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Extend Service Life of Concrete Bridge Decks with Internal Curing

FINAL REPORT

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Submitted by

Hani Nassif, PE, Ph.D.
Professor
Rutgers University

Michael Ruszala
Research Engineer
Rutgers University

Chaekuk Na, Ph.D.
Sr. Research Associate
Rutgers University

Reid Holland
PhD Candidate
Rutgers University

Mohammad Mahgoub, Ph.D. PE
Associate Professor
NJIT

Kaan Ozbay, Ph.D.
Professor
New York University

Jannie Gao, Ph.D.
Assistant Dir. of Research
New York University

Eren Kaval
PhD Candidate
New York University

NJDOT Research Project Manager
Priscilla Ukpah

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16. Abstract

The EPIC2 initiative, one of the Federal Highway Administration's (FHWA) EDC-7 innovations, investigates the implementation of Internally Cured Concrete. This emerging technology shows potential benefits such as improved project life cycle costs and enhanced sustainability when implemented in New Jersey, particularly for bridge deck applications. The process involves replacing a portion of normal fine aggregate with prewetted Lightweight Fine Aggregate (LWFA), which stores water inside fine aggregate particles. These particles are evenly distributed through the concrete matrix and slowly releases their trapped moisture during the curing process, providing a more consistent curing effect. High performance concrete (HPC) particularly benefits from this process due to its low permeability which reduces the effectiveness of conventional curing. HPC is also known for its rapid hydration and strength gain which increases sensitivity to early age cracking under restrained conditions, such as those existing in a cast in place bridge deck. This project investigates numerous internal curing materials for usage in NJDOT internally cured HPC (HPIC) and proposes methodology for implementation in New Jersey.

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EXECUTIVE SUMMARY

Optimal curing of concrete during the hydration process is critical for enhancing durability and extending the service life of bridge decks and pavements. Conventional curing methods (wet burlap with plastic sheeting) rely on supplying moisture from the surface; however, they do not always provide sufficient internal moisture for High-Performance Concrete (HPC), which typically has a low water-to-cement ratio and a dense microstructure that limits permeability. As hydration proceeds, cementitious materials consume the available pore water, causing desiccation within the microstructure and generating negative pore pressures that lead to autogenous shrinkage. Under the restrained conditions present in reinforced bridge decks, the shrinkage strains can produce localized tensile stresses around the reinforcement, which may initiate early-age cracking. Once cracks form, they facilitate the ingress of chloride ions from deicing salts, accelerate corrosion of the steel reinforcement, increase maintenance and repair needs, and ultimately shorten the service life of the structure.

High-Performance Internally Curing Concrete (HPIC) addresses these limitations by incorporating highly absorbent materials, such as Light Weight Fine Aggregate (LWFA) or other internal curing agents (ICA), that act as internal water reservoirs. The ICAs release stored water into the cementitious matrix as hydration progresses, replenishing microstructure pores, supporting more complete hydration, and significantly mitigating autogenous and restrained shrinkage. Testing results indicate that HPIC with LWFA are a technically viable and cost-effective alternative to conventional HPC wherever early-age cracking is a concern. HPIC mixtures incorporating expanded shale LWFA maintained strength and durability comparable to control HPC, while providing substantial reductions in autogenous and restrained shrinkage and showing no loss in freeze-thaw resistance. For effective and precise batching, the centrifuge absorption method yielded faster and more consistent aggregate absorption measurements than the paper towel method, supporting accurate internal curing dosage and improving quality control during production.

Life-cycle cost analysis (LCCA) demonstrates that HPIC can provide a robust, implementable strategy to extend bridge deck service life, reduce the risk of early-age and long-term cracking, and achieve significant economic and environmental benefits over the service life of the structure. The benefits are maximized when HPIC is combined with a 14-day wet curing protocol and targeted field instrumentation of pilot bridge decks to verify performance in service. By enhancing moisture availability during hydration and enabling the concrete to achieve its full durability potential, HPIC offers a cost-effective solution that is highly resistant to the harsh exposure conditions typically encountered in New Jersey bridge decks and pavements.

