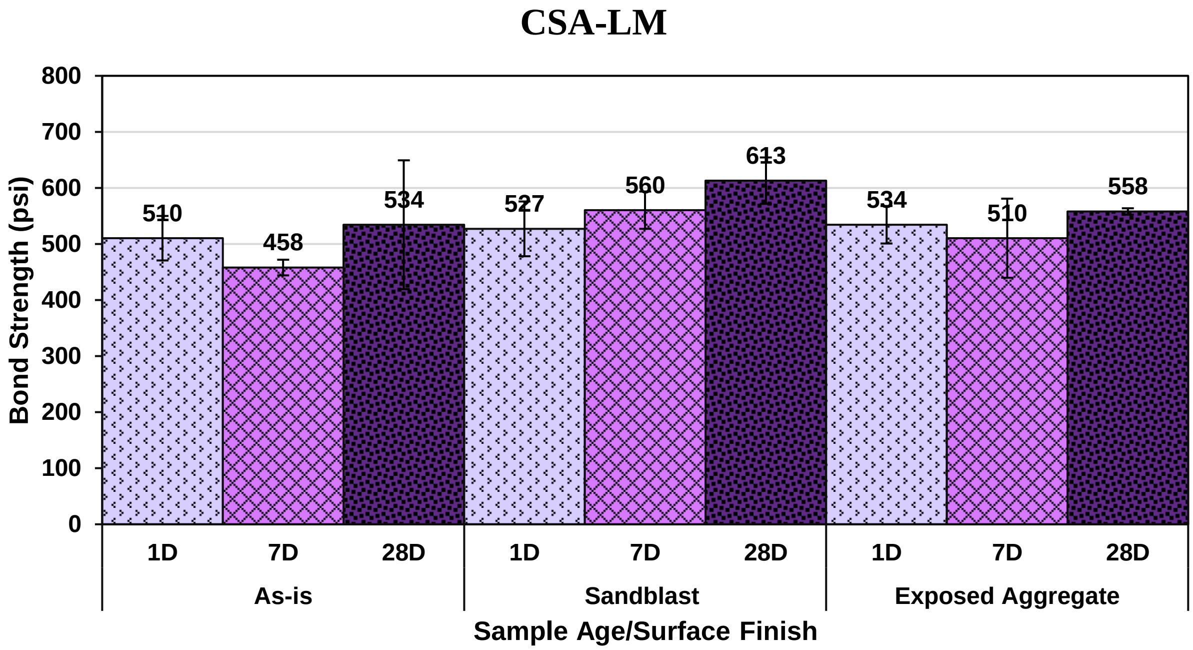


Figure 5.14: CSA-LM Bond Strength Results

Table 5-6: As-is Surface Finish Bond Strength Results

As -is Finish				
Cement ID	**Pull-Off Force (kN)**	**Type**	**Strength (psi)**	**Age**
CSA	7.5	Bond	537	1D
CSA	6.6	Substrate	472	1D
CSA	6.7	Epoxy	479	1D
CSA	7	Bond	501	7D
CSA	5.9	Bond	422	7D
CSA	7.6	Bond	544	7D
CSA	6.3	Bond	451	28D
CSA	7.2	Bond	515	28D
CSA	7.2	Bond	515	28D
CSA-LLP	4.6	Bond	329	1D
CSA-LLP	4.7	Bond	336	1D
CSA-LLP	6.3	Bond	451	1D
CSA-LLP	5.4	Epoxy	386	7D
CSA-LLP	6.4	Bond	458	7D
CSA-LLP	6.4	Epoxy	458	7D
CSA-LLP	4.7	Epoxy	336	28D
CSA-LLP	4.6	Epoxy	329	28D
CSA-LLP	5.5	Epoxy	394	28D
CSAP	2.2	Bond	157	1D
CSAP	3.4	Bond	243	1D
CSAP	8.8	Substrate	630	7D
CSAP	8.8	Bond	630	7D
CSAP	7.8	Bond/Substrate	558	7D
CSAP	7.1	Epoxy	508	28D
CSAP	8.2	Bond	587	28D
CSAP	8.6	Epoxy	615	28D
CSA-LM	6.6	Epoxy	472	1D
CSA-LM	6.9	Bond	494	1D
CSA-LM	7.9	Epoxy	565	1D
CSA-LM	6.6	Bond	472	7D
CSA-LM	6.2	Bond	444	7D
CSA-LM	8.5	Bond	608	28D
CSA-LM	5.2	Bond	372	28D
CSA-LM	8.7	Bond	623	28D

