Internal Curing of Bridge Decks and Concrete Pavement to Reduce Cracking

Jose Pacheco, Ph.D., P.Eng
Pavan Vaddey, Ph.D
Kamran Amini, Ph.D.
Jan Vosahlik, Ph.D.

Construction Technology Laboratories, Inc.
CTLGroup

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16. Abstract

This research project focused on evaluating the performance of internally cured concrete mixtures for bridge deck and pavement with the aim of reducing volumetric changes, i.e., cracking and warping. The specific tasks conducted in this project include a literature review of internal curing technology and experiences in the US, a survey of existing bridge decks using internal curing in the state of Illinois, an evaluation of different materials as internal curing agents, and the effect of the use of internal curing in two different concrete mixtures for concrete bridge decks and pavement, respectively. During the material evaluation stage, fourteen different materials were evaluated for absorption and desorption characteristics. These materials can be categorized in three different groups: lightweight aggregate fines (LWA), superabsorbent polymers (SAP), and fibers. Based on the results of their captivity characteristics, one LWA and one SAP were selected for use and implementation in concrete mixtures. During the evaluation of performance of internally-cured concrete (ICC), determination of fresh and hardened concrete properties was conducted for one control and two ICC (one with LWA and one with SAP) at two different water-to-cementitious materials ratio (w/cm). Results showed evidence of improving the volumetric stability and durability of ICC when the w/cm ratio was 0.36. Negligible improvements were observed at a w/cm ratio of 0.45. Additionally, service life modeling for a bridge deck scenario and a life cycle cost analysis (LCCA) for a pavement project were conducted. It was concluded that the service life of bridge decks can be extended by using ICC, and that the LCCA of a ICC pavement can be reduced compared to a control scenario. Finally, recommendations for implementation into the Wisconsin Department of Transportation Specifications are provided.

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Executive Summary

Volumetric changes in concrete bridge decks and pavements can often result in cracking or warping, leading to reduced performance and durability. Volumetric changes in concrete are caused by changes in the moisture content of hardened concrete or the self-desiccation of cementitious materials with a relatively low water-to-cementitious materials ratio (w/cm).

The main objectives of this research project were: to evaluate different materials available in Wisconsin for use in internally cured concrete, evaluate the performance of fresh and hardened concrete with and without internal curing, and determine the potential impact of using internally cured concrete on the concrete durability and sustainability of bridge deck and pavement placements, respectively. In this study, the following tasks were performed:

i. Literature Review: a literature review of research studies and available project information was conducted. The review focused on identifying the governing mechanisms of internal curing agents and their effect on concrete behavior and performance.
ii. Survey of Structures: Several bridge decks in Illinois that used internally cured concrete (ICC) were surveyed with the specific aim to identify concrete cracking. The survey showed that cracking was significantly mitigated when using ICC.
iii. Mortar Study: The absorption, desorption, and other relevant physical characteristics of fourteen different internal curing agents were evaluated. Subsequently, the effect of using selected internal curing agents on volumetric changes in mortar was conducted. Finally, two internal curing agents were selected for use in concrete.
iv. Concrete Study: The effect of internal curing on fresh and hardened concrete properties of concrete was conducted for one bridge deck and one pavement mixture using two different w/cm ratios and two different internal curing agents.
v. Service Life & Life Cycle Cost Analysis (LCCA): Service life modeling was conducted for a simulated bridge deck scenario, comparing the performance of control and two ICC mixtures. Additionally, an LCCA scenario for a pavement construction project comparing a conventional concrete mixture and an ICC was conducted.

A summary of key findings is as follows:

a. Internal Curing Agents: Lightweight fine aggregate (LWFA) and superabsorbent polymers (SAP) were the most effective internal curing materials. The absorption and desorption characteristics of these materials were compatible with the cementitious material systems evaluated in the study.

b. Autogenous Shrinkage: Early-age strains caused by self-desiccation of mortar were significantly reduced when an adequate dosage of LWFA or SAP was used. It was found that the behavior of shrinkage was dependent on the absorption and desorption of the internal curing agents.
c. Fresh Concrete Properties: Changes in slump, plastic air content, and density were observed when using ICC compared to control mixtures. In general terms, ICC-LWFA resulted in similar or greater slumps than conventional concrete; conversely, ICC-SAP reduced slump when compared to control mixtures. Plastic air content in ICC-LWFA was generally comparable to conventional concrete. With regards to ICC-SAP, an increase in plastic air content was observed in most instances.
d. Hardened Concrete Properties: The behavior of ICC was found to improve the performance of concrete for freeze-thawing resistance generally, salt scaling resistance, chloride penetrability, chloride migration coefficient, cracking tendency, and warping. Compressive strength showed mixed results when using ICC-LWFA or ICC-SAP.
e. Service Life and LCCA: The effect of internal curing on the resistance to chloride penetration resulted in a likely increase in the predicted service life for bridge decks in Wisconsin. Similarly, although the initial cost of ICC in Wisconsin is estimated to be 20 to 30% greater than conventional concrete, the overall LCCA of an internally cured pavement resulted in an approximately 20% reduction in overall costs over 20 years.

Recommendations

The following recommendations are provided based on the analysis of this project:

1) Special Provision: A special provision is recommended to be incorporated into the Department's manuals to allow for concrete producers and contractors to become familiar with ICC in Wisconsin. The special provision provides sufficient flexibility to the producer and contractor to place ICC successfully while providing sufficient performance assurance to the Department.
2) Bridge Decks: To ensure that cracking in bridge decks is significantly mitigated, it is recommended that in addition to ICC, project specifications consider evaluating the potential for cracking using the restrained shrinkage method.
3) Pavement: The benefit of ICC in pavements is directly related to reducing rehabilitation costs during service. It is recommended that monitoring of the performance of ICC concrete is conducted once ICC is incorporated and successfully executed in various pavement projects.

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1. INTRODUCTION

A) ROLE OF WATER IN CEMENTITIOUS SYSTEMS

Concrete is a composite material composed of two primary constituents: cement paste and aggregates. Cement paste is formed through a hydration reaction of cement particles and water, and when supplementary-cementitious materials (SCM) are also used through the pozzolanic reaction. Both reactions rely on water (and availability of calcium hydroxide in the case of the pozzolanic reaction) to form hydrated phases, primarily calcium silicate hydrate (C-S-H), that provide the hardened system with its mechanical and other performance properties.

The total amount of water used in concrete mixtures varies and is highly dependent on specific target performance to be achieved in both plastic and hardened states. The theoretically required water-to-cementitious materials ratio (w/cm) for complete cement hydration (i.e., all of the cement grains reacted with water, gel pores filled with water, and no unhydrated powder is left in the system) is between 0.36 to 0.44 [1], [2]. The degree of hydration describes the relative portion of cementitious grains that have reacted with water to form hardened cement paste. The actual water demand for completed hydration of cement is dependent primarily on its chemical composition. A significant portion of the cementitious system is hydrated within the first few weeks after water addition, while other cementitious particles remain unhydrated even after extended periods of time [3]. Both hydration and pozzolanic reactions remain active as long as sufficient water and unhydrated cementitious materials are present in the system.

The amount of water necessary for complete hydration of the cementitious system is critical in selecting appropriate curing measures for hardened concrete. It is important to note that complete hydration (degree of hydration equal to 1) is an idealized state of the cementitious system rarely achieved in real-world structures.

In a hardened state, two primary forms of water can be distinguished in cementitious systems: evaporable (free) and nonevaporable (bound) water. Free water includes all water that has not reacted with the cementitious materials, and nonevaporable water refers to water that is either chemically combined in the solid phases of the system or is physically adsorbed to the solid surfaces contained in the cementitious system pore network.

B) CONCRETE CURING

The American Concrete Institute has defined concrete curing as ”action taken to maintain moisture and temperature conditions in a freshly placed cementitious mixture to allow hydraulic cement hydration and (if applicable) pozzolanic reactions to occur so that the potential properties of the mixture may develop.” [4]. The hydration and pozzolanic reactions are known to slow down when the system's internal relative humidity (RH) decreases and even completely stops when the internal RH of the concrete drops is less than 80%.

A loss of moisture from the cementitious system adversely affects the progress of the hydration reactions. Therefore, it can negatively affect concrete performance, especially in early ages or while still in the plastic state. For instance, volumetric changes and associated cracking development or plastic shrinkage cracking are distress mechanisms directly related to the loss of moisture in concrete while in a fresh condition or at early ages. Furthermore, deficiencies in moisture retention in concrete at early ages can compromise the exposed surface region of hardened concrete and lead to performance issues such as scaling.

Traditionally, external curing methods have been utilized to prevent moisture release from the cast concrete. These include:

- methods to supply additional moisture after the concrete has set (ponding, immersion, spraying, fogging, and saturated wet covers),
- methods to seal in the mixing water (covering with waterproof sheets or using membrane-forming curing compound), and
- accelerated curing (hot steam or heater elements such as pads or forms).

For conventional concretes containing primarily ordinary portland cement (i.e., with w/cm of approximately 0.40 or more), external curing methods can successfully prevent moisture loss. However, for concrete mixtures with w/cm lower than 0.40, especially for modern high-performance concrete (HPC) mixtures with w/cm in the range of 0.28 to 0.36, external curing methods cannot provide sufficient water for allowing all cementitious material particles to become hydrated. The reduced available water content in high-performance concrete results in limited hydration and in many cases in self-desiccation. When self-desiccation occurs, the hydration reaction stops as the available water reacts with cementitious materials. Tensile stresses are developed during self-desiccation due to capillary tension within the pore structure of the cementitious system. These stresses produce volumetric change that often exhibits micro-cracking on the micro-scale and as (autogenous) shrinkage-induced macro-scale cracking. Therefore, utilizing a concrete mixture with a low w/cm ratio produces a much denser microstructure of the cementitious paste with a lower overall level of capillary porosity. The supply of additional moisture to the system through external curing methods (ponding, spraying, wet covers) only affects the region surrounding the cured surface of the concrete. Still, it does not allow water to penetrate inside the concrete.

Internal curing is a viable alternative to external curing. The premise of the internal curing technology is relatively simple: provide internal water reservoirs designed for a delayed release of water. The primary principles and differences between external and internal curing are shown in Figure 1-1.

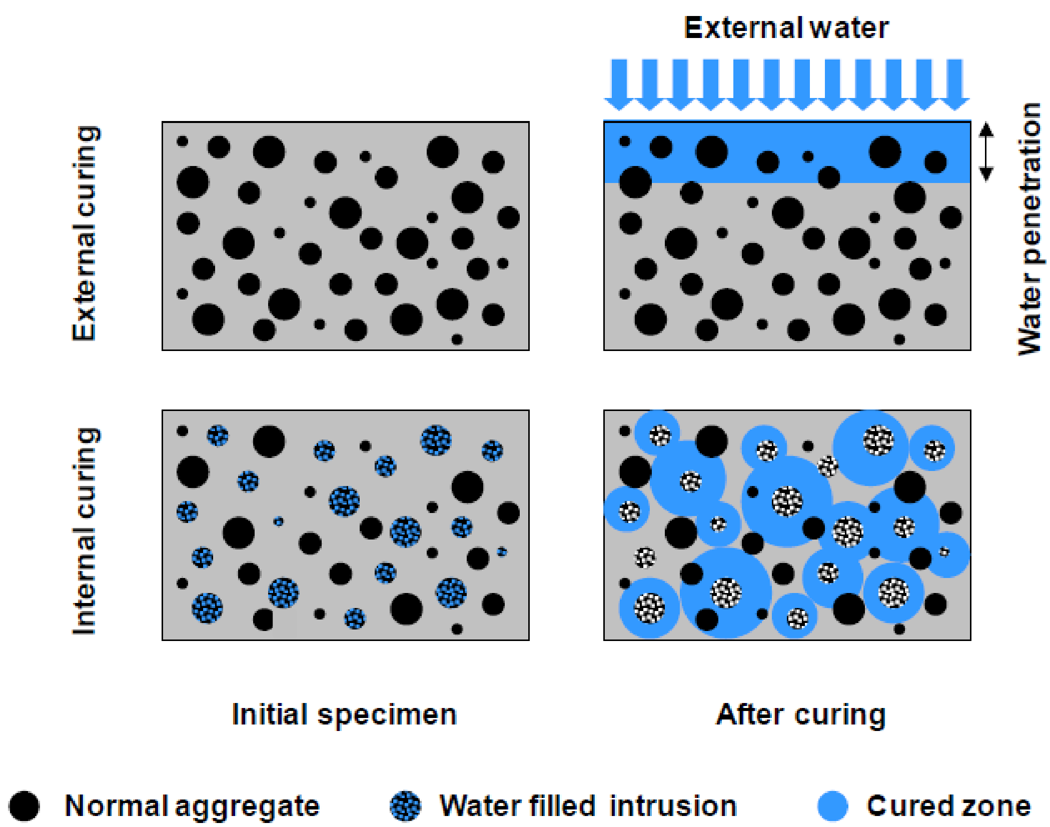


Figure 1-1: External vs Internal Curing [5]

2. LITERATURE REVIEW

A) THE CASE FOR INTERNAL CURING

The two primary objectives of internal curing are (1) to provide enough available water to enhance the hydration of cement and pozzolans in the mixture, resulting in improved mechanical properties and improved durability, and (2) to reduce or prevent distress associated with self-desiccation and autogenous shrinkage.

2.a.1. Chemical Shrinkage, Autogenous Shrinkage, Self-Desiccation

The overall reduction in volume due to the hydration reaction varies among individual hydration products; generally, an 8-10% volume reduction can be expected [6]. The process of volume reduction of the system due to the hydration reaction is typically referred to as chemical shrinkage. As the concrete solidifies, the volume change due to chemical shrinkage and self-desiccation causes a change in volume as the system hydrates, typically referred to as autogenous shrinkage. Self-desiccation, autogenous shrinkage, and chemical shrinkage are frequently incorrectly interpreted, and definitions of these terms frequently lack an agreement in the literature. The current terminology by ACI [4], as shown in Table 2-1, does not define chemical shrinkage; therefore, an alternative set of definitions as developed by RILEM is provided [7].

Table 2-1: Definitions of Elementary Terms Related to Internal Curing

Term	ACI	RILEM
Self-desiccation	The consumption of free water by the chemical reaction so as to leave insufficient water to cover the solid surfaces and cause a decrease in the relative humidity of the system.	A reduction in the internal relative humidity of a sealed system when pores are generated. This occurs when chemical shrinkage takes place at the stage where the paste matrix has developed a self-supportive skeleton, and the chemical shrinkage is larger than autogenous shrinkage
Autogenous shrinkage	The change in volume due to the chemical process of hydration of cement, exclusive of effects of applied load and change in either thermal condition or moisture content	The external-macroscopic (bulk) dimensional reduction (volume or linear) of the cementitious system, which occurs under sealed isothermal unrestrained conditions
Chemical shrinkage	N/A	The internal-microscopic volume reduction, which is the result of the fact that the absolute volume of the hydration products is smaller than that of the reacting constituents

Both chemical and autogenous deformations are critical and can affect the development of internal stresses within the porous hydrated cementitious system. Before setting, autogenous and chemical shrinkage is essentially identical. After the setting of the cementitious system, the autogenous volumetric change starts to significantly lag the chemical shrinkage, creating a negative pressure in the pore fluid, resulting in subsequent cavitation of the vapor-filled pores.

The difference between the overall magnitude of chemical and autogenous deformations results in the development of internal microcracking and can lead to the formation of macro cracks. An example of microcracking induced by self-desiccation is shown in Figure 2-1. Deterioration of mechanical properties due to shrinkage-induced microcracking are common [8]–[11]; if micro-cracks evolve into large cracks on the macro scale, durability and other performance-related aspects of the hardened concrete become compromised.

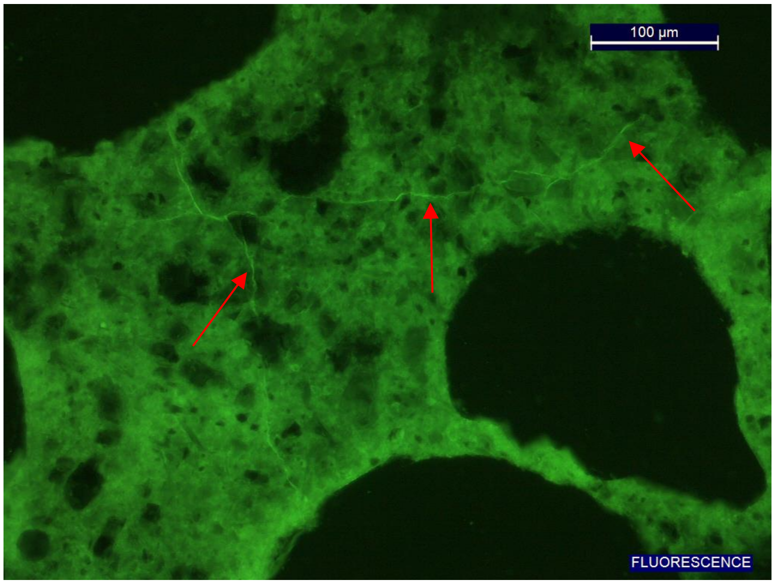


Figure 2-1: Fluorescent Micrograph on Self-Desiccation microcracking (courtesy of Laura Powers, CTLGroup)

The reaction of cement and water during hydration produces a porous cementitious matrix in which the originally water-filled pores begin to empty, resulting in the formation of liquid-vapor menisci on the walls of pores within the cement paste microstructure. The presence of these menisci in the system generates capillary pressure that is ultimately responsible for the shrinkage of the bulk system. The magnitude of the capillary pressure is a direct relationship with the radius of curvature of the meniscus and can be expressed as the Young-Laplace equation (Eq. 2-1):

$$\Delta p = \frac{2\gamma}{R}$$ **Eq. 2-1**

where Δp is the capillary pressure, γ is the surface tension in the pore solution, and R is the radius of the curvature of the meniscus. Thus, the radius of the curvature of the meniscus often referred to as the critical Kelvin radius, can be approximated as the radius of the largest pore that has not been emptied yet and remains fully saturated.

Similarly, the internal capillary pressure can be expressed as a function of internal equilibrium RH (Eq. 2-2):

$$\Delta p = \frac{RT\ln(RH)}{V_m}$$ **Eq. 2-2**

where R is the universal gas constant, T is the thermodynamic temperature, RH is the internal equilibrium relative humidity and V_m is the molar volume of the pore fluid. Subsequently, analytical models exist to predict macro-scale material volumetric change based on the capillary pressure and intrinsic material properties of the solid and liquid phase of the cementitious system [6], [12].

When combining Eq. 2-1 and Eq. 2-2, as demonstrated by Bentz and Weiss [5] and illustrated in Figure 2-2, one can obtain a relationship between internal RH and radius of the meniscus (or the largest pore that has not emptied yet). As expected, the internal RH decreases with a decrease in the Kelvin radius.

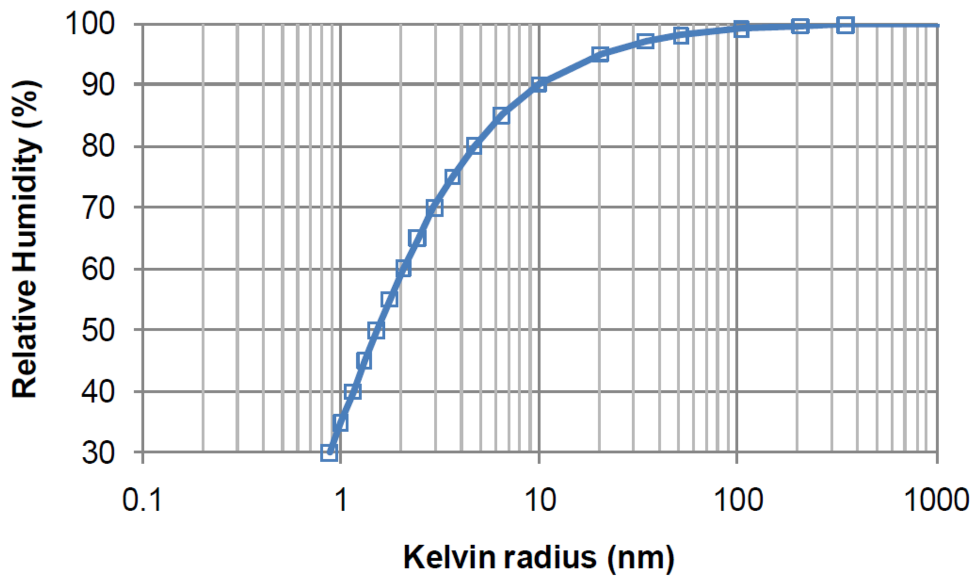


Figure 2-2: External vs Internal Curing [5]

2.a.2. Warping and Curling

Non-uniform distribution of moisture in concrete elements, especially in large unidirectional elements such as pavements or slabs, can lead to RH gradient-induced stresses and subsequent volume changes resulting in curling and warping [13], [14].

As concrete elements undergo long-term deformations due to drying, a volumetric change referred to as drying shrinkage occurs. Drying shrinkage takes place over a significantly longer period of time than autogenous and chemical shrinkages and is driven by slow moisture loss due to environmental conditions. If water is supplied back to the system, typically due to external weather conditions, a portion of the drying strain can be reversed, as shown in Figure 2-3.

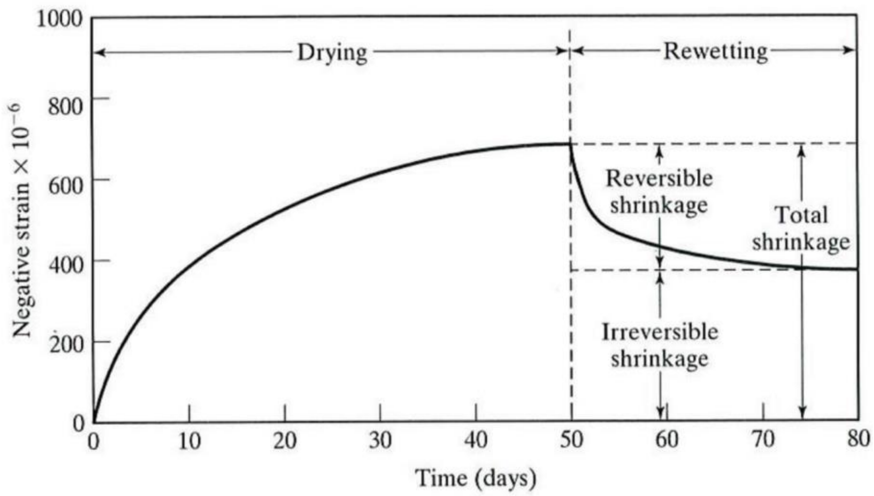


Figure 2-3: Concrete pavement shrinkage due to drying and wetting [15]

In the case of pavements and other similar concrete structures, the boundary conditions are such that non-uniform drying exists as typically the top surface of the element is exposed to ambient conditions while the bottom and side surfaces are protected from moisture loss by the substrate or vice versa. Thus, as the top surface of the pavement dries out faster than the bottom portion of the element, different drying strains are induced, and non-uniform deformation knowns as warping (or curling) can occur. The nature of this type of deformation is very similar to non-uniform temperature-induced deformations (the top surface of the pavement is subject to different temperature conditions compared to the bottom portion of the pavement), and these two phenomena typically co-occur as shown in Figure 2-4.

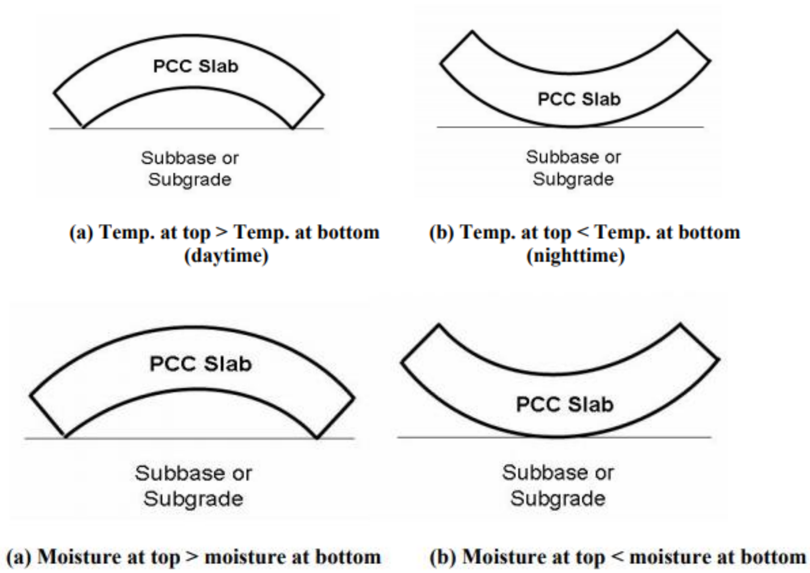


Figure 2-4: Concrete pavement deformations due to temperature and drying shrinkage [15]

2.a.3. Internal Curing Requirements

2.a.3.1 Required Amount of Curing Water

The required amount of free water supplied by the internal curing agent must be sufficient to fill the capillary porosity of a given cementitious system and its maximum attainable degree of hydration. In other words, chemical shrinkage creates the underlying driving force for the occurrence of autogenous shrinkage that is the macroscopic bulk deformation of a closed, isothermal, cementitious material system not subjected to external forces. Therefore, the total volume of available water must be sufficient to offset the difference between chemical and autogenous shrinkage.

As discussed in Section a), complete hydration of a portland cement system occurs at w/cm of approximately 0.42. Powers has shown that one gram of cement binds approximately 0.23 grams of the capillary (free) water and 0.19 grams of gel water (i.e., 0.23 + 0.19 = 0.42) [15]. This is illustrated in a diagram of an idealized closed (i.e., sealed) system with w/cm of 0.30, as shown in Figure 2-5. Since the w/cm of the shown system is less than 0.42, a complete degree of hydration ($\alpha = 1$) is not possible. Additionally, as all capillary water is consumed at point C, self-desiccation occurs between points C and D.

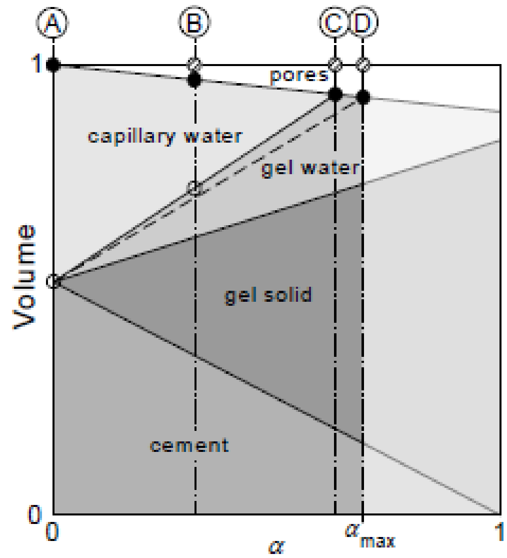


Figure 2-5: Volumetric phase diagram of a sealed system with w/cm of 0.30 [5]

Jensen [15] demonstrated that the necessary amount of internal curing water for portland cement paste systems with w/cm of less than 0.36 is (Eq. 2-3):

$$w_{IC} = 0.18w \qquad \textbf{Eq. 2-3}$$

where w_{IC} is the internal curing water and w is the mixing water. This relationship is based on the assumption that hydration at low w/cm stops when all capillary water is consumed. Subsequently, the amount of internal water required for concrete mixtures can be calculated based on the volumetric relationship of the cement and aggregate phases of the concrete mixture.

Bentz and Snyder [16] developed a water demand relationship for saturated lightweight fine aggregate (LWFA), as shown in Eq. 2-4:

$$M_{LWA} = \frac{C_f C_s \alpha_{max}}{S \phi_{LWA}} \qquad \textbf{Eq. 2-4}$$

where M_{LWA} is the mass of a dry LWFA needed per unit volume of concrete, C_f is a concrete cement factor, C_s is the chemical shrinkage of cement paste expressed as a ratio of the mass of the water to mass of cement (mL/g), α_{max} is a maximum expected degree of hydration of cement (estimated 1 for w/cm 0.36), S is the degree of saturation of aggregate (from 0 to 1) and ϕ_{LWA} is the 24-hour absorption of the lightweight aggregate. Although this equation was developed for use with LWFA, and therefore is typically presented in a form that includes LWFA mixture proportioning parameters (degree of saturation, absorption), the relationship essentially equates the required volume of provided water to the magnitude of chemical shrinkage divided by the density of water (and adjusted for the maximum expected degree of hydration). Therefore, this equation, with proper adjustments for material properties, can be applied to internal curing agents beyond LWFA.

As apparent from Eq. 2-4 and the presented discussion, the required volume of curing water is driven by the chemical shrinkage of the system. Therefore, the chemical shrinkage of the cementitious system must be known for an accurate estimation of the required water content. It has been suggested that a value of 0.07 mL/g can be used as a sufficient approximation [5]. However, in the presence of supplementary cementitious materials, chemical shrinkage can be significantly altered [15], [17]. It was also shown that the curing temperature influences the chemical shrinkage of cementitious systems [18]. Therefore, the required volume of the provided internal curing water will vary with expected curing conditions.

2.a.3.2 Desorption Characteristics of the Internal Curing Agent

As the available water is consumed due to the hydration reactions (and the internal RH drops), the internal water must be released from the curing agent to refill the pores and to prevent self-desiccation. It is critical that the utilized internal curing agent is capable of readily releasing the curing water from its structure at high RH values during the early ages of the cementitious systems to minimize the self-desiccation of concrete [5]. For effective internal curing, the water from the internal reservoirs must be released before reaching an internal RH level of 85 to 95% [17], [19]. The desired and undesired desorption behavior of an internal curing agent is illustrated in Figure 2-6.

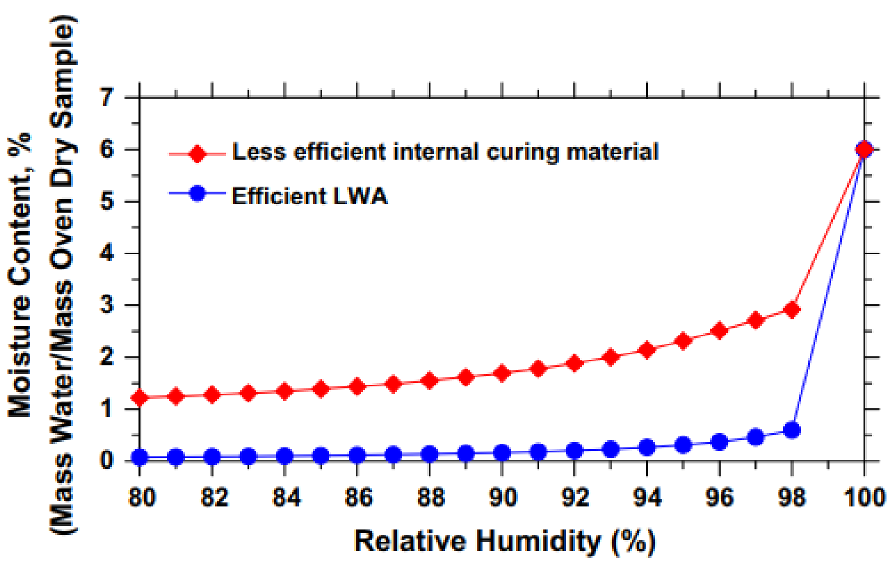


Figure 2-6: Desired and undesired desorption behavior of an IC medium (after [20]**)**

B) INTERNAL CURING MATERIALS

2.b.1. Internal Curing Agents

Various materials have been researched and utilized as an internal curing medium for concrete. To some extent, internal curing has been used unknowingly in many concrete structures incorporating lightweight aggregates dating back to Roman times [21]. Upon formulating the internal curing mechanism and principles [22], saturated lightweight aggregate has become the most popular and utilized IC agent, especially in the United States [5], [23]. However, other materials have been considered for internal curing. A RILEM classification of internal curing agents based on the mechanism of water retention is shown in Table 2-2:

Table 2-2: RILEM classification of internal curing agents [24]

Chemically Bound Water	Physically Adsorbed Water	Physically Held Water	Unbound Water
Calcium aluminates	Superabsorbent polymers (SAP)	Lightweight aggregate (pumice, perlite, expanded clays, and shales)	Microencapsulation [25]
Ettringite	Clays (bentonite) [26]	Recycled concrete aggregate (RCA)	Emulsified water
		Diatomaceous earth	
		Wood-derived powders and fibers	

For purposes of this literature review, only underlined materials shown in Table 2-2 are discussed as they are included in the experimental portion of this research program. Some of the listed materials (calcium aluminates, ettringite, diatomaceous earth, emulsified water) have been proposed as potentially suitable materials for internal curing. However, no attempt to use these in internal curing has been identified [24].

2.b.1.1 Saturated Lightweight Fine Aggregate

Both coarse and fine pre-wetted lightweight aggregates were previously used for internal curing. However, it has been demonstrated that the use of fine lightweight aggregate is much more effective than using coarse-sized aggregate, primarily because a better spatial distribution of the water reservoirs is attained when a smaller fraction aggregate is used.

The family of LWFA that have been successfully utilized for internal curing is extensive and includes manufactured expanded products such as shales, clays, slates, fly ashes, or slags, as well as naturally occurring aggregates such as pumice, perlite, scoria, typically of a volcanic origin [27]. Control and characterization of LWFA absorption capacity and moisture levels is a critical performance aspect of concrete mixtures.

One of the critical tasks in this process is to achieve a saturated-surface dry (SSD) condition of the LWFA at a minimum. The two most common and utilized approaches of moisture and absorption capacity characterization include the paper towel method (shown in Figure 2-7) as defined by ASTM C1761 [28] and the centrifuge method [29]. The centrifuge method, when pre-soaked aggregate is spun in a centrifuge for a pre-determined period of time, has been shown and accepted to be the most suitable approach to the moisture characterization problem [30]. The desorption parameters are also typically obtained using the procedure outlined in ASTM C1761 when small samples of saturated LWFA are exposed to an environment with 94% RH, which can be achieved by using a saturated solution of certain salts placed in a sealed chamber.

Figure 2-7: The towel method, ASTM C1761

2.b.1.2 Super-Absorbent Polymers

A superabsorbent polymer is a polymeric material that can absorb a significant amount of liquid and retain the liquid within its structure without dissolving. SAPs are principally used for absorbing water and aqueous solutions and have been widely utilized in many industries since their major market breakthrough in the 1980s [31].

SAPs are formed by crosslinking chains of polyelectrolytes with various chemistries. The most frequently produced types utilized in the construction industry include acrylamide/acrylic acid copolymer and polyacrylic acid [32], [33]. The ionic nature of the polymer chains is responsible for the swelling (i.e., water absorption) of the SAPs. When dry SAP particles are introduced to a fluid, the high concentration of charged ions in the polymer structure creates an osmotic pressure gradient (i.e., high osmotic pressure within the SAP and low osmotic pressure in the fluid) that is relaxed through the fluid absorption process. The osmotic pressure that is driving the absorption mechanism is directly proportional to the concentration of ions in the aqueous solution [34].

The overall absorption rate of SAP is dependent on the chemical composition of the polyelectrolytes and the concentration and nature of ionic species of the fluid that is to be absorbed. It has been shown that SAP capable of absorbing deionized water of up to 2500-5000 times (i.e., rate of 2500-5000 g/g) their weight can be synthesized [33], [35], the typically utilized SAPs in the construction industry can absorb water up to several hundred times of their weight [34]. The absorbency rates are significantly reduced for fluids with high ionic contents, such as cement paste pore fluid. It has been shown that especially bivalent cations such as Ca^{2+} decrease the absorbency by a much higher rate than other ions due to bonding with the carboxylate groups in the acrylate chains and the formation of additional cross-linking that prohibit further swelling [36], [37].

The desorption mechanism of SAP is different from LWFA. The three primary driving factors for SAP desorption are (1) RH gradient, (2) osmotic gradient due to different ionic concentrations in the pore solution and the SAP system, and (3) capillary suction [36], [38]. These three elements act in parallel during the early-age stage of a cementitious system; therefore, the characterization of desorption properties of the SAP systems is not as straightforward as for the LWFA. Various techniques and procedures of SAP desorption evaluation are available in the literature [39], [40].

The standard for SAP absorbency characterization across industries is the tea bag test. For the use in concrete, the test has been modified and utilized in conjunction with a centrifuge to obtain representative behavior of the SAP when exposed to various fluids. During the tea bag test, a very small sample of the

SAP is placed into a permeable membrane (i.e., the tea bag) and immersed in the fluid, as shown in Figure 2-8. Subsequently, a mass gain is measured at various time intervals. Recently, the tea bag methodology was significantly improved for the use with cement-based systems [36], [41], [42]

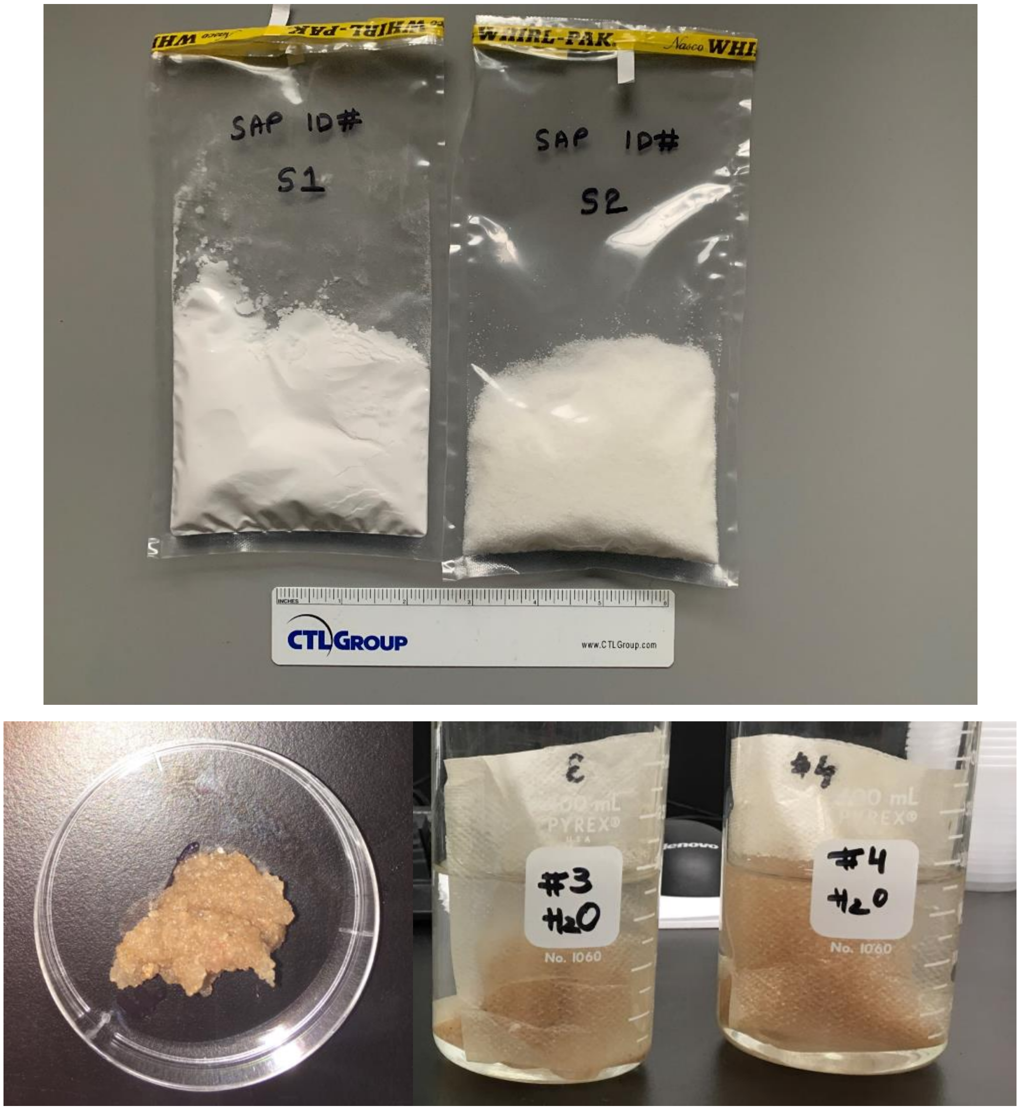


Figure 2-8: Dry SAP (Top), Swollen SAP (Bottom Left), tea-bag test (Bottom Right)

As opposed to LWFA, where pre-wetting of the material is required for internal curing, SAP has been previously used both as a pre-wetted and dry additive in concrete mixtures due to their very high absorption rate. When added dry, the amount of mixing water is adjusted to allow for a certain portion to be absorbed by the SAPs and released later [43].

2.b.1.3 Wood-Derived Products

A large variety of vegetable- or wood-derived fibers has been successfully incorporated in cement-based systems as internal concrete reinforcement. As a by-product of the paper industry, cellulose fiber pulps are the most common form [44]; however, fiber products derived from pinus pulp, eucalyptus, sisal, banana, fique, cotton liners, and many others were researched [45].

Since these products can absorb and retain water, they were proposed as a potential agent for the internal curing of concrete. In addition to providing water for internal curing, these products can help mitigate the effect of self-desiccation and autogenous shrinkage by acting as an internal reinforcement bridging and closing the developed microcracking. Several studies were conducted on the feasibility of wood-derived products, including fibers of various lengths and sizes, as well as nano-sized products and powders [46]–[49]. However, the available research literature only presents work conducted on the cement-paste level and no literature was identified describing experimental work on concrete. Furthermore, absorption and desorption properties of wood-derived products and techniques of determination thereof have not been established.

2.b.1.4 Recycled Concrete Aggregate

RCA is a reclaimed material product acquired by the crushing of disposable hardened concrete. RCA can be reclaimed from a structure or a pavement at the end of its service life or from concrete that has been returned to the concrete plant. It is estimated that more than 140 million tons of RCA are produced in the US every year [50]. According to the FHWA, 38 US states use RCA as an aggregate base while only 11 states recycle it into a new concrete [51].

As an internal curing agent, RCA behaves as an LWFA. Therefore, internal curing programs can be designed using the same means and methods that would be utilized for pre-wetted LWFA. The major difference between RCA and LWFA is the cost as well as sustainability. While LWFA must be (in most cases) produced and very frequently requires long-distance shipping, RCA is a recycled product that can be reclaimed locally. Additionally, the construction carbon footprint can be reduced when RCA is used. Multiple studies have demonstrated that RCA can be successful for the internal curing of concrete mixtures [52]–[54].

C) INTERNAL CURING AND ITS EFFECT ON CONCRETE PROPERTIES

2.c.1. Workability and Air Void Content

In most of the published research studies, LWFA resulted in minor changes to the performance of concrete in a fresh condition when the LWFA is adequately conditioned, batched, and mixed with the other constituents. However, it has been established prior to utilizing LWFA for internal curing that a reduction in workability can be expected for lightweight concrete mixtures if the aggregates are not fully saturated due to absorption of some of the mixing water in the a fresh state [55]. Furthermore, if the LWFA is not adequately saturated, slump loss, pumpability issues, inverse segregation, and finishability difficulties are likely to occur [56].

The effect of SAPs on fresh concrete properties is more pronounced. Changes in workability, plastic air void content, and time of setting due to the introduction of SAPs have been reported. Since SAP is typically added in a dry state to the mixture, a portion of the mixing water is absorbed by the SAP particles. A reduction in workability can be expected unless the additional mixing water is supplied to counterbalance the absorbed water. In some studies, workability-matching was utilized as a tool to determine the amount of water absorbed by the SAPs upon their addition to the mixture [57]. As for the wood-derived products and RCA, a very limited amount of information regarding the fresh properties of concrete mixtures incorporating these IC agents is available.

2.c.1.1 Workability

In the study conducted by Villarreal, the slump of concrete pavement mixtures with a target slump of 2.00 to 5.00 in. was unaffected by the use of saturated lightweight fines for internal curing [58]. Similarly, other studies had shown that slump remained largely unaffected when saturated LWFA was utilized [59], [60]. When used in high-performance concrete mixtures, a reduction in a slump from 8.5 in (215 mm) to 4.0 in (102 mm) was noted when the dosage of pre-soaked lightweight aggregate fines was increased as reported by Cusson and Hoogeveen [9]. They noted that the effective w/cm (i.e., mixing water + water available on the surface of LWFA) decreased with an increase in the amount of utilized LWFA, hence the reduction in slump values with an increase of the LWFA.