INTRODUCTION

External curing is intended to supply sufficient water to the concrete during the early-age hydration process until the concrete surface is fully hardened to resist early-age shrinkage and mitigate self-desiccation. However, external curing may not be adequate due to the high water demand of High-Performance Concrete (HPC) and the high density of its matrix, which reduces the permeability of externally applied curing [1-7]. The internal curing mechanism involves the introduction of an Internal Curing Agent (ICA) into concrete mixtures either before or during mixing. The proper use of ICA can overcome the restrictions of the external-curing process. This significant benefit is achieved when ICA releases water gradually during concrete curing, which maximizes cementitious matrix hydration and reduces autogenous shrinkage. Figure 1 illustrates the two classifications of ICA: (1) porous materials, including lightweight aggregate (LWA) and superfine powders (SP), and (2) physically water-absorbing materials, such as superabsorbent polymers (SAP). The efficiency of each ICA depends on the particle size, absorption, and adsorption capabilities. It illustrates the range of particle sizes for each ICA discussed, as reported by several researchers [8, 9]. Figure 1 illustrates each ICA type, and they are characterized in Table 1.

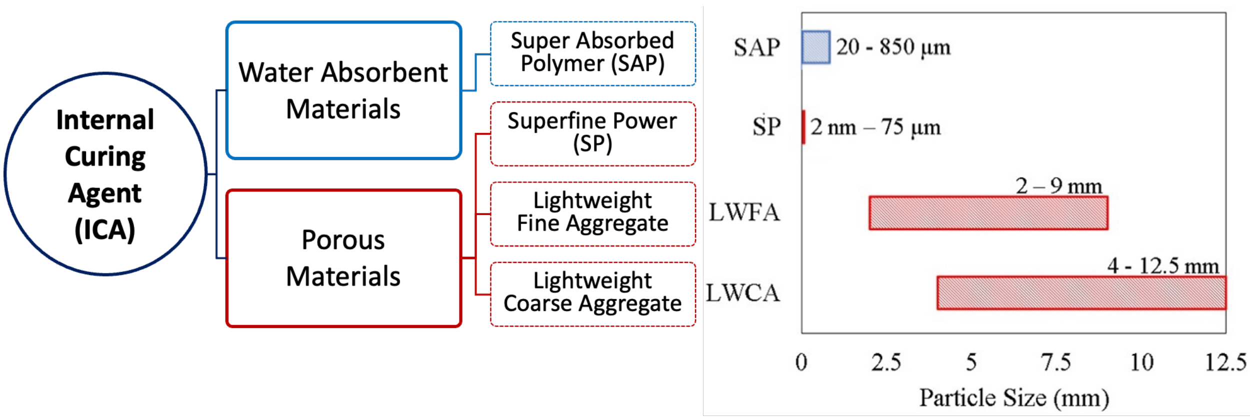


Figure 1. Internal Curing Agents (ICA) Classifications and Particle Size

Porous materials (LWA and SP) are water-filled reservoirs stored within the concrete system, designed to release water on demand to maximize the hydration of the cement paste from the time of mixing until moisture equilibrium is achieved between the reservoirs and the surrounding cement paste [8-10]. This method requires the preparation of the materials prior to adding them to the concrete. The preparation process is crucial for the efficiency of the ICA added to the mix. SP and LWA are both porous materials; however, SP is much smaller in size, which reduces the amount of water absorbed, making it less effective than Lightweight Fine Aggregate (LWFA). In addition, porous ICA is driven by capillary action, which makes it more effective than physically absorbent materials. It is important to note that fine LWA is generally preferred to coarse LWA since it has a smaller distance between the aggregates and provides the beneficial effects of internal curing water to a greater volume of paste [10].

Physically absorbent materials (SAP) have a mechanism that is slightly different compared to porous ICA. SAP is a cross-linked polyelectrolyte that swells when it comes into contact with water or an aqueous solution, resulting in the formation of a hydrogel after swelling [11-13]. The swelling of SAP is due to osmotic pressure proportional to the ion concentration in the aqueous solution, which means the water absorption capacity of SAP is highly dependent on the concentration of ions in the swelling medium [13]. Unlike porous carriers, SAP can absorb up to 5000 times its own weight.