Table 5-7: Sand Blast Surface Finish Bond Strength Results

Sand Blast Finish				
Cement ID	**Pull-Off Force (kN)**	**Type**	**Strength (psi)**	**Age**
CSA-LLP	2.3	Bond	165	1D
CSA-LLP	0.7	Bond	50	1D
CSA-LLP	2.8	Bond	200	1D
CSA-LLP	5.6	Epoxy	401	7D
CSA-LLP	4.3	Epoxy	308	7D
CSA-LLP	2.6	Epoxy	186	7D
CSA-LLP	6.2	Epoxy	444	28D
CSA-LLP	5.7	Epoxy	408	28D
CSA-LLP	7.6	Epoxy	544	28D
CSAP	8.7	Substrate	623	1D
CSAP	8.8	Bond	630	1D
CSAP	3.7	Substrate	265	1D
CSAP	9.5	Substrate	680	7D
CSAP	9	Bond	644	7D
CSAP	8.1	Epoxy	580	7D
CSAP	8.7	Epoxy	623	28D
CSAP	6.4	Epoxy	458	28D
CSAP	8.1	Epoxy	580	28D
CSA-LM	7.8	Bond	558	1D
CSA-LM	6.4	Epoxy	458	1D
CSA-LM	7.9	Bond	565	1D
CSA-LM	8.3	Epoxy	594	7D
CSA-LM	7.2	Bond	515	7D
CSA-LM	8	Substrate	572	7D
CSA-LM	7.9	Bond	565	28D
CSA-LM	9.3	Bond	666	28D
CSA-LM	8.5	Bond	608	28D

Table 5-8: Exposed Aggregate Surface Finish Bond Strength Results

Exposed Aggregate Finish				
Cement ID	**Pull-Off Force (kN)**	**Type**	**Bond Strength (psi)**	**Age**
CSA	7.3	Epoxy	522	1D
CSA	5	Bond	358	1D
CSA	3.6	Bond	258	7D
CSA	8.3	Bond	594	7D
CSA-LLP	1.8	Bond	129	1D
CSA-LLP	2.1	Epoxy	150	1D
CSA-LLP	4	Epoxy	286	7D
CSA-LLP	1	Epoxy	72	7D
CSA-LLP	4.9	Epoxy	351	7D
CSA-LLP	4.2	Epoxy	301	28D
CSA-LLP	6.4	Bond	458	28D
CSA-LLP	8.2	Epoxy	587	28D
CSAP	9	Epoxy	644	1D
CSAP	7.6	Substrate	544	1D
CSAP	7.7	Substrate	551	1D
CSAP	7.3	Epoxy	522	7D
CSAP	5.4	Substrate	386	7D
CSAP	9.5	Epoxy	680	7D
CSAP	7.2	Epoxy	515	28D
CSAP	7.5	Substrate	537	28D
CSAP	7.3	Epoxy	522	28D
CSA-LM	7.8	Bond	558	1D
CSA-LM	6.8	Bond	487	1D
CSA-LM	7.8	Bond	558	1D
CSA-LM	8.5	Bond	608	7D
CSA-LM	6.7	Bond	479	7D
CSA-LM	6.2	Bond	444	7D
CSA-LM	7.9	Bond	565	28D
CSA-LM	7.8	Bond	558	28D
CSA-LM	7.7	Bond	551	28D

CHAPTER 6 SUMMARY, CONCLUSIONS, AND FUTURE WORK

The use of BCSA cements for rapid bridge deck rehabilitation and repairs was studied as a potential high-early strength alternative to portland cement and polymer-based binders. The mechanical properties of BCSA mixtures were investigated with expedited project delivery in mind and with an emphasis in developing bond strengths to a conventional portland cement concrete substrate. Various preliminary mixtures were developed to optimize material quantities and performance. This led to the development of four different optimized mixtures that used a performance-based mixture proportioning procedure. Of the four optimized mixtures, one contained BCSA cement without any additives, while the remaining three were mixture designs included polymer modifiers to investigate any potential bond strength enhancements. Bond strengths using the pull-off method for each optimized mixture was conducted leading to results from four different optimized mixtures overlaying three different surface preparations: as-is, sand blast, and exposed aggregate. Bond pull-off specimens were cured under wet burlap for only 6 hours, similar to what would be possible during an overnight closure window.

Further material characterization was conducted which included fresh and hardened concrete testing. Mechanical testing included early-age compressive and split tensile strength, elastic modulus and drying shrinkage to determine overlay-to-substrate compatibility. Fresh concrete property tests included penetrometer time of set, air content, slump test, and unit weight. Mechanical strengths were compared to standard specifications from various state DOTs to determine when optimized mixture designs would meet opening strength requirements.