Craeye et al. observed a decrease in both slump and slump flow values after the addition of SAP particles to the concrete mixture. Instead of adjusting the water content, the dosage of water-reducing admixture was increased to achieve the required workability [61]. Woyciechowski et al. recorded up to 50% slump reduction when two different SAP products were used in concrete at dosages ranging from 0.047% to

0.204% by cement mass [43]. Mechtcherine et al. conducted a study on rheological properties (i.e., yield stress and plastic viscosity) of mortars with various types of SAPs. They showed that although in the most evaluated case, both yield stress and plastic viscosity increase upon the addition of SAPs, the specific amount and rate of change depends on SAP particle size, absorption characteristics, and the amount of available water in the mixture [62]. Additionally, it was demonstrated that SAPs could alter the rheological properties of the lubrication layer formed during pumping, hence affecting the pumpability of the mixture [63], [64].

Kawashima reported that the introduction of pre-wetted cellulose fibers decreases concrete workability. In her study, 1% of the fiber addition by mass of cement resulted in a significant slump and slump flow reduction at various w/cm [47]. Similarly, studies by Jiang et al., Jongvisuttisun, and Mezencevova et al. showed that a higher dosage of water-reducing admixture is required to compensate for the workability loss due to the utilization of wood-derived fibers as internal curing agents in concrete and mortar mixtures [49], [65], [66].

2.c.1.2 Air Content

Cusson and Hoogeveen [9] noted that the plastic air content of high-performance concrete mixtures was largely unaffected by the use of pre-soaked lightweight fines. In their study, non-entrained concrete was utilized. The plastic air content remained around 3% in their study in all cases except for a mixture with a low dosage of pre-soaked lightweight fines. Similar performance was reported by Browning for concrete mixtures with air entrainment. The plastic air content measured in this study was approximately 8% for control and IC mixtures using saturated lightweight aggregate [67].

No literature data is available on the plastic air void content of concrete mixtures with SAPs. However, it has been proposed that the SAP can create air voids in the cementitious matrix upon discharging the curing water similar in size and distribution to traditional entrained air voids [68]. A study by Olawuyi et al. showed that the amount of creating SAP voids depends on SAP particle size, w/cm ratio, and the amount of water absorbed by the SAPs. Additionally, the size of the SAP voids was proportional to the original particle size of the SAPs [69].

2.c.2. Mechanical Properties

2.c.2.1 Compressive Strength

In the study conducted by Villarreal, the compressive strength of pavement mixtures with LWFA for internal curing exhibited greater compressive strength than mixtures without saturated-LWFA [58].

Similarly, Cusson and Hoogeveen showed that internally cured concrete using varying amounts of saturated LWFA significantly reduced autogenous shrinkage without affecting the strength or elastic modulus of the concrete [9].

The New York State Department of Transportation (NYSDOT) constructed a series of bridges from 2009 to 2011 using saturated lightweight aggregates for internal curing [70]. The mixture proportions for the bridges utilized a replacement of 30% by volume of saturated lightweight aggregates and a water-to-cementitious ratio of 0.40. Results of the study showed that internal curing either had a negligible effect on strength or resulted in higher strengths. However, other studies have shown that some reduction of compressive strength occurred for concretes with LWFA, typically on the order of 10 to 20% [33], [71], [72].

When SAPs are used as an internal curing agent, the available literature is not conclusive as to what are the effects of SAPs on compressive strength. Some studies have shown that a compressive strength can be reduced or even increase when SAPs are utilized [73]–[75], whereas some studies have reported no strength loss due to the SAP addition [76], [77]. The primary concern with the use of SAPs and strength development is the w/cm. As most of the SAP products are typically added dry, the absorption of mixing water by the SAPs is only assumed and difficult to measure directly. The additional water is typically added to the mixture to compensate for the loss of mixing water to SAPs. Therefore, as pointed out by Hasholt, many studies incorporated control mixtures with different w/cm than the SAP-modified mixtures, thereby making their conclusions regarding the strength development questionable [78].

2.c.2.2 Modulus of Elasticity

It is established that the mechanical properties of aggregates have a strong influence on the mechanical performance of concrete and its modulus of elasticity [79]. Golias [80] conducted a study on internally-cured concrete mixtures with w/cm of 0.30 and 0.50 and respective LWFA replacement rates of 28% and 25%. The experimental results showed a reduction in elastic moduli of IC concrete mixtures compared to the control. Similarly, Byard and Schindler [59] also found a reduction in elastic moduli for IC mixtures.

The reduction of the elastic modulus in concrete containing LWFA can be explained by a combination of lower stiffness of the lightweight aggregate compared to normal weight aggregate due to its increased porosity and the weaker bond between lightweight aggregates and paste [59], [79].

2.c.2.3 Flexural Strength

An increase in 3-day and 28-day flexural strength results in concrete mixtures with a w/cm ratio of 0.44 of control and a 100 lb/yd³ of saturated LWFA substitution for the internally cured mixture was reported by Bentz [17]. Another study showed that samples fabricated with internally cured concrete with SAP had a lower flexural strength when compared to control mixtures [81]. This decrease in the mechanical performance of internally cured concrete was also observed in ultra-high performance concrete mixtures [82]

2.c.3. Volumetric Stability

2.c.3.1 Plastic Shrinkage

As reported by Schlitter, the probability of plastic shrinkage cracking decreases as the volume of LWFA replacement increases [83]. Similarly, Henkensiefken found that plastic shrinkage cracks can be prevented if an adequate LWFA replacement quantity is used [19]. The study showed that with an increase in internally cured agent, a decrease in crack widths and plastic shrinkage cracking was observed.

2.c.3.2 Autogenous Shrinkage

One of the original uses investigated for internal curing was the reduction of autogenous shrinkage in low w/cm ratio concrete mixtures [84]. The influence of IC on this property has been studied extensively, and results, in general, have shown that autogenous deformations can be mitigated if sufficient internal curing is provided.

Lura conducted a series of studies on autogenous shrinkage of concrete samples fabricated with conventional normal weight aggregates and lightweight aggregates [85]. Results showed that the autogenous deformation of portland cement concrete showed a bilinear shrinkage behavior like cement paste. Concrete samples fabricated with slag cement replacement showed later development of shrinkage, preceded by expansion, but the shrinkage after one week exceeded portland cement samples. Shrinkage compensation was observed in concrete with saturated LWFA. The volumetric expansion was attributed to the expansion of the cement paste hardening in saturated conditions due to internal curing, as was confirmed by analytical calculations. Similarly, other studies showed that internally cured mortars using either saturated lightweight fines or SAP could reduce autogenous shrinkage [86], [87].

2.c.3.3 Drying Shrinkage

Browning showed the long-term performance of concrete mixtures with and without LWFA for internal curing subject to drying in accordance with ASTM C157 [67]. Results showed that the unrestrained shrinkage of internally cured concrete decreased with an increasing amount of IC agent.

A study on the influence of SAP on drying shrinkage was conducted by Pierard [88], who found that internally cured concrete mixtures with SAP had similar performance to control mixtures. Results indicated that the drying shrinkage of IC concrete was slightly higher due to a higher total moisture loss and the potential increase in porosity caused by SAP.

2.c.3.4 Restrained Shrinkage

Henkensiefken presented results of restrained shrinkage cracking for sealed (autogenous) and total (drying plus autogenous) shrinkage [19]. Results showed that concrete mixtures exposed to drying in addition to autogenous shrinkage are more likely to crack than mixtures experiencing autogenous shrinkage only. The main finding was that the age of cracking is delayed as the volume of the IC agent (lightweight aggregate fines) increases.

In a study conducted by Schlitter, the effect of restrained shrinkage of mortars with superabsorbent polymers was examined [89]. Although the reduction in restrained shrinkage cracking was achieved, a decrease in compressive and tensile strength was also observed in mixtures using SAP. The authors attributed the observed behavior to the reduced modulus of elasticity and a possible increase in creep.

2.c.3.5 Curling and Warping

In a study conducted by Wei and Hansen [23], internally cured concrete mixtures reduced warping by 70%. The mixes used a 0.45 w/cm ratio and were dried for 16 days. A decrease in warping was found to be achieved by providing a uniform relative humidity through the thickness of the slab by allowing desorption of water from saturated LWFA.

2.c.4. Durability

2.c.4.1 Chloride Penetration Resistance

The resistance to chloride penetration of internally cured concrete was studied by Zhutovsky and Kovler [90]. It was found the chloride penetrability resistance determined in accordance with AASHTO T277 was higher for IC concretes with the w/cm ratio of 0.33 or higher. Cusson investigated internally-cured concrete for high-performance bridge deck applications [91]. A similar study conducted by Cusson and Margesson showed that chloride penetration resistance increased by 25% and water permeability decreased by 19% [92].

Hasholt and Jensen [93] evaluated chloride migration in concrete mixtures with SAP. Results indicated that chloride migration was reduced in concrete samples containing SAP in mixtures where SAP absorption was compensated with additional batch water and in those without additional batch water. In the former, observed results were attributed to densification of hydrated cement. In the latter, the reduced chloride migration was linked to a decrease of the concrete effective w/cm.

2.c.4.2 Freeze-Thawing Durability

Cusson et al. subjected concrete samples to 300 rapid freeze-thaw cycles in water and 50 slow freeze-thaw cycles in a 4% $CaCl_2$ solution. The results of the study showed that the mass loss after freeze-thawing cycles of internally-cured concrete was lesser than the reference concrete. An additional potential benefit of the use of saturated lightweight aggregates for internal curing is the capillary voids left by IC water. Bentz and Snyder studied the freeze-thaw durability of concrete with LWFA based on numerical modeling of cement hydration in conventional pastes and internally cured pastes [94]. Similarly, studies have shown the voids left by desorbed SAPs can provide additional freeze-thaw protection to internally cured concrete mixtures [95].

2.c.4.3 Bridge Deck Cracking

Transverse cracking in bridge deck construction has been a recurrent constructability issue in the industry. According to the NCHRP Report 380 [109], cracking in newly constructed bridge decks is typically full-depth and spaced between 3 to 10 ft. apart along the length of the bridge. Transverse cracks may shorten the service life of a bridge and increase maintenance costs [96]. They can accelerate the initiation of reinforcing steel corrosion, shorten the time-to corrosion-induced cracking and deterioration of concrete, and reduce the serviceability of the structure.

Early-age bridge deck cracking is known to be caused by tensile stresses generated by two major driving forces for early-age volume change: thermal deformation due to cement hydration and shrinkage deformation (autogenous shrinkage and drying shrinkage) [97]. A study conducted by Streeter et al. [70] showed an improvement in cracking mitigation obtained by using internal curing of concrete.

As discussed above, the resistance to cracking due to early-age volumetric changes of IC concrete has been found to exceed the performance of conventional concrete. Based on available project literature, cracking of IC bridge decks has been reportedly reduced compared to conventional concrete.

2.c.4.4 Pumping of IC Concrete

Pumpability (i.e., the ability of concrete to be transported by the means of a hydraulic pump) of concrete mixtures is a function of various parameters, including but not limited to: plastic viscosity and yield stress of the mixture, adequate cement paste volume (i.e., water and cement content) to prevent solid-to-solid interactions between aggregate particles, dynamic stability and mixture's resistance to segregation, aggregate size and its moisture state, pump type, pump line size and pumping circuit geometry, pumping speed and others. To this extent, concrete mixtures containing an internal curing agent must meet the same requirements as mixtures without the IC agent. The general guidance for proportioning of pumpable concrete mixtures is provided by ACI [98].

Beyond standard concrete proportioning practices for pumpable concrete, the single most critical aspect related to pumpability of concrete mixtures with lightweight aggregate is their saturation state [99]. If highly-absorbent aggregate (i.e., lightweight aggregate used as an internal curing medium) is below its saturated surface-dry (SSD) state, rheological properties of the cement paste will change under pressure in the pump due to water migration from the cement paste into the pores of the lightweight aggregate [99], [100]. As a result, the volume of available cement paste in the system is reduced and concrete will require higher pumping pressure to achieve a given flow rate or might become not pumpable. This is rarely an issue by design for IC concrete since the objective of using the lightweight aggregate is to provide additional curing water. Therefore, the aggregate is always pre-soaked and over-saturated. However, poor concrete batching practices, such as improper aggregate pile management or incorrect moisture determination methods, can lead to such situations. Additionally, it has been recognized that the full saturation of a lightweight aggregate under the atmospheric pressure might not be achieved and additionally porosity might become available under the pressure of the concrete pump. To address this issue, it is recommended to measure the aggregate absorption capacity under vacuum and subsequently increase the mixing water to compensate for the additional porosity of the aggregate [98].

A laboratory study on pumpability and rheological properties of mixtures with SAPs and fibers revealed that the SAP addition to a concrete mixture increase both plastic viscosity and yield stress of the mixture, resulting in higher required pumping pressure for a given flow rate [64]. Furthermore, it was found out that the lubrication layer that is formed along the wall of the pipeline during pumping is significantly thinner for mixtures with SAPs compared to mixtures without SAPs. This layer facilitated the shearing in the pipeline; it was observed that the primary mode of pumping for the investigated mixtures was a plug flow (i.e., only the lubrication layer is being sheared, and the concrete itself moves as a solid body throughout the pipeline). Moreover, it was shown that SAPs can act as viscosity-modifying admixtures increasing the segregation resistance of a concrete mixture. This characteristic can be beneficial to pumping as one of the major pumping issues of highly-flowable or self-consolidating concretes is segregation, either in the pump line causing a blockage or in the formwork leading to undesirable concrete performance. No literature is available on pumping of concrete with other internal curing agents.

3. EXPERIMENTAL PROGRAM

As discussed in the literature study, the enhancement of concrete performance through internal curing agents can be by (1) increased degree of hydration and by (2) relieving stresses inside capillary pores developed due to the self-desiccation mechanism. The performance of IC agents in concrete is dependent on their ability to retain water during the mixing process and on their ability to maintain the relative humidity of the concrete system during the hydration process [101]. To better assess the influence of internal curing agents on the properties of concrete, two separate experimental studies were conducted. In the first study (herein referred to as mortar study), the influence of two LWFAs and two SAPs on autogenous shrinkage and drying shrinkage was investigated. Materials were investigated via standard test procedures reported in ASTM C1698 and ASTM C596. In the second study, referred to herein as concrete study, the influence of internal curing agents on fresh and hardened properties was investigated. Twelve different concrete mixtures with and without internal curing agents were considered. Fresh properties investigated in this study included slump, air content, temperature, unit weight, edge-slump, V-Kelly, and rheology. Among the LWFAs and SAPs considered in the mortar study, one of each type was considered in the concrete study based on their performance in controlling autogenous and drying shrinkages. More details on the experimental program considered for each study are discussed in the following sections.

A) MORTAR STUDY

3.a.1. Materials and Mixture Proportions

Because the ability of an IC agent to enhance the performance of concrete is dependent on its absorption and desorption characteristics, an experimental study was conducted prior to the mortar study to determine these characteristics. Four LWFAs, five SAPs, and five fibers were investigated, results of which are discussed in Appendix B. Data generated in this study indicated that the LWFAs and SAPs have relatively better absorption and/or desorption characteristics compared to fibers based on the materials tested in this project. Hence, further evaluation of fibers in mortar and concrete studies was discontinued. Among the LWFAs and SAPs considered in absorption and desorption studies, two LWFAs (herein referred as L1 and L2) and two SAPs (herein referred as S1 and S2) were shortlisted for further evaluation in mortar study.

Seventeen different mortar mixtures were designed and evaluated to investigate the effect of IC agents on shrinkage and strength. Table 3-1 summarizes the details on w/cm, LWFA type, SAP type, and their percentage proportions in the mixture. While most mortar mixtures were designed with w/cm of 0.35, three mixtures with w/cm of 0.45 to investigate the efficacy of LWFA to minimize shrinkage at different w/cm. Three different replacement levels of LWFA corresponding to 80%, 100%, and 120% of the required IC water were considered for each LWFA type.

Table 3-1: Types of LWFA and SAP used in different mixtures

Mixture no.	Mixture ID	w/cm	LWFA type	Oven-dry LWFA replacement level (% total oven-dry sand mass)	SAP type	SAP admixed level (% cement mass)
1	W1-C	0.35	--	--	--	--
2	W1-L1-IC1	0.35	L1	19	--	--
3	W1-L1-IC2	0.35	L1	23.7	--	--
4	W1-L1-IC3	0.35	L1	28.4	--	--
5	W1-L2-IC1	0.35	L2	43.3	--	--
6	W1-L2-IC2	0.35	L2	54.1	--	--
7	W1-L2-IC3	0.35	L2	64.9	--	--
8	W1-S1-0.1	0.35	--	--	S1	0.1
9	W1-S1-0.2	0.35	--	--	S1	0.2
10	W1-S1-0.3	0.35	--	--	S1	0.3
11	W1-S2-0.1	0.35	--	--	S2	0.1
12	W1-S2-0.2	0.35	--	--	S2	0.2
13	W1-S2-0.3	0.35	--	--	S2	0.3
14	W2-C	0.4	--	--	--	--
15	W2-L1-IC1	0.4	L1	19.5	--	--
16	W2-L1-IC2	0.4	L1	24.4	--	--
17	W2-L1-IC3	0.4	L1	29.2	--	--

To estimate the required IC water, the water demand relationship for saturated lightweight fine aggregate developed by Bentz and Snyder [102] was used. This is shown below by Eq. 3-1.

$$M_{LWA} = \frac{C_f C_s \alpha_{max}}{S \phi_{LWA}} \qquad \textbf{Eq. 3-1}$$

where M_{LWA} is mass of a dry LWFA needed per unit volume of concrete, C_f is a concrete cement factor, C_s is chemical shrinkage expressed as a ratio of the mass of water to mass of cement, α_{max} is a maximum expected degree of hydration of cement ((w/cm)/0.36 for w/cm < 0.36; 1 for w/cm ≥ 0.36), S degree of saturation of aggregate (from 0 to 1) and ϕ_{LWA} is 24-hour absorption of the lightweight aggregate. For the L1 and L2 used in this study, the LWFA optimal replacement levels that correspond to the required IC water were 23.7% and 54.1%, respectively, when w/cm was 0.35. Similarly, at a w/cm of 0.45, the L1 replacement level was 27.1%. Three admixed levels, 0.1%, 0.2%, and 0.3% by cement mass, were chosen for SAP mixtures based on past research studies [103].

Table 3-2 summarizes the mixture proportions of the mortar mixtures investigated in this study. An ASTM C150 Type I/II ordinary portland cement and silica sand meeting the requirements of ASTM C778 were used for all mixtures. A sand-to-cementitious material ratio (s/cm) of 1.5 was chosen for all mixtures to increase the overall quality of the fabricated specimens. It should be noted that the water contents of the SAP mixtures are different from those considered for the control or LWFA mixtures. In this study, unlike LWFA which was pre-wetted for 24 hours prior to mixing, SAP powder was directly added to the mixture in dry condition during the mixing process [104]. As a result, additional water was considered in the mix design to accommodate for the absorption of water by SAP. The amount of additional water needed for SAP mixtures was determined through a flow test (ASTM C1437). The flow of the SAP mixture was the same as the flow of the control mixture (140%). In addition to the flow, air content (ASTM C185) and setting time (ASTM C807) were evaluated for all mixtures before any specimen fabrication for physical tests. After the desirable flow was achieved, specimens were fabricated to evaluate the mixture for compressive strength (ASTM C109), autogenous shrinkage (ASTM C1698), and drying shrinkage (ASTM C596).

Table 3-2: Constituent material proportions for different mixtures

Mixture ID	Mass of cement (g)	Mass of water (g)	Mass of standard sand (g)	SSD mass of LWFA (g)	Mass of SAP (g)	Superplasticizer (g)
W1-C	3628	1270	5442	--	--	6
W1-L1-IC1	3628	1270	4411	1287	--	6.5
W1-L1-IC2	3628	1270	4153	1609	--	7
W1-L1-IC3	3628	1270	3895	1931	--	12.5
W1-L2-IC1	3628	1270	3087	2571	--	10
W1-L2-IC2	3628	1270	2498	3214	--	10
W1-L2-IC3	3628	1270	1909	3857	--	10
W1-S1-0.1	3628	1410	5442	--	3.6	6
W1-S1-0.2	3628	1503	5442	--	7.3	6
W1-S1-0.3	3628	1597	5442	--	10.9	6
W1-S2-0.1	3628	1324	5442	--	3.6	6
W1-S2-0.2	3628	1348	5442	--	7.3	6
W1-S2-0.3	3628	1402	5442	--	10.9	6
W2-C	3566	1426	5349		--	0
W2-L1-IC1	3566	1426	4306	1309	--	2.5
W2-L1-IC2	3566	1426	4045	1627	--	2.5
W2-L1-IC3	3566	1426	3785	1952	--	2.5

ASTM C1698 requires the usage of corrugated low-density polyethylene molds that are 420 mm in length and 29 mm in diameter. One end of the tube is closed with a plug before pouring the mortar into the mold. The mold is then held vertically, and the mortar is gradually filled and vibrated along the length until the entire mold is filled with the mortar. Following this, the mold is sealed by closing the open end with a plug. The specimens are stored in a standard laboratory environment and the length change readings are recorded soon after the final set is reached. Figure 3-1 shows pictures of typical C1698 specimens and the dilatometer used for length change measurements. The length change readings were recorded until the age of 28 days and the reading recorded at the time of the final set was considered as the reference for length change. ASTM C596 testing requires testing of 1x1x11.25-in. in an environmental chamber maintained at 73ºF and 50%RH. Prior to exposure, specimens are cured for 24 hours in molds and 48 hours in a lime bath. Like C1698, readings were recorded until the age of 28 days. A typical ASTM C596 test setup is shown in Figure 3-2.

Given the small opening of the ASTM C1698 corrugate mold, it is important to ensure reasonable plastic consistency for the mortar mixture to maximize the quality of the fabricated corrugated specimen. Visual examination of initial C1698 specimens cast using low w/cm mixtures indicated issues with quality. To overcome this, a commercially available superplasticizer, which meets the requirement of a high range water reducer, was used. It should be noted that the amounts of superplasticizer used for SAP mixtures and the control mixture were the same.

a) b)

Figure 3-1: ASTM C1698 test setup; a) Specimens, b) Dilatometer bench

a) b)

Figure 3-2: ASTM C596 test setup; a) specimens, b) Length comparator

Nine 2x2x2-in. cubes were fabricated and tested for strength (3 specimens each at 3-day, 7-day, and 28-day ages). Five replicate specimens were fabricated for each mix for ASTM C1698 testing and four replicate specimens were fabricated for ASTM C596 testing. Table 3-3 summarizes the fresh properties and the 28-day compressive strength values measured for all mixtures. A discussion on the data generated from shrinkage tests is provided in section 4 of this document.

Table 3-3: Fresh characteristics of different mixtures

Mixture ID	Flow (%) / No. of blows	Unit Weight (lb/ft^3)	Final Set Time (h:mm)	Average Compressive Strength (psi)		
				3-day	7-day	28-day
W1-C	150 / 25	136	2:45	7980	8694	9521
W1-L1-IC1	148.5 / 25	123	3:15	8035	8880	9541
W1-L1-IC2	150 / 25	121	2:45	7281	7785	8638
W1-L1-IC3	150 / 25	116	3:25	7450	8343	8874
W1-L2-IC1	150 / 25	126	3:25	8310	9168	11279
W1-L2-IC2	150 / 25	124	3:15	8246	9358	10687
W1-L2-IC3	150 / 25	120	3:15	8846	9447	11156
W1-S1-0.1	150 / 25	134	3:25	7293	8008	8648
W1-S1-0.2	150 / 25	132	3:25	6104	7046	9529
W1-S1-0.3	150 / 25	132	3:45	6690	7440	8980
W1-S2-0.1	150 / 25	136	3:30	7496	8215	8853
W1-S2-0.2	150 / 25	132	3:15	7282	7972	8751
W1-S2-0.3	150 / 25	134	3:15	6737	8078	9163
W2-C	150 / 20	136	3:00	7579	9129	11418
W2-L1-IC1	150 / 21	121	3:10	6202	7718	9126
W2-L1-IC2	150 / 21	118	3:15	6320	7486	8978
W2-L1-IC3	150 / 21	115	3:20	6353	7086	7246

B) CONCRETE STUDY

To investigate the effects of IC agents on concrete performance, twelve (12) different mixtures were evaluated. Among the twelve mixtures, six mixtures were designed for pavement applications (PA mixtures) and the remaining mixtures were designed for bridge deck applications (BD Mixtures). For each category (i.e., pavement and bridge deck), two control mixtures, two LWFA mixtures, and two SAP mixtures were considered. For both mixture categories, two w/cm levels, 0.45 and 0.36, were adopted.

The mixture proportions for all mixtures are summarized in Table 3-4. In this study, L1 and S1 as IC agents based on their performance observed in mortar study in mitigating shrinkage. It should be noted that WisDOT requires target w/cm of pavement mixtures to be 0.42 or less. However, mixtures with w/cm values higher than this limit are considered for paving mixtures to evaluate the effectiveness of IC agents in concrete mixtures containing high w/cm values.

Table 3-4: Mixture proportions used in the concrete study

Mixture ID	Mixture Proportions (lbs/yd^3)								
	Type I/II cement	Fly Ash	Slag	Water	Coarse aggregate #4	Coarse aggregate #67	Concrete Sand	LWFA	SAP
PA-C-045	364	156	--	234	676	1216	1294	--	--
PA-LW-045	364	156	--	234	676	1216	843	238	--
PA-SAP-045	364	156	--	234	676	1216	1294	--	0.52
PA-C-036	364	156	--	187	676	1216	1419	--	--
PA-LW-036	364	156	--	187	676	1216	967	238	--
PA-SAP-036	364	156	--	187	676	1216	1419	--	0.52
BD-C-045	432	--	108	243	836	964	1324	--	--
BD-LW-045	432	--	108	243	836	964	855	247	--
BD-SAP-045	432	--	108	243	836	964	1324	--	0.54
BD-C-036	432	--	108	194	836	964	1453	--	--
BD-LW-036	432	--	108	194	836	964	984	247	--
BD-SAP-036	432	--	108	194	836	964	1453	--	0.54
Mixture ID Explanation: PA "Pavement"; BD "Bridge Deck"; LW "Lightweight Fine Aggregate"; SAP "Super Absorbent Polymer"; 045 "W/cm ratio of 0.45.									

All mixtures were evaluated for slump (AASHTO T 119), density (AASHTO T 121), plastic air content (AASHTO T 152), SAM number (AASHTO TP 118), and temperature (AASHTO T 309). Slump, density, and plastic air content were monitored over time. The initial round of tests was conducted immediately after batching and the final round of tests was run 45 minutes after the addition of batch water to the mixture. AASHTO T 152 (pressure method) is not applicable to concretes containing lightweight aggregates. Hence, mixtures with lightweight aggregates were additionally investigated for plastic air content following the volumetric method (AASHTO T 196). To investigate the compatibility of paving (PA) mixtures for slip-form paving construction, all PA mixtures were investigated for edge-slump and surface void characteristics following Box test and V-Kelly index following V-Kelly test.

Guidelines reported in AASHTO PP 84 were followed for both tests. BD mixtures were additionally investigated for time of set (AASHTO T 197) and rheological properties using the ICAR rheometer.

Cast concrete specimens from all mixtures were investigated for strength (AASHTO T 22; 7, 28, and 56 days), modulus of elasticity (ASTM C469; 28 days), flexural strength (AASHTO T 97; 7 and 28 days), unrestrained length change (AASHO T 160), freeze-thaw resistance (AASHTO T 161), scaling resistance (ASTM C672), chloride penetration (NT-Build 492), resistivity (AASHTO TP 119 and AASHTO T 358), and air-void characteristics (ASTM C457). In addition to these tests, all PA mixtures were investigated for their potential to warp based on the test procedure reported in Wei and Hanson [23]. All BD mixtures were investigated for restrained shrinkage following ASTM C1581 requirements. Because the objective of this study is to understand whether the application of IC agents improve or disimprove various concrete properties, data from LW and SAP mixtures were compared to control (C) mixtures at each w/cm level for both PA and BD categories.

Concrete mixtures with saturated LWFA have been more commonly used in the U.S. compared to the mixtures with SAPs. For mixtures with LWFAs, the quantity of saturated LWFA is determined through the water-demand relationship developed by Bentz and Snyder, and the quantity of concrete sand is adjusted to maintain the yield. For SAPs on the other hand, the absorption and desorption characteristics are very different from those of LWFAs. As such, determining the exact quantity of SAP required and the procedure for incorporating SAP in fresh concrete are not straightforward. In this study, an SAP dosage of 0.1% by mass of binder was implemented for all SAP mixtures based on the data generated from mortar study. Also, all SAP were added dry to the fresh concrete mixture after 8 minutes of mixing process based on ASTM C192 guidelines. While addition of SAP in dry condition is more feasible and practical from the perspective of ready-mix industry, more research is needed to develop guidelines for developing SAP-induced concrete mixtures for optimized performance.

4. RESULTS AND DISCUSSION: MORTAR STUDY

4.a.1. Light Weight Fine Aggregate (LWFA)

Figure 4-1 shows the rate of change in average shrinkage strain with time during the early age (< 1 day) for 0.35 w/cm mixtures with and without LWFA. Figure 4-2 shows the average autogenous shrinkage strain data for the same mixtures for a period of 28 days from the casting date. All mixtures exhibited an initial expansion in the early ages. For the control mixture, the initial expansion was followed by significant autogenous shrinkage that increased monotonically with time. For mixtures containing L1, the initial rapid expansion was followed by a slight expansion with time. While the trends exhibited by L2 mixtures were roughly the same as that of the control mixture, the 28-day shrinkage strain was found to be dependent on the LWFA replacement level.

The results generated in this study are in general agreement with the results reported in the literature [9], [87], [105]. Kohno et al.[105] reported that the LWFA mixtures were exhibiting slight expansion after the initial rapid expansion was an indication that LWFA was able to mitigate the autogenous shrinkage completely. While the L1 mixtures investigated in this study showed this behavior, a clear trend between the final autogenous shrinkage and the replacement level was not found between the LWFA replacement level and the 28-day autogenous shrinkage strain. However, the mixture with optimal LWFA replacement level (i.e., the replacement level estimated using Eq. 3-1) exhibited highest 28-day net expansion. In case of L2 mixtures, the 28-day shrinkage strain value was found to depend on the LWFA replacement level. The 28-day shrinkage strain values for L2 mixtures with replacement levels of 43, 54, and 65% were -307, -47, and 8 μm/m, respectively. Data indicated that choosing an optimal LWFA replacement level for L2 mixture had a pronounced effect on minimizing the autogenous shrinkage and any further increase in replacement level showed little or no improvement in shrinkage.

It should be noted that the LWFA replacement levels for mixtures containing L1and L2 were estimated based on the same IC water requirements. For instance, 1609 g of L1 in SSD condition withheld the same amount of IC water as 3214 grams of L2 in SSD condition. When LWFA with similar rates of desorption (see Figure B-8) are used in the mortar mixtures, one would anticipate similar performance in terms of autogenous shrinkage for these mixtures. However, this was not observed in the current study. The differences in the performances of different LWFA mixtures could likely be due to differences in LWFA gradation and differences in the desorption mechanisms between the aggregate particles and the cementitious matrix. Data generated in this study show that ASTM C1698 test can serve as a tool in evaluating the performance of different LWFA for mitigating autogenous shrinkage. Among both LWFA considered in this study, the L1 was found to mitigate the autogenous shrinkage better compared to L2.

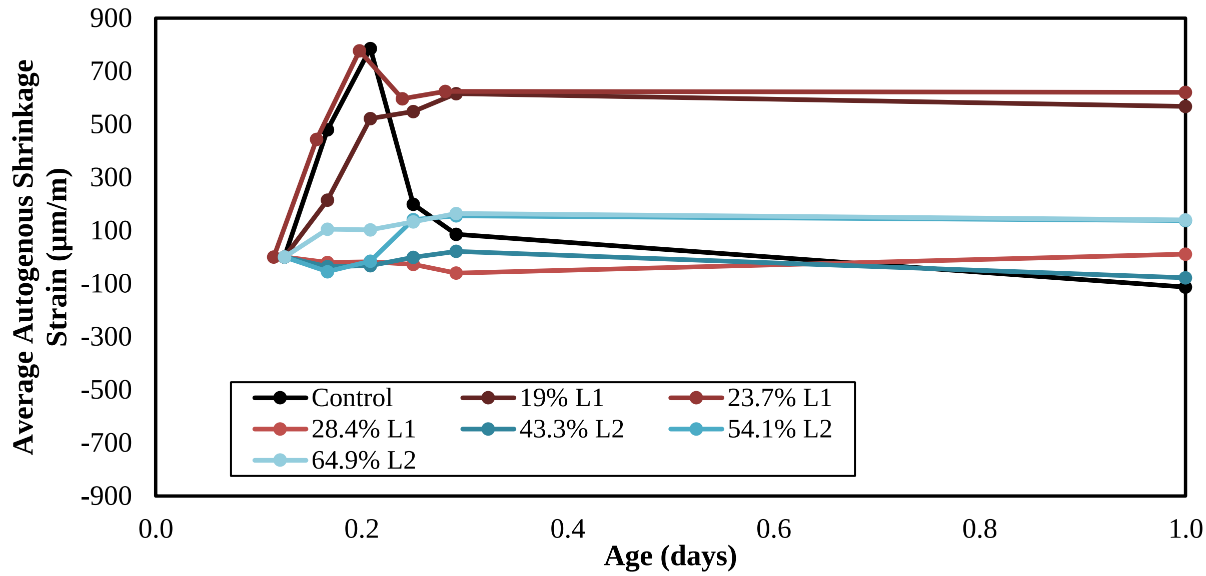


Figure 4-1: Early -age autogenous shrinkage results for 0.35 w/cm mixtures. Positive strains indicate swelling and negative strains indicate shrinkage.

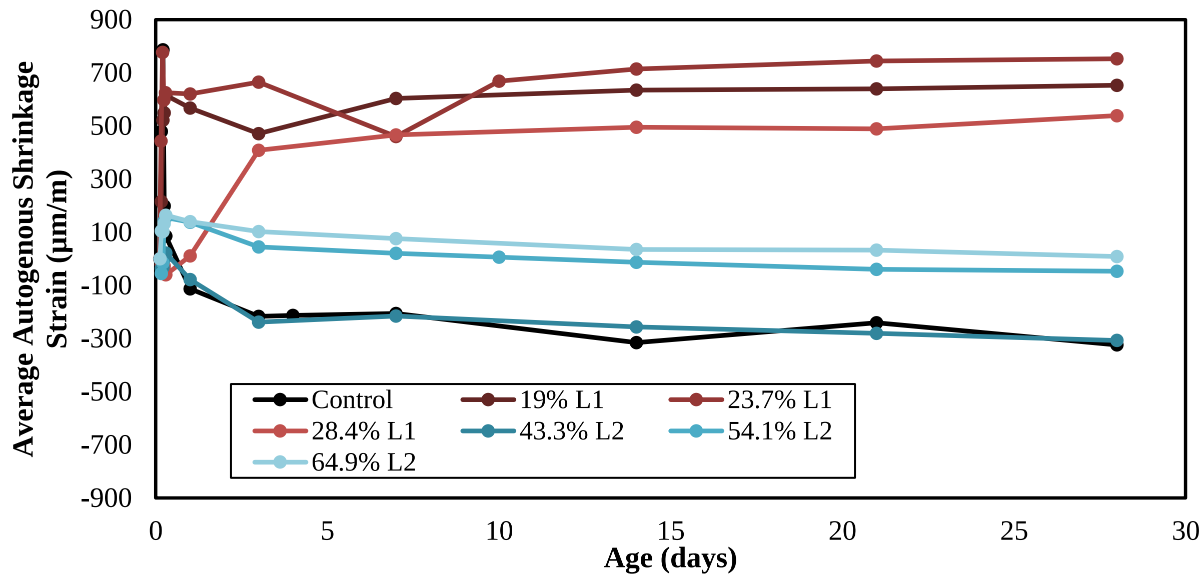


Figure 4-2: Autogenous shrinkage results for 0.35 w/cm mixtures. Positive strains indicate swelling and negative strains indicate shrinkage.

Results presented in Figure 4-3 indicate that the effectiveness of LWFA in reducing autogenous shrinkage strains in mixtures made with a w/cm of 0.4 is reduced as the higher availability of batch water reduces the susceptibility of the mixture to autogenous strain. Results of the effect of LWFA on mortar mixtures with a w/cm of 0.4 are included in Appendix B.

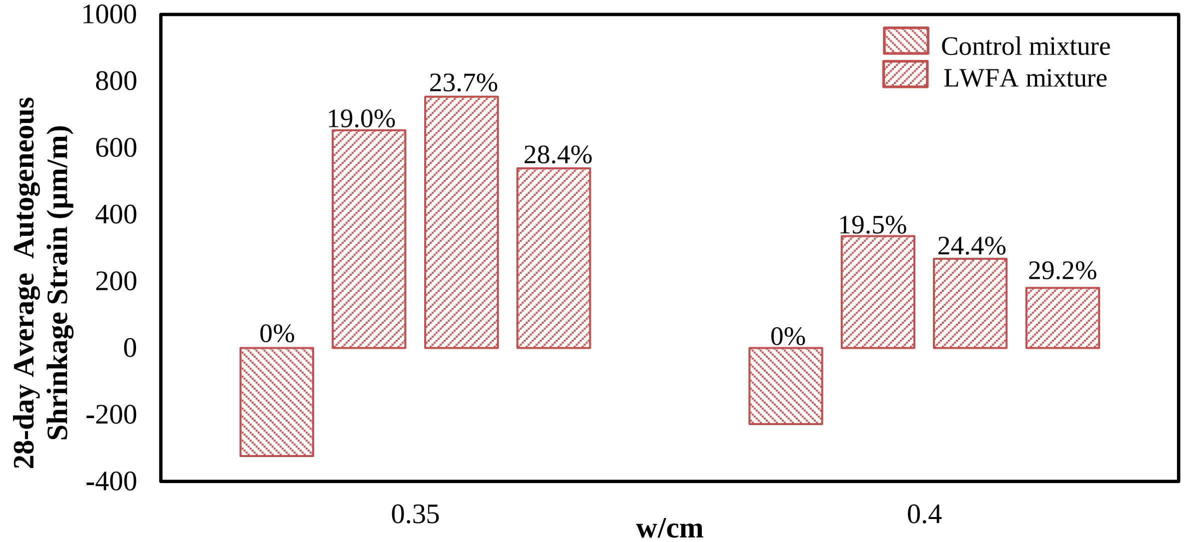


Figure 4-3: 28-day Autogenous shrinkage strains for mixtures with L1 LWFA (the percent values on the chart represent LWFA replacement levels)

Figure 4-4 compares the rate of change in drying shrinkage strain for different 0.35 w/cm mixtures with and without LWFA. Irrespective of the type or the replacement level of LWFA, all LWFA mixtures exhibited similar rates of change in shrinkage and similar 28-day drying shrinkage values. Similar trends were observed in mixtures with 0.4 w/cm with slightly lower 28-day shrinkage strains, as shown in Figure 4-5. Both the rate of change in strain and the 28-day shrinkage strain for LWFA mixtures were slightly lower when compared to the control mixture, which is expected to the presence of IC water in LWFA mixtures [106], [107].

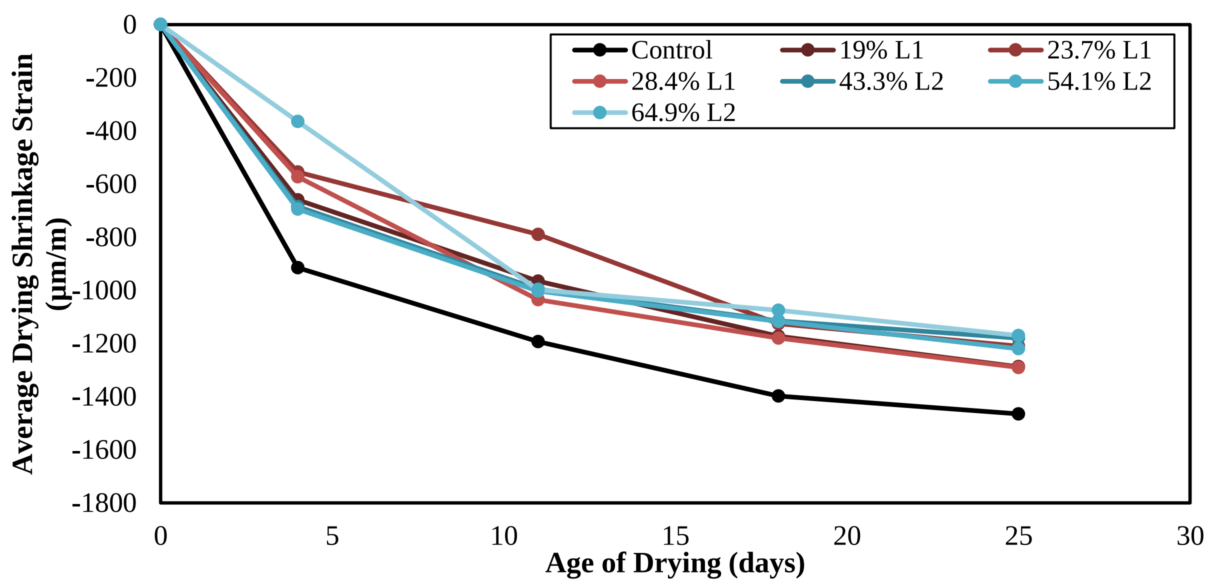


Figure 4-4: Comparison of drying shrinkage strains between control and LWFA mixtures at 0.35 w/cm

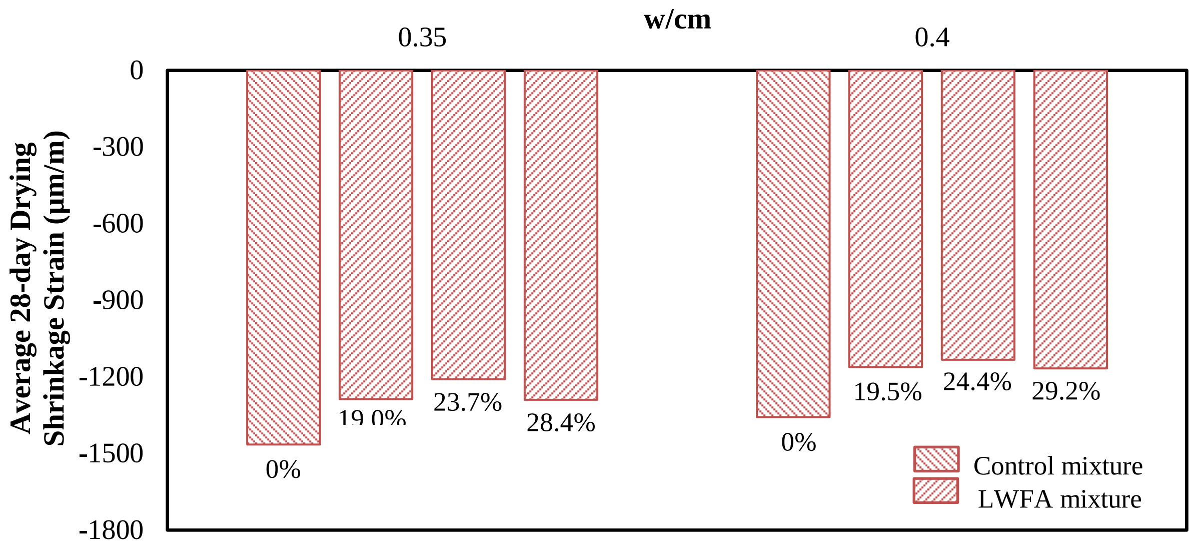


Figure 4-5: 28-day autogenous drying strains for mixtures with L2 LWFA (the percent values below the columns represent LWFA replacement levels)

4.a.2. SAP

The effect of SAP type and dosage on shrinkage strain is illustrated in Figure 4-6 (early age) and Figure 4-7 (later age). While all SAP mixtures exhibited an expansion in early ages, it was significantly lower compared to the control mixture. Figure 4-6 shows that the shrinkage in SAP mixtures was offset in early ages, likely due to counteraction of autogenous shrinkage by SAP during the acceleration period of the hydration mechanism [108]. Figure 4-7 shows that the 28-day autogenous shrinkage strains for mixtures admixed with S2 (0.2% and 0.3%) were higher compared to the control mixture. Apart from these two mixtures, the addition of SAP resulted in a slight decrease in 28-day shrinkage strain compared to the control mixture. The shrinkage strain curves for SAP mixtures were roughly similar to the strain curve of the control mixture, indicating that enough IC water was not provided by the SAP to mitigate shrinkage. Although SAPs have been reportedly considered for mitigating autogenous shrinkage [109]–[111], data generated in this study suggests the shrinkage-reducing benefits of SAP may not always be achieved.