In addition, a comprehensive summary of the ICA mechanisms and reported effects on engineering properties is presented in Figure 2. The pros and cons of each ICA are listed, and the differences between carriers are highlighted. Major differences are as follows:
The size of the porous ICA particles (LWFA, LWCA, and SP) is directly correlated to absorption capacity. As illustrated in Figure 2, larger particle size translates to a higher moisture level for internal curing and the hydration process, especially since the water absorbed does not affect the water/cement ratio of the mixture. On the other hand, SAP can absorb up to 5000 times its own weight, which makes it a viable alternative for internal curing.
The proper dosage of porous ICA is not reported to affect concrete workability significantly. However, SAP is reported to have an adverse effect on concrete workability. The concrete strength has been reported to improve with the addition of porous ICA; however, the same is not observed with SAP.

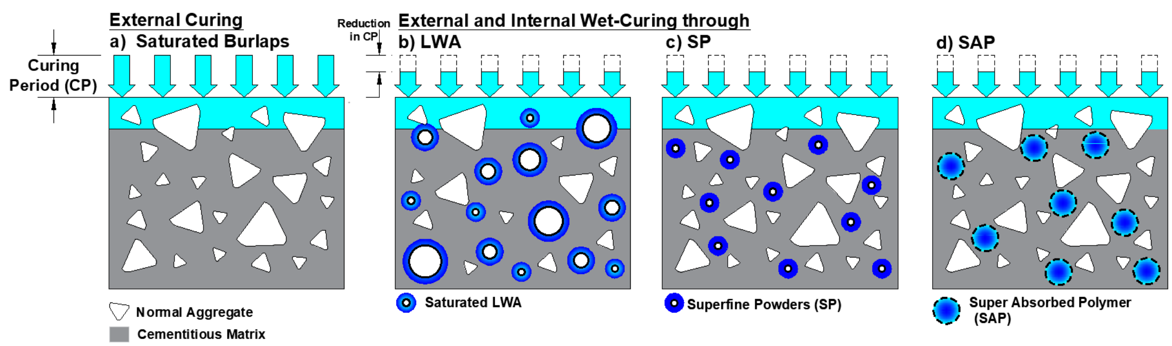


Figure 2. Schematic Description of the Internal Curing Process; (a) External Curing, External Curing Combined with Internal Curing using (b) LWA, (c) SP, and (d) SAP

The utilization of locally produced or available ICA materials, such as cement and LWA (coarse and fine), is a critical consideration for ensuring the long-term sustainability of future projects. By incorporating local ICA materials, the DOT can effectively pursue its current objective of reducing greenhouse gas (GHG) emissions by 80 percent before 2050. As stated in NJ's Global Warming Response Act 80x50 Report of 2020, the transportation sector is the primary contributor to GHG emissions in New Jersey, accounting for 42 percent of the total, closely followed by residential and commercial sectors at 26 percent. The transportation of ICA materials and other concrete components within New Jersey would improve sustainability and contribute to the reduction of emissions, aligning with the Department's goals and the Commissioner's initiatives.

Furthermore, using local ICA materials would enhance the sustainability of infrastructure in New Jersey. To support these efforts, our industry partner, Northeast Solite Corporation, supplies lightweight fine aggregate (LWFA) and lightweight coarse aggregate (LWCA), which are essential for a reduction in GHG emissions. However, chemical admixtures/SP/SAP are chemical compositions that are not sensitive to the local climate and do not contribute to GHG emissions. The team explored local suppliers of chemical admixtures/SP/SAP to improve sustainability and meet the Department's current goals and Commissioner's initiatives with the help of our industry partners, Euclid Chemical (which has several local distributors in NJ) and Clayton Concrete (which closely works with a local admixture supplier, Great Eastern Technology).

The assessment of the ICA mechanisms aims to evaluate the potential of each material in providing the expected benefits when implemented in NJ bridges. LWFA implementation (decks, pavements, concrete, and pilot slabs) has been significantly more common than other ICA. The popularity of LWFA in transportation agencies develops a comprehensive understanding of the challenges and benefits under actual loading and weather conditions, which makes LWFA the most attractive option for HPIC.