The results of this study led to the following conclusions:

- For the BCSA mixture designs investigated, the required dosages and effectiveness of commercially available water-reducing and air-entraining admixtures were found to vary significantly. Often, dosages beyond the manufacturer's recommendations for OPC concretes were required to meet specific targets. For mixtures containing the low-permeability (Low-P) polymer additive, air entrainment was particularly challenging.
- The average 1-day compressive strengths for all four of the optimized BCSA mixtures was 7700 psi. When compared to a 3750 psi minimum compressive strength for reopening a pavement to traffic (an average value from a survey of 4 state DOTs in 2020 [70]), all optimum mixtures achieve this opening requirement within one day of mixing and two of the optimum mixtures, reached the necessary strength in 6 hours.
- The average 1-day split tensile strengths for all four of the optimized BCSA mixtures was 580 psi. When compared to a 500 psi minimum modulus of rupture for reopening a concrete overlay to traffic (an average value from a survey of 4 state DOTs in 2020 [70]), all optimum mixtures achieved this opening requirements within one day of mixing and two of the optimum mixtures, reached the necessary strength in 6 hours.
- For three of the four optimized BCSA mixture designs, final set was achieved within two hours of mixing. The latex-modified BCSA mixture design achieved final set within four hours after mixing, however colder laboratory temperatures on that day may have been a contributing factor to the slower setting time.
- The time to reach final set or a specific compressive or tensile strength target could be further shortened by adjusting the amount of citric acid set retarder used in the mixture design. However, there is a tradeoff between rapid strength gain and working time, which

must be balanced for a particular application. The dosage rate of 0.25 lbs/cwt was used for all of the optimized mixture designs to allow enough time to mix, place, and consolidate the specimens in the laboratory.

- The drying shrinkage of the BCSA optimized mixtures were less than 0.050% at 8 weeks and equal to roughly 0.030% for those mixture designs modified with a proprietary Low-P™ polymer additive.
- Pull-off bond tests indicated that the optimized BCSA concrete mixtures containing polymer additives cements had “Excellent” (>300 psi) 28-day bond strengths. The bond strengths for the latex-modified BCSA concrete mixture and the BCSA concrete mixture with the integral Low-P additive achieved bond strengths in excess of 500 psi in one day, which remained roughly constant, thereafter. The optimized mixture design with the liquid Low-P additive had lower average 1-day and 7-day bond strengths, however many of these tests failed in the overlay near the epoxy-overlay interface making interpretation of the results challenging.
- Significant compressive strength differences (12%) were measured for BCSA samples from the same mixture that were cured using two different commonly used curing methods (lime water bath and fog room at 100% RH). This could prove critical if independent labs are used to verify strengths meet specifications, since the reported values may vary based on curing method available to the laboratory contracted to do testing.

The following are recommendations for future work on the implementation of BCSA cements in overlay applications:

- Further bond testing using slant shear tests or three-point flexural beam tests should be conducted to validate results and study more complicated stress states.
- Future field deployment should include in-situ bond testing as a form of verification testing to standardize and correlate bond strength to field performance and expected service life.
- WSDOT funded follow on project will provide more information on long-term durability aspects of BCSA cements and further optimization of polymer additions.

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APPENDIX A

The testing program's primary objectives were to screen potential high performing BSCA mixture designs and evaluate bond characteristics on selected mixtures. Literature review information was used to inform the research team on relative admixture dosages and BCSA behavior for trial batches. The construction of forms, concrete casting, and testing was carried out at the UW Center for Education and Research in Construction (an off-campus research facility) as well as More Hall (Civil and Environmental Engineering building), both in Seattle, WA.

A.1. Materials Testing

A.1.1. Cements

A total of three different cements were used for this project. Two BCSA cements were used for the overlays; one had Low-P™ polymers integral with the cement and the second was an BCSA cement without additives. The BCSA cement without additives was used to produce a Liquid Low-P™ modified BCSA mixture, a latex modified BCSA mixture, and a BCSA mixture without polymer additives. For the substrate, portland cement Type I-L was used alongside fly ash as the only supplementary cementitious material (SCM). The cementitious materials used for the substrate were dictated by the local ready-mix producer that delivered the WSDOT Concrete Class 4000D mixture, used for bridge decks.

A.1.2. Aggregates

Figure A.1 shows the gradation of the fine aggregate as compared to the ASTM C33 [48] requirements. Aggregates used in this research were sourced from Dupont, Washington and consisted of pea gravel and river sand. Gradation analysis was conducted for both aggregates to verify compliance with ASTM C33.