A comparison between Figure 4-2 and Figure 4-7 indicates that LWFA used in this study has a better water-retention capacity compared to the utilized SAP. In other words, SAP desorbs fluid at a faster rate compared to LWFA, which was confirmed in the previous task study of this project (See Appendix B). The absorption capacities of the SAP used in this study S1: ~230 g/g; S2: ~255 g/g) were also on the lower end of the spectrum of absorption capacities reported for the SAPs in the literature [33], [112]. The use of SAP with a higher absorption capacity will likely further reduce the autogenous shrinkage. While increasing the dosage of SAP was anticipated to decrease the overall shrinkage strain due to the release of more IC water [82], it was not observed in this study. SAP mixtures with a dosage rate of 0.1 % by cement mass performed better compared to SAP mixtures with other dosage levels for both SAP types.

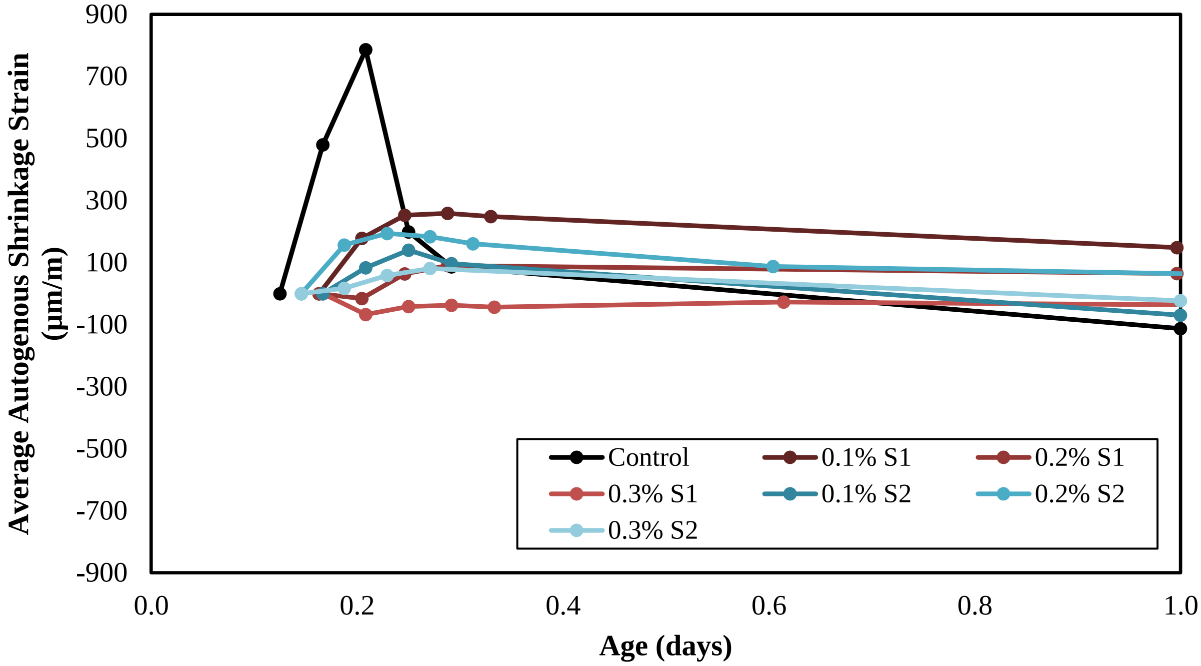


Figure 4-6: Early-age autogenous strain for 0.35 w/cm mixtures with SAPs

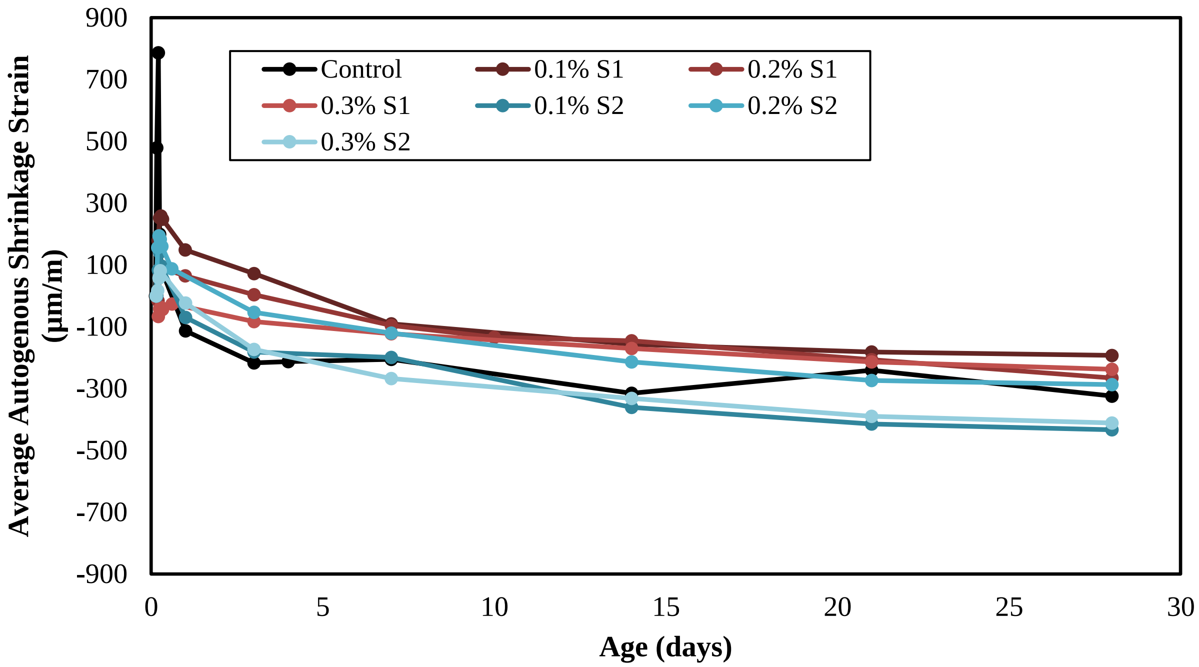


Figure 4-7: Autogenous strain for 0.35 w/cm mixtures with SAPs

A comparison of the rates of drying shrinkage strains between control and SAP mixtures is shown in Figure 4-8. Unlike LWFA mixtures, where an improvement in autogenous shrinkage strains was associated with an improvement in drying shrinkage strains, SAP mixtures that showed lower 28-day autogenous shrinkage strain (compared to control) exhibited higher 28-day drying shrinkage strain or vice versa. Possible reasons for the disparities between the performance of LWFA and SAP mixtures could be:

- SAPs may not have reached their true absorption capacity when added as dry powder to the mixture during the mixing process. As a result, it is likely that the additional water could have increased the w/cm of the mixture.
- The distribution of SAP particles throughout the mixture is less uniform when compared to the distribution of LWFA particles.
- Potential differences in absorption and desorption rates of the SAP and LWFA particles.

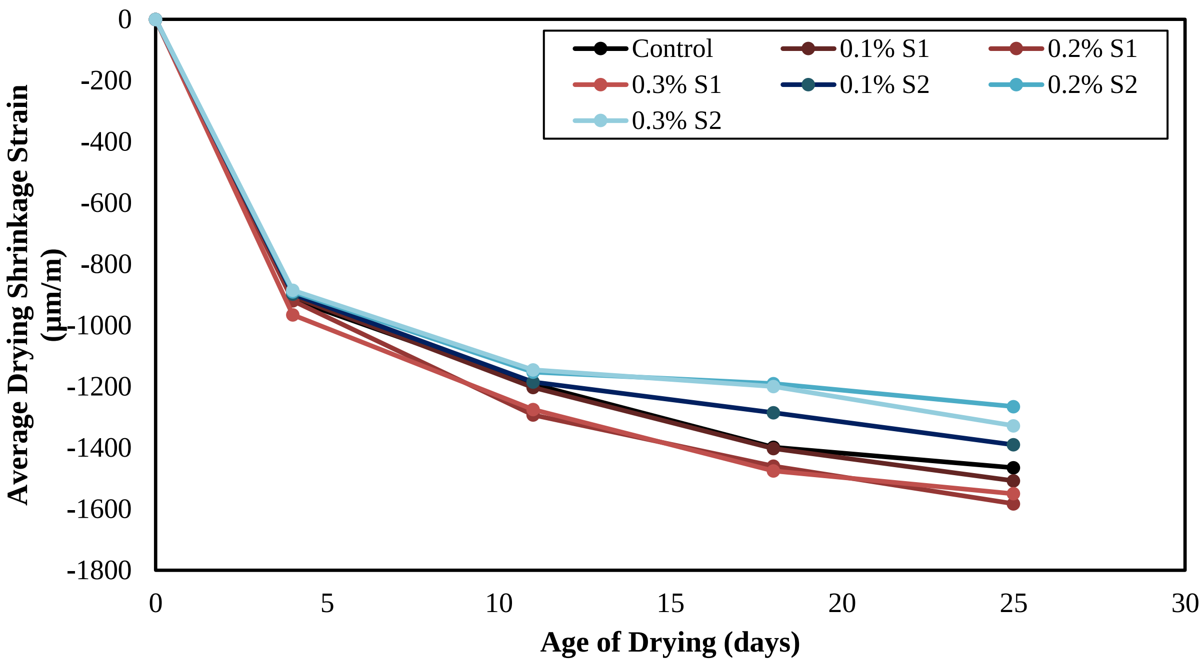


Figure 4-8: Comparison of drying shrinkage strains between control and SAP mixtures at 0.35 w/cm

5. RESULTS AND DISCUSSION: CONCRETE STUDY

A) EFFECT OF IC MATERIALS ON FRESH PROPERTIES

A summary of the mixtures' fresh properties is tabulated in Table 5-1 (shown in the next page due to size constraints) for the pavement (PA) and bridge deck (BD) mixture, respectively. The data collected from the workability performance tests (i.e., box and V-Kelly tests) as well as the effect of wait time, i.e., 45 minutes, on the workability of the mixtures are also presented in the table. WisDOT specifies a slump of 2.5 inches or less and an edge-slump value of 0.38 in. or less at free edges. As anticipated, concrete mixtures with w/cm of 0.45 failed to meet these requirements due to the high water content in the mixture. According to Table 5-1, mixtures containing LWFA required a lower admixture dosage to obtain a similar slump and/or air content, while SAP mixtures demanded a higher dosage of admixtures.

Taylor et al. [113] have reported that a V-Kelly Index in the range of 0.8 to 1.2 in./√s seems to indicate a mixture that is likely to be suitable for slip forming. In other words, a value beyond this limit may present a dry or a wet mixture. Except for PA-LW-045 and PA-C-036, the tested mixtures obtained a V-Kelly Index close or within the specified limit. The low V-Kelly index of the PA-LW-045 mixture was a consequence of the high slump (6.75-inch), indicating that this mix does not fit for slip forming. With respect to PA-C-036, however, the low V-Kelly index cannot be explained by the low/high slump of the mixture. It can be seen from Table 5-1 and Figure 5-1 that the mixture exhibited a Box test overall surface voids visual rating of 2 (equivalent to the numerical surface void value of 10-30%) and an edge-slump of 0.13 in., which are acceptable test values for typical slip-form pavement mixtures [114].

As expected, slump loss was more pronounced for BD mixtures which contained higher cement content than the PA mixtures. For a given mixture and w/cm, the amount of slump loss in mixtures containing internal curing (IC) materials (i.e., LWFA and SAP) appeared to be similar to that of the reference mixtures. Based on the rheology data shown in the table, the BD mixtures show an increase in the yield stress when the IC materials are incorporated. Mixtures containing LWFA exhibited lower plastic viscosity than those of the reference mixture, while the incorporation of SAP appeared to influence the plastic viscosity in a different direction and led to higher viscosity.

Table 5-1: Fresh characteristics of PA and BD mixtures

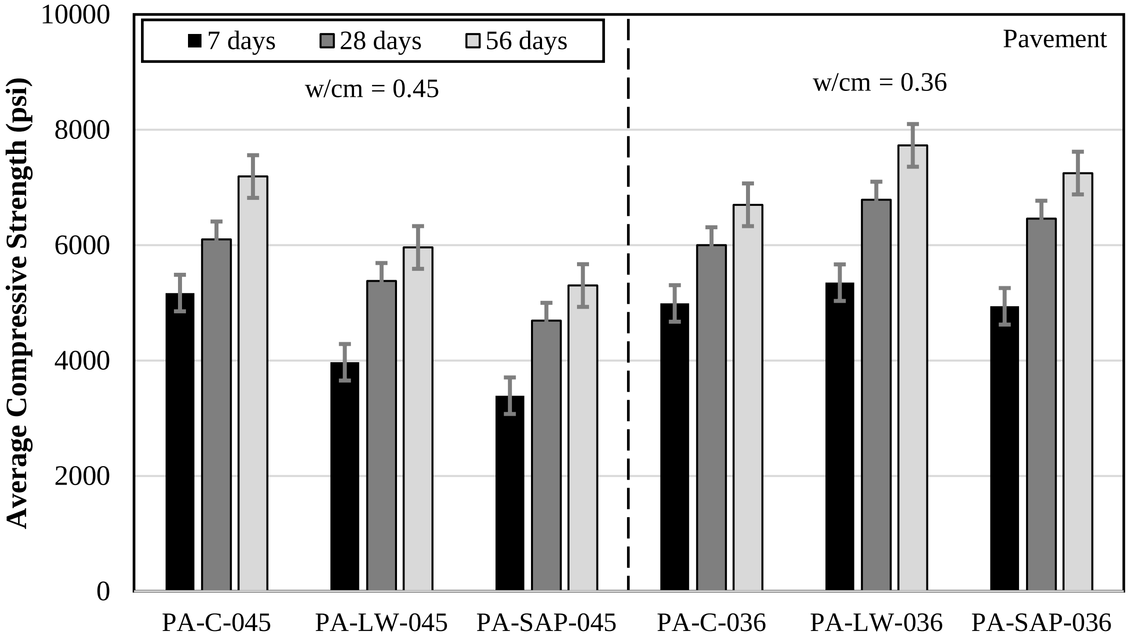
Fresh Properties	Test Time	Mixture ID											
		PA-C-045	**PA-LW-045**	**PA-SAP-045**	**PA-C-036**	**PA-LW-036**	**PA-SAP-036**	**BD-C-045**	**BD-LW-045**	**BD-SAP-045**	**BD-C-036**	**BD-LW-036**	**BD-SAP-036**
Slump, in.	Immediately after mixing	2.75	6.75	2.50	1.00	0.75	0.50	8.50	5.75	5.25	7.50	8.50	6.50
	45 min. after mixing	1.25	4.75	1.00	0.50	0.25	0.25	8.25	4.00	3.00	2.25	4.00	1.75
Air Content, %	Immediately after mixing	5.1	6.4	7.9	6.8	5.5	7.6	8.5	7.6	8.5	6.2	9.5	8.5
	45 min. after mixing	3.9	4.8	6.0	5.2	5.0	5.5	7.9	8.6	7.5	5.5	6.1	7.2
SAM Number	Immediately after mixing	0.34	0.52	0.36	0.27	0.54	0.25	0.05	0.31	0.15	0.09	0.25	0.10
Density, lbs/ft³	Immediately after mixing	146.7	139.9	140.7	148.6	142.4	146.2	141.7	137.1	140.2	148.4	137.9	145.2
	45 min. after mixing	151.0	140.6	142.2	148.8	142.8	147.2	143.4	135.2	143.2	148.6	140.8	144.4
Temperature, °F	Immediately after mixing	65	68	67	67	68	68	67	73	69	68	70	68
Box Test Edge slump, in.	Immediately after mixing	0.31	Fail[$]	0.44	0.13	0.22	0.21	N/A	N/A	N/A	N/A	N/A	N/A
Box Test Visual Rating	Immediately after mixing	2	Fail[$]	2	2	2	2	N/A	N/A	N/A	N/A	N/A	N/A
V-Kelly index	Immediately after mixing	0.94	0.23	0.70	0.43	0.70	0.79	N/A	N/A	N/A	N/A	N/A	N/A
Yield Stress, Pa	Immediately after mixing	N/A	N/A	N/A	N/A	N/A	N/A	245.0	517.0	>1000	308.4	396.5	>1000
Plastic Viscosity, Pa.s	Immediately after mixing	N/A	N/A	N/A	N/A	N/A	N/A	32.2	18.8	42.3	39.1	46.4	87.2
Yield Stress, Pa	45 min. after mixing	N/A	N/A	N/A	N/A	N/A	N/A	392.5	712.3	>1000	555.8	695.1	>1000
Plastic Viscosity, Pa.s	45 min. after mixing	N/A	N/A	N/A	N/A	N/A	N/A	22.0	8.4	70.0	48.4	57.0	136.6

[$]Box test specimen collapsed during test; N/A= Not Applicable

Figure 5-1: Mixture BD-C-036 overall surface voids visual rating; 2 which is equivalent a surface void value of 10-30%

B) EFFECT OF IC MATERIALS ON MECHANICAL PROPERTIES

The effect of the IC materials on the compressive strength of PA and BD mixtures is shown in Figure 5-2. As expected, incorporation of LWFA resulted in lower compressive strength, which is more pronounced at higher w/cm. The slightly higher compressive strength of the LWFA mixture at the w/cm compared to that of the reference mixture could be attributed to the lower air content.



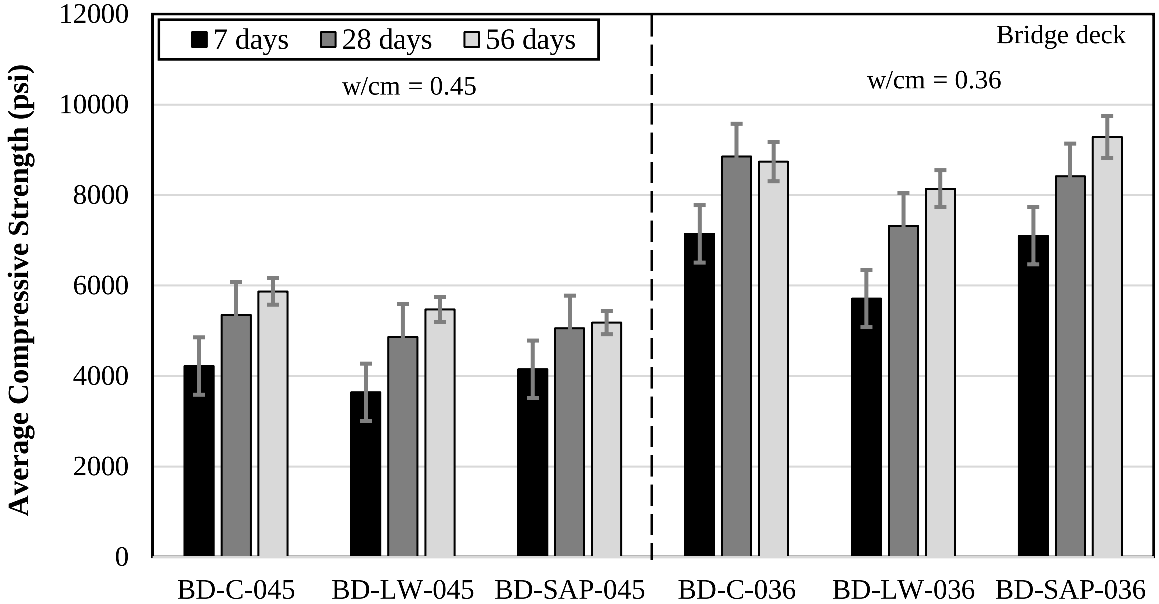


Figure 5-2: Average compressive strengths for PA and BD mixtures (1000 psi = 6.9 MPa)

On the other hand, the mixtures containing SAP exhibited similar or slightly higher compressive strength than the reference mixtures. This can be explained by the fact that some of the mixing water is absorbed by SAP during the mix leading to a lower w/cm in the SAP mixtures and consequently higher compressive strength. As discussed in Section 3.a), the absorbent capacity of the SAP's was not included in the mixture design for production practicality. The nonlinearity observed in the figure may be explained by the difference in the mixture's air content (see Table 5-1). In general, it can be observed that the incorporation of the IC materials does not influence the strength-grow rate compared to the reference mixtures. Similar trends to the compressive strength are observed for the modulus of elasticity (MOE) and flexural strength of the mixtures, shown in Figure 5-3 and Figure 5-4, respectively.

Data indicates that adding LWFA to any mixture (i.e., pavement or bridge deck) within limits used in this study has led to about 500 to 1,000 ksi reduction in MOE values compared to that of reference mixtures. The reduction of the elastic modulus in mixtures made with LWFA may be explained by the lower stiffness of the LWFA compared to normal weight aggregate as well as its increased porosity and the weaker bond between LWFAs and the paste. With respect to flexural strength, which was evaluated for pavement mixtures only, although a similar trend can be observed, the effect of the IC materials on the 7-day and 28-day flexural strength values seems to be negligible.

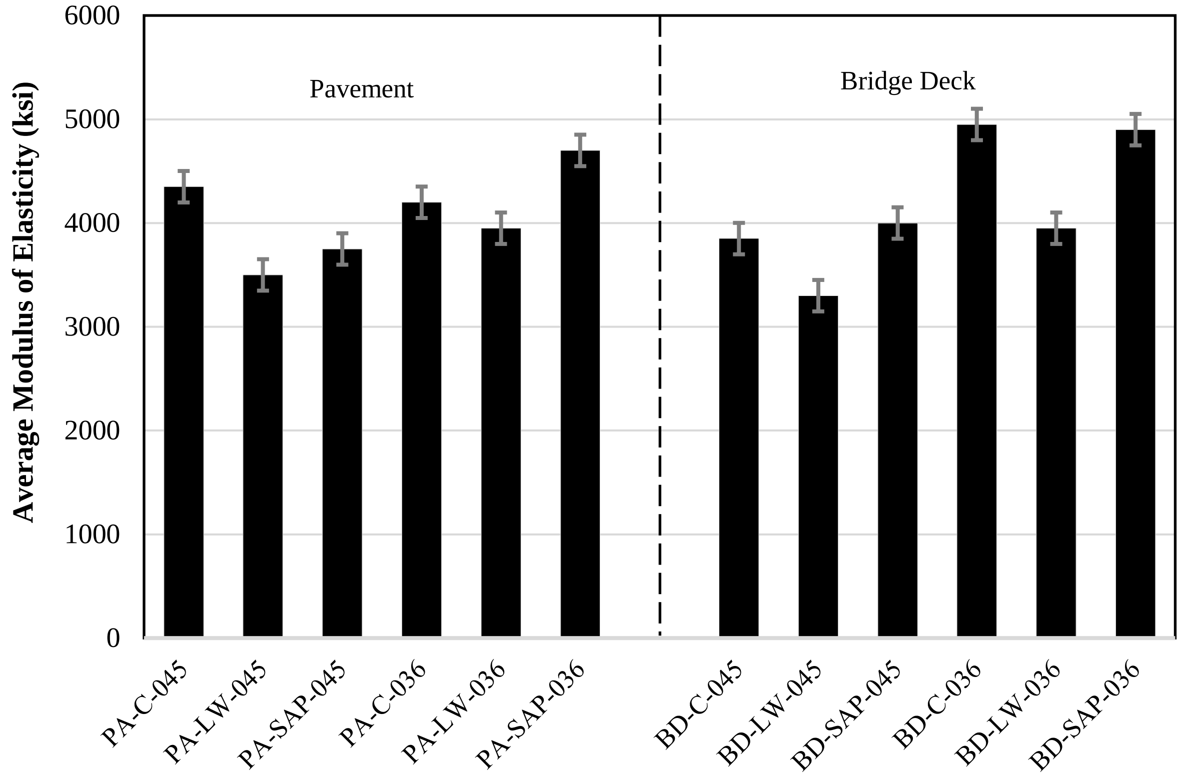


Figure 5-3: Modulus of elasticity of the PA and BD mixtures at 28 days (1 ksi = 6.89 MPa).

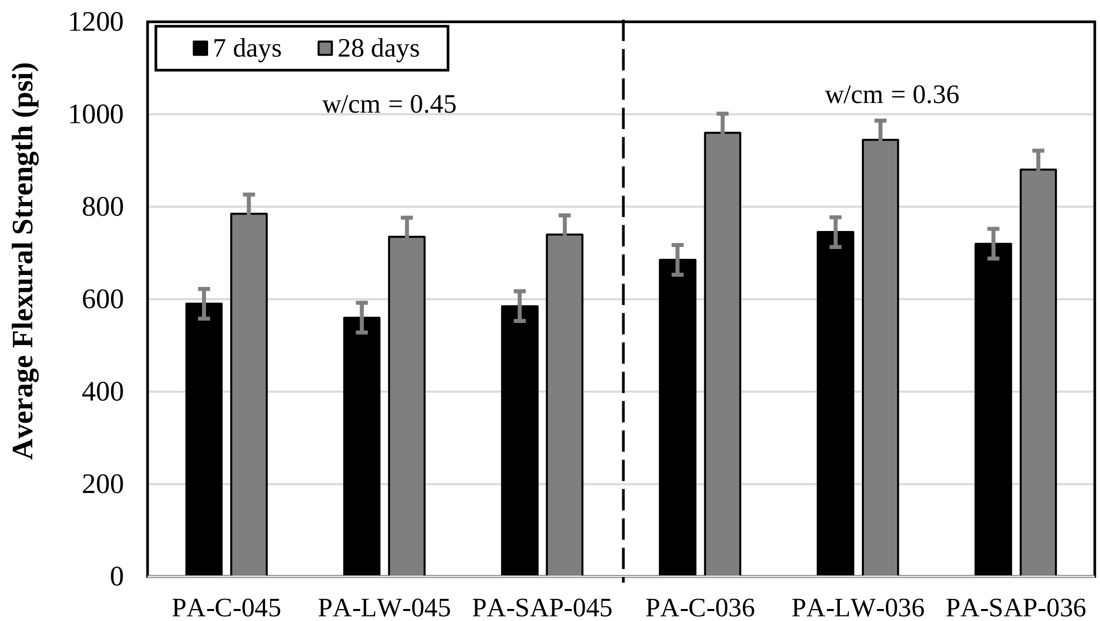


Figure 5-4: Flexural strength of the PA mixtures (1000 psi = 6.9 MPa).

C) EFFECT OF IC MATERIALS ON DURABILITY

The relative dynamic modulus (RDM) of the specimens after 300 freezing and thawing cycles is shown in Figure 5-5.

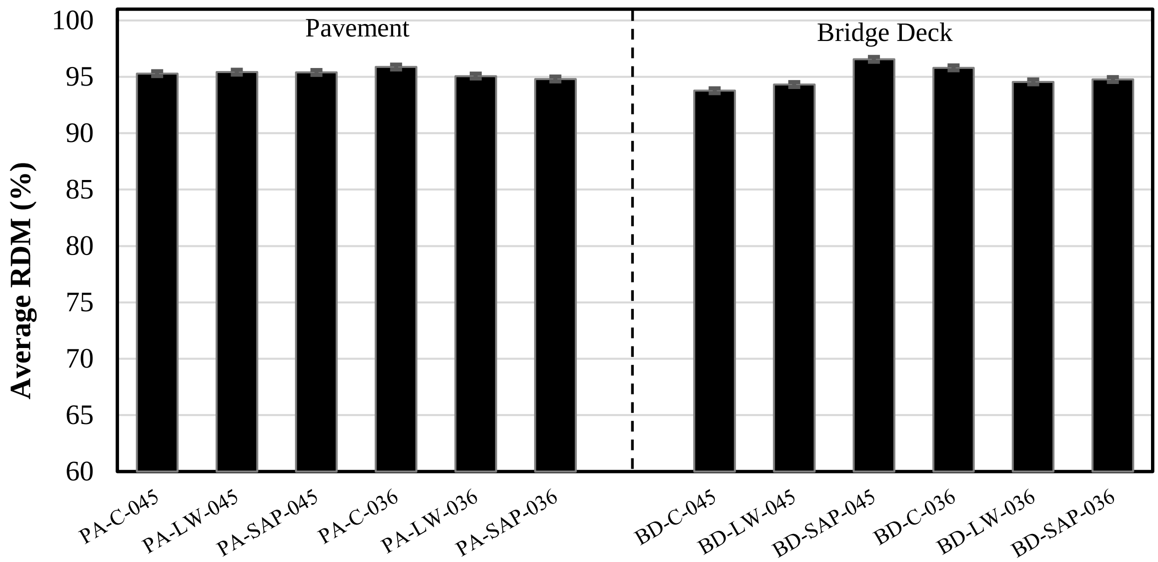


Figure 5-5: Relative Dynamic Modulus of the PA and BD specimens after 300 F-T cycles.

It is recognized that the resistance of concrete to freezing and thawing can be significantly improved by the intentional use of entrained air [115]–[118]. Given that all the fabricated specimens contained adequate air entrainment (~5-8.5%), an appropriate F-T resistance was expected. It can be observed that all mixtures exhibited an RDM of above 80%, which is an indication of excellent F-T resistance [119]. The slight variation in the results could be attributed to the actual air content and different mixture designs and ingredients.

The effect of IC materials on the salt-scaling resistance of concrete mixtures is shown in Figure 5-6. It is evident that w/cm played a dominant role regardless of the cementitious and air content. Mixtures containing LWFA demonstrated slightly higher surface mass loss compared to the reference mixtures, which could be due to the floating of some of the LWFA to the surface and forming a weaker layer at the top surface compared to reference mixtures. On the other hand, the addition of SAP to the mixtures not only did not show any undesirable effect on the salt scaling resistance of the specimens but also led to some improvement.

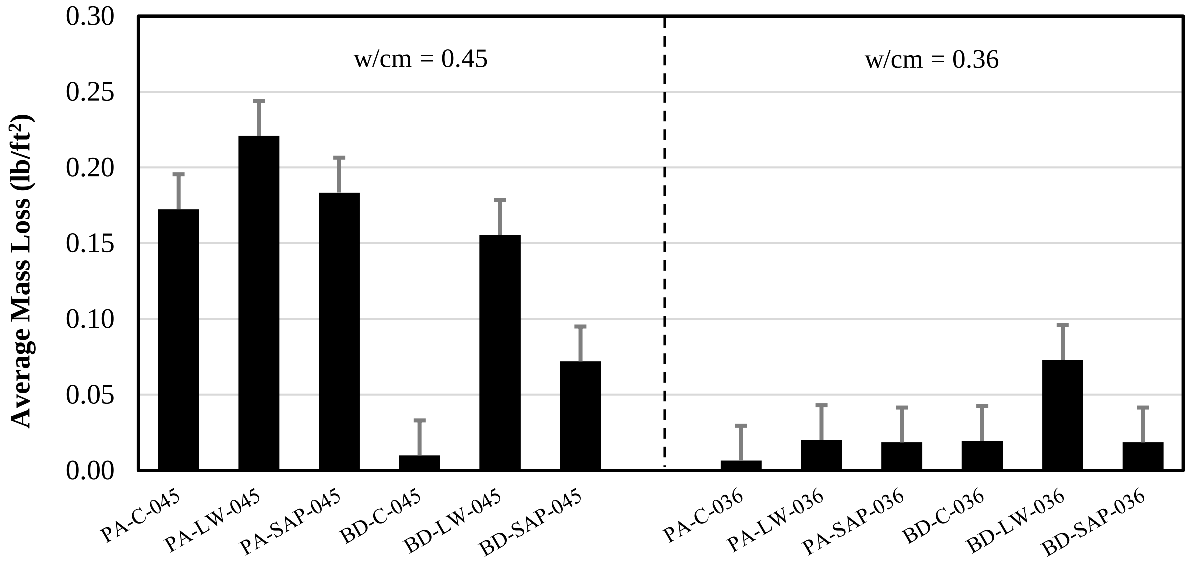


Figure 5-6: Salt-scaling mass loss of the PA and BD specimens after 50 F-T cycles (1 lb/ft^2 = 42.1 g/m^2).

Figure 5-7 shows the results of the chloride migration coefficient at the age of 28-days. Overall, the BD mixtures demonstrated a lower chloride ion migration coefficient than that of PA mixtures. This may be attributed to the higher supplementary cementitious content in the PA mixtures which results in lower calcium silicate hydrate (C-S-H) gel at the tested ages and consequently lowers the porosity and increases the resistance to chloride-ion penetration.

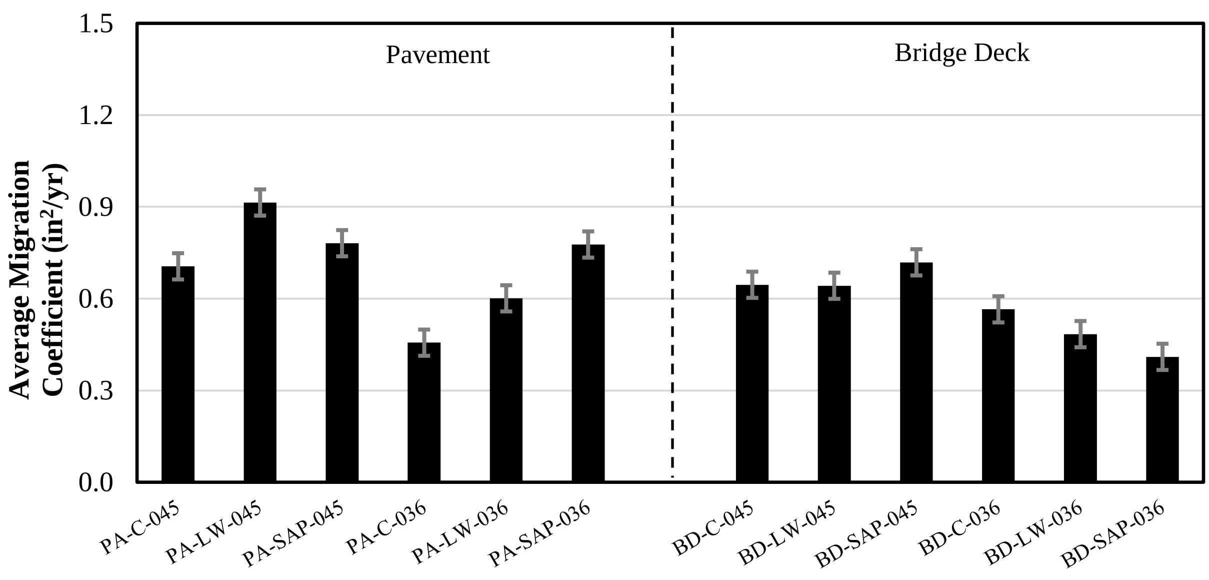


Figure 5-7: Chloride migration potential of the PA and BD specimens (1 in^2/yr = 2.05 x 10^{-11} m^2/sec).

The effect of the IC materials on chloride penetration based on RCP testing is shown in Figure 5-8. It can be observed from the figure that incorporation of the IC materials resulted in a slightly higher chloride ion migration coefficient for PA mixtures compared to those of the BD mixtures. In general, all mixtures made with a w/cm of 0.36 exhibited a charge passed between 1000 and 2000 coulomb, which indicates a low chloride ion penetrability. On the other hand, mixtures made the w/cm of 0.45 exhibited a charge passed between 2000 and 4000 coulomb showing moderate chloride ion penetrability.

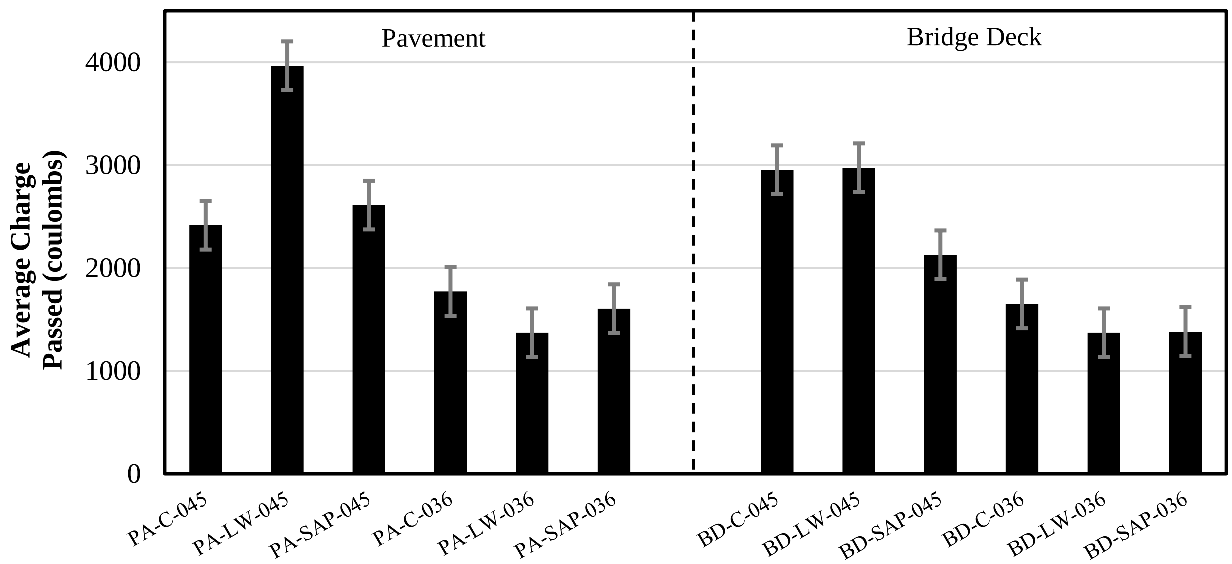


Figure 5-8: Chloride ion penetrability of the PA and BD mixtures.

The results presented in the figure indicate that the effect of the IC materials on the chloride penetration resulted in a comparable or improved resistance against chloride ingress. The exception to this was PA-LW-45 which at a higher w/cm was likely affected by the incorporation of LWFA and the porosity of the LWFA [120]. On the other hand, incorporation of LWFA in mixtures made with lower w/cm is possibly improving the degree of hydration and refining the pore structure, which can improve the permeability and prevent the expected increase due to the use of high-porosity aggregates [121].

Figure 5-9 and Figure 5-10 demonstrate the surface and bulk electrical resistivity of the tested specimens. As expected, lower w/cm has led to higher resistivity. The BD mixtures exhibited slightly higher electrical resistance, which may be attributed to the higher cement content in those mixtures resulting in a faster hydration process and possibly lower porosity at the age that specimens were tested. The effect of the IC materials on the electrical resistivity of the concrete mixtures appears to be insignificant at the incorporation levels used in this study. AASHTO T 358 and AASHTO TP 119 methods report the singleoperator precision of the results from these tests as 21% and 12.3%, respectively. The variations observed in the figures are within the reported expected precision.

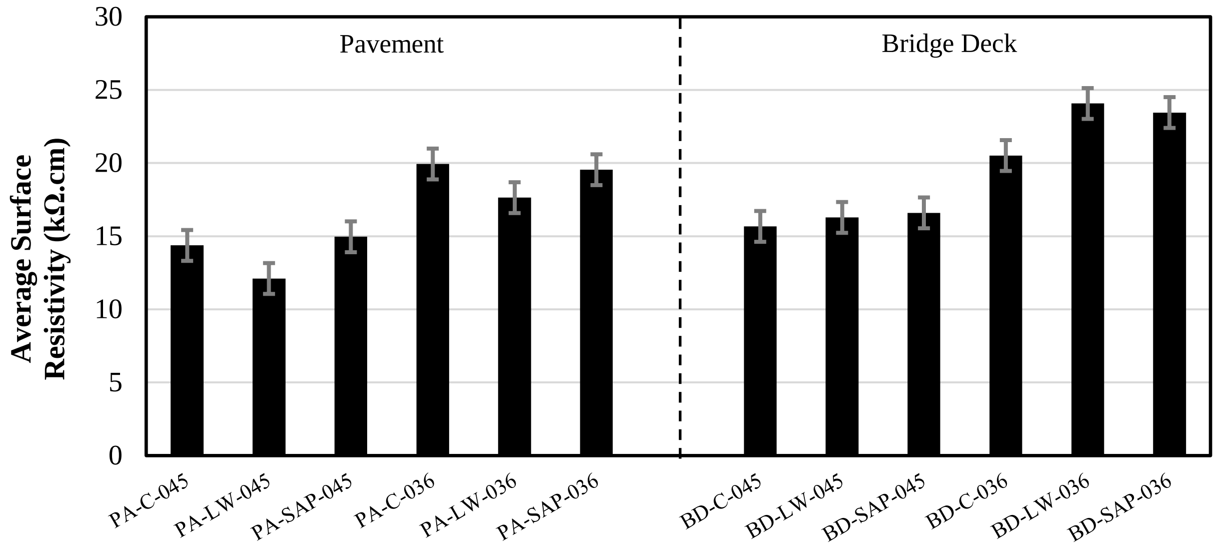


Figure 5-9: Surface electrical resistivity of the PA and BD mixtures

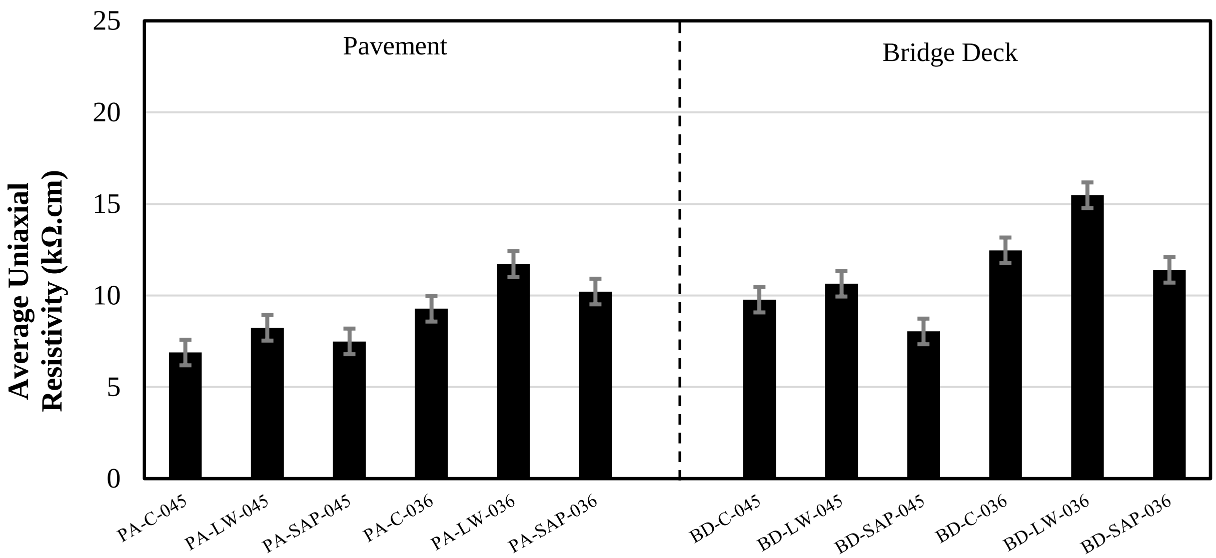


Figure 5-10: Bulk electrical resistivity of the PA and BD mixtures

D) EFFECT OF IC MATERIAL ON SHRINKAGE

When the moisture content inside concrete begins to decrease, IC materials release the pre-absorbed water to delay the drying shrinkage of the concrete. Figure 5-11 and Figure 5-12 show the unrestrained shrinkage of the specimens after 28 days of drying condition and the age of cracking under restrained shrinkage, respectively. It is evident that for a given mixture and w/cm, incorporation of LWFA had a remarkable impact on the length change potential of the specimens and considerably extended the service life of the concrete with respect to shrinkage cracking, especially at lower w/cm. The effect of mixing SAP, at the dosage used in this study, on the shrinkage of mixtures made with a w/cm of 0.45 appeared to be negligible while showing some improvement for the PA mixtures at lower w/cm. Although BD-SAP-036 exhibited higher shrinkage than that of the reference mixture, it still extended the days to cracking by more than 40%.