Table 2 describes the LWA materials available in the United States that have been previously used by state DOTs. DOTs typically approve the use of expanded shale material, with only a few studies on expanded clay. Clay has been observed to reduce the mechanical performance of concrete members as well as durability metrics such as freeze-thaw resistance and chloride penetration [14] and therefore is largely used in locations that do not experience a winter season. The primary reason each material type was used is the proximity of the material source. Regardless of performance differences between certain expanded aggregates, DOTs typically use materials that are most accessible.

Currently, three lightweight aggregate producers are approved in New Jersey's qualified materials fine aggregate suppliers, which are Stalite, Norlite, and Northeast Solite. The LWA market is primarily comprised of expanded shale, slate, and clay, with some expanded slag available in the Great Lakes Region. Typically, aggregate selection is based on availability and economic feasibility, which is largely decided by geographic region and transportation options. Several expanded shale products are available on the East Coast, including Arcosa's Hydrolite, Northeast Solite, and Norlite. Riverlite from Arcosa is the primary expanded clay aggregate, while Stalite is the primary expanded slate aggregate.

Table 1 – Preliminary Summary of the Effect of ICA on Concrete Properties [8-25]

ICA	**Porous Materials**			**Absorbent Materials**
Designation	LWFA	LWCA	SP	SAP
Particle size	2 mm – 9 mm	4 mm – 12.5 mm	2nm – 75 μm	20 – 850 μm
Mechanism	Water-filled reservoirs within the concrete that supply water during the hydrating process when internal humidity decreases		Micro-water reservoirs during hydration process	Physically adsorb water up to 5000 times of own weight
Used as a replacement of	Fine aggregate, cement	Coarse aggregate	Cement, Silica fume	Fine aggregate, cement
Preparations	24h soaking in water before using, then drained for 12-15h		Premix with water	Pre-saturation not required
Mixing	Limited contact with dry parts during mixing		Added during mixing	
Internal Humidity	Increases		Increases	Increases
Workability	Negligible or increases	Negligible	Reduces	Can significantly reduce
Autogenous Shrinkage	Reduces early age shrinkage			
Comp. Strength	Negligible or increases			Reduces
Elastic Modulus	Decreases		Negligible	Decreases
Tensile Strength	Increases		Negligible or increases	Decreases
Permeability	Negligible or increases			
Initial Cost	$3-10/yd^3$		NA	NA
Implementations	Decks/Pavements	Decks	NA	NA

Table 2 – LWFA Products used in State DOT Studies

Company	Product	Plant	Material	Absorption	S.G. Dried	S.G. Saturated	NJ Approved?
Northeast Solite	Hydrocure	Saugerties, NY	Expanded Shale	18.0%	-	1.8	Yes
Northeast Solite	Greenlite	Saugerties, NY	Expanded Shale	10.0%	-	1.8	Yes
Norlite	Norlite	Cohoes, NY	Expanded Shale	19.0%	1.55	-	Yes
Arcosa	Hydrolite	Brooks, KY	Expanded Shale	17.3%	1.51	1.77	No
Holcim/Utelite	Utelite	Coalville, UT	Expanded Shale	19.4%	1.49	1.84	No
Buildex	Haydite	Dearborn, MO	Expanded Shale	10.0%	1.45	1.8	No
Stalite	Stalite	Gold Hill, NC	Expanded Slate	10-14%	1.69	1.8	Yes
Arcosa	Riverlite	Erwinville, LA	Expanded Clay	16.0%	1.29	1.5	No
Arcosa	Riverlite	Livingston, AL	Expanded Clay	30.0%	1.1	1.43	No
Note: Absorption rate is completed in accordance with ASTM C127/C128 for 24-hour absorption. Information not supplied is unreported by manufacturer.							