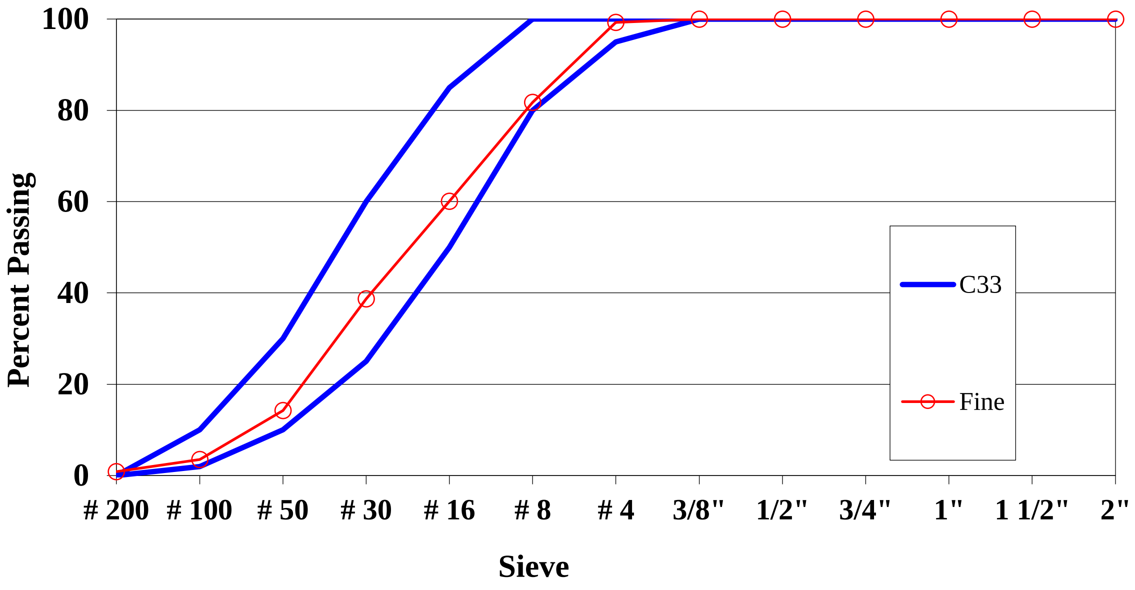

Figure A.1: Fine Aggregate Gradation as compared to ASTM C33 [48]

Figure A.2 shows the coarse aggregate gradation as compared to the ASTM C33 requirements for Size 7 and Size 8 aggregate classifications. This figure shows that the aggregate tested is slightly out of bounds of each aggregate classification previously mentioned. This deviation may be attributed to material loss during sieving as well as potential non-representative sampling from laboratory supersacks that may have occurred.

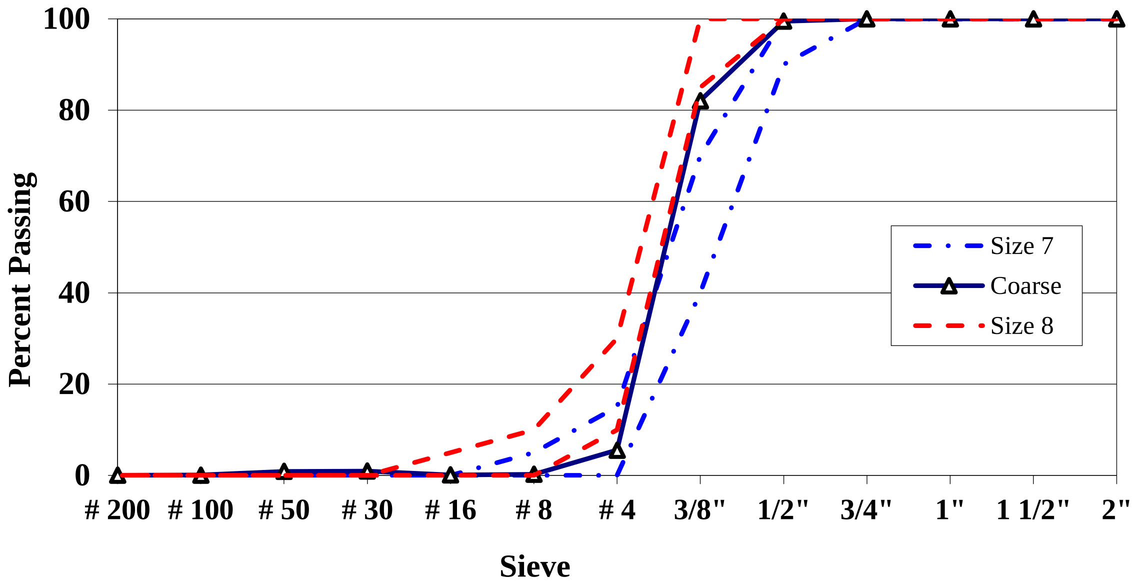

Figure A.2: Coarse Aggregate Gradation

Table A-1 summarizes the material properties of the aggregates used to produce concrete mixtures. Since these aggregates have been used for previous research projects at the University of Washington, absorption capacities as well as specific gravities have been extensively tested and the respective values previously recorded were used when determining mixture proportions and moisture corrections

Table A-1: Aggregate Properties

Aggregate	Specific Gravity	Absorption Capacity (%)
River Sand	2.65	2.10
Pea Gravel	2.68	1.12

A.1.3. Mineral and Chemical Admixtures

Various admixtures were used for achieving specific concrete properties. This included air entrainers and high-range water reducers. The air entrainers used consisted of a variety of formulations due to particular challenges with air entraining Low-P™ polymer modified mixtures. When concrete was made that consisted of Low-P™ polymers, a vinsol-resin based air entrainer called MasterAir® VR 10 was used. MasterAir® AE 200 was used for BCSA cement mixtures without polymers to achieve the target air content. Other air entrainers that were tested for preliminary mixture designs included Daravair® 1000 and MasterAir® AE 90.