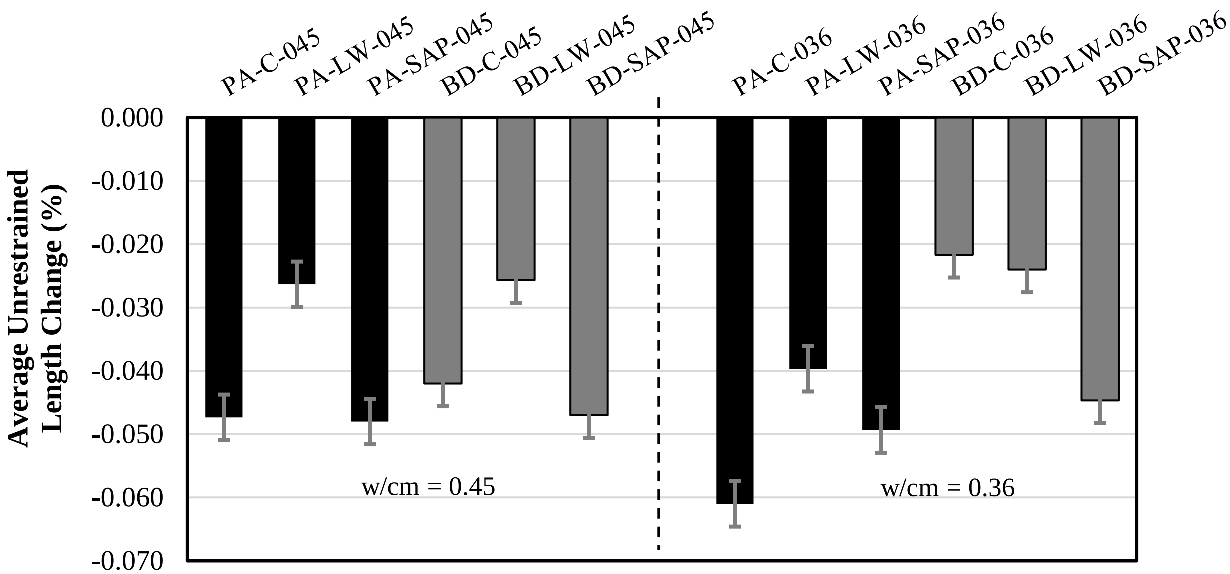


Figure 5-11: Length change of the PA and BD mixtures after 28 days of drying.

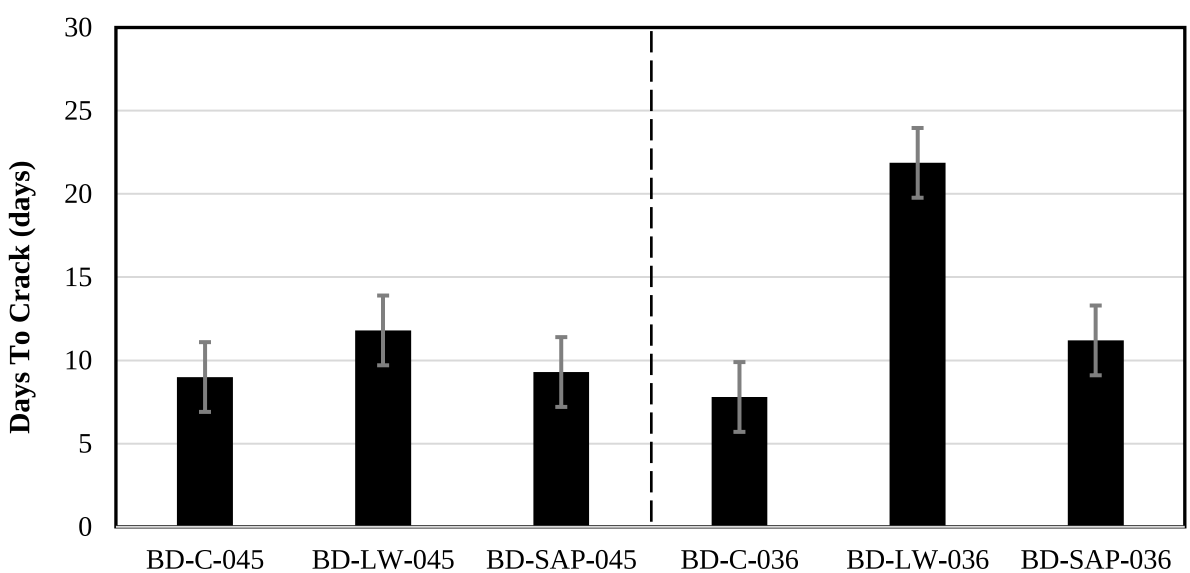


Figure 5-12: Age of cracking of the PA and BD mixtures under restrained shrinkage.

E) EFFECT OF IC MATERIAL ON WARPING

The performance of concrete under warping is shown in Figure 5-13. The results indicate that the mixtures made with the w/cm of 0.45 resulted in less warping compared to those made a w/cm of 0.36. The increased warping in the mixtures made with the lower w/cm may be explained by the higher likelihood of self-desiccation in those mixtures. On the other hand, although mixtures made with the w/cm of 0.45 may exhibit a faster moisture loss from the surface compared to those made with a w/cm of 0.36, they may lead to a lower moisture gradient throughout the depth of the pavement by increasing the sorption potential of the concrete.

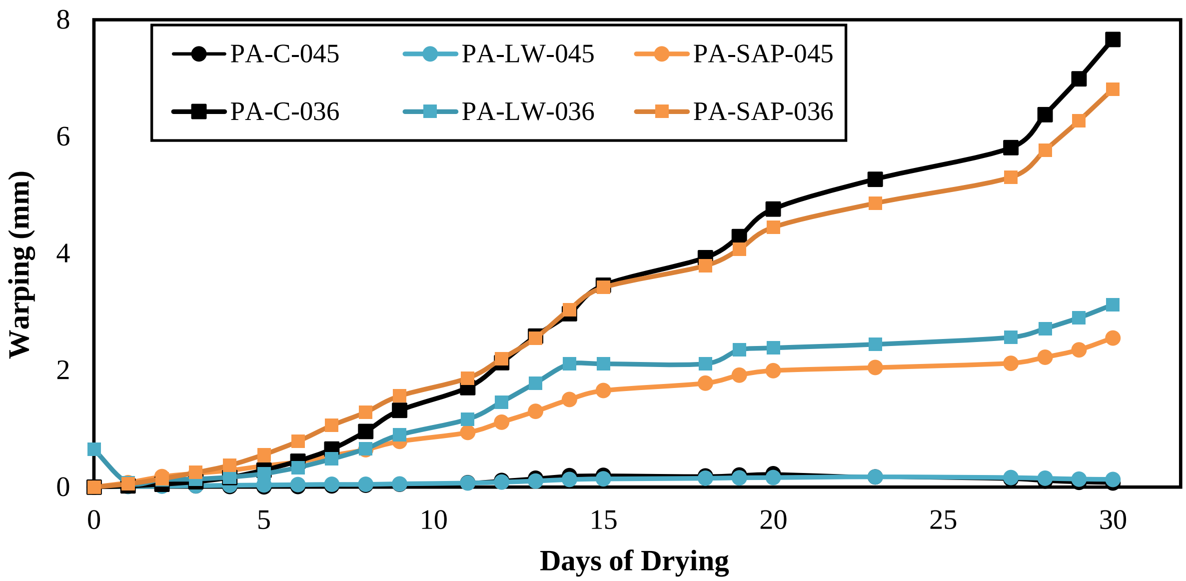


Figure 5-13: Warping of PA mixtures at 0.45 and 0.36 w/cm levels.

Based on the results shown in Figure 5-13, the effect of LWFA on warping is substantial while the incorporation of the SAP led to a considerable increase in the warping, while slightly improved the warping at the lower w/cm. The mixtures made with LWFA performed superior at both tested w/cm compared to other mixtures. The improving effect of IC materials on the warping is mainly due to the reduction in the moisture ingredient through the desorption of the initially absorbed water.

6. SERVICE LIFE AND LIFE-CYCLE COST ANALYSIS

A) SERVICE LIFE

Since the 1990's an increase in the design of durable concrete structure to achieve specific life spans became the focus of various research groups in Europe and North America. Since then, the concept of service life modeling has developed from mathematical simulations to specification language in the recent years [150].

In simple terms, service life modeling of concrete bridges is focused on using a modeling methodology to describe the time necessary to achieve a specific condition, i.e., limit state. For concrete bridges, AASHTO LFRD 2017 has recently adopted a requirement of 75 years of service life. The methodology used for the estimation in the AASHTO guidelines is the fib Bulletin 34 [151].

In fib Bulletin 34, the approach for the durability of concrete structures is based on reliability methods commonly used in structural design. For the estimation of service life, the resistance of concrete structures R(t) and the environmental loads S(t) acting on these structures are defined as probabilistic distributions that change over time.

Service life predictions conducted in this part of the study included the following parameters:

- Concrete Mixtures – Bridge deck mixtures with a w/cm ratio of 0.36 (BD-C-36, BC-LW-36 and BD-SAP-36)
- Chloride Migration Coefficient – Figure 5-7
- Ageing Coefficient – 0.4 [fib Bulletin 34]
- Concrete Cover Thickness – 2.5 in.
- Chloride Exposure – 4.0% by mass of cementitious content as reported in [152]
- Environmental conditions – Annual Weather for Madison, WI – Figure 6-1.

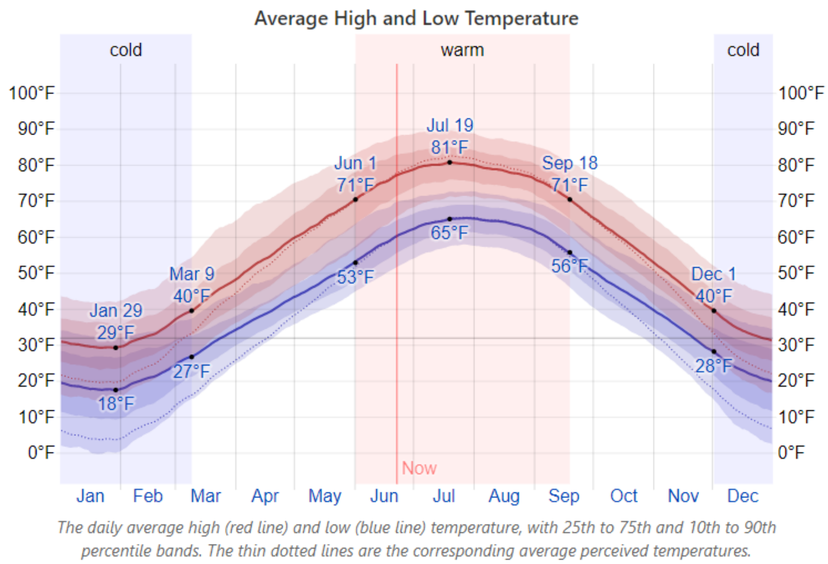


Figure 6-1: Annual Weather for Madison, WI.

Service life predictions for concrete mixtures BD-C-36 and those with internal curing, i.e., BC-LW-36 and BD-SAP-36 are shown in Table 6-1. Results indicate that the predicted time to corrosion initiation for a concrete bridge with a concrete cover thickness of 2.5 in in the state of Wisconsin would be approximately 35 years.

Table 6-1: Predicted Service Life of Concrete Mixtures.

Mixture	Time to Corrosion Initiation, Years	% Improvement
BD-C-036	34	100%
BD-LW-036	38	111%
BD-SAP-036	39	114%

Service life prediction results show that an increase in service life of up to 15% was achieved when IC concrete is used compared to conventional bridge deck concrete mixtures. Mixture proportioning for IC bridge deck placements will be likely necessary to increase the predicted service life for meeting the requirements of AASHTO LFRD.

B) LIFE-CYCLE COST ANALYSIS

Life Cycle Cost Analysis (LCCA) is a tool for estimating the economic impact of construction materials throughout their entire life cycle [122]. LCCA is an asset management and planning technique based on economic principles used to evaluate the long-term economic efficiency between competing for alternative investment options. LCCA can be applied to different types of assets and a wide variety of investment-related decision levels. LCCA for pavements is typically performed to compare different pavement designs, over a defined analysis period, considering all significant present and future costs (agency, user, and other relevant costs) over the life of the pavement and expressing these costs in present value.

For this study, WisPAVE was used for estimating the LCCA of for a 25 mile long concrete pavement project in the state of Wisconsin. The simulation considered an increase in the cost of IC concrete, compared to a conventional pavement mixture, while considering the reduction in rehabilitation costs due to reduced cracking and warping as shown in Table 6-2. The complete report is included in the Appendix.

Table 6-2: WisPAVE LCCA of Conventional and IC Concrete.

Concrete Type	Conventional Concrete	IC Concrete
Initial Cost	100%	101%
Reduction in Rehabilitation Costs	100%	80%
LCCA	100%	99%

Since the WisPAVE software has a pre-determined service life of 25 years for pavements regardless of the type of concrete used, a simplified LCA analysis utilizing basic economic engineering equations was used to determine the benefits of utilizing IC concrete. For this purpose, an increase in the service life of the pavement for the first rehabilitation cycle was increased to 39 years, instead of 25 years. The increase to 39 years was deemed to be reasonable based on the improvement on the resistance to warping and volumetric changes of IC concrete compared to conventional concrete. Table 6-3 shows the summarized results of the LCA analysis. All other parameters including the length of the project, initial costs, discount rate, etc. remained identical to the WisPAVE analysis.

Table 6-3: Estimated LCCA of Conventional and IC Concrete.

	Concrete Alt#1 Conventional Concrete	**Concrete Alt#2 Internally Cured Concrete**
Initial Construction Costs	$53,682,996.70	$54,465,463.30
Maintenance Costs	$572,946.73	$80,640.25
Rehabilitation Costs	$1,302,688.96	$77,768.11
Rehabilitation Salvage Value	($72,090.98)	($3,394.16)
Total Facility Costs	$55,486,541.41	$55,112,783.98

Results presented in Table 6-2 and Table 6-3 show that although a higher initial costs may be anticipated for IC concrete due to an increase material costs, the potential reduction in rehabilitation costs can substantially justify the use of IC for achieving a lower LCCA compared to conventional concrete.

7. CONCLUSION

Based on the work conducted in this study, the following conclusions can be derived:

1. The inclusion of LWFA had a predominant effect on minimizing the autogenous shrinkage. The efficacy of LWFA to mitigate autogenous shrinkage is found to dependent on LWFA type and its replacement level, Among the two LWFAs considered for shrinkage study, L1 outperformed L2. Data indicates that considering an LWFA replacement level that is estimated using the equation proposed by Bentz and Snyder results in optimal performance of the mixture. Data also indicates that a lower replacement level may be adopted depending on the aggregate type.
2. The inclusion of LWFA minimized the drying shrinkage to a certain extent, however, this ability was less significant compared to the ability of LWFA in controlling autogenous shrinkage.
3. The effectiveness of SAP investigated in this study on drying shrinkage was reduced when compared to LWFA likely due to inconsistencies associated with absorption and distribution of SAP particles in the mortar mixture.
4. The fresh concrete properties of concrete can be affected by the incorporation of IC agents. Although simple adjustments can be made to compensate for this effect, caution is recommended when using SAP as IC agents. Verification of performance by trial batching is recommended.
5. Plastic air content values determined by AASHTO TP 118 cannot reliably predict the hardened air void structure from the presence of IC agents.
6. Hardened concrete properties showed a general improvement when IC was incorporated, especially durability and volume related performance. Compressive strength was negatively affected by the use of IC. This challenge can be easily overcome in the design stage when adjustments to the concrete mixture or project specification can be made.
7. The use of IC concrete resulted in a substantial increase in the resistance against cracking of bridge deck concrete mixtures under restrained conditions. In non-restrained conditions, shrinkage was comparable to the control concrete mixtures.
8. Pavement warping was substantially reduced when LWA was used as internal curing agent. In the case of SAP, mixed results were observed for this performance.
9. Service life of bridge deck concrete can be increased when IC concrete is used in lieu of conventional concrete mixtures. For achieving the AASHTO LFRD requirement of 75 years, modifications to approved concrete mixtures is anticipated to be necessary.
10. The LCCA of IC concrete showed an overall reduction in total costs once the reduction in rehabilitation costs is considered. An increase in initial costs should be anticipated.

8. RECOMMENDATIONS

The following recommendations for future research projects and implementation in WisDOT specifications are provided:

a. Concrete producers and contractors to participate in projects using IC concrete should be aware of the effects of the evaluated IC agents on concrete performance. Appendix B and the contents of this report can be used as a guide for familiarization of the available materials, their characteristics, and performance of concrete in both fresh and hardened conditions.
b. IC Concrete will require a greater level of attention by the concrete producer and contractor to ensure that the concrete is batched consistently and that its placement is conducted effectively.
c. The Specifier or Engineer-of-Record should consider that IC concrete can result in a reduction in compressive strength. The benefits of using IC concrete in durability and reduced cracking can overcome this challenge.
d. A Special Provision is included in Appendix C for potential use in projects where IC concrete can be used for construction of concrete bridge deck and pavement.

REFERENCES

[1] T. C. Powers and T. L. Brownyard, "Studies of the Physical Properties of Hardened Portland Cement Paste," *J. Am. Concr. Inst.*, vol. 43, no. 249, 1947.

[2] B. Mather and W. G. Hime, "Amount of water required for complete hydration of portland cement," *Concr. Int.*, no. June, pp. 56–58, 2002.

[3] G. Ye, K. Van Breugel, and A. L. A. Fraaij, "Three-dimensional microstructure analysis of numerically simulated cementitious materials," *Cem. Concr. Res.*, vol. 33, no. 2, pp. 215–222, 2003, doi: 10.1016/S0008-8846(02)00889-X.

[4] ACI CT-13, "ACI Concrete Terminology," American Concrete Institue, Farmington Hills, MI, 2017.

[5] D. P. Bentz and W. J. Weiss, "Internal Curing : A 2010 state of the art review," *Natl. NISTIR 7765*, p. 82, 2011, doi: 10.1016/j.jvcir.2009.09.004.

[6] O. M. Jensen and P. F. Hansen, "Autogenous deformation and RH-change in perspective," *Cem. Concr. Res.*, vol. 31, no. 12, pp. 1859–1865, 2001, doi: 10.1016/S0008-8846(01)00501-4.

[7] K. Kovler and o M. Jensen, "Chapter 2 - General Concept and Terminology," *Intern. Curing Concr. RILEM TC 196-ICC State-of-the-Art Rep.*, no. June, pp. 5–13, 2007.

[8] S. Igarashi, A. Bentur, and K. Kovler, "Autogenous shrinkage and induced restraining stresses in high-strength concretes," *Cem. Concr. Res.*, vol. 30, no. 11, pp. 1701–1707, Nov. 2000, doi: 10.1016/S0008-8846(00)00399-9.

[9] D. Cusson and T. Hoogeveen, "Internal curing of high-performance concrete with pre-soaked fine lightweight aggregate for prevention of autogenous shrinkage cracking," *Cem. Concr. Res.*, vol. 38, no. 6, pp. 757–765, 2008, doi: 10.1016/j.cemconres.2008.02.001.

[10] C. G. De Schutter, "Chapter 8 - Effect of Ic on Other Concrete Properties," *Intern. curing Concr.*, no. June, pp. 105–126, 2007.

[11] E. Tazawa, "Autogenous Shrinkage of Concrete," in *Proceedings of the International Workshop organized by JCI (Japan Concrete Institute)*, 1998.

[12] W. Hansen, “Viscoelastic Stress Modeling in Cementitious Materials Using Constant Viscoelastic Hydration Modulus,” in *Proceedings of the 1st International Conference on Ageing of Materials & Structures*, 2014, no. October, doi: 10.13140/2.1.4511.4886.

[13] S. Liang and Y. Wei, “Modelling of creep effect on moisture warping and stress developments in concrete pavement slabs,” *Int. J. Pavement Eng.*, vol. 19, no. 5, pp. 429–438, May 2018, doi: 10.1080/10298436.2017.1402595.

[14] R. E. Asbahan and J. M. Vandenbossche, “Effects of Temperature and Moisture Gradients on Slab Deformation for Jointed Plain Concrete Pavements,” *J. Transp. Eng.*, vol. 137, no. 8, pp. 563–570, 2011, doi: 10.1061/(asce)te.1943-5436.0000237.

[15] O. M. Jensen, “Chapter 3 - Mechanisms of Internal Water Curing,” *Intern. Curing Concr. RILEM TC 196-ICC State-of-the-Art Rep.*, no. June, pp. 15–27, 2007.

[16] K. A. Snyder and D. P. Bentz, “Protected Paste Volume in Concrete : Extension to Internal Curing Using Saturated Lightweight Fine Aggregate,” *Cement and Concrete Research*, vol. 29, no. 11. pp. 1863–1867, 1999.

[17] D. P. Bentz, P. Lura, and J. W. Roberts, “Mixture Proportioning for Internal Curing,” *Concr. Int.*, vol. 27, no. 2, pp. 35–40, 2005, doi: 10.1016/j.cede.2012.01.005.

[18] P. Mounanga, A. Khelidj, A. Loukili, and V. Baroghel-Bouny, “Predicting Ca(OH)2 content and chemical shrinkage of hydrating cement pastes using analytical approach,” *Cem. Concr. Res.*, vol. 34, no. 2, pp. 255–265, 2004, doi: 10.1016/j.cemconres.2003.07.006.

[19] R. Henkensiefken, D. Bentz, T. Nantung, and J. Weiss, “Volume change and cracking in internally cured mixtures made with saturated lightweight aggregate under sealed and unsealed conditions,” *Cem. Concr. Compos.*, vol. 31, no. 7, pp. 427–437, 2009, doi: 10.1016/j.cemconcomp.2009.04.003.

[20] J. Castro, L. Keiser, M. Golias, and J. Weiss, “Absorption and desorption properties of fine lightweight aggregate for application to internally cured concrete mixtures,” *Cem. Concr. Compos.*, vol. 33, no. 10, pp. 1001–1008, 2011, doi: 10.1016/j.cemconcomp.2011.07.006.

[21] B. T. W. Bremner and J. Ries, “Stephen J . Hayde : Father of the Lightweight Concrete Industry,” no. august, pp. 35–38, 2009.

[22] R. Philleo, "Concrete Science and Reality," in *Materials Science of Concrete II*, 1991, pp. 1–8.

[23] W. Wei, Y., and Hansen, "Pre-soaked Lightweight Fine Aggregates as Additives for Internal Curing in Concrete," *Am. Concr. Inst. - SP 256*, vol. 256, no. December 2015, pp. 35–44, 2008, doi: 10/1/2008.

[24] RILEM TC 196-ICC Rep 41-5, O. M. Jensen, and P. Lura, "Chapter 5 - Materials and Methods for Internal," *Intern. Curing Concr. RILEM TC 196-ICC State-of-the-Art Rep.*, no. June, pp. 45–55, 2007.

[25] F. Liu, J. Wang, X. Qian, and J. Hollingsworth, "Cement and Concrete Research Internal curing of high performance concrete using cenospheres," *Cem. Concr. Res.*, vol. 95, pp. 39–46, 2017, doi: 10.1016/j.cemconres.2017.02.023.

[26] S. Afzal, K. Shahzada, M. Fahad, S. Saeed, and M. Ashraf, "Assessment of early-age autogenous shrinkage strains in concrete using bentonite clay as internal curing technique," *Constr. Build. Mater.*, vol. 66, pp. 403–409, 2014, doi: 10.1016/j.conbuildmat.2014.05.051.

[27] J. Ries, S. Jeff, and K. S. Harmon, "Lightweight Aggregate Optimizes the Sustainability of Concrete, Through Weight Reduction, Internal Curing, Extended Service Life, and Lower Carbon Footprint," in *NRMCA Concrete Sustainability Conference*, 2010, no. 801, pp. 1–15.

[28] ASTM C1761, "Standard Specification for Lightweight Aggregate for Internal Curing of Concrete," West Conshohocken, PA, 2017. doi: 10.1520/C1761.

[29] A. E. Miller, T. J. Barrett, A. R. Zander, and W. J. Weiss, "Using a Centrifuge to Determine Moisture Properties of Lightweight Fine Aggregate for Use in Internal Curing," *Adv. Civ. Eng. Mater.*, vol. 3, no. 1, p. 20130111, Feb. 2014, doi: 10.1520/ACEM20130111.

[30] F. Antico, R. Spragg, W. Ashraf, A. Miller, T. Barrett, and A. Behnood, "Determining the Moisture Content of Pre-Wetted Lightweight Aggregate: Assessing the Variability of the Paper Towel and Centrifuge Methods," no. July, pp. 312–316, 2014, doi: 10.5703/1288284315475.

[31] F. L. Buchholz, "Superabsorbent Polymers: An Idea Whose Time Has Come," *J. Chem. Educ.*, vol. 73, no. 6, p. 512, 2009, doi: 10.1021/ed073p512.

[32] "Improved Concrete Materials with Hydrogel-Based Internal Curing Agents," *Gels*, vol. 3, no. 4, p. 46, 2017, doi: 10.3390/gels3040046.

[33] J. Liu, C. Shi, X. Ma, K. H. Khayat, J. Zhang, and D. Wang, "An overview on the effect of internal curing on shrinkage of high performance cement-based materials," *Constr. Build. Mater.*, vol. 146, pp. 702–712, 2017, doi: 10.1016/j.conbuildmat.2017.04.154.

[34] "STAR 225-SAP Application of Superabsorbent Polymers (SAP) in Concrete Construction," 2012.

[35] T. K. Mudiyanselage and D. C. Neckers, "Highly absorbing superabsorbent polymer," *J. Polym. Sci. Part A Polym. Chem.*, vol. 46, no. 4, pp. 1357–1364, 2008, doi: 10.1002/pola.22476.

[36] L. Montanari, C. Villani, J. Weiss, M. T. Chang, and P. Suraneni, "Absorption and Desorption of Superabsorbent Polymers for Use in Internally Cured Concrete," *Adv. Civ. Eng. Mater.*, vol. 7, no. 4, p. 20180008, 2018, doi: 10.1520/acem20180008.

[37] H. X. D. Lee, H. S. Wong, and N. R. Buenfeld, "Effect of alkalinity and calcium concentration of pore solution on the swelling and ionic exchange of superabsorbent polymers in cement paste," *Cem. Concr. Compos.*, vol. 88, no. February, pp. 150–164, 2018, doi: 10.1016/j.cemconcomp.2018.02.005.

[38] K. Farzanian and A. Ghahremaninezhad, "The effect of the capillary forces on the desorption of hydrogels in contact with a porous cementitious material," *Mater. Struct.*, vol. 50, no. 5, p. 216, Oct. 2017, doi: 10.1617/s11527-017-1068-9.

[39] J. Yang, F. Wang, X. Liang, J. Wu, and H. Cheng, "Study on Mechanism of Desorption Behavior of Saturated Superabsorbent Polymers in Concrete," *ACI Mater. J.*, vol. 112, no. 3, pp. 463–470, 2014, doi: 10.14359/51686996.

[40] J. Yang, F. Wang, Z. Liu, Y. Liu, and S. Hu, "Early-state water migration characteristics of superabsorbent polymers in cement pastes," *Cem. Concr. Res.*, vol. 118, pp. 25–37, Apr. 2019, doi: 10.1016/J.CEMCONRES.2019.02.010.

[41] D. Snoeck, C. Schröfl, and V. Mechtcherine, "Recommendation of RILEM TC 260-RSC: testing sorption by superabsorbent polymers (SAP) prior to implementation in cement-based materials," *Mater. Struct. Constr.*, vol. 51, no. 5, 2018, doi: 10.1617/s11527-018-1242-8.

[42] V. Mechtcherine *et al.*, "Testing superabsorbent polymer (SAP) sorption properties prior to implementation in concrete: results of a RILEM Round-Robin Test," *Mater. Struct. Constr.*, vol.

51, no. 1, 2018, doi: 10.1617/s11527-018-1149-4.

[43] P. P. Woyciechowski and M. Kalinowski, “The influence of dosing method and material characteristics of superabsorbent polymers (SAP) on the effectiveness of the concrete internal curing,” *Materials (Basel).*, vol. 11, no. 9, 2018, doi: 10.3390/ma11091600.

[44] O. M. Jensen and P. Lura, “Chapter 5 - Materials and Methods for Internal,” *Intern. Curing Concr. RILEM TC 196-ICC State-of-the-Art Rep.*, no. June, pp. 45–55, 2007.

[45] M. Ardanuy, J. Claramunt, and R. D. Toledo Filho, “Cellulosic fiber reinforced cement-based composites: A review of recent research,” *Constr. Build. Mater.*, vol. 79, pp. 115–128, 2015, doi: 10.1016/j.conbuildmat.2015.01.035.

[46] B. J. Mohr, L. Premenko, H. Nanko, and K. E. Kurtis, “Examination of wood-derived powders and fibers for internal curing of cement-based materials,” in *4th International Seminar on Self-Desiccation and Its Importance in Concrete Technology, Gaithesburg, Maryland, USA, June 2005*, 2005.

[47] S. Kawashima and S. P. Shah, “Early-Age Autogenous and Drying Shrinkage Behavior of Cellulose Fiber-Reinforced Cementitious Materials,” *Cem. Concr. Compos.*, vol. 33, no. 2, pp. 201–208, 2011, doi: 10.1016/j.cemconcomp.2010.10.018.

[48] X. Sun, Q. Wu, S. Lee, Y. Qing, and Y. Wu, “Cellulose Nanofibers as a Modifier for Rheology, Curing and Mechanical Performance of Oil Well Cement,” *Sci. Rep.*, vol. 6, pp. 1–9, 2016, doi: 10.1038/srep31654.

[49] Z. Jiang, X. Guo, W. Li, and Q. Chen, “Self-Shrinkage Behaviors of Waste Paper Fiber Reinforced Cement Paste considering Its Self-Curing Effect at Early-Ages,” *Int. J. Polym. Sci.*, vol. 2016, pp. 1–12, 2016, doi: 10.1155/2016/8690967.

[50] K. Obla, “Recycled Concrete As An Aggregate In The Concrete Mix.” 2018, doi: 10.3850/978-981-07-5354-2_m-51-426.

[51] “Recycled Concrete Aggregate Federal Highway Administration National Review - Recycling - Sustainability - Pavements - Federal Highway Administration.” Accessed: Feb. 04, 2019. [Online]. Available: https://www.fhwa.dot.gov/pavement/recycling/rca.cfm.

[52] S. Y. Abate, K. Il Song, J. K. Song, B. Y. Lee, and H. K. Kim, “Internal curing effect of raw and

carbonated recycled aggregate on the properties of high-strength slag-cement mortar," *Constr. Build. Mater.*, vol. 165, pp. 64–71, 2018, doi: 10.1016/j.conbuildmat.2018.01.035.

[53] C. G. Fakitsas, P. E. A. Papakonstantinou, P. D. Kiousis, and A. Savva, "Effects of Recycled Concrete Aggregates on the Compressive and Shear Strength of High-Strength Self-Consolidating Concrete," *J. Mater. Civ. Eng.*, vol. 24, no. 4, pp. 356–361, 2011, doi: 10.1061/(asce)mt.1943-5533.0000397.

[54] H. Kim and D. P. Bentz, "Internal curing with crushed returned concrete aggregates," *NRMCA Concr. Technol. Forum Focus Sustain. Dev.*, no. May, pp. 1–12, 2008.

[55] ACI Committee 213, "Guide for Structural Lightweight Aggregate Concrete," Farmington Hills, MI, 2014. doi: 10.14359/7576.

[56] V. H. Villareal, "Internal curing-Real World ready mix production and applications: a practical approach to lightweighr modified concret," 2014.

[57] V. Mechtcherine, "Use of Superabsorbent Polymers (SAP) as Concrete Additive," *RILEM Tech. Lett.*, vol. 1, no. 1, pp. 81–87, 2016, doi: 10.21809/rilemtechlett.2016.18.

[58] V. Villarreal and D. Crocker, "Better pavements through internal hydration," *Concr. Int.*, vol. 29, no. 2, pp. 32–36, 2007.

[59] B. E. Byard, A. K. Schindler, and R. W. Barnes, "Cracking tendency of lightweight aggregate bridge deck concrete," *ACI Mater. J.*, vol. 111, no. 2, pp. 179–188, 2014, doi: 10.14359/51686499.

[60] G. R. de Sensale and A. F. Goncalves, "Effects of Fine LWA and SAP as Internal Water Curing Agents," *Int. J. Concr. Struct. Mater.*, vol. 8, no. 3, pp. 229–238, 2014, doi: 10.1007/s40069-014-0076-1.

[61] B. Craeye, M. Geirnaert, and G. De Schutter, "Super absorbing polymers as an internal curing agent for mitigation of early-age cracking of high-performance concrete bridge decks," *Constr. Build. Mater.*, vol. 25, no. 1, pp. 1–13, 2011, doi: 10.1016/j.conbuildmat.2010.06.063.

[62] V. Mechtcherine, E. Secrieru, and C. Schröfl, "Effect of superabsorbent polymers (SAPs) on rheological properties of fresh cement-based mortars - Development of yield stress and plastic viscosity over time," *Cem. Concr. Res.*, vol. 67, pp. 52–65, 2015, doi: 10.1016/j.cemconres.2014.07.003.

[63] E. Secrieru, C. Schröfl, and V. Mechtcherine, “Evolution of rheological properties of fresh concrete enriched with superabsorbent polymers (SAP) in time at various temperatures,” *Appl. SAP other new Admixtures Concr. Constr. 14-17 Sept. Dresden*, pp. 95–104, 2014.

[64] E. Secrieru, V. Mechtcherine, C. Schröfl, and D. Borin, “Rheological characterisation and prediction of pumpability of strain-hardening cement-based-composites (SHCC) with and without addition of superabsorbent polymers (SAP) at various temperatures,” *Constr. Build. Mater.*, vol. 112, pp. 581–594, 2016, doi: 10.1016/j.conbuildmat.2016.02.161.

[65] P. Jongvisuttisun, “Utilization of Eucalyptus Pulp Fibers in Cementitious Materials,” Georgia Institute of Technology, 2014.

[66] A. Mezencevova, V. Garas, H. Nanko, and K. E. Kurtis, “Influence of Thermomechanical Pulp Fiber Compositions on Internal Curing of Cementitious Materials,” *J. Mater. Civ. Eng.*, vol. 24, no. 8, pp. 970–975, 2012, doi: 10.1061/(ASCE)MT.1943-5533.0000446.

[67] J. Browning, Da. Darwin, D. Reynolds, and B. Pendergrass, “Lightweight Aggregate as Internal Curing Agent to Limit,” *ACI Mater. J.*, vol. 108, no. December 2011, pp. 2011–2013, 2012.

[68] A. Klemm and K. Sikora, “Superabsorbent Polymers in Cementitious Composites – Review,” *J. Constr. Optim. potential (Budownictwo o zoptymalizowanym potencjale Energ.*, vol. Czestochow, no. Poland, 2011.

[69] B. J. Olawuyi and W. P. Boshoff, “Influence of SAP content and curing age on air void distribution of high performance concrete using 3D volume analysis,” *Constr. Build. Mater.*, vol. 135, pp. 580–589, 2017, doi: 10.1016/j.conbuildmat.2016.12.128.

[70] D. A. Streeter, W. H. Wolfe, and R. E. Vaughn, “Field Performance of Internally Cured Concrete Bridge Decks in New York State,” *Spec. Publ.*, vol. 290, pp. 1–16, Sep. 2012, doi: 10.14359/51684176.

[71] B. Craeye and G. De Schutter, “Experimental evaluation of mitigation of autogenous shrinkage by means of a vertical dilatometer for concrete,” in *International RILEM Conference on Volume Changes of Hardening Concrete: Testing and Mitigation*, 2006, pp. 21–30, doi: 10.1617/2351580052.003.

[72] B. Akcay, “Influence of lightweight aggregates on internal curing and fracture of concrete,” in

International RILEM Conference on Volume Changes of Hardening Concrete: Testing and Mitigation, 2006, pp. 31–40, doi: 10.1617/2351580052.004.

[73] H. Lam and Hoo, “Effects of internal curing methods on restrained shrinkage and permeability,” in *Proceedings of the 4th International Seminar on Self-Dessication and its Importance in Concrete Technology*, 2005, pp. 210–28.

[74] and D. B. A. D. Gao, R. B. Heimann, “Box—Behnken design applied to study the strengthening of aluminate concrete modified by a superabsorbent polymer/clay composite,” *Adv. Cem. Res.*, vol. 9, no. 35, pp. 93–97, Jul. 1997, doi: 10.1680/adcr.1997.9.35.93.

[75] A. J. Klemm and K. S. Sikora, “The Effect of Superabsorbent Polymers (SAP) on Microstructure and Mechanical Properties of Fly Ash Cementitious Mortars,” *Constr. Build. Mater.*, vol. 49, pp. 134–143, 2013.

[76] P. Lura, “Compressive strength of cement pastes and mortars with superabsorbent polymers,” in *International RILEM Conference on Volume Changes of Hardening Concrete: Testing and Mitigation*, 2006, pp. 117–125, doi: 10.1617/2351580052.013.

[77] E. F. Silva, M. A. R. Manzano, A. N. M. Lopes, and R. D. T. Filho, “Effect of SAP on the autogenous shrinkage and compressive strength of high-strength fine-grained concrete,” in *International RILEM Conference on Application of Superabsorbent Polymers and other New Admixtures in Concrete Construction*, 2014, pp. 211–219.

[78] M. T. Hasholt, O. M. Jensen, K. Kovler, and S. Zhutovsky, “Can Superabsorent Polymers Mitigate Autogenous Shrinkage of Internally Cured Concrete without Compromising the Strength?,” *Constr. Build. Mater.*, vol. 31, pp. 226–230, 2012, doi: 10.1016/j.conbuildmat.2011.12.062.

[79] H. Beushausen and L. Fernández Luco, *Performance-based specifications and control of concrete durability : state-of-the-art report RILEM TC 230-PSC.* .

[80] M. R. Golias, “The use of soy methyl ester-polystyrene sealants and internal curing to enhance concrete durability,” *Theses Diss. Available from ProQuest*, Jan. 2010, [Online]. Available: https://docs.lib.purdue.edu/dissertations/AAI1490651.

[81] V. Mechtcherine, L. Dudziak, J. Schulze, O. M. Jensen, P. Lura, and K. Kovler, “Internal curing by super absorbent polymers (SAP)-Effects on material properties of selfcompacting fibre-

reinforced high performance concrete," in : *International RILEM Conference on Volume Changes of Hardening Concrete: Testing and Mitigation*, 2006, pp. 87–96, doi: 10.1617/2351580052.010.

[82] J. Justs, M. Wyrzykowski, D. Bajare, and P. Lura, "Internal curing by superabsorbent polymers in ultra-high performance concrete," *Cem. Concr. Res.*, vol. 76, pp. 82–90, 2015, doi: 10.1016/j.cemconres.2015.05.005.

[83] J. Schlitter, R. Henkensiefken, J. Castro, K. Raoufi, and Weiss, "Development of Internally Cured Concrete for Increased Service Life," Indiana Department of Transportation, 2010. doi: 10.5703/1288284314262.

[84] O. M. Jensen and P. F. Hansen, "Water-entrained cement-based materials: I. Principles and theoretical background," *Cem. Concr. Res.*, vol. 31, no. 4, pp. 647–654, Apr. 2001, doi: 10.1016/S0008-8846(01)00463-X.

[85] P. Lura, *Autogenous Deformation and Internal Curing of Concrete*. 2003.

[86] M. Geiker, D. Bentz, and O. Jensen, "Mitigating autogenous shrinkage by internal curing," *ACI Spec. Publ.*, vol. 218, no. January, pp. 143–148, 2004, doi: 10.1639/0007-2745-114.3.545.

[87] A. Bentur, S. Igarashi, and K. Kovler, "Prevention of autogenous shrinkage in high-strength concrete by internal curing using wet lightweight aggregates," *Cem. Concr. Res.*, vol. 31, no. 11, pp. 1587–1591, Nov. 2001, doi: 10.1016/S0008-8846(01)00608-1.

[88] J. Piérard, "Mitigating autogenous shrinkage in HPC by internal curing using superabsorbent polymers," vol. C, no. August, pp. 97–106, 2006, doi: 10.1617/2351580052.011.

[89] J. L. Schlitter, T. Barrett, and W. J. Weiss, "Restrained Shrinkage Behavior Due To Combined Autogenous and Thermal Effects in Mortars Containing Super Absorbent Polymer (Sap)," *Int. RILEM Conf. use*, no. August, 2010.

[90] S. Zhutovsky and K. Kovler, "Effect of internal curing on durability-related properties of high performance concrete," *Cem. Concr. Res.*, vol. 42, no. 1, pp. 20–26, Jan. 2012, doi: 10.1016/J.CEMCONRES.2011.07.012.

[91] D. Cusson, Z. Lounis, and L. Daigle, "Benefits of internal curing on service life and life-cycle cost of high-performance concrete bridge decks – A case study," *Cem. Concr. Compos.*, vol. 32, no. 5, pp. 339–350, May 2010, doi: 10.1016/J.CEMCONCOMP.2010.02.007.

[92] P. Castro-Borges and J. Margeson, "Development of low-shrinkage high-performance concrete with improved durability," in *Concrete under severe conditions : environment and loading : proceedings of the 6th International Conference on Concrete Under Severe Conditions (CONSEC '10), Mérida, Yucatán, Mexico, 7-9 June 2010*, Jul. 2010, p. 1720, [Online]. Available: https://trid.trb.org/view/1196578.

[93] M. T. Hasholt and O. M. Jensen, "Chloride migration in concrete with superabsorbent polymers," *Cem. Concr. Compos.*, vol. 55, pp. 290–297, 2015, doi: 10.1016/j.cemconcomp.2014.09.023.

[94] E. B. Persson, D. P. Bentz, and L. Nilsson, "Self-Desiccation and its Importance in Concrete Technology," 2005.

[95] H. Dong and G. Ye, "Freezing and Thawing Resistance of High Performance Concrete Incorporating Superabsorbent Polymer," in *Application of Superbasorbent Polymers and Other New Admixtures in Concrete Construction*, 2014, pp. 279–289.

[96] J. Pacheco, "Corrosion of Steel in Cracked Concrete: Chloride Microanalysis and Service Life Predictions," Delft University of Technology, 2015.

[97] ACI 231R-10, "Early-age Cracking: Causes, Measurement, and Mitigation," Framington Hills, MI, 2010.

[98] ACI Committee 211, "211.9R-18 Guide to Selecting Proportions for Pumpable Concrete." Farmington Hills, MI, p. 13, 2018.

[99] ACI Committee 304, "Guide to Placing Concrete by Pumping Methods," *304.2R-17*. American Concrete Institute, Farmington Hills, MI, p. 20, 2017.

[100] E. O. Goeb, "Pumping structural lightweight concrete," p. 4, 1985.

[101] Á. Paul and M. Lopez, "Assessing lightweight aggregate efficiency for maximizing internal curing performance," *ACI Mater. J.*, vol. 108, no. 4, pp. 385–393, 2011, doi: 10.14359/51683111.

[102] D. P. Bentz and K. A. Snyder, "Protected paste volume in concrete: Extension to internal curing using saturated lightweight fine aggregate," *Cem. Concr. Res.*, vol. 29, no. 11, pp. 1863–1867, 1999, doi: 10.1016/S0008-8846(99)00178-7.

[103] J. Yang, L. Liu, Q. Liao, J. Wu, J. Li, and L. Zhang, "Effect of superabsorbent polymers on the

drying and autogenous shrinkage properties of self-leveling mortar," *Constr. Build. Mater.*, vol. 201, pp. 401–407, 2019, doi: 10.1016/j.conbuildmat.2018.12.197.

[104] M. Wyrzykowski, S. I. Igarashi, P. Lura, and V. Mechtcherine, "Recommendation of RILEM TC 260-RSC: using superabsorbent polymers (SAP) to mitigate autogenous shrinkage," *Mater. Struct.*, vol. 51, 2018, doi: https://doi.org/10.1617/s11527-018-1241-9.

[105] K. Kohno, T. Okamoto, Y. Isikawa, T. Sibata, and H. Mori, "Effects of artificial lightweight aggregate on autogenous shrinkage of concrete," *Cem. Concr. Res.*, vol. 29, no. 4, pp. 611–614, 1999, doi: 10.1016/S0008-8846(98)00202-6.