Table 3 shows that the HPIC is not a new concept for local transportation agencies. In recent years, several states have examined the internal curing efficiency of concrete bridge decks to address early-age cracking. The team reviewed the state-of-practice and highlighted the findings, challenges, lessons learned and solutions. Numerous bridges have incorporated HPIC with LWFA into their design in New York. In 2008, it was reported that NYSDOT experimentally used internally cured concrete on 20 bridges. After service, it was reported that these bridges were found to have a 70 percent reduction in deck cracking. Contractors reported that HPIC is similarly or more workable than conventional HPC. The initial material cost was higher for HPIC due to the extra work for the concrete produced associated with soaking and pre-wetting the LWA. As a neighboring state to NJ, NYSDOT experience with LWA is especially important to develop a comprehensive methodology for implementing ICA in NJ bridge decks and pavement concrete. NYDOT specifications for ICA are as follows:

- NYSDOT Standard Construction and Material specifications specify substituting LWFA, meeting the requirements of AASHTO M 195, for 30 percent (by volume) of standard fine aggregate to develop their HPIC. For this LWFA to be approved, it should have 15 percent absorbed moisture at batching;

- NYSDOT requires the construction of an LWFA stockpile at the production facility to maintain uniform moisture throughout the pile using an approved sprinkler system. It is required for the sprinkling to be steady on the LWFA for a minimum of 48h or until SSD conditions are at least 15 percent;

- In 2015, NYSDOT summarized its positive experience on internally cured bridge decks, which increased in durability and cracking resistance. In addition, the external curing period has been reduced from 14 to 7 days for HPIC, which is a major construction saving in time and cost.

Other states have also investigated HPIC with various related projects. INDOT led projects to evaluate the impact of internal curing on low-cracking HPC [26]. Five years later, INDOT documented the construction of four internally cured bridge decks, which applied the findings of the previous study. Several pavement applications in Texas with HPIC indicated that the initial crack pattern in the internally cured section exhibited much longer spacing than in normal concrete, and the cracks were much thinner.

Each available DOT study was reviewed. The important takeaways for performance, construction, and application were highlighted for each study. Information on the completed work as well as the scope is also noted, with an emphasis on real world applications and large-scale use, such as deck pours. Figure 3 showcases the current extent of EPIC2 bridge decks incorporating Internal Curing technology.

As of December 2025, over 180 bridge decks exist in the Enhancing Performance with Internally Cured Concrete (EPIC2) FHWA program. [27]

Table 3 – Available DOT Projects on HPIC

DOT	Year	Description
OH	2007	Pilot study
NY	2008/2015	20 bridge decks
IN	2010/2013	Two Bridge Decks (Buckets) / Four bridge decks (Pumping)
KS	2011/2012	Redocking/overlay for existing bridge; 3-span haunch slab bridge
VA	2012/2013	Three bridge decks
OR	2013	Laboratory testing of LWA
IA	2013	Pavement systems
CO	2014	Pilot study
KS	2014	Pavement Concrete
AR	2014	Laboratory testing of LWA
UT	2014	Four bridge decks
FL	2015	Two pilot pavement slabs
PA	2015	Pilot Study
TN	2015	Five bridge decks
NC	2015	Pilot bridge deck
LA	2016	Two Bridge deck/ Pavement
NB	2020	Pilot Study/pilot bridge deck
WI	2021	Pilot study