All of the high-range water reducers (HRWR) used to produce the desired workability were polycarboxylate-based admixtures. However, there were differences in performance based on supplier therefore a few different HRWR were used for preliminary mixtures. These included MasterGlenium® 7920 and ADVA® 195 with the former being used for optimized mixtures and further testing. Both HRWR conform to ASTM C494 [49] requirements for Type A – water reducing, and Type F – high range water reducing admixtures.

Citric acid was used to control set times of BCSA concrete mixtures for both preliminary and optimized mixtures. The citric acid was incorporated by dissolving into the batch water after bringing the aggregate to saturated surface dry conditions. The dosage rates varied per preliminary mixture designs however all optimized mixtures used a 0.25 lbs/cwt dosage rate. The citric acid used was an anhydrous fine granular powder.

Two different polymer admixtures were used. Liquid Low-P® is a proprietary polymer made to produce low permeability concrete to inhibit corrosion of reinforcement steel. The polymer is reported to be 50% solids by mass, with recommended addition rates being as low as 10.0 fl-oz/cwt. STYROFAN® 1186 is a styrene-butadiene emulsion polymer which was used to produce latex modified BCSA concrete. The latex polymer is reported to be 48% solids by mass with current WSDOT Standard Specifications recommending addition rates almost 50 times that of Liquid® Low-P. Since the dosage rates for the two polymers were significantly different, water adjustments to account for the water content in the polymer was done for mixes incorporating STYROFAN® 1186 to preserve the targeted W/CM ratio.

A.2. Substrate Selection, Casting, Surface Preparation, and Laboratory Testing

A.2.1. Substrate Selection

The substrate concrete mixture design was selected to be representative of current bridges that may be in need of repairs and/or rehabilitation. For this purpose, a 2004 WSDOT bridge deck mixture design, “Concrete Class 4000D,” was selected. This historical, prescriptive concrete specification was selected to maintain the project focus on bridge deck rehabilitation, since bridges where protective overlays are considered are typically at least 20 years old.

Figure A.3 shows the form drawings for each type of field cast substrate. Form drawings were developed to determine the quantity of material required to produce the formwork for the anticipated substrate sample sizes. The research team consulted with WSDOT for the larger substrates (6’x6’x7.5”), herein after referred to as bridge deck slabs, to determine a sample size and a reinforcement layout that would be representative of most bridge decks in Washington. The follow-on research project is funded by WSDOT and will use these bridge deck slabs for durability related studies and will include a larger aggregate size to directly address bridge decks in need of more extensive repairs.