[106] M. H. Zhang, L. Li, and P. Paramasivam, "Shrinkage of high-strength lightweight aggregate concrete exposed to dry environment," *ACI Mater. J.*, vol. 102, no. 2, pp. 86–92, 2005, doi: 10.14359/14301.

[107] O. Kayali, "Fly ash lightweight aggregates in high performance concrete," *Constr. Build. Mater.*, vol. 22, no. 12, pp. 2393–2399, 2008, doi: 10.1016/j.conbuildmat.2007.09.001.

[108] C. Schröfl, V. Mechtcherine, and M. Gorges, "Relation between the molecular structure and the efficiency of superabsorbent polymers (SAP) as concrete admixture to mitigate autogenous shrinkage," *Cem. Concr. Res.*, vol. 42, no. 6, pp. 865–873, 2012, doi: 10.1016/j.cemconres.2012.03.011.

[109] D. Shen, T. Wang, Y. Chen, M. Wang, and G. Jiang, "Effect of internal curing with super absorbent polymers on the relative humidity of early-age concrete," *Constr. Build. Mater.*, vol. 99, pp. 246–253, 2015, doi: 10.1016/j.conbuildmat.2015.08.042.

[110] X. Wang, G. Jiang, D. Cheng, D. Shen, and J. Zhang, "Effect of internal curing with super absorbent polymers on autogenous shrinkage of concrete at early age," *Constr. Build. Mater.*, vol. 106, no. 1, pp. 512–522, 2015, doi: 10.1016/j.conbuildmat.2015.12.115.

[111] D. P. Bentz, S. Z. Jones, M. A. Peltz, and P. E. Stutzman, "Mitigation of autogenous shrinkage in repair mortars via internal curing," *Concr. Aust.*, vol. 41, no. 4, pp. 35–39, 2015.

[112] T. K. Mudiyanselage and D. C. Neckers, "Highly absorbing superabsorbent polymer," *Polym. Sci.*, vol. 46, no. 4, pp. 1357–1364, 2008, doi: 10.1002.

[113] P. Taylor, X. Wang, and X. Wang, "Concrete Pavement Mixture Design and Analysis (MDA):

Development and Evaluation of Vibrating Kelly Ball Test (VKelly Test) for the Workability of Concrete," Ames, Mar. 2015. Accessed: Jun. 23, 2021. [Online]. Available: http://lib.dr.iastate.edu/intrans_reports.

[114] M. D. Cook, M. T. Ley, and A. Ghaeezadah, "A workability test for slip formed concrete pavements," *Constr. Build. Mater.*, vol. 68, pp. 376–383, Oct. 2014, doi: 10.1016/j.conbuildmat.2014.06.087.

[115] W. Piasta and H. Sikora, "Effect of air entrainment on shrinkage of blended cements concretes," *Constr. Build. Mater.*, vol. 99, pp. 298–307, Nov. 2015, doi: 10.1016/j.conbuildmat.2015.09.018.

[116] E. Siebel, "Air-Void Characteristics And Freezing and Thawing Resistance of Superplasticized Air-Entrained Concrete With High Workability," Sep. 1989. doi: 10.14359/2506.

[117] H. Shang, Y. Song, and J. Ou, "Behavior of air-entrained concrete after freeze-thaw cycles," *Acta Mech. Solida Sin.*, vol. 22, no. 3, pp. 261–266, Jun. 2009, doi: 10.1016/S0894-9166(09)60273-1.

[118] L. Tang and P.-E. Petersson, "Slab test: Freeze/thaw resistance of concrete—Internal deterioration," *Mater. Struct.*, vol. 37, no. 10, pp. 754–759, Dec. 2004, doi: 10.1007/bf02480522.

[119] K. Obla, H. Kim, and CL Lobo -, "Criteria for Freeze-Thaw Resistant Concrete Mixtures," *Adv. Civ. Eng. Mater.*, vol. 5.2, pp. 119–141, 2016, Accessed: Jun. 23, 2021. [Online]. Available: https://www.astm.org/DIGITAL_LIBRARY/JOURNALS/ACEM/PAGES/ACEM20150005.htm.

[120] C. M. Tam, V. W. Y. Tam, and K. M. Ng, "Assessing drying shrinkage and water permeability of reactive powder concrete produced in Hong Kong," *Constr. Build. Mater.*, vol. 26, no. 1, pp. 79–89, Jan. 2012, doi: 10.1016/j.conbuildmat.2011.05.006.

[121] A. Alaskar, M. Alshannag, and M. Higazey, "Mechanical properties and durability of high-performance concrete internally cured using lightweight aggregates," *Constr. Build. Mater.*, vol. 288, p. 122998, Jun. 2021, doi: 10.1016/j.conbuildmat.2021.122998.

[122] ACPA, "Life - Cycle Cost Analysis : A Tool for Be er Pavement Investment and Engineering Decisions," p. 120, 2012.

[123] J. Castro, P. Lura, F. Rajabipour, R. Henkensiefken, and J. Weiss, "Internal Curing : Discussion of the Role of Pore Solution on Relative Humidity Measurements and Desorption of Lightweight Aggregate (LWA)," *ACI Spec. Publ.*, vol. 270, no. 1, pp. 89–100, 2010, doi: 10.14359/51663741.

[124] J. P. Ries *et al.*, "Guide for Structural Lightweight-Aggregate Concrete Reported by ACI Committee 213," pp. 1–38, 2010.

[125] J. Weiss, J. Schlitter, C. Di Bella, and N. Carboneau, "Documenting the Construction of a Plain Concrete Bridge Deck and an Internally Cured Bridge Deck," no. June, 2012.

[126] X. Liu, K. S. Chia, and M. H. Zhang, "Water absorption, permeability, and resistance to chloride-ion penetration of lightweight aggregate concrete," *Constr. Build. Mater.*, vol. 25, no. 1, pp. 335–343, 2011, doi: 10.1016/j.conbuildmat.2010.06.020.

[127] W. Weiss and L. Montanari, *Guide Specification for Internally Curing Concrete*, vol. 5, no. November. 2017.

[128] D. P. Bentz, P. Lura, and J. W. Roberts, "Mixture Proportioning for Internal Curing," *Concr. Int.*, vol. 27, no. 2, pp. 35–40, 2005, doi: 10.1016/j.cede.2012.01.005.

[129] T. C. Powers, "A Discussion of Cement Hydration in Relation to the Curing of Concrete," *Highw. Res. Board Proc.*, 1948.

[130] RILEM TC 196-ICC Rep 41-5, "State of the Art Report of RILEM technical committee Internal curing of concrete," no. June, pp. 45–55, 2007.

[131] A. M. Neville, *Properties of Concrete*. 2011.

[132] T. A. Hammer, Ø. Bjøntegaard, and E. J. Sellevold, "Internal Curing — Role of Absorbed Water in Aggregates," pp. 131–142.

[133] V. H. Villarreal, "Internal Curing - Real World Ready Mix Production and Applications: A Practical Approach to Lightweight Modified Concrete," *Spec. Publ.*, vol. 256, pp. 45–56, Oct. 2008, doi: 10.14359/20230.

[134] V. Mechtcherine and H. W. Reinhardt, *Application of Super Absorbent Polymers (SAP) in Concrete Construction*. Springer Science and Media, 2012.

[135] ITM, "ITM 222-15T Specific Gravity Factor and Absorption of Lightweight Fine Aggregate," 2015.

[136] L. Greenspan, "HUMIDITY FIXED POINTS OF BINARY SATURATED AQUEOUS

SOLUTIONS.," *J Res Natl Bur Stand Sect A Phys Chem*, 1977, doi: 10.6028/jres.081A.011.

[137] C. Schröfl, D. Snoeck, and V. Mechtcherine, "A review of characterisation methods for superabsorbent polymer (SAP) samples to be used in cement-based construction materials: report of the RILEM TC 260-RSC," *Mater. Struct. Constr.*, vol. 50, no. 4, 2017, doi: 10.1617/s11527-017-1060-4.

[138] B. J. Olawuyi and W. P. Boshoff, "Compressive strength of high-performance concrete with absorption capacity of super-absorbing-polymers (SAP)," *Res. Appl. Struct. Eng. Mech. Comput. - Proc. 5th Int. Conf. Struct. Eng. Mech. Comput. SEMC 2013*, no. September, pp. 1679–1683, 2013.

[139] N. Banthia, O. Onuaguluchi, and D. Cui, "Bio-inspired, internally cured cellulose fiber reinforced concrete for next generation infrastructure," *Am. Concr. Institute, ACI Spec. Publ.*, vol. 2018-June, no. SP 326, pp. 1–18, 2018.

[140] G. Mercedes and Beltran Sierra, *Ductile cement based composites with wood fibers -Material design and experimental approach*, no. december. 2011.

[141] S. Q. Shi, D. J. Gardner, and J. Z. Wang, "Estimating maximum water absorption of wood fiber/polymer fluff composites," *Wood Fiber Sci.*, vol. 32, no. 3, pp. 269–277, 2000.

[142] E. Muñoz and J. A. García-Manrique, "Water absorption behaviour and its effect on the mechanical properties of flax fibre reinforced bioepoxy composites," *Int. J. Polym. Sci.*, vol. 2015, pp. 16–18, 2015, doi: 10.1155/2015/390275.

[143] P. Upadhyaya, M. Garg, V. Kumar, and A. K. Nema, "The Effect of Water Absorption on Mechanical Properties of Wood Flour/Wheat Husk Polypropylene Hybrid Composites," *Mater. Sci. Appl.*, vol. 03, no. 05, pp. 317–325, 2012, doi: 10.4236/msa.2012.35047.

[144] M. El Kouali and J. M. Vergnaud, "Modeling the process of absorption and desorption of water above and below the fiber saturation point," *Wood Sci. Technol.*, 1991, doi: 10.1007/BF00226172.

STANDARD SPECIFICATIONS

AASHTO PP 84, Standard Practice for Developing Performance Engineered Concrete Pavement Mixtures. AASHTO, 2020.

ASTM C1761/C1761M-17 Standard Specification for Lightweight Aggregate for Internal Curing of Concrete. West Conshohocken, PA; ASTM International, 2017.

ASTM C150/C150M-20 Standard Specification for Portland Cement. West Conshohocken, PA; ASTM International, 2020.

ASTM C618-19 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. West Conshohocken, PA; ASTM International, 2019.

ASTM C989/C989M-18a Standard Specification for Slag Cement for Use in Concrete and Mortars. West Conshohocken, PA; ASTM International, 2018.

STANDARD TEST METHODS

AASHTO T 22, Standard Method of Test for Compressive Strength of Cylindrical Concrete Specimens. AASHTO, 2020.

AASHTO T 97, Standard Method of Test for Flexural Strength of Concrete (Using Simple Beam with Third- Point Loading). AASHTO, 2018.

AASHTO T 119M/T 119, Standard Method of Test for Slump of Hydraulic Cement Concrete. AASHTO, 2018

AASHTO T 121M/T 121, Standard Method of Test for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete. AASHTO, 2019

AASHTO T 152, Standard Method of Test for Air Content of Freshly Mixed Concrete by the Pressure Method. AASHTO, 2019.

AASHTO T 160, Standard Method of Test for Length Change of Hardened Hydraulic Cement Mortar and Concrete. AASHTO, 2017.

AASHTO T 161, Standard Method of Test for Resistance of Concrete to Rapid Freezing and Thawing. AASHTO, 2017.

AASHTO T 196M/T 196, Standard Method of Test for Air Content of Freshly Mixed Concrete by the Volumetric Method. AASHTO, 2011.

AASHTO T 197M/T 197, Standard Method of Test for Time of Setting of Concrete Mixtures by Penetration Resistance. AASHTO, 2011.

AASHTO T 277, Standard Method of Test for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration. AASHTO, 2015.

AASHTO T 309, Standard Method of Test for Temperature of Freshly Mixed Portland Cement Concrete. AASHTO, 2020.

AASHTO T 358, Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration. AASHTO, 2019.

AASHTO TP 118, Standard Method of Test for Characterization of the Air-Void System of Freshly Mixed Concrete by the Sequential Pressure Method. AASHTO, 2017.

AASHTO TP 119, Standard Method of Test for Electrical Resistivity of a Concrete Cylinder Tested in a Uniaxial Resistance Test. AASHTOm 2015.

AASHTO TP 129, Standard Method of Test for Vibrating Kelly Ball (VKelly) Penetration in Fresh Portland Cement Concrete. AASHTO, 2018.

ASTM C39/C39M-21 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. West Conshohocken, PA; ASTM International, 2021

ASTM C78/C78M-21 Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading). West Conshohocken, PA; ASTM International, 2021.

ASTM C109/C109M-20b Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50 mm] Cube Specimens). West Conshohocken, PA; ASTM International, 2020.

ASTM C143/C143M-20 Standard Test Method for Slump of Hydraulic-Cement Concrete. West Conshohocken, PA; ASTM International, 2020

ASTM C157/C157M-17 Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete. West Conshohocken, PA; ASTM International, 2017.

ASTM C185-20 Standard Test Method for Air Content of Hydraulic Cement Mortar. West Conshohocken, PA; ASTM International, 2020

ASTM C192/C192M-19 Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory. West Conshohocken, PA; ASTM International, 2019.

ASTM C457/C457M-16 Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete. West Conshohocken, PA; ASTM International, 2016

ASTM C469/C469M-14e1 Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression. West Conshohocken, PA; ASTM International, 2014.

ASTM C496/C496M-17 Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. West Conshohocken, PA; ASTM International, 2017

ASTM C596-18 Standard Test Method for Drying Shrinkage of Mortar Containing Hydraulic Cement. West Conshohocken, PA; ASTM International, 2018

ASTM C778-17 Standard Specification for Standard Sand. West Conshohocken, PA; ASTM International, 2017.

ASTM C666/C666M-15 Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing. West Conshohocken, PA; ASTM International, 2015.

ASTM ASTM C672/C672M-12 (Withdrawn Version) Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals (Withdrawn 2021)

ASTM C807-20 Standard Test Method for Time of Setting of Hydraulic Cement Mortar by Modified Vicat Needle. West Conshohocken, PA; ASTM International, 2020.

ASTM C1202-19 Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration. West Conshohocken, PA; ASTM International, 2019.

ASTM C1437-20 Standard Test Method for Flow of Hydraulic Cement Mortar. West Conshohocken, PA; ASTM International, 2020.

ASTM C1581/C1581M-18a Standard Test Method for Determining Age at Cracking and Induced Tensile Stress Characteristics of Mortar and Concrete under Restrained Shrinkage. West Conshohocken, PA; ASTM International, 2018.

ASTM C1698-19 Standard Test Method for Autogenous Strain of Cement Paste and Mortar. West Conshohocken, PA; ASTM International, 2019

NT BUILD 492, 'Concrete, mortar and cement-based repair materials: Chloride migration coefficient from non-steady state migration experiments', Nordtest, Espoo, Finland, (1999)

APPENDIX A: CONDITION ASSESSMENT OF EXISTING TOLLWAY BRIDGES WITH IC

INTRODUCTION

As part of Task 1 of the Internal Curing of Bridge Decks and Concrete Pavements to Reduce Cracking research project, CTLGroup conducted a field survey of multiple bridges of the Illinois State Toll Highway Authority (Illinois Tollway). The field inspection was conducted on August 30, 2019, and consisted of visiting six bridge structures that were constructed as part of the Elgin O'Hare Western Access (EOWA) project between 2016 and 2017. A total of twelve bridge decks were inspected; one bridge deck in each direction (EB and WB) per each bridge structure. All of the surveyed bridge decks were constructed with concrete mixtures utilizing internal curing technology. The goal of this survey was to evaluate real-world structures that utilized internal curing technology and have been in service for several years.

SURVEYED BRIDGES

The bridge deck survey was conducted with the permission of the Illinois Tollway on the Illinois Route 390 (IL 390) connecting Elgin, IL, and the O’Hare International Airport (ORD). According to the latest available data, the visited highway sees on average approximately 100,000 vehicles per day[1]. Due to the high traffic volumes, the survey was performed on the shoulder of each bridge deck. The visited bridges are located east of the I-90/IL 390 intersection and west of ORD. The following bridge structures were surveyed: IL 390 over Hamilton Lakes Dr, IL 390 over N Arlington Heights Rd, IL 390 over N Prospect Ave, IL 390 over Salt Creek, IL 390 over Mittel Dr, IL 390 over Lively Blvd. A general location of the visited bridges is shown in Figure A-1, and aerial images of each corresponding bridge structure are shown in Figure A-2 thru Figure A-6.

[1] 2018 Illinois Tollway System Traffic Data Report.

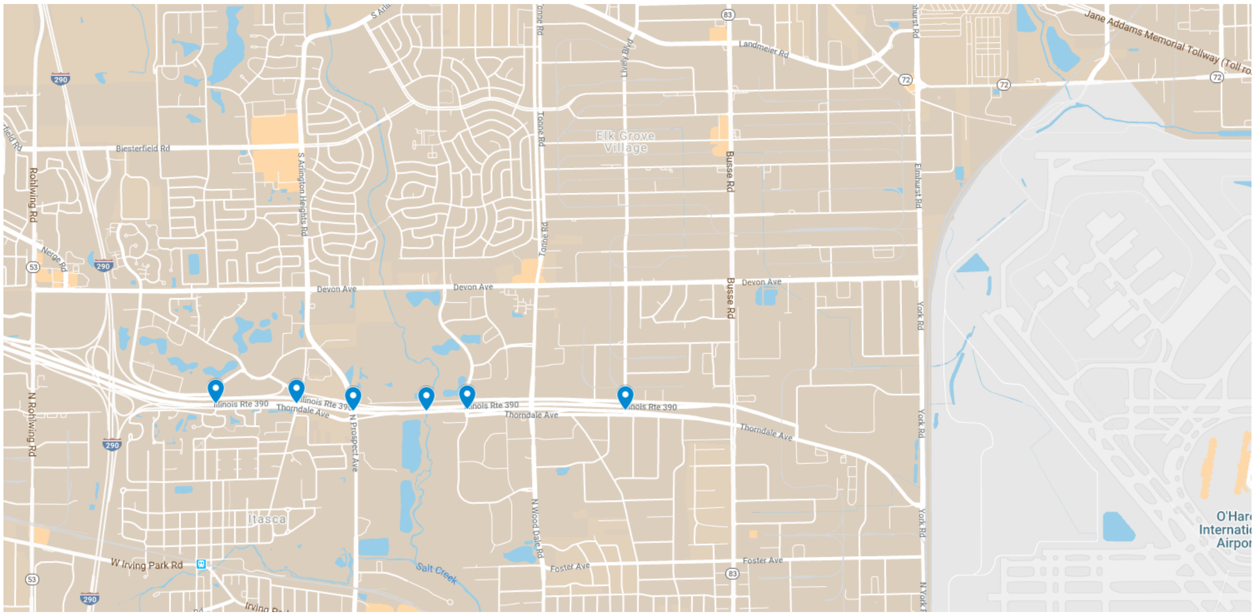


Figure A-1: General Location of the Surveyed IL-390 Bridges

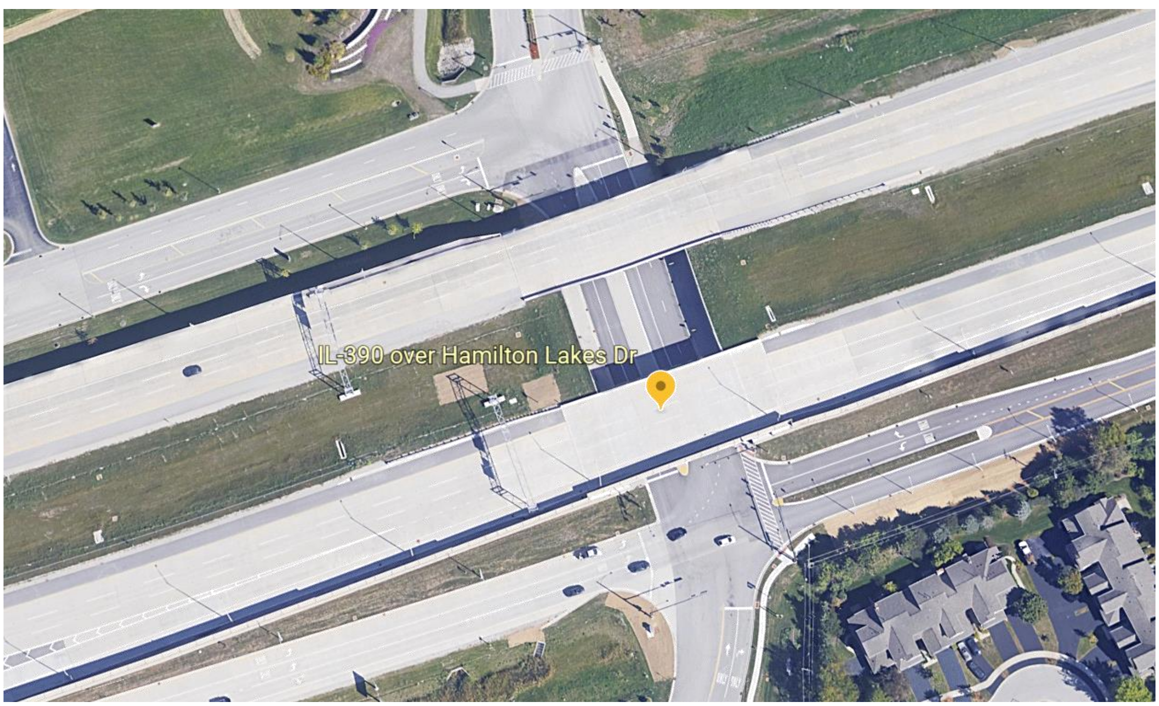


Figure A-2: IL 390 over Hamilton Lakes Dr (Image Obtained from Google Earth)

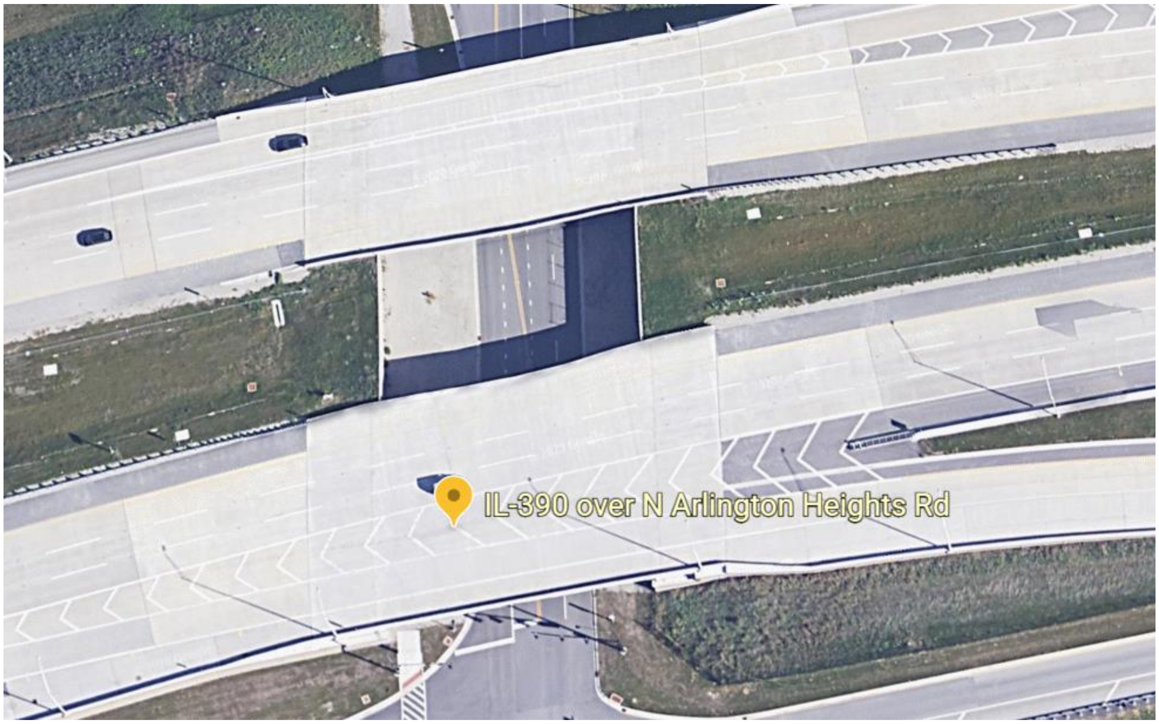


Figure A-3: IL 390 over N Arlington Heights Rd (Image Obtained from Google Earth)

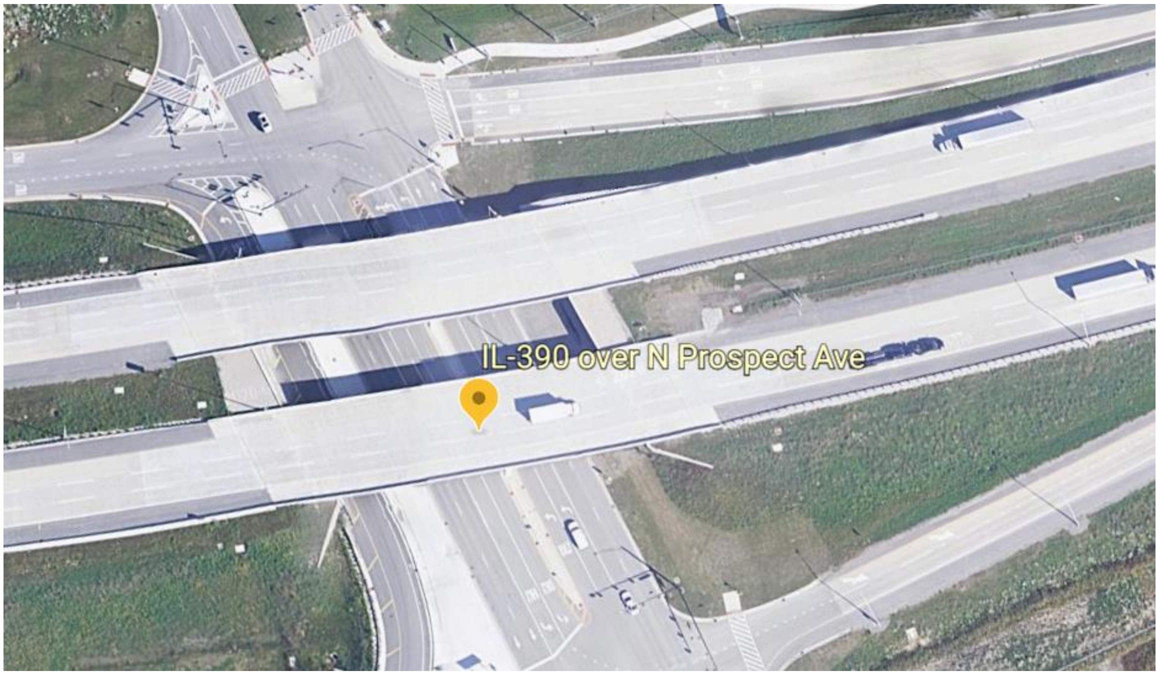


Figure A-4: IL 390 over N Prospect Ave (Image Obtained from Google Earth)

Figure A-5: IL 390 over Salt Creek (Image Obtained from Google Earth)

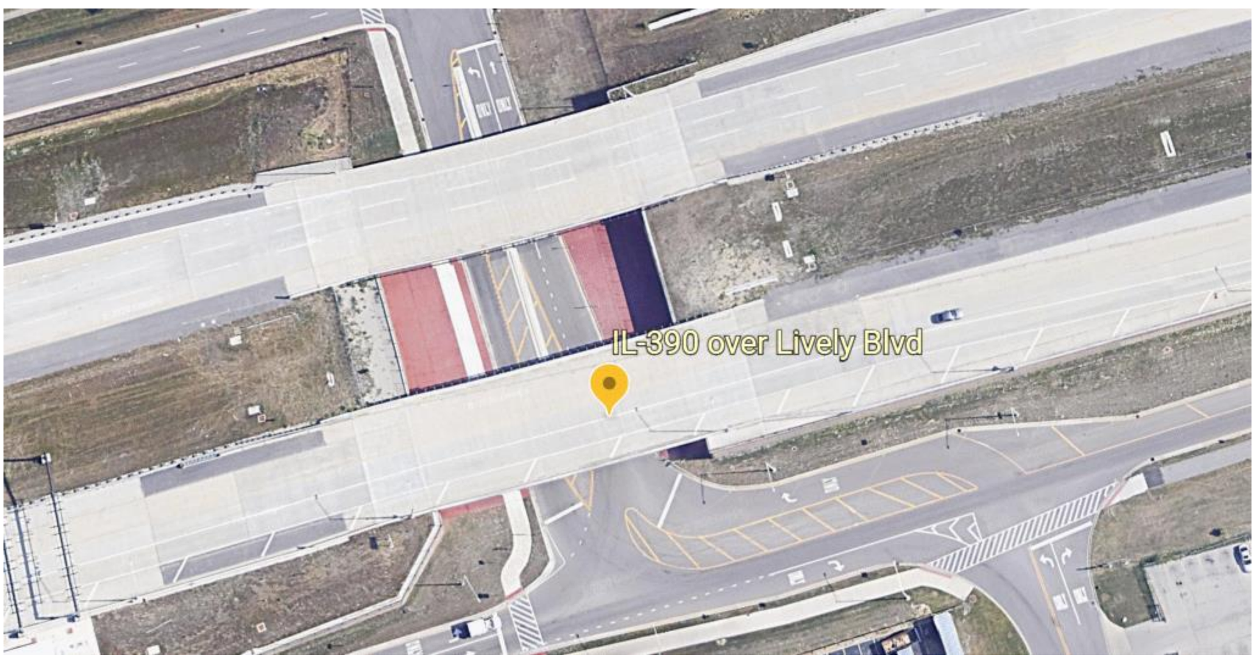


Figure A-6: IL 390 over Lively Blvd (Image Obtained from Google Earth)

SURVEY SCOPE

As part of the performed survey, each of the twelve visited bridges were visually inspected for the presence of visible cracking. If cracking was observed, a simplified mapping was conducted to record the general location of the observed cracks. For each of the visited bridge decks, not only the deck itself but also both approach slabs (before and after the deck) were surveyed. Additionally, surface resistivity measurements were recorded in general accordance with AASHTO T358.[2] The surface resistivity measurements were conducted in several locations for each of the bridge decks, and the measurements were done on the bridge deck surface in dry condition. The tips of the surface resistivity probes were immersed in water prior to taking a measurement.

CONCRETE MIXTURES

Three different concrete mixtures were used to construct the surveyed bridge decks. The Illinois Tollway mixture numbers and the bridge decks where these concrete mixtures were utilized are shown in Table A-and Figure A-7, and mixture proportions for each of the utilized mixtures are shown in Table A-3. Please note that mixtures '90PCC1612' and '90PCC1674' have identical mixture proportions but are listed as two different mixtures since the used materials came from different sources. All concrete mixtures utilized expanded slag saturated lightweight fine aggregate. The absorption capacity of the utilized aggregate was approximately 15%, providing approximately 50-55 lbs/yd³ of internal curing water for each of the mixtures.

Table A-2: Utilized Concrete Mixtures

Illinois Tollway Mixture Number Bridge Deck	90PCC1327	90PCC1612	90PCC1674
IL 390 over Hamilton Lakes Dr	Not used	WB	EB
IL 390 over N Arlington Heights Rd	WB	Not used	EB
IL 390 over N Prospect Ave	Not used	Not used	EB, WB
IL 390 over Salt Creek	EB, WB	Not used	Not used
IL 390 over Mittel Dr	EB, WB	Not used	Not used
IL 390 over Lively Blvd	EB, WB	Not used	Not used

[2] AASHTO T 358-19, *Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration*, 2019.

Figure A-7: An Overview of the Utilized Concrete Mixtures: Red – 90PCC1327; Yellow – 90PCC1674; Blue – 90PCC1612 (Image Obtained from Google Earth)

Table A-3: Utilized Concrete Mixtures – Mixture Proportions

	Illinois Tollway Mixture Number	**90PCC1327**	**90PCC1612**	**90PCC1674**
Material	**Type**		lb/yd³ (SSD)	
Portland Cement	ASTM C150 Type I/II	409	335	335
Fly Ash	ASTM C618, Class C	--	90	90
Slag Cement	ASTM C989, Grade 100	136	150	150
Coarse Aggregate		1714	1700	1700
Fine Aggregate		966	860	869
Lightweight Aggregate	True Lite 444, Lafarge	364	395	395
Water		234	229	229
Shrinkage-Reducing Admixture (gal/yd°)		N/A	0.5	0.5
Total Cementitious Content		545	575	575
w/cm		0.43	0.40	0.40

CTLGroup aided the concrete producer in qualification testing for mixture approval. Some of the measured concrete performance (based on field trials with the exception of the drying shrinkage testing that was performed in the laboratory) are listed in Table A-4.

Table A-4: Utilized Concrete Mixtures – Concrete Performance

Illinois Tollway Mixture Number		90PCC1327	90PCC1612	90PCC1674
Concrete Fresh Properties			**Test Results**	
Slump, in.		8.00	7.00	6.75
Air Content, %		5.9%	7.4%	7.1%
Hardened Concrete			**Test Results**	
Compressive Strength, psi (AASHTO T 22)	1 day	2,140		
	3 days	--	2,700	3,030
	4 days	4,370	5,870	--
	7 days	5,880	4,740	4,690
	14 days	6,920	5,700	6,610
	28 days	6,930	7,430	7,860
Chloride Penetrability, Coulombs (AASHTO T 277)*		1110	802	690
Length Change, % (AASHTO T 160)**		0.022	--	0.019
Resistance To Cracking - The Ring Test (ASTM C1581)		> 28 days	> 28 days	> 28 days

* Accelerated Curing Procedure (7 days in limewater at 73°F, 21 days in limewater at 100°F)

** 7 days in limewater at 73°F, 7 days of drying at 73°F/50% RH

Both drying shrinkage measurements and especially the ring test results suggested that the potential of these mixtures for early-age cracking in the field was relatively low.

RESULTS

The summary of the observed cracks is provided in the following sections. In general, very little concrete cracking was observed in the bridge decks as the majority of the visible cracking was detected in the approach slabs. Based on the information provided by the Illinois Tollway, it is believed that the cracking present in the precast approach slabs is of a structural character, and the Illinois Tollway is currently undergoing a research project with the University of Illinois to determine the root cause of this cracking.

IL 390 OVER HAMILTON LAKES DR

Only two cracks were observed in the decks of this bridge structure, each in one direction. The cracks were diagonal and appeared to follow the pattern of the cracking stemming from the approach slabs. Concrete mixtures utilized for these two bridge decks utilized both saturated lightweight aggregate as well as 0.5 gal/yd³ of the shrinkage-reducing admixture. Observed cracking is illustrated in Figure A-8 and Figure A-9.

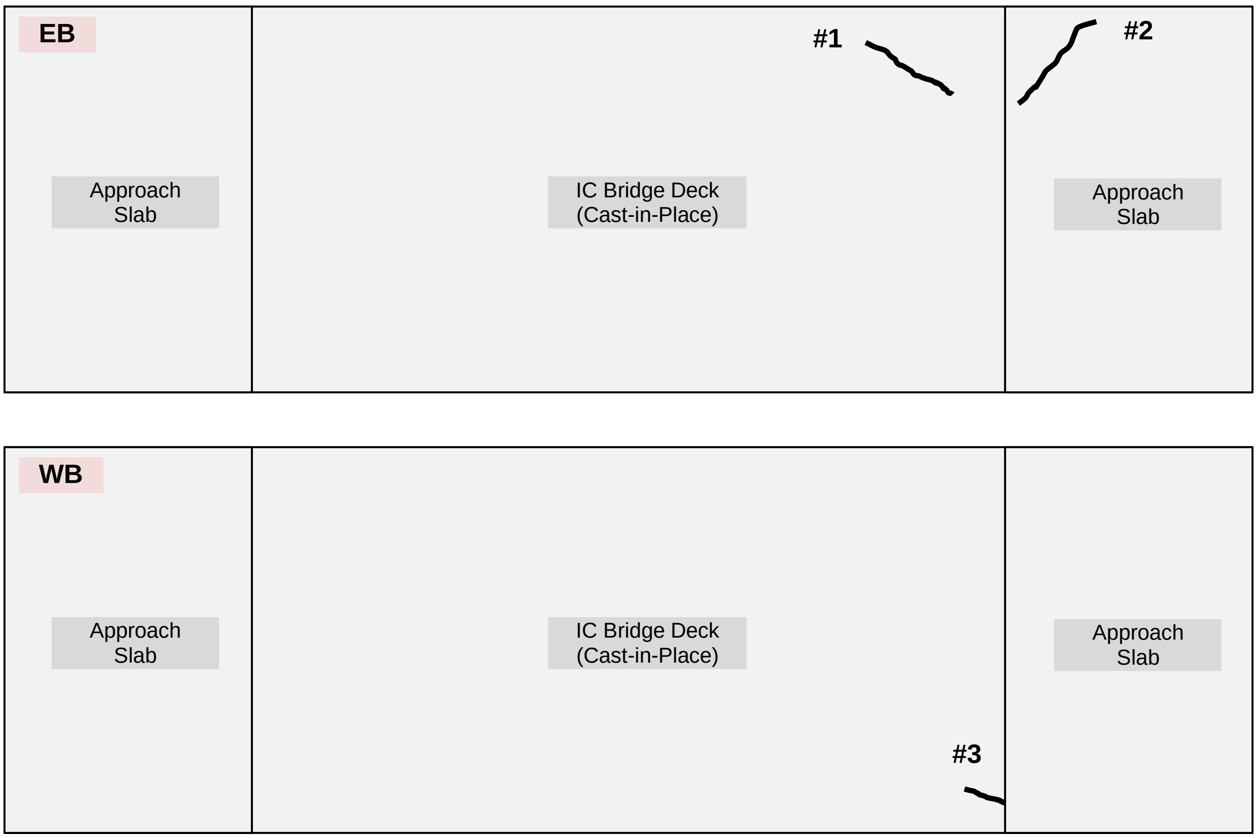


Figure A-8: IL 390 over Hamilton Lakes Dr – Observed Cracking Pattern (Not to Scale)

#1

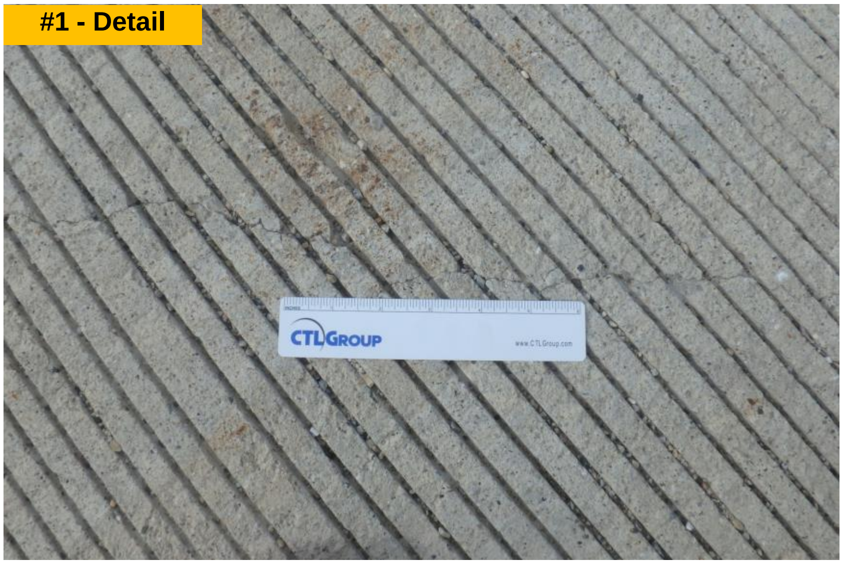


Figure A-9: IL 390 over Hamilton Lakes Dr – Observed Cracking Photos

IL 390 OVER N ARLINGTON HEIGHTS RD

Two visible cracks were observed in the EB bridge deck. One diagonal consistent with the structurally-related cracking in the proximity of the approach slab (at this location, the approach slab and the bridge deck were instrumented with sensors to evaluate the nature of the cracking by the University of Illinois research team), and one longitudinal stemming from the joint between the approach slab and the bridge deck.

In the WB slab, two short, parallel longitudinal cracks stemming from the joint between the bridge deck and the approach slab were observed on both ends. Additional, concrete cracking following the corner cracking pattern of the approach slab was observed on one end of the bridge deck.

The EB slab concrete mixture used 0.5 gal/yd³ of the shrinkage-reducing admixture while the WB bridge deck only incorporate saturated fine lightweight aggregate. Details of cracking are shown in Figure A-10 and A-11.

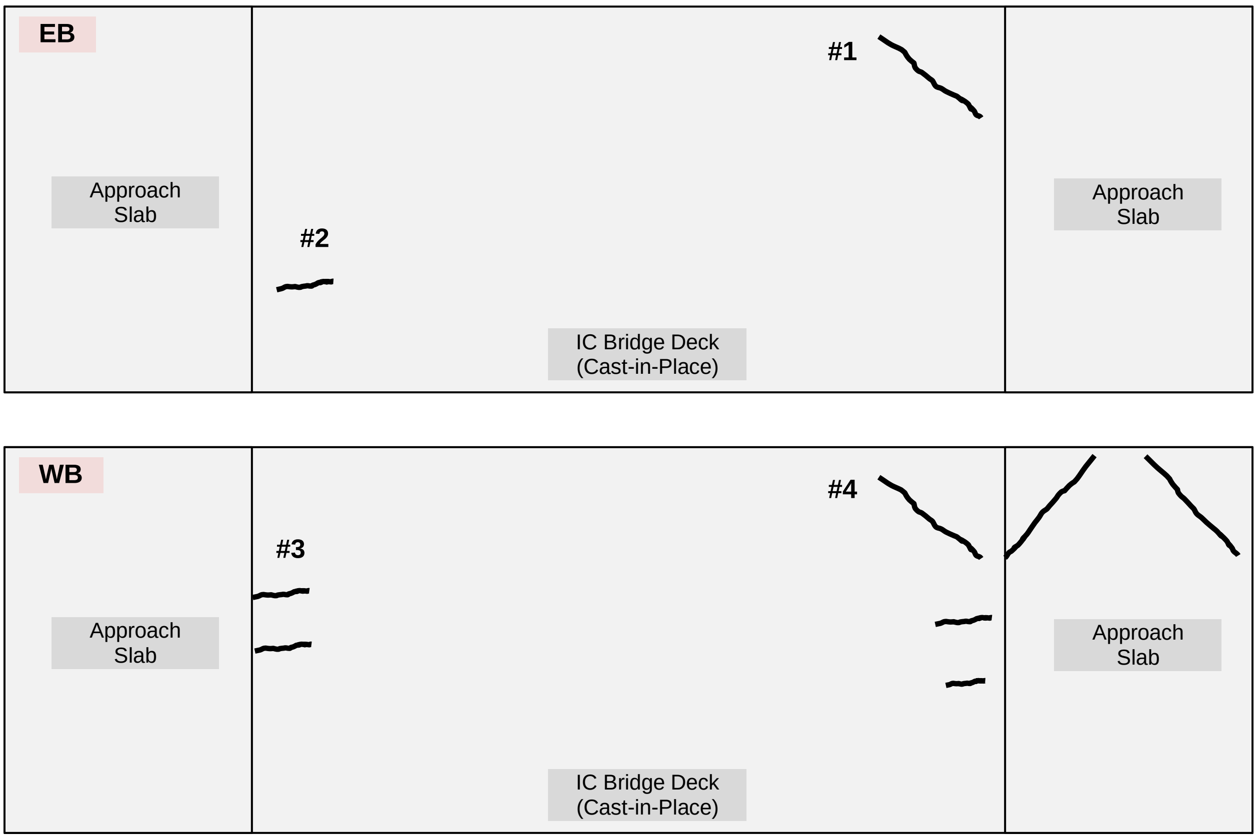


Figure A-10: IL 390 over N Arlington Heights Rd – Observed Cracking Pattern (Not to Scale)


#1


#1 - Detail
CTLGROUP
2019/08/30

#2

#2 - Detail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#3


#4

Figure A-11: IL 390 over N Arlington Heights Rd – Observed Cracking Photos

IL 390 OVER N PROSPECT AVE

Only one crack was observed in this bridge structure. A corner crack following the previously-discussed cracking pattern was observed in the EB bridge. No visible cracking was found on the WB structure. Concrete mixtures used for both the EB and WB bridges utilized shrinkage-reducing admixture and saturated lightweight fine aggregate. Details of the observed cracking are shown in Figure A-12 and Figure A-13.