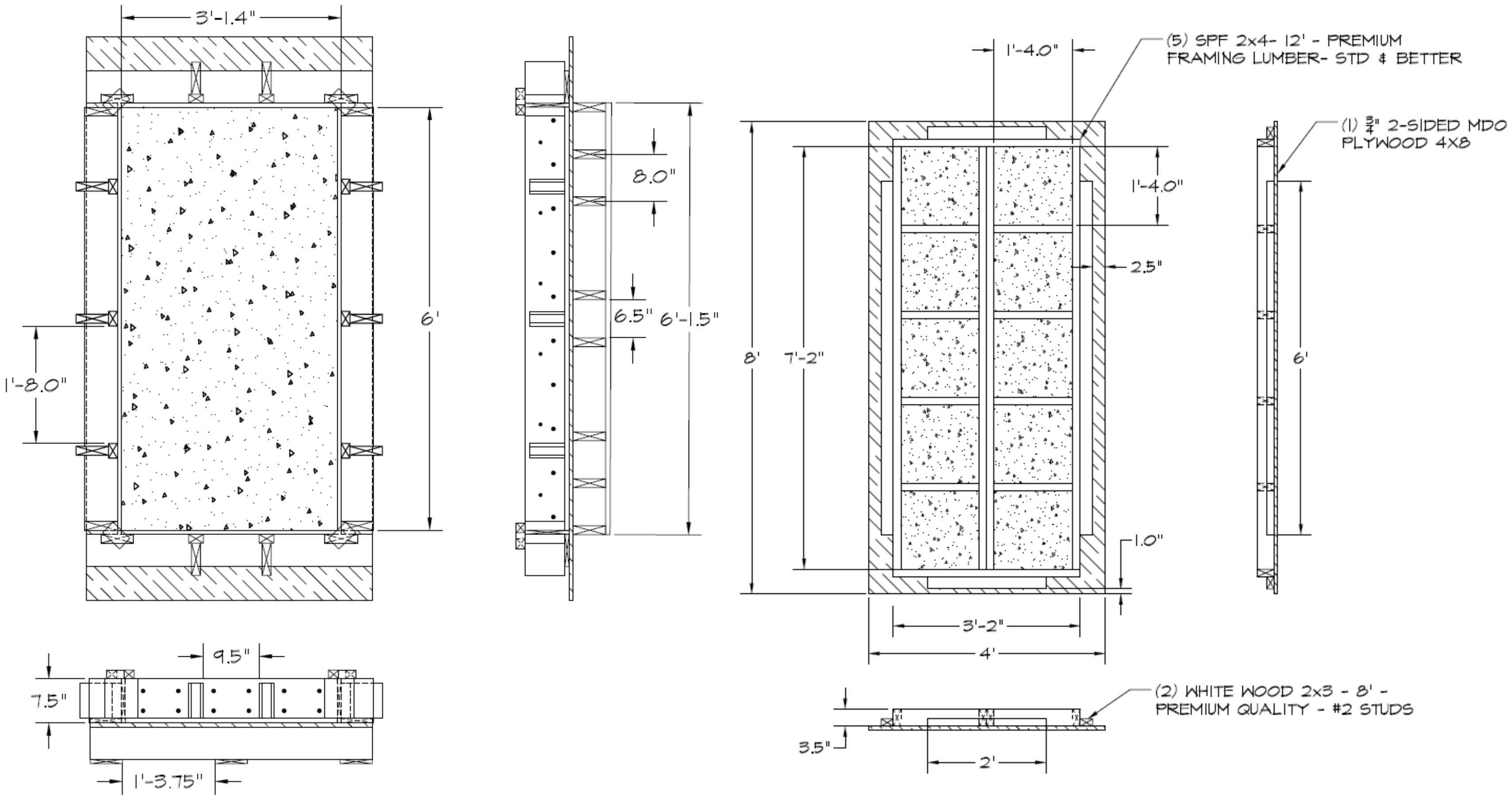

Figure A.3: Form Drawings for 6’x6’x7.5” (left) and 16”x16”x3.5” (right) Specimens.

Figure A.4 summarizes the reinforcement layout provided for the bridge deck slabs. Once material quantities were known, the team contacted a local material supplier to purchase lumber and plywood and had it delivered to the laboratory. The lumber and plywood were then cut to size and secured together according to the formwork drawings using in-house tools. Holes were cut into the sides of the forms used for the bridge deck slabs as further research on rebar corrosion that will be conducted in the follow on WSDOT project required the reinforcement to be exposed to the environment. The placement of these holes matched the reinforcement layout recommended by WSDOT representatives.