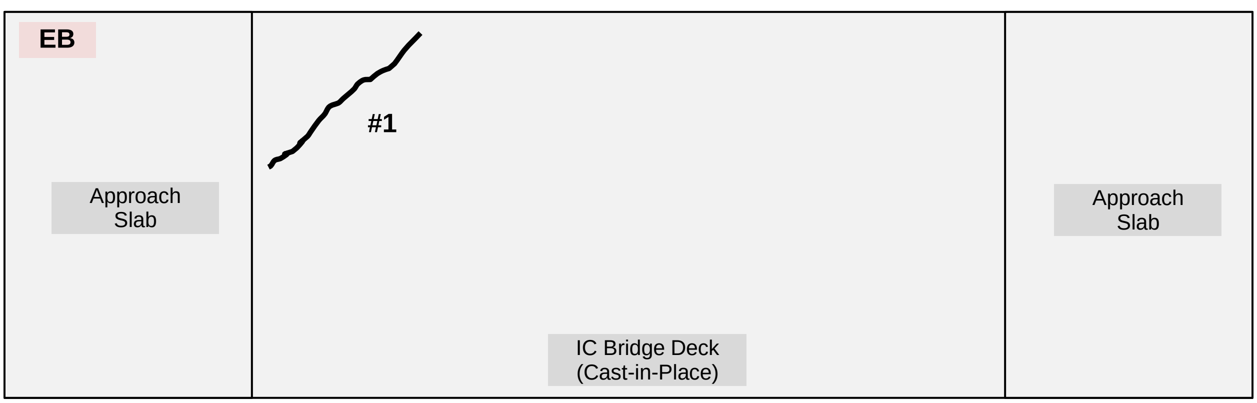

Figure A-12: IL 390 over N Prospect Ave – Observed Cracking Pattern (Not to Scale)


#1
Crack Highlighted with the Black Line

Figure A-13: IL 390 over N Prospect Ave – Observed Cracking Photos

IL 390 OVER SALT CREEK

No cracking was observed in either bridge deck of this bridge deck structure. Both bridge decks utilized a concrete mixture with the saturate lightweight aggregate only. However, a cracking pattern of several parallel diagonal cracks was observed in both approach slabs of the EB bridge decks. As observed on the previous bridge decks, the cracking induced in the approach slabs might transfer to the bridge deck over time. Please note that the approach slab was precast and did not utilize any internal curing measures. The observed approach slab cracking is shown in Figure A-14A-14 and Figure A-15.

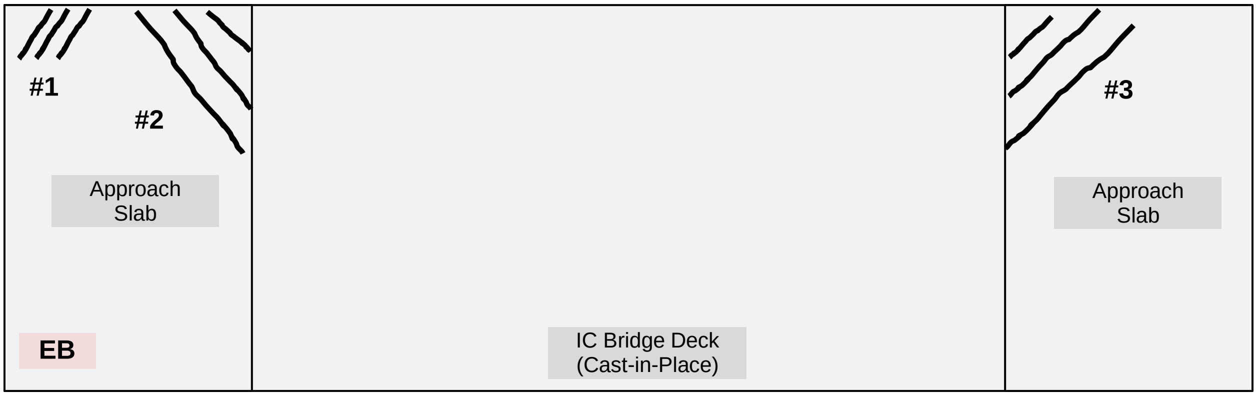

Figure A-14: IL 390 over Salt Creek – Observed Cracking Pattern (Not to Scale)

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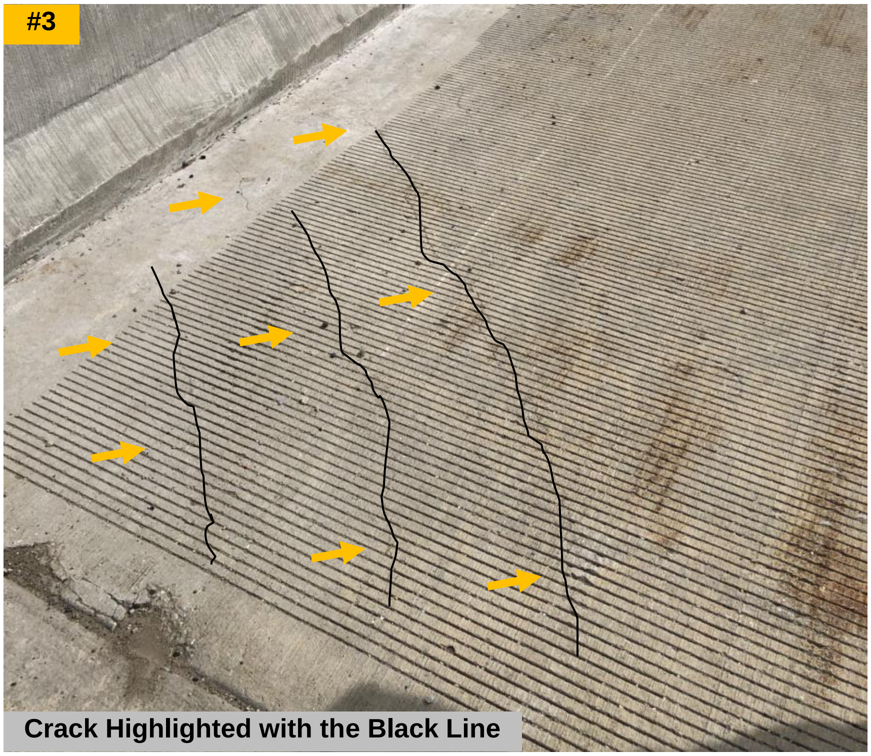

Figure A-15: IL 390 over Salt Creek – Observed Cracking Photos

IL 390 OVER MITTEL DR

Corner cracking consistent with the cracking pattern observed in the previously-discussed bridge structures was identified in both EB and WB bridges. Both bridge decks utilized a concrete mixture with the saturate lightweight aggregate only. Observed cracking is shown in Figure A-16A-16 and Figure A-17.

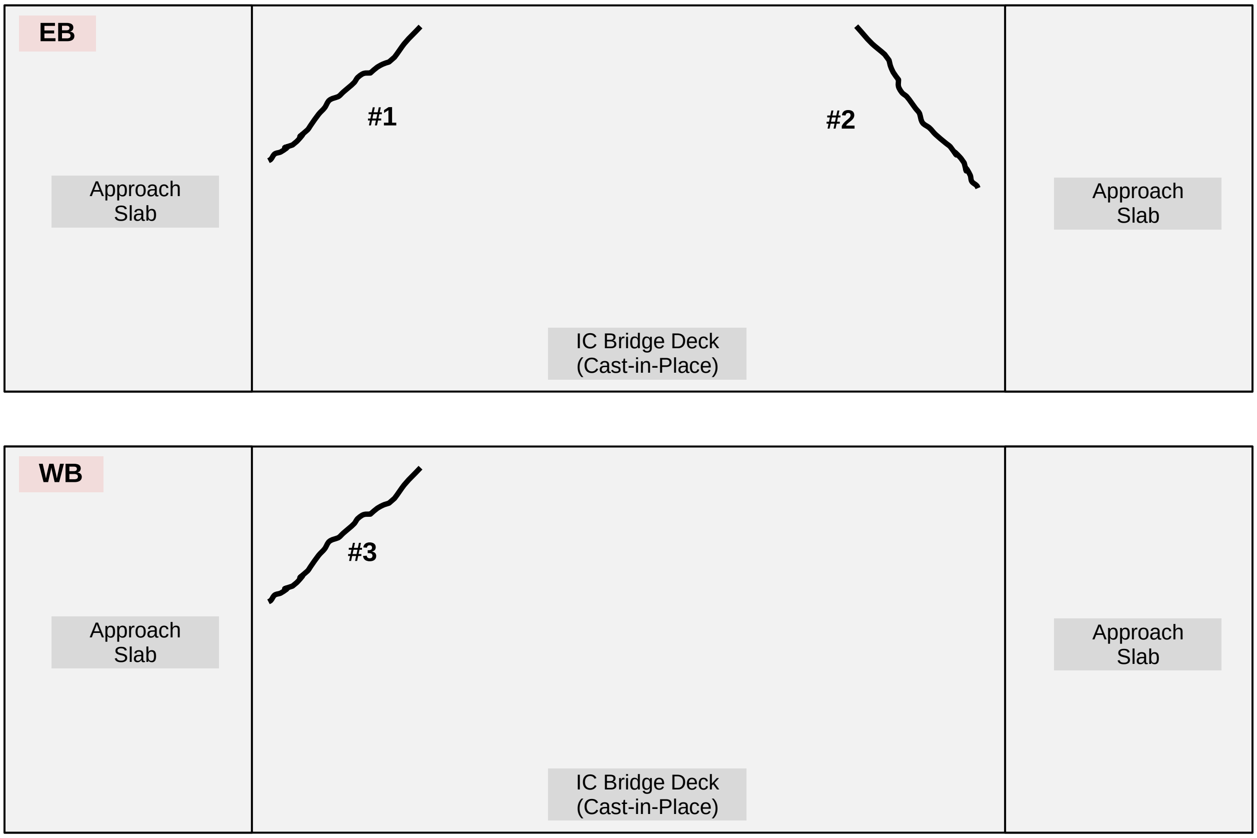

Figure A-16: IL 390 over Mittel Dr – Observed Cracking Pattern (Not to Scale)


#1


#1 - Detail
CTLGROUP
2019/08/30

Figure A-17: IL 390 over Mittel Dr – Observed Cracking Photos

IL 390 OVER LIVELY BLVD

One corner crack consistent with the cracking identified on the previous structures was observed on the EB bridge of this bridge structure. Similar cracking was observed on the WB bridge. However, an additional transverse crack was observed on the WB bridge deck, in approximately one-third of the bridge deck span. This is the only crack observed during this survey that could be potentially associated with early-age volumetric changes. However, further investigation would be required to determine the exact root cause of this crack. Both bridge decks utilized a concrete mixture with the saturate lightweight aggregate only. Observed cracking is shown in Figure A-18 and Figure A-19.

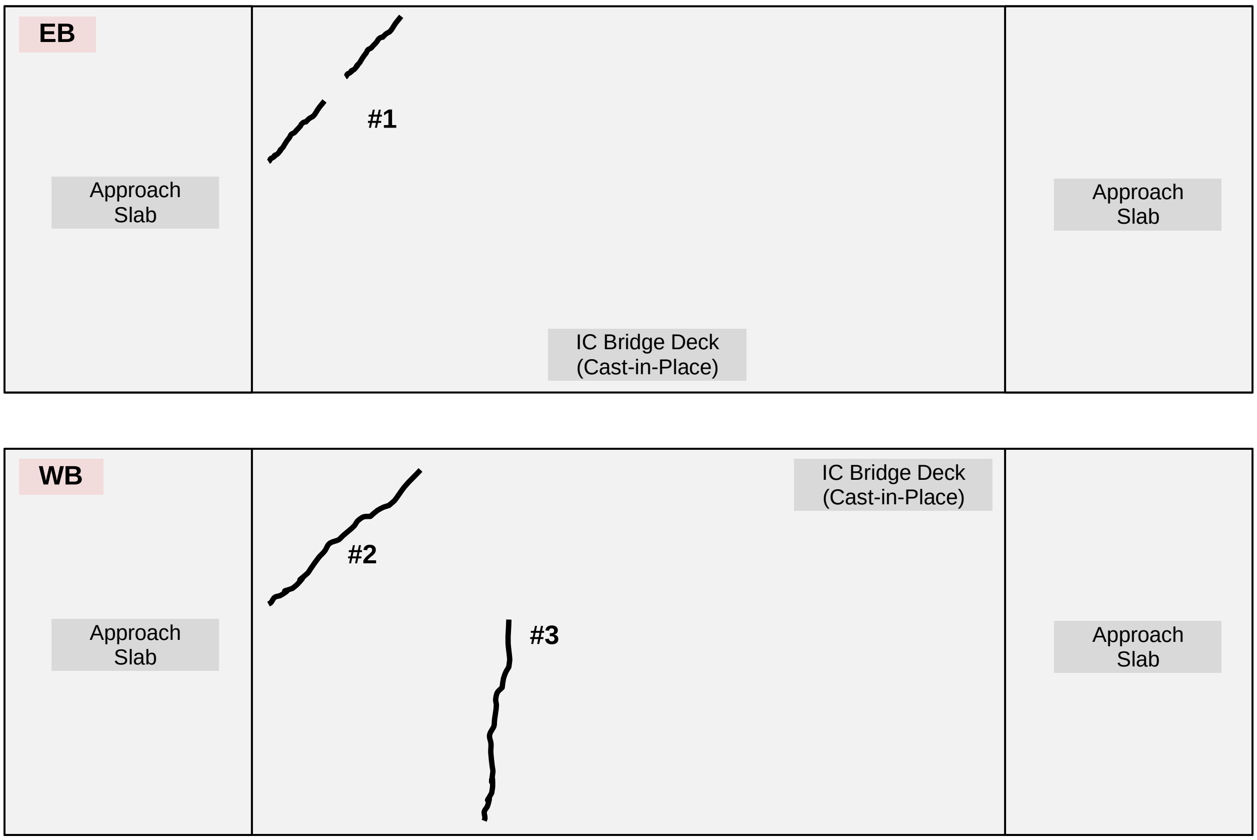

Figure A-18: IL 390 over Lively Blvd – Observed Cracking Pattern (Not to Scale)


#1 - Detail
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#1


#2


#3
Crack Highlighted with the Black Line

Figure A-19: IL 390 over Lively Blvd – Observed Cracking Photos

SURFACE RESISTIVITY MEASUREMENTS

The measured values of surface resistivity for each of the surveyed bridge decks are shown in Table A-5.

Table A-5: Measured Surface Resistivity, kΩ-cm

Bridge Deck	EB	EB
IL 390 over Hamilton Lakes Dr	127	98
IL 390 over N Arlington Heights Rd	94	66
IL 390 over N Prospect Ave	134	129
IL 390 over Salt Creek	77	55
IL 390 over Mittel Dr	52	63
IL 390 over Lively Blvd	56	63

SUMMARY

CTLGroup performed a survey of 12 bridge decks of the Illinois Tollway system that were built incorporating the internal curing technology. Seven of the surveyed bridges utilized saturated fine lightweight aggregate to mitigate the effects of early volume changes due to chemical and drying shrinkage, and five of the visited bridges utilized a combination of saturated fine lightweight aggregate and shrinkage-reducing admixture.

Minimal cracking was observed in all of the surveyed structures. The majority of the observed cracking was associated with structural-related cracking stemming from cracking patterns observed in the precast approach slabs on both ends of each bridge deck. The only crack that could be potentially associated with volumetric changes due to shrinkage was observed in the WB bridge deck of the IL 390 over the Lively Blvd structure. Based on the observed condition of the bridge decks, it appears that the goal of reducing cracking through the implementation of internal curing was achieved on these projects.

APPENDIX B: ABSORPTION & DESORPTION STUDY

INTRODUCTION

As discussed in the previous chapter of this report, internal curing (IC) agents allow additional hydration water to be contained in the concrete mixture which can be released after the concrete has achieved its final setting [123]. The internal curing benefits are attained when IC agents increase the available water in the concrete without affecting the batch water and overall water-to-cementitious ratio (w/cm) [124]. Once released, the IC water contributes to a higher degree of hydration of the cementitious materials in high-performance concrete (HPC) mixtures [86], [125]–[128].

The degree of hydration of a cementitious system is dependent on the availability of space for hydration products to form and the availability of water for the cement hydration. Research conducted by Powers [129] established a theoretical lower limit of 0.36 for the w/cm to have enough space for the formation of the hydration products whereas, for w/cm between 0.36 and 0.42, the batch water is insufficient to achieve complete hydration. In such cases, the cementitious matrix is composed of small disconnected capillary pores that significantly reduce the transport of moisture through concrete and dramatically reduce the effectiveness of external curing [101].

Due to the inherently disconnected pore structure of the cementitious matrix in HPC, IC is especially beneficial in concrete with a low (w/cm) where external curing has little effect on hydration in the internal portion of the concrete. Therefore, the ability of materials to absorb and maintain water during mixing and the ability to release such water when the concrete relative humidity decreases due to hydration determines the performance of internal curing agents in concrete.

LIGHTWEIGHT AGGREGATE

Numerous studies on the use of LWFA aggregates have shown that both absorption and desorption characteristics can influence the rate of supply of internal curing water in cementitious paste, mortars, and concretes [130]. At the same time, the characteristics of the concrete constituent materials and proportions, especially w/cm, determine the demand for internal curing water to avoid or mitigate self-desiccation. Self-desiccation in concrete is a mechanism in which the amount of water included in the mixture is insufficient for continuous hydration of the cementitious materials in the concrete, and can result in internal micro-cracking of the cementitious matrix [73]. Self-desiccation is a particular concern for mixtures where the w/cm is below 0.36 [131].

Pre-saturated lightweight aggregates (LWFA) have been utilized successfully for mitigating early-age volume changes in concrete that can otherwise result in early-age cracking [28], [127]. As reported by Hammer[132], the efficiency of LWFA as an internal curing agent depends primarily on three factors:

1) the amount of water in the LWFA;
2) the LWFA particle spacing factor; and
3) the LWFA pore structure.

The amount of water in LWFA is directly dependent on the absorption capacity of the aggregate. Villarreal reported that the approximate absorption capacity of expanded shale is 20%[133]. Other sources of LWFA for IC applications were reported to have absorption values ranging between 5 and 25%. The effect of particle spacing is related to the gradation of LWFA for homogeneous distribution of IC water in the concrete[128]. LWFA fines have been utilized more frequently due to the improved spacing factor in hardened concrete, compared to coarse aggregates. Villarreal reported that the replacement of both a portion of coarse and fine aggregate by LWFA can be effective for internal curing[133]. Finally, the pore structure of LWFA affects the desorption capacity of the aggregate during the release of IC water[101].

SUPER-ABSORBANT POLYMERS

Compared to LWFA, the available literature of absorption and desorption characteristics of other IC agents such as super-absorbant polymers (SAP) and fibers are more recent. Specifically, a RILEM Technical Committee published a State-of-the-Art report on the characteristics and use of SAPs in concrete in 2012[134]. The overall absorption rate of SAP has been reported to be dependent on the chemical composition of the polyelectrolytes, concentration, and nature of ionic species of the fluid that is to be absorbed. It has been shown that SAP capable of absorbing deionized water of up to 250-500 times (i.e., rate of 250-500 g/g) their weight can be synthesized [33], [35]. The typically utilized SAPs in the construction industry can absorb water up to several hundred times of their weight [34]. The absorbency rates are significantly reduced for fluids with high ionic contents, such as cement paste pore fluid. It has been shown that especially bivalent cations such as Ca^{2+} decrease the absorbency by a much higher rate than other ions due to bonding with the carboxylate groups in the acrylate chains and formation of additional cross-linking that effectively prohibit further swelling [36], [37].

The desorption mechanism of SAP is different from LWFA. The three primary driving factors for SAP desorption are (1) RH gradient, (2) osmotic gradient due to different ionic concentrations in the pore solution and the SAP system, and (3) capillary suction[36], [38]. These three elements act in parallel during the early-age stage of a cementitious system, therefore the characterization of desorption properties of the SAP systems is not as straightforward as for the LWFA. Various techniques and procedures of SAP desorption evaluation are available in the literature [39], [40].

Absorption and swelling characteristics of SAP are also not trivial. Several challenges exist when one attempts to measure the absorption capacity of SAP materials: the SSD concept cannot be directly employed as would be done with standard LWFA, and the so-called gel blocking can occur when the swollen particles at the interface between the SAP material and the fluid quickly expand and block further fluid absorption. The standard for SAP absorbency characterization across industries is the tea bag test. For cementitious systems, the test has been modified and utilized in conjunction with a centrifuge to obtain representative behavior of the SAP when exposed to various fluids. During the tea bag test, a very small sample of the SAP is placed inside a permeable membrane (i.e., the tea bag) and immersed into the fluid. Subsequently, a mass gain is measured at various time intervals. Recently, the tea bag methodology was significantly improved for use with cement-based systems [36], [41], [42].

As opposed to LWFA where pre-wetting of the material is required for internal curing, SAP has been previously used both as a pre-wetted and dry additive in concrete mixtures due to their very high absorption rate. When added dry, the amount of mixing water is adjusted to allow for a certain portion of the batch water to be absorbed by the SAPs and released later [43].

WOOD-DERIVED FIBERS

A large variety of vegetable- or wood-derived fibers has been successfully incorporated in cement-based systems as internal concrete reinforcement. As a by-product of the paper industry, cellulose fiber pulps are the most common form[44], however, fiber products derived from pine pulp, eucalyptus, sisal, banana, fique, cotton liners, and many others were researched [45].

Since these products can absorb and retain water, they were proposed as potential agents for internal curing of concrete. In addition to providing water for internal curing, these products can help mitigate the effect of self-desiccation and autogenous shrinkage by acting as an internal reinforcement bridging and closing the developed microcracks. Several studies were conducted on the feasibility of wood-derived products, including fibers of various lengths and sizes, as well as nano-sized products and powders [46]–[49]. However, the available research literature only presents work conducted on the cement-paste level and no literature was identified describing experimental work on concrete. Furthermore, absorption and desorption properties of wood-derived products, and techniques of determination thereof have not been established.

EXPERIMENTAL METHODS

Absorption of Lightweight Aggregates

To evaluate the absorption capacity of LWFA included in this study, the centrifuge method was utilized in accordance with ITM 222-15T [135] to determin the specific gravity and absorption of lightweight fine aggregate. The test procedure consists of the saturation of LWFA and determination of its absorption capacity with the use of a centrifuge. The specifics of the method and its use have been reported elsewhere[20], [30], [135]. A representative portion of each LWFA was first oven-dried at 100°F to constant weight. Subsequently, the material was allowed to cool down at room temperature for about an hour with the use of forced ventilation and movement of the material. During this process, the centrifuge bowl was placed in the oven in order to eliminate any surface moisture for an hour. After the bowl and the aggregate reached equilibrium with room temperature, the weight of the bowl was measured, and approximately 600 grams of LWFA was placed in the bowl. The bowl was then placed in the centrifuge apparatus, and deionized water was poured on top of it, ensuring at least an inch of water on top of all the aggregates, as shown in Figure B-1(a). The LWFA was allowed to be saturated for one day with a paper filter covering the top surface of the material, ensuring not to lose any materials during this process. The next day, the centrifuge was turned on for three minutes at 2000 RPM to remove superficial moisture in the aggregate and achieve a saturated surface dry (SSD) condition, as illustrated in Figure B-1(b). After completion of centrifuge spinning, the mass of the bowl containing the LWFA at SSD was determined, including any fine material that was brushed off the filter paper, and the absorption was calculated using Equation B-1.

$$\mathrm{AC} = \frac{\mathrm{W_{SSD}} - \mathrm{W_{OD}}}{\mathrm{W_{OD}}} \times 100 \qquad \textbf{Equation B-1}$$

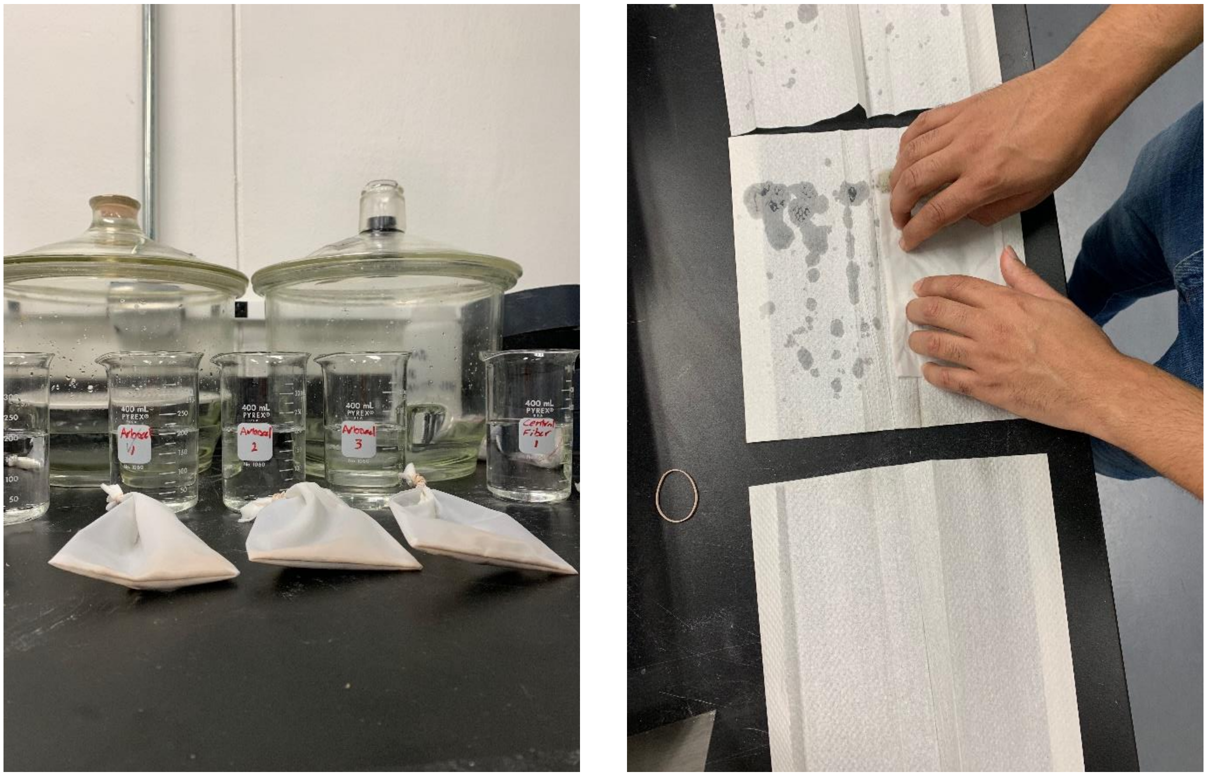
where AC is the absorption capacity (%), W_{SSD} is the weight of LWFA in SSD condition and W_{OD} is the weight of LWFA in dry condition.

(a) (b)

Figure B-1 – - Centrifuge testing: (a) LWFA in saturating stage (b) LWFA in SSD stage

Absorption of SAP and Fibers

The absorption of SAP and fibers was determined in accordance with a proposed provisional AASHTO test method [127]. The methodology consists of determining the absorption of SAP and fibers by placing dry material in tea bags, as shown in Figure B-2(a) which are stored in a liquid at intervals of 10 and 30 minutes. Subsequently, the tea bags are manually dried using paper towels to remove superficial moisture from the tea bags, Figure B-2(b). The complete procedure is attached to this report for reference.



(a) (b)

Figure B-2 – Tea bag method: (a) Dry tea bags prior to immersion; (b) Tapping of wet bags prior to weighing.

Desorption of LWFA, SAP, and Fibers

The desorption characteristics of IC agents were obtained using a procedure similar to that outlined in ASTM C1761[28]. Samples of saturated IC agents were exposed to an environment with various relative humidity values in which the rate of desorption can be determined more accurately. Table B-1 shows the range of RH values selected for this test and their corresponding saturated salt solutions[136]. The salt solutions remained in a desiccator once prepared.

Table B-1 - Binary salt solutions and corresponding relative humidity.

Salt	Chemical Formula	Relative Humidity at 73°F, %	Completion
Potassium sulfate	K_2SO_4	97	Complete

The procedure consists of obtaining a sample of saturated surface-dry (SSD) IC as outlined in the absorption procedure. For LWFA, test specimens consisted of approximately 20 g of SSD LWFA. For

SAP and Fibers, each sample of IC agent was approximately 5 g. Measurements of mass of the empty weighing pan, and pan plus IC agent were recorded. Subsequently, pans with IC agents were subject to controlled temperature (73°F) and relative humidity environment. Daily measurement of the mass loss was conducted until the material reached equilibrium. According to the test method, equilibrium is reached when there is not more than 0.01 g change in mass in a 24-h period. Figure B-3 shows the condition of the materials during desorption testing.

(a) (b)

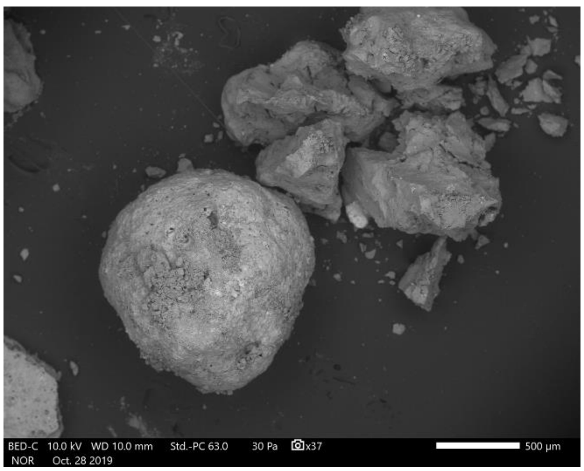
Figure B-3 – Desorption: (a) LWFA samples; (b) SAP and Fiber samples.

SELECTED MATERIALS FOR INTERNAL CURING

Overall, fifteen different products consisting of four lightweight aggregates (LWFA), five super-absorbent polymers (SAP), and five fiber products were chosen to study their absorption and desorption behaviors. In the case of LWFA, these materials were selected based on their past experience as IC agents. For SAP and fibers, CTLGroup conducted market research related to the identification of the sources and discussions with the manufacturers on their potential use in concrete construction. All selected materials can be potentially available in the Wisconsin construction market.

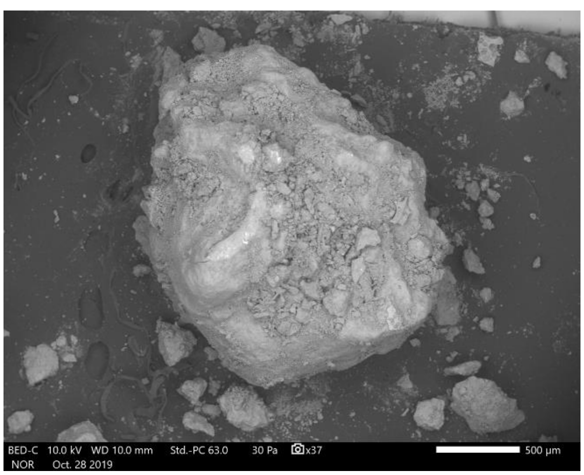
The determination of the absorption capacity of LWFA was conducted in accordance with ITM 222. Additionally, the absorption capacity of an SAP-coated fine aggregate was determined in accordance with ITM 222. The tea bag method was utilized for SAP and Fiber IC agents.

Dry particle mounts were prepared for visual examination with the Scanning Electron Microscope. The approximate particle size and general morphology of selected IC materials, obtained from Secondary Electron Imaging, are shown in Figure B-4 (LWFA + Coated SAP Fine Aggregate), Figure B-5 (SAP), and Figure B-6 (fibers). Field of view varies for different materials due to their size.



(a)

(b)



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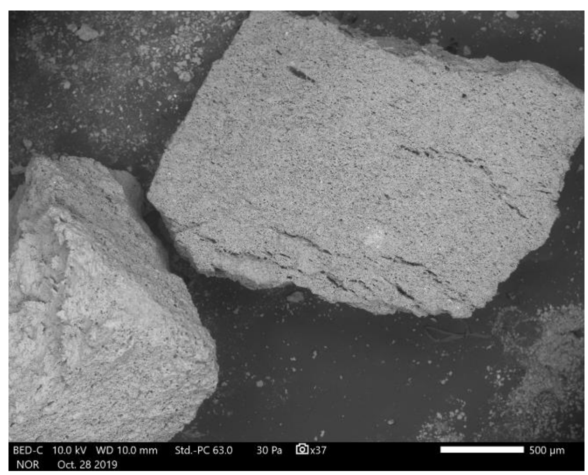
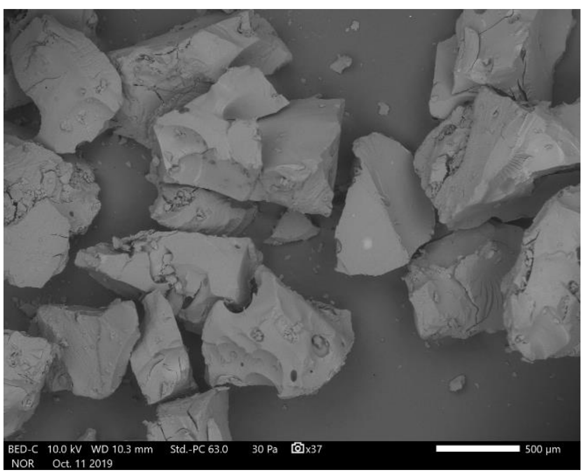


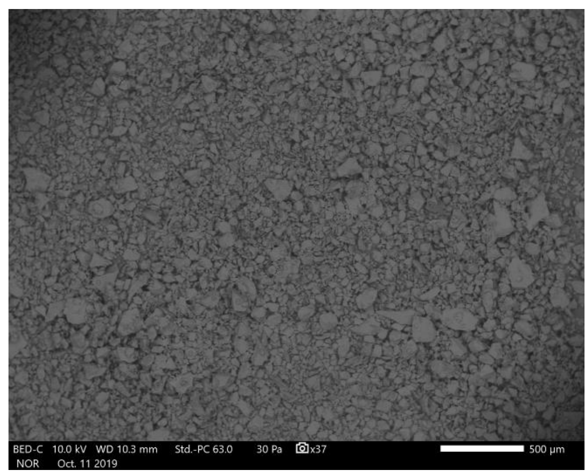
(d)

(e)

Figure B-4 – LWFA Morphology – (a) L1; (b) L2; (c) L3; (d) L4; e) L5.



(a)



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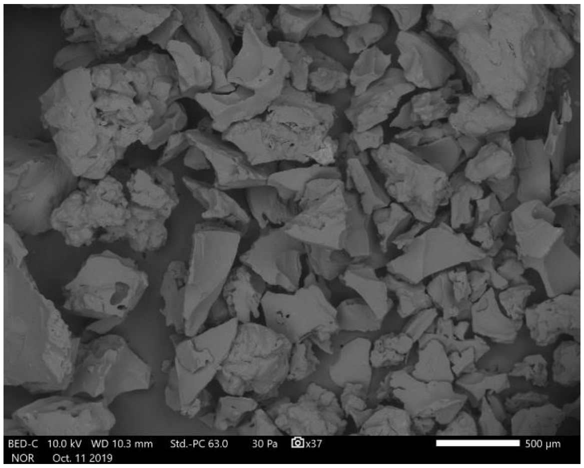

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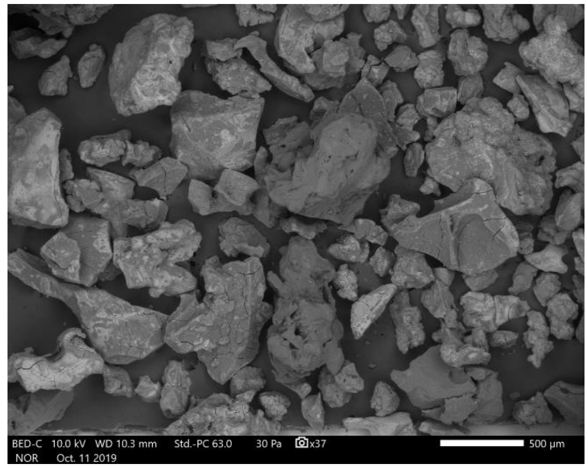
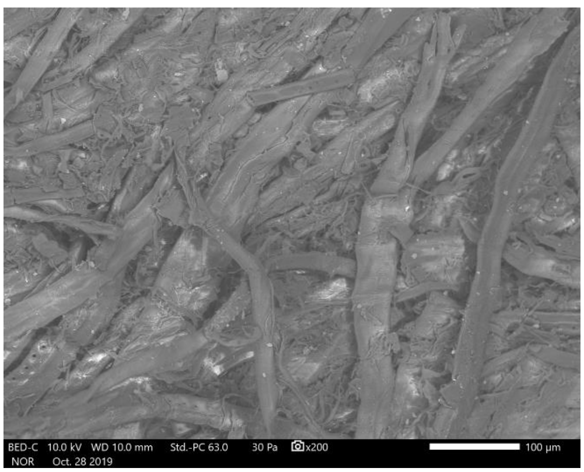
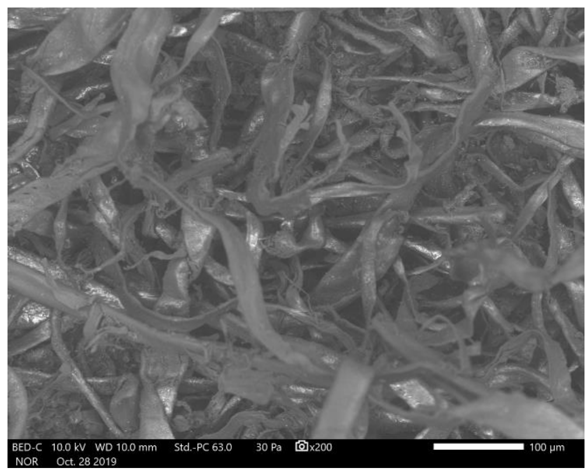


(d)

Figure B-5 – SAP Morphology – (a) S1; (b) S2; (c) S3; (d) S4



(a)



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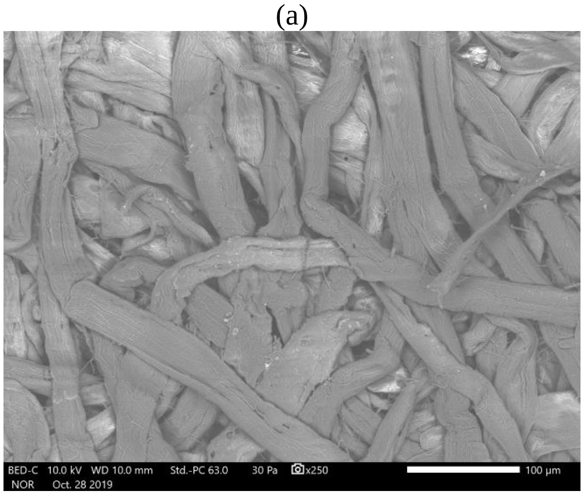

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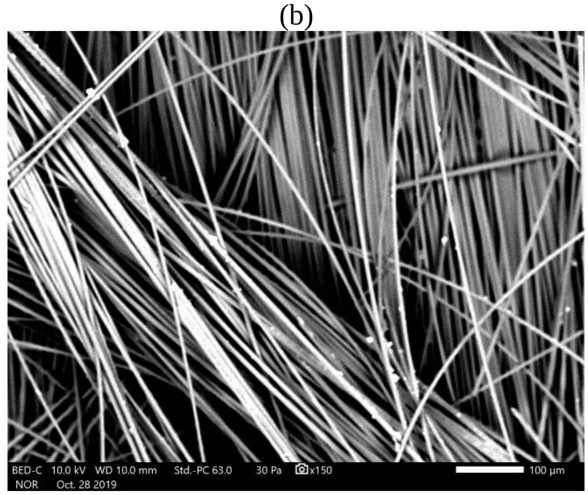

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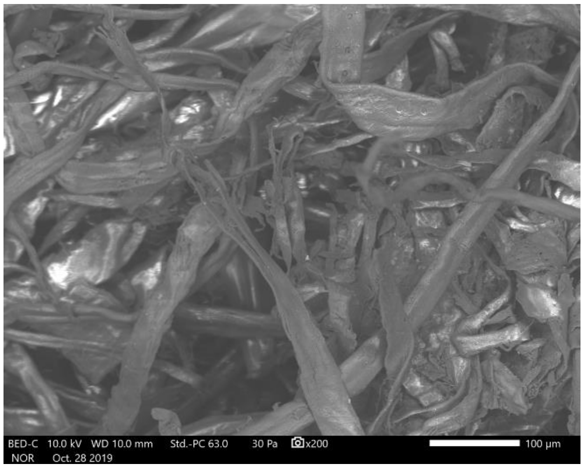


(e)

Figure B-6 – Fiber Morphology – (a) F1; (b) F2; (c) F3; (d) F4; (e) F5

As Figure B-4 thru Figure B-6 show, significant differences in particle size and morphology were observed in the selected IC materials. Overall, particle size ranged approximately from 50 to 600 µm with the BASF material having the smallest particle size distribution (PSD). The fineness of materials plays an important role in absorption capacity due to conglomeration and larger surface area that increases absorption capacity of materials.

RESULTS AND DISCUSSION

Lightweight Aggregates

Four different LWFAs, details of which are summarized in Table B-7 were first evaluated for absorption capacities and desorption. The purpose of this evaluation was to identify two LWFAs with potentially different absorption and/or desorption characteristics for use in mortar mixtures.

Table B-7: Sources of different LWFA

Material name	Source
L1	Livingston, AL
L2	Gold Hill, NC
L3	Brook, KY
L4	Erwinville, LA

The absorption test was conducted in accordance with ITM 222-15T, which requires the usage of a centrifuge on LWFA sample pre-wetted in deionized water. The mass of the oven-dry sample was recorded before wetting, and the mass of the saturated surface dry (SSD) was measured after performing the centrifuge. These values were used to determine the absorption capacity. Three replicate samples were tested for absorption capacity for each LWFA. Testing for desorption of LWFA followed the requirements of section 11 of ASTM C1761-17. Approximately 5 grams of SSD LWFA sample was subjected to a temperature of 73ºF and relative humidity of 94%, and the mass change was monitored daily. Four replicate samples were tested for each LWFA. The testing was continued until the test sample reached an equilibrium mass. The sample was considered to reach equilibrium when the difference in consecutive mass readings was no more than 0.01 g over 24 hours. The initial SSD mass and the final equilibrium mass were compared to estimate the mass of water released due to the exposure of the sample to the tested environment.

Table B-7 shows a comparison between the average values of the absorption capacity of LWFA and the mass of water released during the desorption test. The number of days required to reach equilibrium mass at 94% RH was found to be proportional to the absorption capacity. Both values are expressed as the percent of oven-dry mass of LWFA. The absorption capacities for different LWFA ranged between 8.8% (L2) and 25.2% (L1). Results indicate that irrespective of the absorption capacity of LWFA, more than 95% of the absorbed water was released after LWFA sample reached equilibrium mass at an RH of 94%. The average amount of water retained by the sample was lowest for L2 LWFA (0.8% of OD mass) and highest for L4 LWFA (2.6% of OD mass).