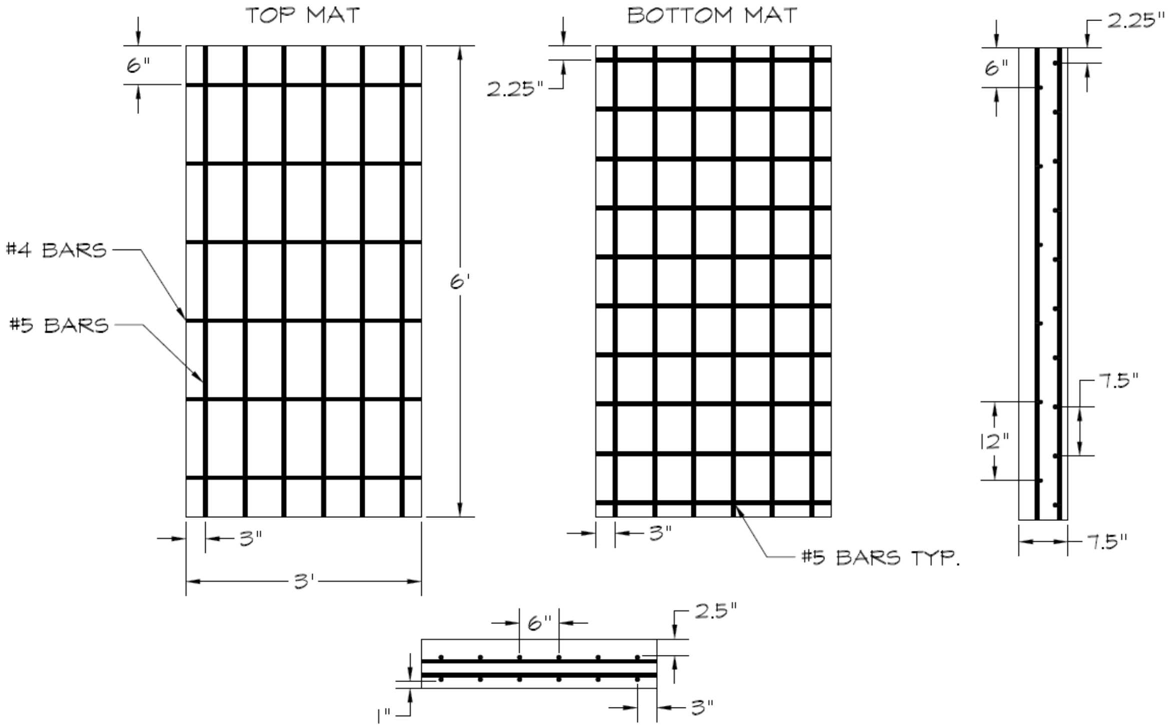

Figure A.4: Reinforcement Layout Provided for Bridge Deck Slabs.

Figure A.5 shows a completed bridge deck slab formwork with holes sealed and reinforcement secured. The team emphasized replicating current construction standards and procedures in order to produce concrete substrates that closely resembled what a professional contractor would produce for WSDOT. Reinforcement chairs were used to maintain the bottom mat clear cover for the bridge deck slabs and reinforcement wire ties were used to secure the rebar. The reinforcement provided was as recommended by WSDOT including bar sizes (No. 4 and 5), grade (A706 Grade 60), and spacing. This rebar was purchased and delivered from a local rebar fabricator after estimating material quantities based on the reinforcement layout drawing. Prior to the concrete pour, the holes were sealed using acrylic latex caulk to prevent paste seepage.

Figure A.5: Bridge Deck Slab Formwork.

Figure A.6 shows a completed formwork that was used for the paver-sized substrates. Formwork for the paver-sized substrates was put together simultaneously and similarly to the formwork for the bridge deck slabs. However, the paver-sized substrates did not use any rebar as this project's focus was on overlay-to-substrate bond strengths using small overlay thicknesses. In total, formwork for (6) bridge deck slabs and (30) paver-sized substrates were constructed for concrete casting.

Figure A.6: Paver-Sized Substrate Formwork.

A.2.2. Substrate Casting

Figure A.7 – A.11 shows multiple stages during the pouring operation. Once the formwork for the specimens was constructed, the substrate mixture design was chosen, and the total concrete volume required was calculated, a local ready-mix producer was contacted to schedule a concrete pour using one of their ready-mix trucks. They produced and delivered a total of 3.5 cubic yards of a Concrete Class 4000D mixture meeting the 2004 WSDOT Standard Specification. The concrete was poured at 1 pm on September 19th, 2023, with partly cloudy skies, an ambient temperature of 65° F, and 0 mph wind gusts. As part of the follow-on project funded by WSDOT, one bridge deck slab specimen was purposely filled just below the top of the reinforcement steel from the top mat to address rehabilitation of bridges in poor condition using larger aggregates in what will be a structural overlay. The remaining bridge deck slab specimens mirrored the paver-sized substrates cast.

During cast day, the research team received help from the local student chapter of the American Concrete Institute (ACI). With their experience with concrete and with direction from the research team, samples were cast according to ASTM standards and current construction processes. First the concrete was poured into the formwork by attaching several chutes to the ready-mixture truck. As the concrete was being poured, the team uniformly distributed the concrete with shovels and a second group followed by consolidating using multiple stingers. Care was taken to avoid reinforcement mats when vibrating. Following the complete consolidation of the specimens, a third team struck off the excess concrete using a 2x6 stud that was previously cut to size and the concrete was allowed to sit before final surface finishing using hand floats. Once the concrete was firm to the touch, surface retarders were sprayed on the surface using a weed sprayer and the concrete was allowed to cure until the following day. Further information on the surface retarders used will be discussed in the following section.

Figure A.7: Paver-Sized Substrate Formwork Placed Outside Awaiting Ready-Mixture Truck

Figure A.8: Bridge Deck Slab Formwork Placed Outside Awaiting Ready-Mixture Truck

Figure A.9: Read-Mixture Truck Before Pouring with Chutes Attached

Figure A.10: Concrete Pour in Progress

Figure A.11: Concrete Pour Finished

A.2.3. Substrate Surface Preparation

To simulate different surface preparation conditions, the top surface of the slabs were treated with two different spray-on surface retarders to obtain different surface textures. The two spray-on surface retarders used were Top-Cast® 05 (sandblast finish) and Top-Cast® 150 (exposed aggregate finish ⅜” to ⅝” etch). Bridge deck slab specimens that will be subjected to durability testing following the conclusion of this project were also treated similarly. Specimens were stored outdoors to ensure they had gone through most of their shrinkage before the overlays were placed. The sandblast finish (SB) surface retarder had a blue-tinged color were as the exposed aggregate (EA) finish surface retarder had a green-tinged color.

Figure A.12-A.14 shows the different stages of surface retarder application after the concrete pour. In total (4) bridge deck slabs were sprayed with the EA surface retarder, one of which was the slab that was filled just below the top of the top reinforcement mat here-in referred to as the significantly deteriorated bridge deck slab. The objective for spraying the significantly deteriorated bridge deck slab with the EA surface retarder was to simulate concrete removal using a hydro-demolition machine. Additionally, (13) paver-sized substrates were treated with the EA surface retarder, (12) paver-sized substrates were treated with the SB surface retarder, and the remaining (5) were not treated with any surface retarders here-in referred to as as-is paver-sized substrates. These as-is paver-sized substrates served as the controls when bond testing to quantify how surface preparation affects bond strength. In Figure A.12, the five paver-sized specimens that were left without surface retarders can be seen.

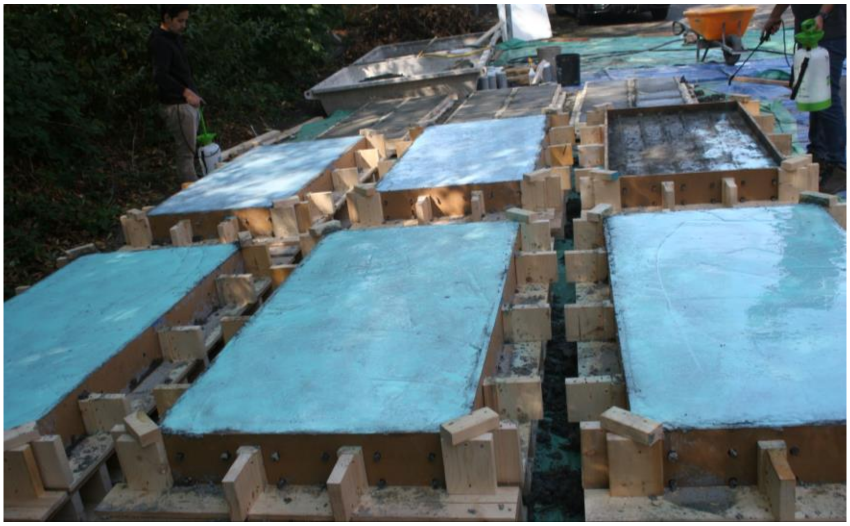

Figure A.12: Surface Retarder Application using Weed Sprayers

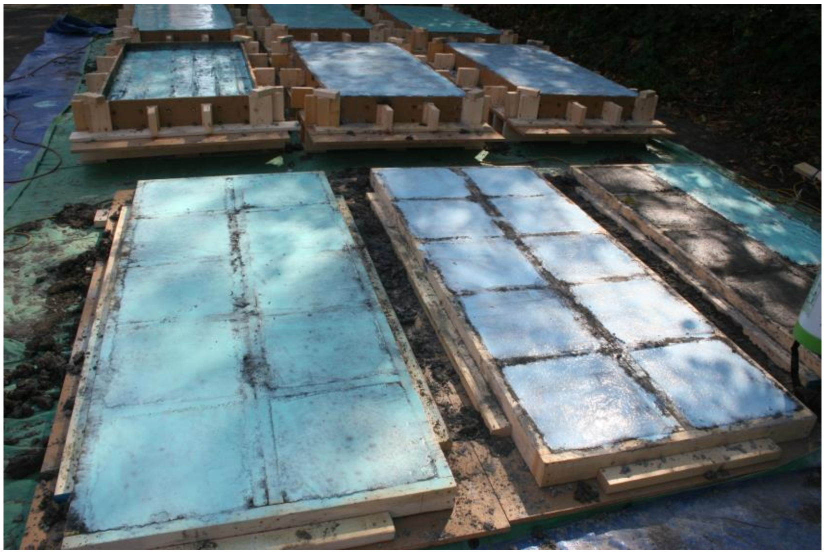

Figure A.13: Close-Up of Surface Retarders and the 5 As-is Paver-Sized Substrates

Figure A.14: Top-Surface Retarders Applied

Figure A.15 – A.18 shows the surface etching left behind by each of the surface retarders. The following day, the top surface was washed out using a pressure washer and a metal wire brush to remove unhardened cement paste and expose the surface etching. Specimens were covered with tarp and wet burlap following final set and when pressure washing was finished.

Figure A.15: Picture of Exposed Aggregate Etching on “Significantly Deteriorated” Deck

Figure A.16: Picture of Exposed Aggregate Etching

Figure A.17: Close-up Picture of Sandblast Etching

Figure A.18: Surface Etching of Paver-Sized Specimens