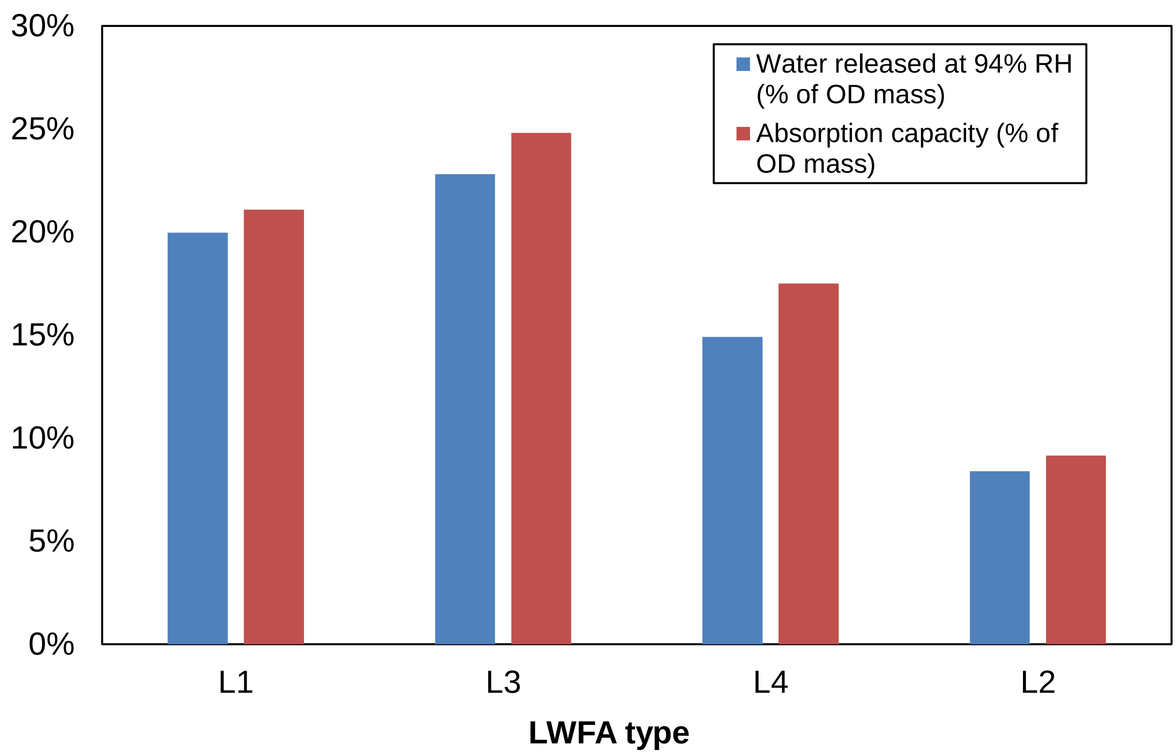


Figure B-7: Comparison of SSD mass and equilibrium mass (OD: Oven-dry)

The rates of desorption for different LWFA are shown in Figure B-8. Except for L4 LWFA, the average rates of desorption for all LWFA types were approximately similar till the point where ~75-80% of water initially present in the SSD LWFA sample was desorbed. The average rate of desorption for L4 LWFA was lower than other types of LWFA. The actual performance of LWFA as an IC agent, in terms of the ability to provide IC water by desorption, is dependent on the LWFA characteristics. However, under the standard conditions considered in this study, data suggested that L3, L1, and L2 aggregates performed well compared to L4 aggregates. To evaluate the shrinkage in mortar specimens, L1 and L2 were considered due to their significant differences in absorption capacities. For the sake of simplicity, these LWFA types are referred to by the acronyms ‘L1’ and ‘L2’ in the following sections.

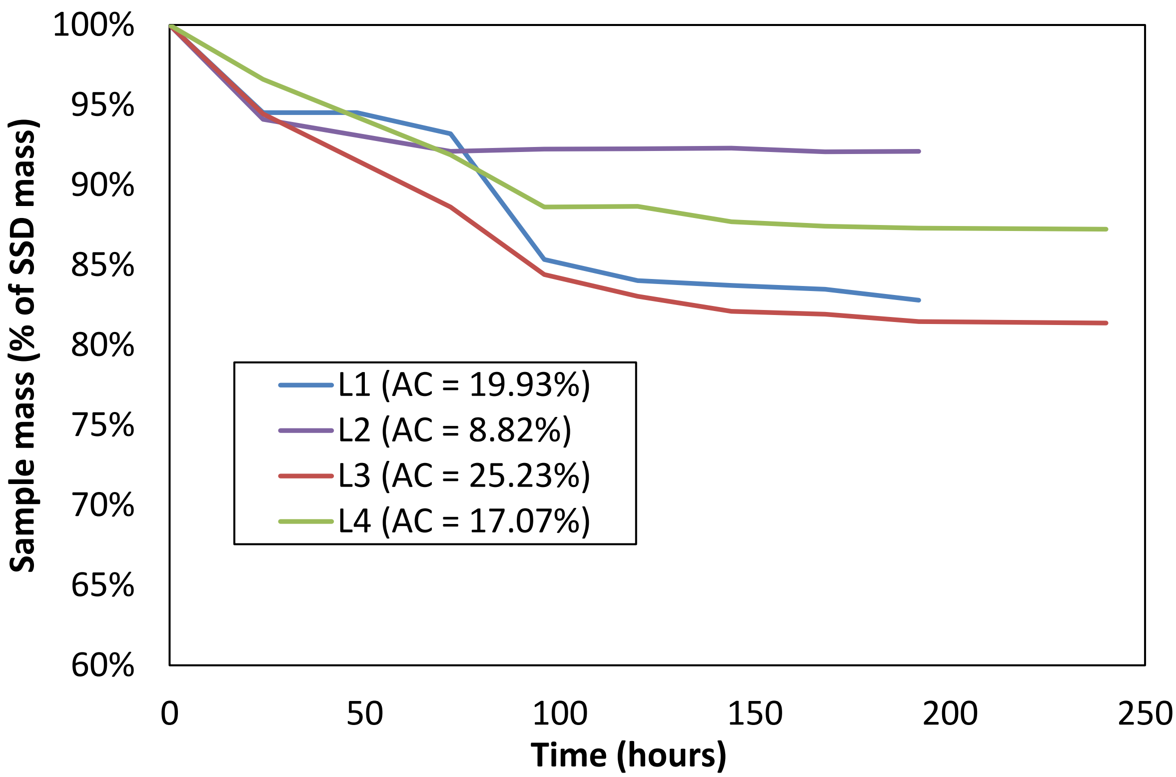


Figure B-8: Rate of desorption for different aggregates

SAP

The absorption capacity of SAP is shown inFigure B-9 Figure B-9. The absorption capacity of SAP was found to be at least three orders of magnitude greater than LWFA. Measured absorptions are in the range of 200 to 300 g/g after 24 hours of immersion. Similar results have been reported for SAP materials elsewhere [40], [82], [134]. Overall, the absorption capacity of SAP is strongly dependent on the chemical composition of the polymer and the saturating solution. Results presented in Figure B-9 are representative of SAP exposed to distilled water. When combined with cementitious materials, SAPs are exposed to an ionic solution of calcium and alkalis (sodium, potassium) that affects the overall absorption capacity [37], [137], [138].

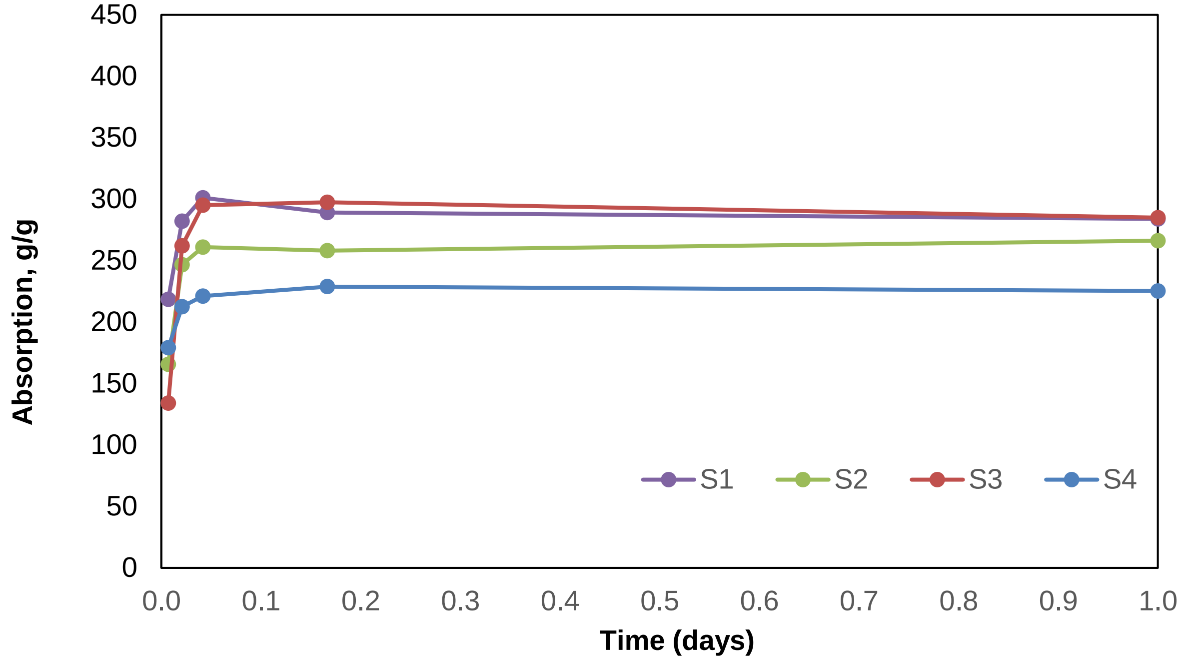


Figure B-9 – Absorption Capacity of SAP.

The desorption of SAP materials at 97% RH is shown in Figure B-10. Compared to LWFA, the desorption performance of SAP indicates a faster loss of moisture over the same period of time. Similar findings were reported elsewhere where the desorption of SAP was found to exceed 85% [36] when evaluated in accordance with ASTM C1761. As indicated in Figure B-5, the morphology of SAP materials is significantly different. However, the observed behavior of moisture loss in SAP materials due to drying as shown in Figure B-10 is not significantly dissimilar from one another. This suggests that differences in the chemical composition of the polymer, agglomeration of saturated SAP particles, or other mechanisms play a more significant role in the desorption behavior than the morphology of the material itself.

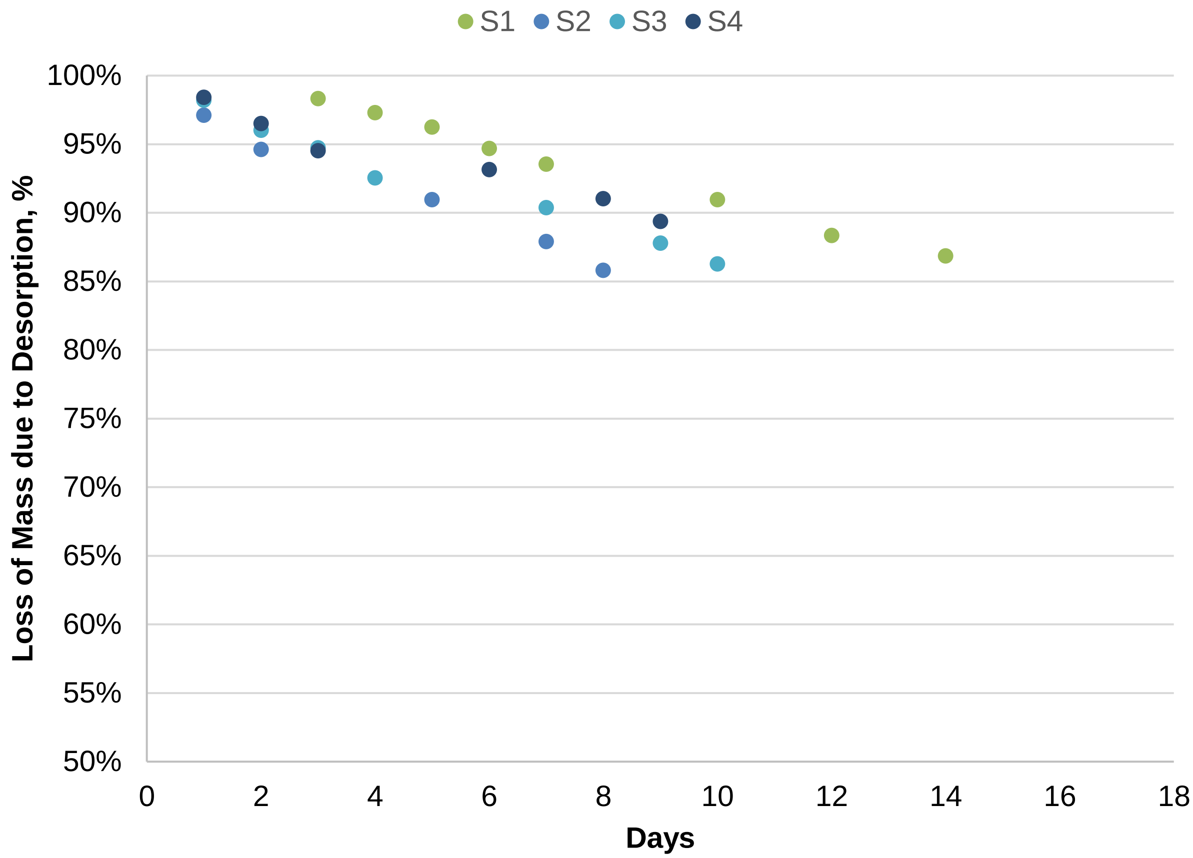


Figure B-10 - Desorption of SAP at 97%

As mentioned previously, the three primary driving factors for SAP desorption are (1) RH gradient, (2) osmotic gradient due to different ionic concentrations in the pore solution and the SAP system, and (3) capillary suction [36], [38]. Results obtained in the desorption experiments described herein are applicable for variable RH gradients and capillary suction. Since absorption was conducted using distilled water – i.e., no ionic concentration, the fundamental desorption behavior of SAP was determined.

Fibers

Figure B-11 shows the measured absorption capacity of fibers over a 24-hour exposure period. As the results indicate, the absorption of fibers was found to be one order of magnitude greater than LWFA. The absorption after 24 hours of most fibers ranged between 2 and 4 g/g with the exemption of F5 which reported an absorption capacity of 8 g/g. Differences in performance are attributed to the overall geometry, fibrillation, and distribution of fibers during sampling. The reported absorption of fibers for internal curing was in the range of 160% or 1.6 g/g [139]. Differences in the observed behavior of fibers in this study are attributed to the differences in fiber composition and experimental procedures used herein. For example, the tea bag method used herein has not been utilized to evaluate the absorption capacity of fibers for internal curing.

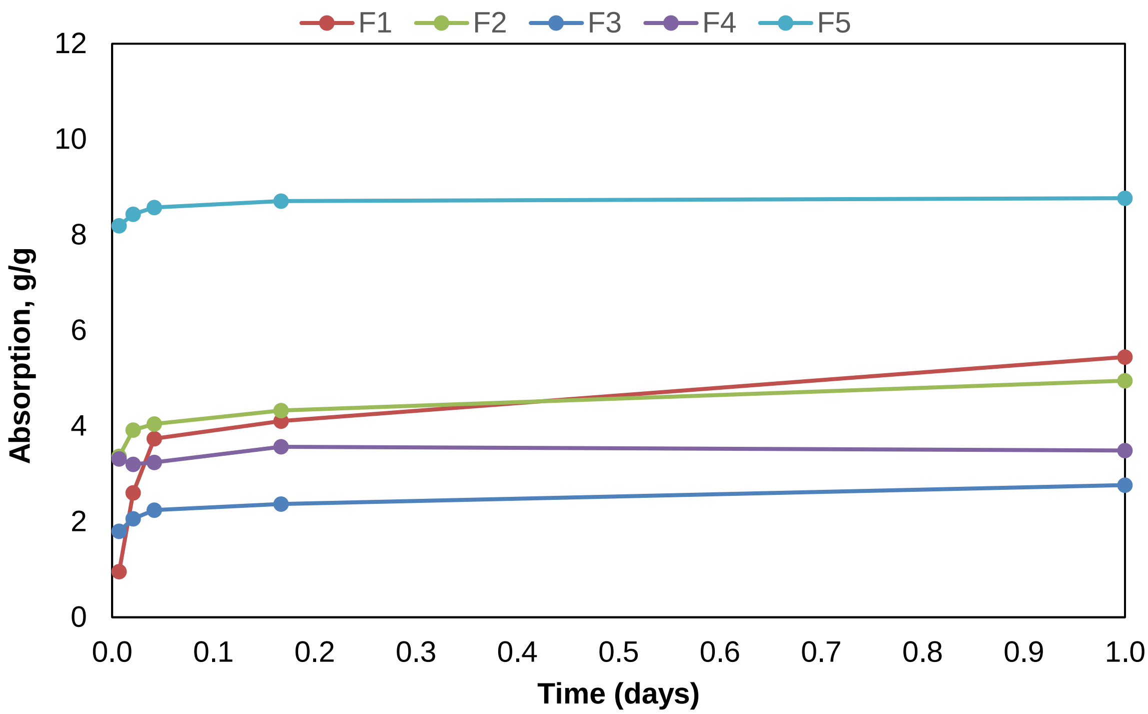


Figure B-11 – Absorption Capacity of Fibers.

A fairly limited amount of desorption studies of wood-derived fibers is available in the literature. Most use for this type of fibers has been related to the improvements of mechanical and volumetric change performance of cementitious paste systems [46], [139]–[141]. Other available studies on composite wood-polymer fibers are available [142], [143].

The desorption behavior of studied fibers is shown in Figure B-12. Compared to other IC agents studied herein, fibers released a greater percentage of internal moisture when exposed to an environment of 97% RH. The behavior of moisture transport in wood fibers was studied and modeled by El Kouali and Vergnaud [144], who determined that the transport of moisture in wood can be attributed to two distinct schools of thought. The first one assumes that moisture transport in wood can be described as a diffusion mechanism obeying Fick's laws, and the other considers that bound-water diffusion takes place as a response to vapor pressure gradients and not a moisture concentration gradient. In the case of desorption, the latter mechanism appears to explain the observed behavior more accurately as the release of moisture in desorption due to differences in relative humidity can lead to vapor pressure gradients. As the results presented in Figure B-12 indicate, internal moisture of fibers was lower than the ambient relative humidity of 97% RH environment. Due to the size of the desiccator, it may be reasonable to assume that moisture loss due to evaporation in fibers is not sufficient to increase the ambient relative humidity and thus decrease the vapor pressure gradient applied to the saturated fibers. This performance is relevant for their use in concrete since it would mean that moisture contained in saturated fibers would be released quickly after the internal relative humidity of the hardened concrete reaches 97%.

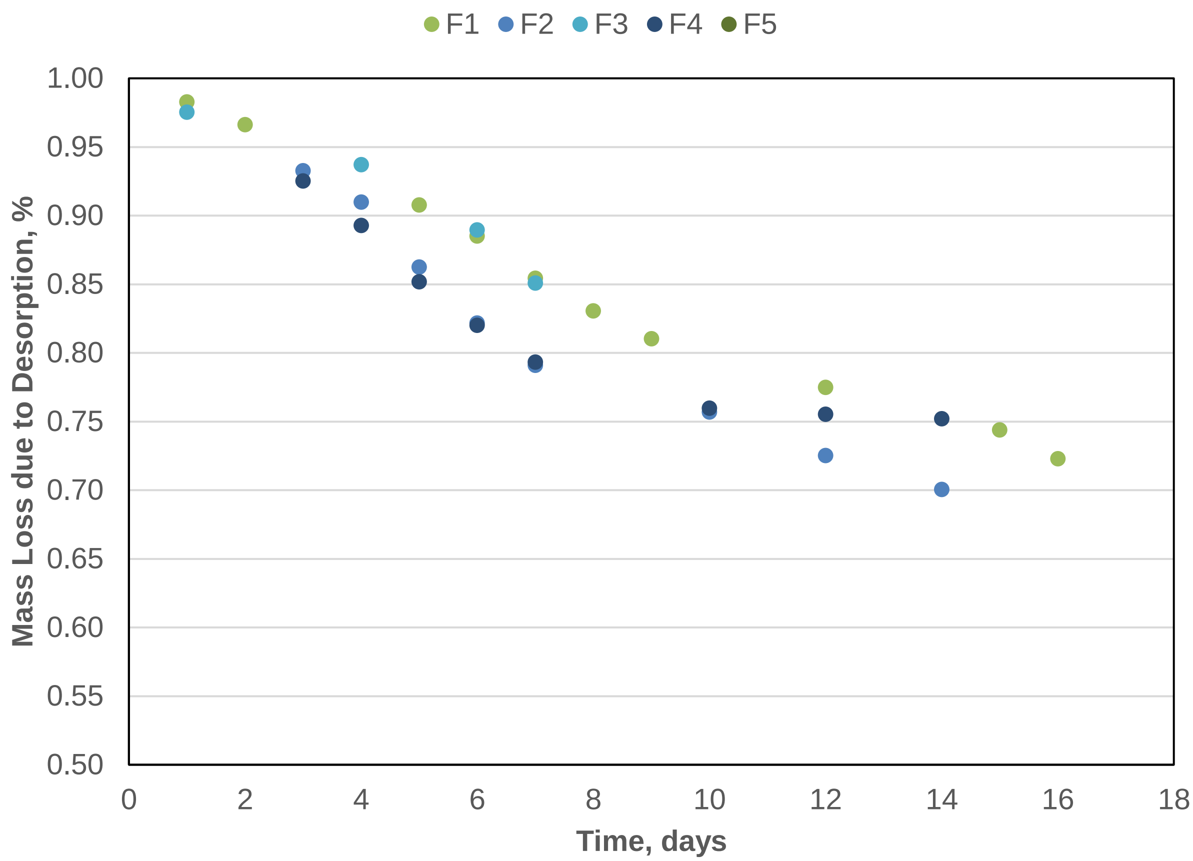


Figure B-12 - Desorption of fibers at 97% RH.

SUMMARY AND KEY FINDINGS

This section of the report presents the current progress on the evaluation of the sorption behavior of internal curing agents. Overall, the absorption and desorption performance of fifteen candidate materials for internal curing were studied. For absorption evaluation, two different test methods were utilized. For LWFA, absorption capacity was determined in accordance with ITM 222 which uses a centrifuge instrument. For SAP and fibers, the tea bag method (a research methodology currently being developed) was utilized following other studies available in the literature. The desorption of all studied materials was conducted at 73°F and 97% RH.

The most important findings of this study are summarized below:

1. Five sources of LWFA were studied. Absorption capacity and desorption ranged between 0.09 to 0.25 g/g and 90 to 96%, respectively. Results obtained resemble those reported elsewhere for the same sources of LWFA.
2. The measured absorption of four SAP materials ranged from 220 to 290 g/g. Other studies conducted on SAP reported similar results. Desorption of SAP at 97% RH ranged between 86 and 90% after 10 days of exposure.
3. Results of fibers indicate an absorption capacity in the range of 2 to 4 g/g. One source of fiber reported an absorption capacity two times greater. Loss of moisture during desorption of all fibers was found to be significantly greater than LWFA and SAP materials. The desorption of fibers ranged between 70 and 75% after 14 days.

APPENDIX C: SPECIAL PROVISION FOR INTERNALLY CURED CONCRETE WITH SATURALED LIGHTWEIGHT FINE AGGREGATE FOR PORTLAND CEMENT CONCRETE PAVEMENT AND BRIDGE DECK

Description

This work consists of designing and furnishing internally cured Portland Cement Concrete (PCC) for concrete pavement and bridge deck construction. The objective of this performance-related special provision is to provide the WisDOT with a methodology to assure high-quality concrete, while simultaneously allowing the Contractor the freedom in deciding how to develop and implement internally cured concrete mixture designs.

Class IC (internally cured) concrete incorporates pre-wetted lightweight aggregate (IC-LWA). Class IC-LWA concrete incorporates hydraulic Portland cement, slag cement, fly ash, or other supplementary cementitious materials (SCM) to produce a mixture meeting the specified performance. A Type IT blended cement in accordance with AASHTO M 240 shall be acceptable. A Type IP or IS blended cement in accordance with AASHTO M 240 may be used with ternary mixtures when an SCM is combined as a third constituent material to produce a cementitious materials blend. Type IL blended cement in accordance with AASHTO M 240 may be combined with two SCM's to a blended mixture. The limestone in a blended cement is not considered an SCM. Slag cement, fly ash, and any other SCM's combined as constituent materials or as part of a blended cement may consist of no less than 35% and no more than 50% of the total cementitious material content.

REFERENCE STANDARDS

Except where modified by the Wisconsin Department of Transportation, the following Standards shall apply:

Wisconsin Department of Transportation (WisDOT)

- Standard Specifications for Highway and Structure Construction, Current Edition.
  - Part 4 – Pavement
  - Part 5 – Structures
- Test Procedures referenced herein, as described in the current edition of the Manual of Test Procedures for Materials, as well these test procedures:

  - AASHTO T 105 Chemical Analysis of Hydraulic Cement
  - AASHTO T 160 Length Change of Hardened Hydraulic-Cement Mortar and Concrete
  - AASHTO T 161 Procedure A Modified Resistance of Concrete to Rapid Freezing and Thawing
  - AASHTO T 22 Compressive Strength of Cylindrical Concrete Specimens
  - AASHTO TP 118 Characterization of the Air-Void System of Freshly Mixed Concrete by the Sequential Pressure Method
  - AASHTO TP 129 Vibrating Kelly Ball (V-Kelly) Penetration in Fresh Portland Cement Concrete
  - ASTM C457 Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete
  - ASTM C856 Petrographic Examination of Hardened Concrete

- ASTM C1293 — Determination of Length Change of Concrete Due to Alkali-Silica Reaction
- ASTM C1761 — Standard Specification for Lightweight Aggregate for Internal Curing of Concrete
- ASTM C1581 — Determination of Age at Cracking and Induced Tensile Stress Characteristics of Mortar and Concrete under Restrained Shrinkage
- ITM 222-15T — Specific Gravity and Absorption of Lightweight Fine Aggregate

REQUIREMENTS FOR CLASS IC CONCRETE MIXTURE DESIGNS

Contractor shall provide a concrete mixture design according to the following performance requirements for Class IC concrete. The testing shall be performed by an AASHTO-accredited laboratory.

Performance qualification testing shall be performed by the Contractor to determine compliance with the specified performance for IC mixtures as indicated below. Candidate mixture proportions shall be evaluated through field or laboratory trials, to confirm that the performance requirements of this Special Provision are achieved. The Contractor is required to contact the WisDOT Engineer a minimum of 5 days prior to any plant trial batch mixing so that a WisDOT representative can observe the process. The same 5-day notification is required prior to conducting physical testing on hardened concrete samples.

Concrete Mixture Constituents

Unless otherwise specified, concrete mixture constituents for Class IC concrete shall meet the requirements of Section 501 of Standard Specifications for Highway and Structure Construction, Current Edition.

Lightweight aggregates (LWA) for use in Class IC Concrete shall meet the requirements of ASTM C1761. The specific gravity and absorption capacity of LWA shall be determined in accordance with ITM 222-15T. LWA shall be incorporated into concrete during mixing in a saturated condition. Moisture corrections shall be conducted such that the water-to-cementitious materials ratio (w/cm) of the concrete mixture is not affected. LWA shall be prevented from freezing.

Dosage of LWA into concrete shall be determined by mass of LWA in accordance with:

$$M_{LWA} = \frac{C_f C_S \alpha_{max}}{S \varphi_{LWA}} \qquad \text{Eq. (1)}$$

where $MLWA$ is mass of dry LWA needed per unit volume of concrete, C_f is the concrete cement factor, C_S is chemical shrinkage expressed as a ratio of mass of the water to mass of cement, α_{max} is a maximum expected degree of hydration of cement ((w/cm)/0.36 for w/cm $<$ 0.36; 1 for w/cm $\geq$ 0.36), S is the degree of saturation of aggregate (from 0 to 1) and ϕ_{LWA} is 24-hour absorption of the lightweight aggregate.

Class IC-LWA Concrete Fresh Properties

Slump

For slipform concrete pavement placement, place the concrete with a slump value that optimizes placement, except ensure the concrete does not slough or slump and is adequately consolidated and meets all other requirements. Maintain the concrete at a uniform consistency. Unless otherwise specified, slump range shall meet the requirements of 415.2.1 for concrete pavement.

For bridge deck concrete, the specified slump shall be achieved. Alternative slump ranges for bridge deck concrete can be submitted for review and approval by the Engineer.

For IC-LWA pavement, determine the V-index of Class IC concrete for pavement applications in accordance with AASHTO TP 129.

Plastic Air Content

Plastic Air Content determined using AASHTO T 196 test method shall be from 5.5 to 8.0 percent for slip form pavement, and 5.0 to 8.0 percent for other placements. As an optional requirement, determine the plastic air content in accordance with AASHTO TP 118 (Super Air Meter) could be determined from trial batches and compared to measurements taken in the field.

Class IC-LWA Concrete Hardened Properties

Compressive Strength

Concrete specimens shall be fabricated and cured in accordance with AASHTO T 23. Compressive strength for Class IC concrete shall meet the specification requirements as tested in accordance with AASHTO T 22. Interim compressive strength for Class IC concrete for public traffic shall be a minimum of 3,500 psi at no less than 7 days age.

Ultimate compressive strength shall not be less than 3500 psi at 28 days and strengths greater than 6,500 psi at 28 days will require approval. When this Class IC-LWA concrete is used in conjunction with performance-related construction specifications, strengths greater than 6,500 psi may be acceptable by the Engineer provided that the other performance requirements are achieved.

Flexural Strength

Flexural strength shall be determined in accordance with AASHTO T 97 for third point loading shall be a minimum of 650 psi at 28 days for Class IC-LWA concrete.

Length Change

Measured shrinkage shall not be greater than 0.030 percent after 21 days of air drying when determined in accordance with AASHTO T 160. Specimens shall be wet cured for 7 days prior to air-drying. The initial reading for the calculation of shrinkage shall be taken at the initiation of drying.

Restrained Shrinkage – Bridge Deck Concrete

Determination of the potential for cracking under restrained shrinkage shall be conducted in accordance with ASTM C1581. IC-LWA concrete shall not show cracking of any test specimen for at least 21 days and at least 2 out of 3 specimens shall achieve 28 days without cracking. Concrete mixtures utilizing a coarse aggregate with a maximum size greater than 0.50 in shall be reproportioned to incorporate an equivalent volume of coarse aggregate with a maximum size of 0.50 in. No changes in cementitious content, fine aggregate content or water-cement ratio shall be permitted. Adjustments to admixtures shall be conducted to achieve the desired slump and plastic air content.

Hardened Air Content

Air-void system having the following characteristics as determined by ASTM C 457:

- Spacing factor not exceeding 0.008-in.
- Specific surface not less than 630 in^2/in^3
- Total air content not less than 4.0 percent

Materials

(a) Portland Cement. The portland cement used in any mix or as a part of any blended cement shall conform to the requirements of Section 1001 of the Standard Specifications.

(b) Supplementary Cementitious Materials. Fly ash and Slag cement used in any mixture shall conform to the requirements of Section 1010 of the Standard Specifications. Blended cement with a percentage of supplementary cementitious materials differing by more than 5% shall be considered different cementitious materials. If a blended cement is used in a mix, a certification of compliance shall be provided and include a statement signed by the blended cement supplier that indicates the actual percentage by weight of supplementary cementitious materials in the blend.

(c) Fine Aggregates. The fine aggregate shall be in accordance with the WisDOT special provision for Fine Aggregate for Portland Cement Concrete Pavement Mixtures.

(d) Pre-wetted Lightweight Aggregate. Pre-wetted lightweight aggregate shall be expanded slate, shale, clay, or slag that complies with ASTM C 1761.

(e) Coarse Aggregates. The coarse aggregate shall be in accordance with Section 501.2 of the Standard Specifications in addition to the following:

All Coarse Aggregate shall be in accordance with the Standard Specifications for Coarse Aggregate for Portland Concrete Pavement Mixtures. Approved Materials shall be used. Non-approved materials can be submitted for approval by the Engineer provided that they demonstrate adequate durability in accordance with Section 501.2.5 of the Standard Specifications.

(f) Mixing Water. Water shall be in accordance with Section 501.2.4 of the Standard Specifications.

(g) Concrete Admixtures. Concrete admixtures shall be in accordance with Section 501.2.2 thru 501.3.4 of the Standard Specifications.

AGGREGATE GRADATION

Coarse aggregates for use in Class IC concrete shall meet the requirements of Section 501.2.5.4.5 of the Standard Specifications.

SIEVE	PERCENT PASSING BY WEIGHT SIZE NO. 1 AASHTO No. 67[1]	SIZE NO. 2 AASHTO No. 4[1]
2-inch	-	100
1 1/2-inch	-	90-100
1-inch	100	20-55
3/4-inch	90-100	0-15
3/8-inch	20-55	0-5
No. 4	0-10	-
No. 8	0-5	-

(1) Size No. According to AASHTO M43

MIXTURE SUBMITTAL (JOB MIXTURE)

Submittal for any Class IC mixture design shall include:

1. Job Mixture Design, showing:
    a. Quantities, description, sources, and mill certifications of all mixture ingredients, including internal curing agents.
    b. Design water-cementitious materials ratio (w/cm)(does not include water absorbed in the LWA).
    c. Design Slump
    d. Design Air content
    e. Gradation of all aggregates
    f. Absorption of all aggregates., including lightweight aggregate fine aggregate.
    g. Bulk specific gravity (SSD) of all cementitious materials and aggregates
    h. Theoretical mass and fresh density
    i. Admixture dosage (including internal curing water)
2. A trial batch report demonstrating that the concrete complies with the performance requirements herein specified.

MATERIAL TOLERANCES

Portland Cement. The portland cement used in any mix or as a part of any blended cement shall conform to the requirements of Section 1001 of the Standard Specifications.

Supplementary Cementitious Materials. Fly ash and Slag cement used in any mixture shall conform to the requirements of Section 1010 of the Standard Specifications. Blended cement with a percentage of supplementary cementitious materials differing by more than 5% shall be considered different cementitious materials. If a blended cement is used in a mix, a certification of compliance shall be provided and include a statement signed by the blended cement supplier that indicates the actual percentage by weight of supplementary cementitious materials in the blend.

Fine Aggregates. The fine aggregate shall be in accordance with the WisDOT special provision for Fine Aggregate for Portland Cement Concrete Pavement Mixtures.

Lightweight Fine Aggregates. Lightweight fine aggregates for use in IC concrete shall meet the specification requirements of ASTM C1761.

Coarse Aggregates. The coarse aggregate shall be in accordance with Section 501.2 of the Standard Specifications in addition to the following:

All Coarse Aggregate shall be in accordance with the Standard Specifications for Coarse Aggregate for Portland Concrete Pavement Mixtures. Approved Materials shall be used. Non-approved materials can be submitted for approval by the Engineer provided that they demonstrate adequate durability in accordance with Section 501.2.5 of the Standard Specifications.

Mixing Water. Water shall be in accordance with Section 501.2.4 of the Standard Specifications.

Concrete Admixtures. Concrete admixtures shall be in accordance with Section 501.2.2 thru 501.3.4 of the Standard Specifications.

TEMPERATURE CONTROL FOR PLACEMENT

The ambient air temperature during concrete placement and the temperature of surfaces to receive ternary concrete shall not be less than 40°F. The concrete temperature when placed shall not be less than 60°F for ternary mixtures of any concrete with more than 20% fly ash or 35% slag replacement of Portland cement. Heating of the mixing water or aggregates will be required to regulate the concrete placing temperature with cold-weather placements. The use of accelerating admixtures conforming to ASTM C 494, Type C, or E is allowed.

QUALITY MANAGEMENT PLAN

At least 14 days prior to the first concrete placement, the Contractor shall submit a Quality Management Plan (QMP), for materials and construction in accordance with Section 715 of the Standard Specifications.

Production Facility and Transportation Equipment

The production facility and transportation equipment shall conform to the certification requirements of the Wisconsin Department of Transportation.

The certified plant shall be capable of mixing Class IC concrete as recommended by the manufacturer of LWA.

FIELD ACCEPTANCE

Acceptance to this specification shall be based on the following key characteristics:

- Strength
  - Interim – 7 day
  - Ultimate – 28 day
- Plastic air content – 5.0 to 8.0 percent (5.5 to 8.0 percent for slipform placement)
- Slump (Formed Placement) – Design ± 1.5 inches
- Slump (Slipform Placement) - Maintain the concrete at a uniform consistency. The Engineer will not allow an edge slump greater than ½ inch where no additional concrete work is to be constructed immediately adjacent to the pavement being placed. The Engineer will not allow an edge slump greater than ¼ inch where additional concrete work is to be constructed immediately adjacent to the pavement being placed.
- Water / cementitious materials ratio – Design -0.03, +0.00 (proper correction for surface moisture with LWA)

APPENDIX D: SPECIAL PROVISION FOR INTERNALLY CURED CONCRETE WITH SUPER ABSORBENT POLYMERS FOR PORTLAND CEMENT CONCRETE PAVEMENT AND BRIDGE DECK

Description

This work consists of designing and furnishing internally cured Portland Cement Concrete (PCC) for concrete pavement and bridge deck construction. The objective of this performance-related special provision is to provide the WisDOT with a methodology to assure high-quality concrete, while simultaneously allowing the Contractor the freedom in deciding how to develop and implement internally cured concrete mixture designs.

Class IC (internally cured) concrete incorporates super absorbent polymers (IC-SAP). Class IC concrete incorporates hydraulic Portland cement, slag cement, fly ash, or other supplementary cementitious materials (SCM) to produce a mixture meeting the specified performance. A Type IT blended cement in accordance with AASHTO M 240 shall be acceptable. A Type IP or IS blended cement in accordance with AASHTO M 240 may be used with ternary mixtures when an SCM is combined as a third constituent material to produce a cementitious materials blend. Type IL blended cement in accordance with AASHTO M 240 may be combined with two SCM's to a blended mixture. The limestone in a blended cement is not considered an SCM. Slag cement, fly ash, and any other SCM's combined as constituent materials or as part of a blended cement may consist of no less than 35% and no more than 50% of the total cementitious material content.

REFERENCE STANDARDS

Except where modified by the Wisconsin Department of Transportation, the following Standards shall apply:

Wisconsin Department of Transportation (WisDOT)

- Standard Specifications for Highway and Structure Construction, Current Edition.
  - Part 4 – Pavement
  - Part 5 – Structures
- Test Procedures referenced herein, as described in the current edition of the Manual of Test Procedures for Materials, as well these test procedures:

• AASHTO T 105	Chemical Analysis of Hydraulic Cement
• AASHTO T 160	Length Change of Hardened Hydraulic-Cement Mortar and Concrete
• AASHTO T 161	Procedure A Modified Resistance of Concrete to Rapid Freezing and Thawing
• AASHTO T 22	Compressive Strength of Cylindrical Concrete Specimens
• AASHTO TP 118	Characterization of the Air-Void System of Freshly Mixed Concrete by the Sequential Pressure Method
• AASHTO TP 129	Vibrating Kelly Ball (V-Kelly) Penetration in Fresh Portland Cement Concrete
• ASTM C457	Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete
• ASTM C856	Petrographic Examination of Hardened Concrete

- ASTM C1293 Determination of Length Change of Concrete Due to Alkali-Silica Reaction
- ASTM C1761 Standard Specification for Lightweight Aggregate for Internal Curing of Concrete
- ASTM C1581 Determination of Age at Cracking and Induced Tensile Stress Characteristics of Mortar and Concrete under Restrained Shrinkage
- ITM 222-15T Specific Gravity and Absorption of Lightweight Fine Aggregate

REQUIREMENTS FOR CLASS IC CONCRETE MIXTURE DESIGNS

Contractor shall provide a concrete mixture design according to the following performance requirements for Class IC concrete. The testing shall be performed by an AASHTO-accredited laboratory.

Performance qualification testing shall be performed by the Contractor to determine compliance with the specified performance for IC mixtures as indicated below. Candidate mixture proportions shall be evaluated through field or laboratory trials, to confirm that the performance requirements of this Special Provision are achieved. The Contractor is required to contact the WisDOT Engineer a minimum of 5 days prior to any plant trial batch mixing so that a WisDOT representative can observe the process. The same 5-day notification is required prior to conducting physical testing on hardened concrete samples.

Concrete Mixture Constituents

Unless otherwise specified, concrete mixture constituents for Class IC concrete shall meet the requirements of Section 501 of Standard Specifications for Highway and Structure Construction, Current Edition.

Use of Super Absorbent Polymers (SAP) shall be approved by WisDOT Engineer prior to qualification testing. A submittal of documentation of the candidate SAP shall include the trading name or product name, the absorption capacity of the SAP, the desorption capacity of the SAP. Dosage of SAP into concrete shall be determined by mass of dry SAP as a percentage of the total cementitious material content. Typical dosages will range between 0.1% to 0.3% by mass of cementitious materials.

Class IC-SAP Concrete Fresh Properties

Slump

For slipform concrete pavement placement, place the concrete with a slump value that optimizes placement, except ensure the concrete does not slough or slump and is adequately consolidated and meets all other requirements. Maintain the concrete at a uniform consistency. Unless otherwise specified, slump range shall meet the requirements of 415.2.1 for concrete pavement. For bridge deck concrete, the specified slump shall be achieved. Alternative slump ranges for bridge deck concrete can be submitted for review and approval by the Engineer.

The addition of dry SAP to the concrete will result in a loss in slump. Adjustments to the slump shall be conducted by adjusting the dosage of chemical admixtures

Plastic Air Content

Plastic Air Content determined using AASHTO T 196 test method shall be from 5.5 to 8.0 percent for slip form pavement, and 5.0 to 8.0 percent for other placements. As an optional requirement, determine the plastic air content in accordance with AASHTO TP 118 (Super Air Meter) could be determined from trial batches and compared to measurements taken in the field.

Class IC-SAP Concrete Hardened Properties

Compressive Strength

Concrete specimens shall be fabricated and cured in accordance with AASHTO T 23. Compressive strength for Class IC concrete shall meet the specification requirements as tested in accordance with AASHTO T 22. Interim compressive strength for Class IC concrete for public traffic shall be a minimum of 3,500 psi at no less than 7 days age.

Ultimate compressive strength shall not be less than 3500 psi at 28 days and strengths greater than 6,500 psi at 28 days will require approval. When this Class IC-LWA concrete is used in conjunction with performance-related construction specifications, strengths greater than 6,500 psi may be acceptable by the Engineer provided that the other performance requirements are achieved.

Flexural Strength

Flexural strength shall be determined in accordance with AASHTO T 97 for third point loading shall be a minimum of 650 psi at 28 days for Class IC-LWA concrete.

Length Change

Measured shrinkage shall not be greater than 0.030 percent after 21 days of air drying when determined in accordance with AASHTO T 160. Specimens shall be wet cured for 7 days prior to air-drying. The initial reading for the calculation of shrinkage shall be taken at the initiation of drying.

Restrained Shrinkage – Bridge Deck Concrete

Determination of the potential for cracking under restrained shrinkage shall be conducted in accordance with ASTM C1581. IC-SAP concrete shall not show cracking of any test specimen for at least 21 days and at least 2 out of 3 specimens shall achieve 28 days without cracking. Concrete mixtures utilizing a coarse aggregate with a maximum size greater than 0.50 in shall be reproportioned to incorporate an equivalent volume of coarse aggregate with a maximum size of 0.50 in. No changes in cementitious content, fine aggregate content or water-cement ratio shall be permitted. Adjustments to admixtures shall be conducted to achieve the desired slump and plastic air content.

Hardened Air Content

Air-void system having the following characteristics as determined by ASTM C 457:

- Spacing factor not exceeding 0.008-in.
- Specific surface not less than 630 in^2/in^3
- Total air content not less than 4.0 percent

MATERIALS

Portland Cement. The portland cement used in any mix or as a part of any blended cement shall conform to the requirements of Section 1001 of the Standard Specifications.

Supplementary Cementitious Materials. Fly ash and Slag cement used in any mixture shall conform to the requirements of Section 1010 of the Standard Specifications. Blended cement with a percentage of supplementary cementitious materials differing by more than 5% shall be considered different cementitious materials. If a blended cement is used in a mix, a certification of compliance shall be provided and include a statement signed by the blended cement supplier that indicates the actual percentage by weight of supplementary cementitious materials in the blend.

Fine Aggregates. The fine aggregate shall be in accordance with the WisDOT special provision for Fine Aggregate for Portland Cement Concrete Pavement Mixtures.

Coarse Aggregates. The coarse aggregate shall be in accordance with Section 501.2 of the Standard Specifications in addition to the following:

All Coarse Aggregate shall be in accordance with the Standard Specifications for Coarse Aggregate for Portland Concrete Pavement Mixtures. Approved Materials shall be used. Non-approved materials can be submitted for approval by the Engineer provided that they demonstrate adequate durability in accordance with Section 501.2.5 of the Standard Specifications.

Super Absorbent Polymer. Super Absorbent Polymers shall demonstrate compatibility for use in concrete by trial batching. Adjustments to admixture dosages are permissible to achieve the required fresh concrete properties.

Mixing Water. Water shall be in accordance with Section 501.2.4 of the Standard Specifications.

Concrete Admixtures. Concrete admixtures shall be in accordance with Section 501.2.2 thru 501.3.4 of the Standard Specifications.

AGGREGATE GRADATION

Coarse aggregates for use in Class IC concrete shall meet the requirements of Section 501.2.5.4.5 of the Standard Specifications.

	PERCENT PASSING BY WEIGHT	
SIEVE	SIZE NO. 1 AASHTO No. 67[1]	SIZE NO. 2 AASHTO No. 4[1]
2-inch	-	100
1 1/2-inch	-	90-100
1-inch	100	20-55
3/4-inch	90-100	0-15
3/8-inch	20-55	0-5
No. 4	0-10	-
No. 8	0-5	-

(2) Size No. According to AASHTO M43

MIXTURE SUBMITTAL (JOB MIXTURE)

Submittal for any Class IC mixture design shall include:

3. Job Mixture Design, showing:
    a. Quantities, description, sources, and mill certifications of all mixture ingredients, including internal curing agents.
    b. Design water-cementitious materials ratio (w/cm)(does not include water absorbed in the LWA).
    c. Design Slump
    d. Design Air content
    e. Gradation of all aggregates
    f. Absorption of all aggregates and SAP.
    g. Bulk specific gravity (SSD) of all cementitious materials and aggregates
    h. Theoretical mass and fresh density
    i. Admixture dosage (including internal curing water)
4. A trial batch report demonstrating that the concrete complies with the performance requirements herein specified.

MATERIAL TOLERANCES

Portland Cement

No re-submittal shall be required under the condition that the Portland cement (AASHTO M 85 and M 240) source complies with the following tolerances:

Acceptable tolerance for alkali content (Na_2O_{eq}): ± 0.10 percent.

Acceptable tolerance for tri-calcium aluminate content: - 2.0 percent, + 1.0 percent.

Acceptable tolerance for supplementary cementitious materials in a blended cement: ± 2%.

Fine Aggregate

Substitution of fine aggregates from different sources shall not be permitted without re-submittal.

Acceptable tolerance for fineness modulus: ± 0.20.

Coarse Aggregate

Substitution of coarse aggregate from different sources or different size classification shall not be permitted without re-submittal.

Supplementary Cementitious Materials

No change in type or classification shall be permitted without resubmittal.

Concrete Admixtures

Contractor may change between Type A and Type D admixtures as seasonal conditions warrant. With cold weather placements, the use of an accelerating admixture conforming to non-chloride containing ASTM C 494, Type C or E will be allowed without the need for a re-submittal. Chloride-containing accelerating admixtures will require approval by the Department.

Other Materials

No change in brand or type shall be permitted without re-submittal.

TEMPERATURE CONTROL FOR CONCRETE PLACEMENT

The ambient air temperature during concrete placement and the temperature of surfaces to receive ternary concrete shall not be less than 40°F. The concrete temperature when placed shall not be less than 60°F for ternary mixtures of any concrete with more than 20% fly ash or 35% slag replacement of Portland cement. Heating of the mixing water or aggregates will be required to regulate the concrete placing temperature with cold-weather placements. The use of accelerating admixtures conforming to ASTM C 494, Type C, or E is allowed.

QUALITY MANAGEMENT PLAN

At least 14 days prior to the first concrete placement, the Contractor shall submit a Quality Management Plan (QMP), for materials and construction in accordance with Section 715 of the Standard Specifications.

Production Facility and Transportation Equipment

The production facility and transportation equipment shall conform to the certification requirements of the Wisconsin Department of Transportation.

The certified plant shall be capable of mixing Class IC concrete as recommended by the manufacturer of LWA.

FIELD ACCEPTANCE

Acceptance to this specification shall be based on the following key characteristics:

- Strength
  - Interim – 7 day
  - Ultimate – 28 day
- Plastic air content – 5.0 to 8.0 percent (5.5 to 8.0 percent for slipform placement)
- Slump (Formed Placement) – Design ± 1.5 inches
- Slump (Slipform Placement) - Maintain the concrete at a uniform consistency. The Engineer will not allow an edge slump greater than ½ inch where no additional concrete work is to be constructed immediately adjacent to the pavement being placed. The Engineer will not allow an edge slump greater than ¼ inch where additional concrete work is to be constructed immediately adjacent to the pavement being placed.

- Water / cementitious materials ratio – Design -0.05, +0.00 (proper correction for surface moisture with LWA). The addition of SAP in a dry condition will reduce the w/cm ratio of the fresh concrete. Adjustment of slump must be achieved with the use of chemical admixtures.

APPENDIX E: COMMENTARY ON SECTION 05-10 CONSTRUCTION MANUAL

510.1 – General

The use of Internally Cured (IC) Concrete requires the approval of the Department. A submittal showing the performance of fresh and hardened concrete properties of the proposed IC Concrete mixture must be provided and approved by the Department prior to its use.

510.2 – Stockpiling Aggregates

When lightweight fine aggregate is used for internal curing, stockpiling of the aggregate is permitted provided that the stockpile is prevented from contamination, erosion, fracturing, and freezing. The use of sprinklers is recommended to maintain saturation of the aggregate stockpile prior to its use. Moisture content of stockpiled lightweight fine aggregate must be determined in accordance with ITM 222 prior to its batching for ready-mix concrete.

510.3 – Ready-Mixed Concrete

510.3.1 – Central-Mixed Concrete

IC concrete is recommended to be batched at central-mixed ready-mix concrete batch plants.

510-.3.2 – Transit-Mixed Concrete

Batching of IC concrete in transit-mixed concrete batching operations requires approval by the Department. A trial batch of IC concrete in a transit-mixed operation is recommended to verify that the performance of the IC Concrete meets the required fresh and hardened concrete properties.

510.3.3 – Shrink-Mixed Concrete

Batching of IC concrete in shrink-mixed concrete batching operations requires approval by the Department. A trial batch of IC concrete in a shrink-mixed operation is recommended to verify that the performance of the IC Concrete meets the required fresh and hardened concrete properties.

510.3.4 – Commercial Ready-Mix Plants

Unless otherwise approved, IC Concrete is only recommended for batching at commercial ready-mix plants.

510.3.5 – On-Site Mixer

Unless otherwise approved, IC Concrete is not recommended for batching at on-site mixer operations.

510.4 – Types of Batching Plants

510.4.1 Manual Plants

Unless otherwise approved, IC Concrete is not recommended for batching at manual plant operations.

510.4.2 Automatic or Semi-Automatic Plants

Automatic are recommended for batching of IC Concrete. Semi-automatic plants, when approved by the Department, can be used for batching of IC Concrete.

510.5 – Ready-Mixed Concrete Plant Operation

510.5.1 Background

Batching of IC Concrete is generally consistent with the batching of conventional concrete provided that the subsequent recommendations are followed.

510.5.2 Production Sequence

When lightweight fine aggregate is used, the lightweight fine aggregate must be on a saturated surface dry condition (SSD) or in a condition in which the aggregate is over saturated. Lightweight fine aggregate must be batched by mass Exceeding moisture must be determined in accordance with ITM 222 and the batch water must be adjusted to account for it. Lightweight fine aggregate must be added to the mixer through the conveyor belt in a similar manner as the other aggregates.

Super absorbent polymers must be weighed in a dry condition and added directly to the conveyor belt after other materials have been batched.

510.7 Control of Concrete Mix

510.7.1 Water-Cement Ratio

To ensure that the water-cement ratio of an IC Concrete mixture is equal to or less than specified, consistent and accurate determination of aggregate moisture is essential. The moisture content of lightweight fine aggregate must be determined periodically and at least three measurements must be taken in the 48 hours prior to its use. Adjustments of batch water may be required if the lightweight fine aggregate is in a over saturated moisture condition.

The use of super absorbent polymers will result in a reduction of the water-cement ratio when added in a dry condition. When dosed, mixed, and adjusted properly, this reduction should not result in a detrimental performance of the concrete in either fresh or hardened condition.

Refer to Special Provision for Internally Cured Concrete for tolerances on the water-cement ratio.

510.7.1.2 Slump

Unless otherwise approved, the slump of IC concrete must be measured after the batching of each load. If necessary, adjustments to slump of IC concrete should be conducted by the addition of chemical admixtures only.

510.7.2 Air-entrainment

Measurement of air content in fresh IC concrete must be conducted in accordance with ASTM C173. Due to the presence of lightweight fine aggregate or super absorbent polymers, measurements of plastic air content in accordance with ASTM C231 or AASHTO TP 118 can result in air contents that are not representative of the IC concrete mixture. If approved, plastic air content is recommended to be determined by both ASTM C173 and ASTM C231 or AASHTO TP 118.

510.8 Production

510.8.1 Computation of Batch Quantities

When IC Concrete is produced, the amounts of lightweight fine aggregate or super absorbent polymers must be included in the batch quantities. If the addition of either lightweight fine aggregate or super absorbent polymers is conducted manually, this must be included in the computations for batching of all concrete materials.

510.8.2 Batch Records and Cement Usage Check

Records of the use of lightweight fine aggregate or super absorbent polymer must be preserved when IC concrete is produced.

510.8.3 Batch Delivery

Refer to the Special Provision for Internally Cured Concrete for batch delivery requirements.

510.8.4 Ready-Mix Concrete Deliver and Inspection Tickets

All batch tickets of IC Concrete must include the following:

- Mixture identification
- Quantities of materials
- Manual adjustments or batching weights, if applicable
- Admixture adjustments
- Field adjustments, if necessary

510.9 Sampling and Testing of Concrete

Refer to the Special Provision for Internally Cured Concrete.

APPENDIX F: COMMENTARY ON SECTION 05-15 CONSTRUCTION MANUAL

515.1 – Preliminary Review

With regards to Internally Cured (IC) Concrete, consideration should be given to the change in fresh and hardened properties of the concrete. Attention should be given to carefully reviewing the mixture proportions, batching operations, field adjustments, placing and finishing of IC Concrete.

515.6 – Placing, Finishing and Curing Concrete

515.6.1 – Placing Concrete

IC Concrete mixture designs should have been qualified for use by laboratory testing or approval by the Department. When IC Concrete is to be used, batch tickets showing the materials and proportions of each load of concrete should be reported and recorded throughout the placement.

Considerations to the changes in the fresh concrete properties of IC Concrete are necessary. Specifically, it should be noted if the introduction of an internal curing agent resulted in an effect in the slump, plastic air content, bleeding, and time of setting. IC Concrete mixtures can result in less bleeding than ordinary concrete and prevention of evaporation is important to avoid plastic shrinkage cracking.

515.6.3 – Finishing Concrete

Finishing of IC Concrete requires the same general procedures as conventional concrete. The timing to the beginning of finishing, however, can be dependent on the IC concrete characteristics and weather conditions applicable for the placement. A mock trial is recommended to identify the optimum time for finishing based on the anticipated IC Concrete and weather conditions.

515.6.4 – Curing Concrete

Curing of IC Concrete should follow the procedures outlined in the Construction Manual. Depending on the IC concrete characteristics, attention should be paid on the application of wet curing so that additional water is not included in the concrete mixture. The application of wetted burlap, a membrane curing compound or surface applied curing compounds remains unchanged.

515.6.5 – Cold Weather Protection

Protection of IC concrete in cold weather conditions is critical. When using lightweight fine aggregates as the internal curing agent, lightweight fine aggregate must be protected from freezing prior to or during saturation prior to its use. Frozen lightweight fine aggregate must not be used. When concrete batched under cold weather conditions is conducted, water absorbed by super absorbent polymers can be less than in ordinary conditions. Is generally recommended that super absorbent polymers are not recommended as IC agent when the concrete temperature after batching is expected to be less than 60°F.

515.6.6 – Hot Weather Protection

In hot weather conditions, IC concrete can be used provided that the following recommendations are followed

- If pre-cooling of aggregates is conducted, lightweight fine aggregates must not be subject to freezing temperatures prior to batching.

- When liquid nitrogen is used for cooling ready-mix concrete, the temperature of the concrete after cooling must not be less than 50°F.
- Saturated lightweight aggregate must be used when using ice as a replacement of batch water. Moisture content of the aggregate shall be determined in accordance with ITM 222 and exceeding water over the saturated surface dry condition should be accounted as batch water.
- When utilizing super absorbent polymers, ensure that the evaporation rate is less than 0.2 lb/sq. ft./hr. IC Concrete with super absorbent polymers will bleed less than conventional concrete and measures to prevent excessive evaporation must be taken.

APPENDIX G: LIFE-CYCLE COST ANALYSIS FOR CONCRETE PAVEMENTS

Pavement Design General Information

Project ID:	9999-99-99	Designer's Name:	Jose Pacheco
Design Name:	WHRP Internal Curing	Design Date:	06/23/2021
Roadway Name:	Trial	Type:	State
Project Termini:	Trial	Status:	Draft
Highway Name:	Interstate Highway	Design Source:	WisPave
Comments:	Internal Curing Project		

Region	County
SE	Milwaukee
SE	Racine
SW	Juneau
SW	Monroe

Soil Parameters

Design Group Index (DGI):	10
Subgrade Improvement:	No
Subgrade Soil Support Value (SSV):	4.6
Subgrade Modulus of Subgrade Reaction (K):	200

Traffic Parameters

Construction Year:	2021	Design Year:	2041
Construction Year AADT:	9100	Design Year AADT:	12100
Directional Factor (DF):	0.50	Lane Distribution Factor (LDF):	1.00

Truck Classification	% of AADT
2D	3.2
3SU	1.5
2S-1,-2	1.7
3S-2	6.4
2-S1-2	0.3
Total % Truck Traffic	**13.1**

Concrete Pavement Design

Truck Type	% of AADT	DLT	# of Trucks	ESAL Load Factor	ESALs
2D	3.2	5,300	170	0.3	51
3SU	1.5	5,300	80	1.2	95
2S-1,-2	1.7	5,300	90	0.6	54
3S-2	6.4	5,300	339	1.6	543
2-S1-2	0.3	5,300	16	2.1	33

Design Lane Daily ESALs: 776

Design Lane Total Life ESALs: 5,668,085 Rounded to: 5,700,000

Soil Parameters

Subgrade Improvement Flag Selected: No

K: 200

Design Calculation

Calculated Pavement Thickness 9.0

Pavement Thickness (ALT# 1): 9.0

Pavement Thickness (ALT# 2): 9.0

HMA Pavement Design

Truck Type	% of AADT	DLT	# of Trucks	ESAL Load Factor	ESALs
2D	3.2	5300	170	0.3	51
3SU	1.5	5300	80	0.8	64
2S-1,-2	1.7	5300	90	0.5	45
3S-2	6.4	5300	339	0.9	305
2-S1-2	0.3	5300	16	2.0	32

Design Lane Daily ESALs: 497

Design Lane Total Life ESALs: 3,628,100 Rounded to: 3,700,000

Soil Parameters

DGI: 10

Subgrade Improvement Flag Selected: No

SSV: 4.6

Design Calculation

Calculated Required SN: 4.62

HMA ALT#1 Layer Thickness Design

Layers	Existing Pavement	Uppermost Base Agg.	Other	Material Type	Unit Type	Layer Coefficient	Thickness in.	Structural Number
1	N	N	N	3 LT 58-28 S	-----	0.44	4.00	1.76
2	N	N	N	Concrete Base, 6 inch	-----	0.4	6.00	2.4
3	N	N	N	Concrete Pavement, 9 inch	-----	0.1	9.00	0.9

Note: You can add only 10 layers (including 'Other' layers)

No.of Layers: 3 No.of Other Layers: 0 Total SN: 5.06

Required SN: 4.62

LCCA Parameters

Project Type: Urban

LCCA Length: 25 Miles

No. of HMA Alternatives: 1

Select HMA Alternatives to include in LCCA: HMA Alt# 1

No. of Concrete Alternatives: 2

Select Concrete Alternatives to include in LCCA: Concrete Alt# 1 Concrete Alt# 2

HMA Alt# 1 Description

Layers	Existing Pavement	Material Type	Thickness in.	Unit Weight lbs/SY/in	# of Tack Coat Layers	Tack Coat Coverage Gal/SY
1	N	3 LT 58-28 S	4.00	112.0	1	0.05
2	N	Concrete Base, 6 inch	6.00	0.0	-----	-----
3	N	Concrete Pavement, 9 inch	9.00	0.0	-----	-----

Shoulders

Material Type	Thickness in.	# of Tack Coat Layers	Tack Coat Coverage Gal/SY
4 MT 58-28 S	5.00	1	0.05

Additional Construction Process

Layers	Other	Process Description	% of LCCA Length Requiring Process	Existing Pavement Width ft.	% of Surface Area Requiring Repair	# of stations
N/A	N	Pulverize and Relay	100.0			

HMA Alt#1 Quantities

Layers	Bid Item No	Bid Item Desc	Units	Quantity
1	460.5223	3 LT 58-28 S	TON	85,418.7
	455.0605	Tack Coat	GAL	19,066.7
2	320.0125	Concrete Base, 6 inch	SY	381,333.3
3	415.0090	Concrete Pavement, 9 inch	SY	381,333.3

Additional Initial Construction Quantities:

Bid Item No	Bid Item Desc	Units	Quantity
460.6224	4 MT 58-28 S (Shoulders)	TON	36,960.0
455.0605	Tack Coat (Shoulders)	GAL	6,600.0
325.0100	Pulverize and Relay	SY	513,333.3
601.0411	Concrete Curb & Gutter 30-Inch Type D	LF	264,000.0

HMA Alt#1 Urban Cross Section

Roadway Width: 42

% of Project Length for new Curb & Gutter: 100

Paved Left Shoulder Width: 3.0

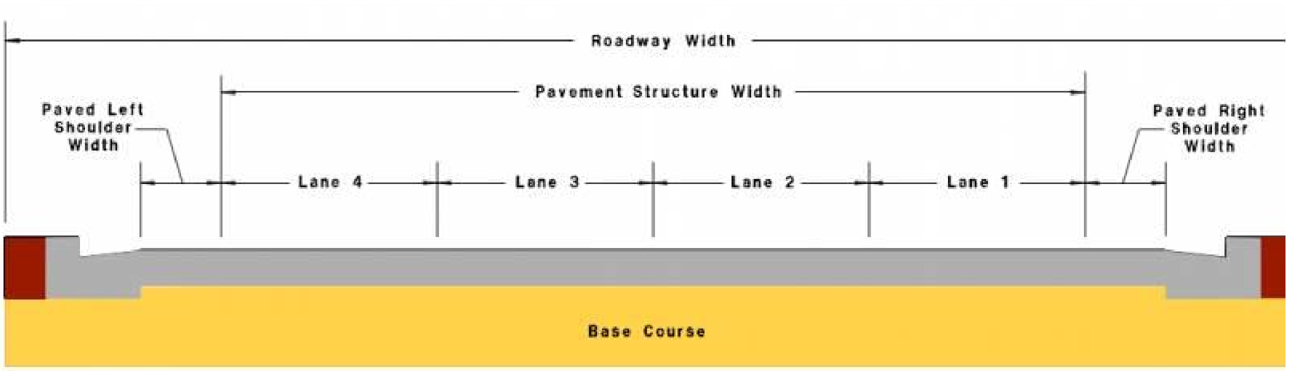
Paved Right Shoulder Width: 6.0

Number of Travel Lanes: 2

Paved Lane1 Width: 14 Paved Lane2 Width: 12

Number of Center/Shared Lanes: 0

Pavement Structure Width: 26



HMA Alternative - Maintenance & Rehabilitation Summary - Alt #1

Year	Type of Work	Activity	Service Life	Cost per Lane Mile
0	HMA (drained) - Traditional or Deep-Strength		22	
7	HMA Maintenance	1st Cycle		$2,000.00
14	HMA Maintenance	2nd Cycle		$2,500.00
22	HMA Rehabilitation	Mill and HMA Overlay (over Traditional or Deep-Strength HMA Pavement)	12	
26	HMA Maintenance	1st Cycle		$2,000.00
30	HMA Maintenance	2nd Cycle		$2,500.00
34	HMA Rehabilitation	Mill and HMA Overlay (over Traditional or Deep-Strength HMA Pavement)	12	
38	HMA Maintenance	1st Cycle		$2,000.00
42	HMA Maintenance	2nd Cycle		$2,500.00
46	HMA Rehabilitation	Mill and HMA Overlay (over Traditional or Deep-Strength HMA Pavement)	12	
50	HMA Maintenance	1st Cycle		$2,000.00
54	HMA Maintenance	2nd Cycle		$2,500.00
		Total Service Life	**58**	

Rehabilitation #1: Mill and HMA Overlay (over Traditional or Deep-Strength HMA Pavement)

Milling Limits: Pavement Structure and Shoulders Milling Depth: 5 (in)

Overlay Limits: None

Type	HMA Mix Type	Thickness	# of Tack Coat Layers	Tack Coat Coverage GAL/SY
Overlay	4 MT 58-28 S	3.50	1	0.05

Item	Units	Quantity
Removing Asphaltic Surface Milling	SY	513,333.3
4 MT 58-28 S	TON	0
Tack Coat (Pavement Structure)	GAL	0
Base Aggregate Dense ¾-inch (Shoulder Gravel)	TON	0

Rehabilitation #2: Mill and HMA Overlay (over Traditional or Deep-Strength HMA Pavement)

Milling Limits: Pavement Structure and Shoulders Milling Depth: 1 (in)

Overlay Limits: Pavement Structure and Shoulders

Type	HMA Mix Type	Thickness	# of Tack Coat Layers	Tack Coat Coverage GAL/SY
Overlay	4 MT 58-28 S	5.00	1	0.05

Item	Units	Quantity
Removing Asphaltic Surface Milling	SY	513,333.3
4 MT 58-28 S	TON	0
Tack Coat (Pavement Structure)	GAL	0
Base Aggregate Dense ¾-inch (Shoulder Gravel)	TON	0

Rehabilitation #3: Mill and HMA Overlay (over Traditional or Deep-Strength HMA Pavement)

Milling Limits: Pavement Structure and Shoulders Milling Depth: 1 (in)

Overlay Limits: Pavement Structure and Shoulders

Type	HMA Mix Type	Thickness	# of Tack Coat Layers	Tack Coat Coverage GAL/SY
Overlay	4 MT 58-28 S	5.00	1	0.05

Item	Units	Quantity
Removing Asphaltic Surface Milling	SY	513,333.3
4 MT 58-28 S	TON	0
Tack Coat (Pavement Structure)	GAL	0
Base Aggregate Dense ¾-inch (Shoulder Gravel)	TON	0

Concrete Alt# 1 Description

Title: Conventional Concrete

Layers	Existing Pavement	Uppermost Base Agg.	Other	Material Type	Unit Type	Thickness in.	# of Tack Coat Layers	Tack Coat Coverage Gal/SY
1	N	N	N	Concrete Pavement, 9 inch	-----	9.00	-----	-----
2	N	N	N	Base Aggregate Dense 1 1/4-inch	-----	6.00	-----	-----

Shoulders

Shoulder Materials: Concrete

Material Type	Thickness in.	# of Tack Coat Layers	Tack Coat Coverage Gal/SY
Concrete Base, 9 inch	9.00	0	0

Additional Construction Process

Layers	Other	Process Description	% of LCCA Length Requiring Process	Existing Pavement Width ft.	% of Surface Area Requiring Repair	# of stations
N/A	N	Prepare Foundation for Concrete Pavement (project)				
N/A	N	Removing Pavement	100.0	32.0		

Concrete Alt#1 Quantities

Title: Conventional Concrete

Layers	Bid Item No	Bid Item Desc	Units	Quantity
1	415.0090	Concrete Pavement, 9 inch	SY	381,333.3
2	305.0120	Base Aggregate Dense 1 1/4-inch	TON	205,333.3

Additional Initial Construction Quantities:
Conventional Concrete

Bid Item No	Bid Item Desc	Units	Quantity
320.0155	Concrete Base, 9 inch (Shoulders)	SQUARE YARD	132,000.0
204.0100	Removing Pavement	SY	469,333.3
211.0200	Prepare Foundation for Concrete Pavement (project)	LS	1.0
601.0409	Concrete Curb & Gutter 30-Inch Type A	LF	264,000.0

Concrete Alt#1 Urban Cross Section
Conventional Concrete

Roadway Width: 42 % of Project Length for new Curb & Gutter: 100

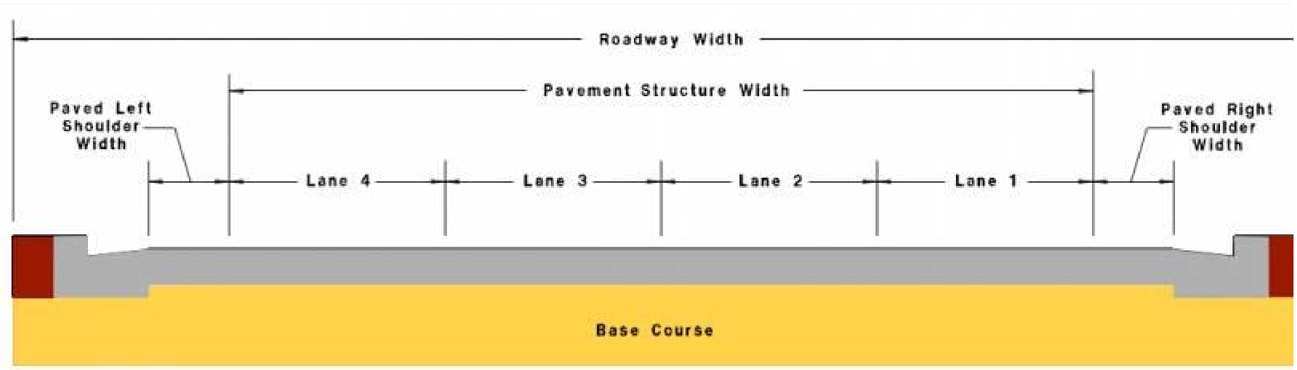
Paved Left Shoulder Width: 3.0 Paved Right Shoulder Width: 6.0

Number of Travel Lanes: 2

Paved Lane1 Width: 14 Paved Lane2 Width: 12

Number of Center/Shared Lanes: 0

Pavement Structure Width: 26



Concrete Alternative - Maintenance & Rehabilitation Summary - Alt #1
Conventional Concrete

Year	Type of Work	Activity	Service Life	Cost per Lane Mile
0	Concrete		25	
8	Concrete Maintenance	1st Cycle		$4,000.00
16	Concrete Maintenance	2nd Cycle		$8,000.00
25	Concrete Rehabilitation	Concrete Pavement Repair and Grind	8	
28	Concrete Maintenance	1st Cycle		$4,000.00
31	Concrete Maintenance	2nd Cycle		$8,000.00
33	Concrete Rehabilitation	Concrete Pavement Repair and Grind	8	
36	Concrete Maintenance	1st Cycle		$4,000.00
39	Concrete Maintenance	2nd Cycle		$8,000.00
41	Concrete Rehabilitation	Concrete Repair & HMA Overlay	15	
46	Concrete Maintenance	1st Cycle		$2,000.00
51	Concrete Maintenance	2nd Cycle		$2,500.00
		Total Service Life	**56**	

Concrete Alt #1: Conventional Concrete

Rehabilitation #1: Concrete Pavement Repair and Grind

% of Surface Area to be Repaired: 2.0

Grind Limits: None

Item	Units	Quantity
Concrete Pavement Repair	SY	7,632
Drilled Dowel Bars	EACH	15,264
Sawing Concrete	LF	34,344
Concrete Pavement Continuous Diamond Grinding	SY	0

Concrete Alt #1: Conventional Concrete

Rehabilitation #2: Concrete Pavement Repair and Grind

% of Surface Area to be Repaired: 2.0

Grind Limits: Pavement Structure Only

Item	Units	Quantity
Concrete Pavement Repair	SY	7,632
Drilled Dowel Bars	EACH	15,264
Sawing Concrete	LF	34,344
Concrete Pavement Continuous Diamond Grinding	SY	381,333.3

Concrete Alt #1: Conventional Concrete

Rehabilitation #3:Concrete Repair & HMA Overlay

% of Surface Area to be Repaired: 2.0

Removing Concrete Surface Partial Depth Limits: None

Overlay Limits: Pavement Structure Only

Type	HMA Mix Type	Thickness	# of Tack Coat Layers	Tack Coat Coverage GAL/SY
Overlay	4 MT 58-28 S	4.00	2	0.07

Item	Units	Quantity
Base Patching Concrete	SY	7,632
Drilled Dowel Bars	EACH	15,264
Sawing Concrete	LF	34,344
Removing Concrete Surface Partial Depth	SF	0
4 MT 58-28 S	TON	85,418.7
Tack Coat (Pavement Structure)	GAL	53,386.7
Base Aggregate Dense ¾-inch (Shoulder Gravel)	TON	0

Concrete Alt# 2 Description

Title: Internally Cured Concrete

Layers	Existing Pavement	Uppermost Base Agg.	Other	Material Type	Unit Type	Thickness in.	# of Tack Coat Layers	Tack Coat Coverage Gal/SY
1	N	N	N	Concrete Pavement, 9 inch	-----	9.00	-----	-----
2	N	N	N	Base Aggregate Dense 1 1/4-inch	-----	6.00	-----	-----

Shoulders

Shoulder Materials: Concrete

Material Type	Thickness in.	# of Tack Coat Layers	Tack Coat Coverage Gal/SY
Concrete Base, 9 inch	9.00	0	0

Additional Construction Process

Layers	Other	Process Description	% of LCCA Length Requiring Process	Existing Pavement Width ft.	% of Surface Area Requiring Repair	# of stations
N/A	N	Prepare Foundation for Concrete Pavement (project)				
N/A	N	Removing Pavement	100.0	32.0		

Concrete Alt#2 Quantities

Title: Internally Cured Concrete

Layers	Bid Item No	Bid Item Desc	Units	Quantity
1	415.0090	Concrete Pavement, 9 inch	SY	381,333.3
2	305.0120	Base Aggregate Dense 1 1/4-inch	TON	205,333.3

Additional Initial Construction Quantities

Internally Cured Concrete

Bid Item No	Bid Item Desc	Units	Quantity
320.0155	Concrete Base, 9 inch (Shoulders)	SQUARE YARD	132,000.0
455.0605	Tack Coat (Shoulders)	GAL	6,600.0
204.0100	Removing Pavement	SY	469,333.3
211.0200	Prepare Foundation for Concrete Pavement (project)	LS	1.0
601.0409	Concrete Curb & Gutter 30-Inch Type A	LF	264,000.0

Other Quantities:

Other Description	Unit	Quantity
Internally Cured Concrete	SY	381,333.3

Concrete Alt#2 Urban Cross Section

Internally Cured Concrete

Roadway Width: 42

% of Project Length for new Curb & Gutter: 100

Paved Left Shoulder Width: 3.0

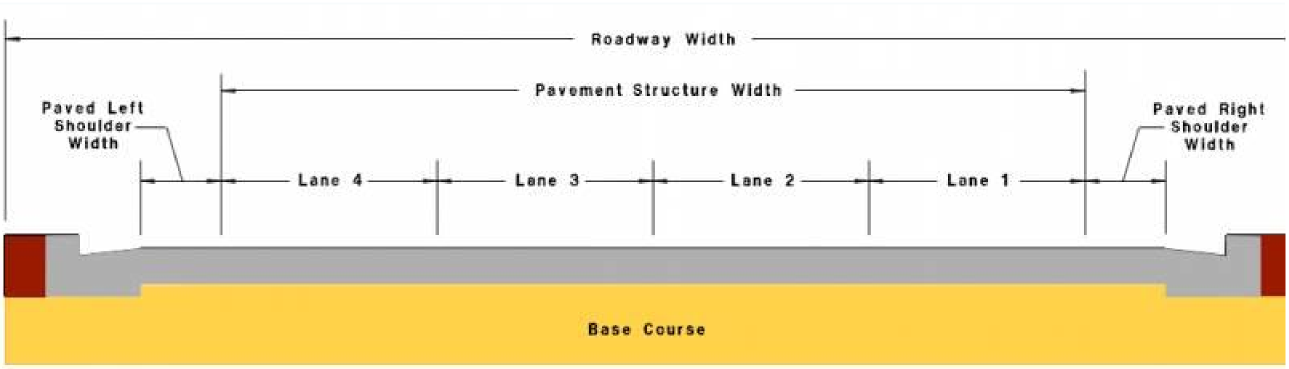
Paved Right Shoulder Width: 6.0

Number of Travel Lanes: 2

Paved Lane1 Width: 14 Paved Lane2 Width: 12

Number of Center/Shared Lanes: 0

Pavement Structure Width: 26



Concrete Alternative - Maintenance & Rehabilitation Summary - Alt #2
Internally Cured Concrete

Year	Type of Work	Activity	Service Life	Cost per Lane Mile
0	Concrete		25	
8	Concrete Maintenance	1st Cycle		$4,000.00
16	Concrete Maintenance	2nd Cycle		$8,000.00
25	Concrete Rehabilitation	Concrete Pavement Repair and Grind	8	
28	Concrete Maintenance	1st Cycle		$4,000.00
31	Concrete Maintenance	2nd Cycle		$8,000.00
33	Concrete Rehabilitation	Concrete Pavement Repair and Grind	8	
36	Concrete Maintenance	1st Cycle		$4,000.00
39	Concrete Maintenance	2nd Cycle		$8,000.00
41	Concrete Rehabilitation	Concrete Repair & HMA Overlay	15	
46	Concrete Maintenance	1st Cycle		$2,000.00
51	Concrete Maintenance	2nd Cycle		$2,500.00
		Total Service Life	**56**	

Concrete Alt #2: Internally Cured Concrete
Rehabilitation #1: Concrete Pavement Repair and Grind

% of Surface Area to be Repaired: 0.2

Grind Limits: None

Item	Units	Quantity
Concrete Pavement Repair	SY	768
Drilled Dowel Bars	EACH	1,536
Sawing Concrete	LF	3,456
Concrete Pavement Continuous Diamond Grinding	SY	0

Concrete Alt #2: Internally Cured Concrete
Rehabilitation #2: Concrete Pavement Repair and Grind

% of Surface Area to be Repaired: 0.2

Grind Limits: None

Item	Units	Quantity
Concrete Pavement Repair	SY	768
Drilled Dowel Bars	EACH	1,536
Sawing Concrete	LF	3,456
Concrete Pavement Continuous Diamond Grinding	SY	0

Concrete Alt #2: Internally Cured Concrete

Rehabilitation #3: Concrete Repair & HMA Overlay

% of Surface Area to be Repaired: 0.2

Removing Concrete Surface Partial Depth Limits: None

Overlay Limits: None

Type	HMA Mix Type	Thickness	# of Tack Coat Layers	Tack Coat Coverage GAL/SY
Overlay	4 MT 58-28 S	4.00	2	0.07

Item	Units	Quantity
Base Patching Concrete	SY	768
Drilled Dowel Bars	EACH	1,536
Sawing Concrete	LF	3,456
Removing Concrete Surface Partial Depth	SF	0
4 MT 58-28 S	TON	0
Tack Coat (Pavement Structure)	GAL	0
Base Aggregate Dense ¾-inch (Shoulder Gravel)	TON	0

HMA Bid Items

Bid Item Desc	Bid Item No	Units	Unit Cost
Tack Coat	455.0605	GAL	3.00
3 LT 58-28 S	460.5223	TON	11.00
4 MT 58-28 S	460.6224	TON	11.00
Concrete Curb & Gutter 30-inch Type D	601.0411	LF	1.50

Concrete Bid Items

Bid Item Desc	Bid Item Number	Units	Unit Cost
Concrete Base, 6 inch	320.0125	SY	55.00
Concrete Base, 9 inch	320.0155	SY	78.00
Base Patching Concrete	390.0303	SY	85.00
Concrete Pavement, 9 inch	415.0090	SY	65.00
Concrete Pavement, 10 inch	415.0100	SY	5.50
Drilled Dowel Bars	416.0620	EACH	13.20
Concrete Pavement Repair	416.1710	SY	128.18
Concrete Pavement Continuous Diamond Grinding	420.1000	SY	5.00
Concrete Curb & Gutter 30-inch Type A	601.0409	LF	30.00
Sawing Concrete	690.0250	LF	3.40

Base Course Bid Items

Bid Item Desc	Bid Item No	Units	Unit Cost
Base Aggregate Dense 1 1/4-inch	305.0120	TON	20.00
Pulverize and Relay	325.0100	SY	1.60

Sub-base Bid Items

Bid Item Description	Bid Item Number	Bid Item Unit Type Code	Bid Item Unit Cost
Prepare Foundation for Concrete Pavement (project)	211.0200	LS	3000.00

Remove Pavement Bid Items

Bid Item Desc	Bid Item No	Units	Unit Cost
Removing Pavement	204.0100	SY	14.00

Other Alternative Items:

Other Cost Description	Units	Unit Cost
Internally Cured Concrete	SY	2.00

Costs For All Alternatives

Concrete Alt# 1 Initial Construction Costs
Conventional Concrete

Bid Item Desc	Bid Item No	Units	Costs
Concrete Pavement, 9 inch	415.0090	SY	$24,786,664.50
Base Aggregate Dense 1 1/4-inch	305.0120	TON	$4,106,666.00
Concrete Curb & Gutter 30-Inch Type A	601.0409	LF	$7,920,000.00
Removing Pavement	204.0100	SY	$6,570,666.20
Prepare Foundation for Concrete Pavement (project)	211.0200	LS	$3,000.00
Concrete Base, 9 inch (Shoulders)	320.0155	QUARE YARD	$10,296,000.00
		Total:	**$53,682,996.00**

Concrete Alt# 1 Rehabilitation #1: Concrete Pavement Repair and Grind

Bid Item Desc	Bid Item No	Units	Costs
Drilled Dowel Bars	416.0620	EACH	$201,484.80
Concrete Pavement Repair	416.1710	SY	$978,269.76
Sawing Concrete	690.0250	LF	$116,769.60
		Total:	**$1,296,524.00**

Concrete Alt# 1 Rehabilitation #2: Concrete Pavement Repair and Grind

Bid Item Desc	Bid Item No	Units	Costs
Drilled Dowel Bars	416.0620	EACH	$201,484.80
Concrete Pavement Continuous Diamond Grinding	420.1000	SY	$1,906,666.50
Concrete Pavement Repair	416.1710	SY	$978,269.76
Sawing Concrete	690.0250	LF	$116,769.60
		Total:	**$3,203,190.00**

Concrete Alt# 1 Rehabilitation #3: Concrete Repair & HMA Overlay

Bid Item Desc	Bid Item No	Units	Costs
Tack Coat(Pavement Structure)	455.0605	GAL	$160,160.10
4 MT 58-28 S	460.6224	TON	$939,605.70
Base Patching Concrete	390.0303	SY	$648,720.00
Drilled Dowel Bars	416.0620	EACH	$201,484.80
Sawing Concrete	690.0250	LF	$116,769.60
		Total:	**$2,066,740.00**

Concrete Alt# 1 Maintenance Costs

Maintenance Cycle	Cost per Lane Mile	Total Cycle Cost
1	$4,000.00	$200,000.00
2	$8,000.00	$400,000.00
3	$4,000.00	$200,000.00
4	$8,000.00	$400,000.00
5	$4,000.00	$200,000.00
6	$8,000.00	$400,000.00
7	$2,000.00	$100,000.00
8	$2,500.00	$125,000.00
	Total:	**$2,025,000.00**

Concrete Alt# 2 Initial Construction Costs
Internally Cured Concrete

Bid Item Desc	Bid Item No	Units	Costs
Concrete Pavement, 9 inch	415.0090	SY	$24,786,664.50
Base Aggregate Dense 1 1/4-inch	305.0120	TON	$4,106,666.00
Concrete Curb & Gutter 30-Inch Type A	601.0409	LF	$7,920,000.00
Removing Pavement	204.0100	SY	$6,570,666.20
Prepare Foundation for Concrete Pavement (project)	211.0200	LS	$3,000.00
Concrete Base, 9 inch (Shoulders)	320.0155	QUARE YARD	$10,296,000.00
Track Coat (Shoulders)	455.0605	GAL	$19,800.00
Internally Cured Concrete	Other	SY	$762,666.60
		Total:	**$54,465,463.00**

Concrete Alt# 2 Rehabilitation #1: Concrete Pavement Repair and Grind

Bid Item Desc	Bid Item No	Units	Costs
Concrete Pavement Repair	416.1710	SY	$98,442.24
Drilled Dowel Bars	416.0620	EACH	$20,275.20
Sawing Concrete	690.0250	LF	$11,750.40
		Total:	**$130,467.00**

Concrete Alt# 2 Rehabilitation #2: Concrete Pavement Repair and Grind

Bid Item Desc	Bid Item No	Units	Costs
Concrete Pavement Repair	416.1710	SY	$98,442.24
Drilled Dowel Bars	416.0620	EACH	$20,275.20
Sawing Concrete	690.0250	LF	$11,750.40
		Total:	**$130,467.00**

Concrete Alt# 2 Rehabilitation #3: Concrete Repair & HMA Overlay

Bid Item Desc	Bid Item No	Units	Costs
Base Patching Concrete	390.0303	SY	$65,280.00
Drilled Dowel Bars	416.0620	EACH	$20,275.20
Sawing Concrete	690.0250	LF	$11,750.40
		Total:	**$97,305.00**

Concrete Alt# 2 Maintenance Costs

Maintenance Cycle	Cost per Lane Mile	Total Cycle Cost
1	$4,000.00	$200,000.00
2	$8,000.00	$400,000.00
3	$4,000.00	$200,000.00
4	$8,000.00	$400,000.00
5	$4,000.00	$200,000.00
6	$8,000.00	$400,000.00
7	$2,000.00	$100,000.00
8	$2,500.00	$125,000.00
	Total:	**$2,025,000.00**

HMA Alt# 1 Initial Construction Costs

Bid Item Desc	Bid Item No	Units	Costs
Tack Coat (Pavement Structure)	455.0605	GAL	$57,200.10
3 LT 58-28 S	460.5223	TON	$939,605.70
Concrete Base, 6 inch	320.0125	SY	$20,973,331.50
Concrete Pavement, 9 inch	415.0090	SY	$24,786,664.50
Pulverize and Relay	325.0100	SY	$821,333.28
Tack Coat (Shoulders)	455.0605	GAL	$19,800.00
4 MT 58-28 S (Shoulders)	460.6224	TON	$406,560.00
Concrete Curb & Gutter 30-Inch Type D	601.0411	LF	$396,000.00
		Total:	**$48,400,495.00**

HMA Alt# 1 Rehabilitation #1: Mill and HMA Overlay (over Traditional or Deep-Strength HMA Pavement)

Bid Item Desc	Bid Item No	Units	Costs
Removing Asphaltic Surface Milling	Other	SY	$513,333.30
		Total:	**$513,333.00**

HMA Alt# 1 Rehabilitation #2: Mill and HMA Overlay (over Traditional or Deep-Strength HMA Pavement)

Bid Item Desc	Bid Item No	Units	Costs
Removing Asphaltic Surface Milling	Other	SY	$513,333.30
		Total:	**$513,333.00**

HMA Alt# 1 Rehabilitation #3: Mill and HMA Overlay (over Traditional or Deep-Strength HMA Pavement)

Bid Item Desc	Bid Item No	Units	Costs
Removing Asphaltic Surface Milling	Other	SY	$513,333.30
		Total:	**$513,333.00**

HMA Alt# 1 Maintenance Costs

Maintenance Cycle	Cost per Lane Mile	Total Cycle Cost
1	$2,000.00	$100,000.00
2	$2,500.00	$125,000.00
3	$2,000.00	$100,000.00
4	$2,500.00	$125,000.00
5	$2,000.00	$100,000.00
6	$2,500.00	$125,000.00
7	$2,000.00	$100,000.00
8	$2,500.00	$125,000.00
	Total:	**$900,000.00**

LIFE CYCLE COST ANALYSIS RESULTS

Current Year: 2021 **Project Length:** 25 Miles

Construction Year: 2021 **Analysis Basis:** LCCA Length

Analysis Period: 50 yrs **Discount Rate(%):** 5

Present Worth Costs

	Concrete Alt# 1 Conventional Concrete	Concrete Alt# 2 Internally Cured Concrete	HMA Alt# 1
Initial Construction Costs	$53,682,996.70	$54,465,463.30	$48,400,495.08
Maintenance Costs	$572,946.73	$572,946.73	$240,701.58
Rehabilitation Costs	$1,302,688.96	$77,768.11	$0.00
Rehabilitation Salvage Value	($72,090.98)	($3,394.16)	$0.00
Total Facility Costs	$55,486,541.41	$55,112,783.98	$48,641,196.66
	+14.07%	+13.30%	+0.00%