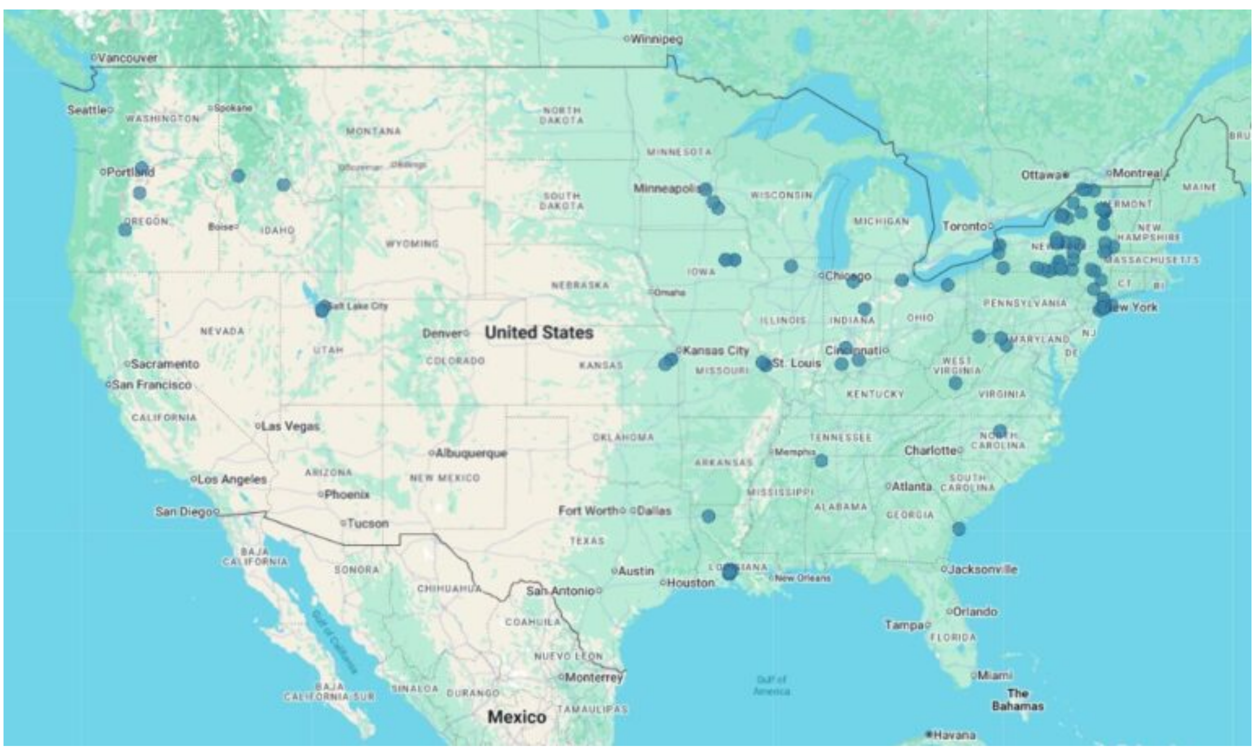


Figure 3. EPIC2 Bridges in service according to FHWA [27]

Literature Review

Ohio DOT [2008] [28]

In 2008, Ohio DOT conducted lab and field investigations in conjunction with Cleveland State University for the implementation of internal curing in transportation concrete. The study discusses three mixtures that were tested: two pavement mixtures and one overlay mixture. All three mixtures meet or exceed Ohio DOT strength requirements. The LWA effect of modulus of rupture is inconclusive due to high variability of the test as well as limited data, although a general decreasing trend was observed. In terms of cracking, it was determined that mixtures with LWA cracked in less time or had a lower cracking tendency.

Four field tests were conducted to verify lab results and to implement internal curing in concrete structures. The fourth field test included a HP#4 mix with LWA and was used on a new bridge, located in Ohio DOT District 12, that was placed in early May of 2007. The deck was approximately 289 yd^3 of concrete, and no complaints or workability issues were recorded. A visual inspection was done five weeks after placing, before traffic was allowed on the bridge. Two cracks were found on the underside of the bridge. Both cracks occurred at a location where two pieces of formwork met and were below the sidewalk. The cracks were small and did not continue through to the deck. It was concluded that since LWA is routinely used in concrete construction, the added cost of incorporating the material may be low. The cost has the potential to be outweighed by the reduced life-cycle costs due to a reduction in cracking.

New York State DOT [2010] [29]

Using prior knowledge of pre-wetting coarse aggregate for structural lightweight concrete, the NYSDOT study concluded that the use of a sprinkler was the most ideal method to pre-wet LWFA in the stockpile. The sprinkler system is shown below in Figure 4. No adjustments in batching to accommodate internal curing concrete were reported. Due to small concrete batch plants, there was a deficit in the number of bins. This resulted in two aggregates being blended into a single bin to have the bin space to batch LWFA.

Figure 4. Sprinkler System Used to Pre-wet LWFA before Batching [29]

All concrete on these bridges was placed using the pumps shown in Figure 5. Internal curing mixes showed no variation in pumpability from similar mixes without internal curing. Similar finishability was observed between conventional and internal curing mixes. The engineer compared air content by pressure and volumetric methods at the beginning of the job. The pressure meter was used the duration of the pour and a difference within 0.5 percent was found. Burlap and soaker hoses were left in place to provide continuous curing for the entire 14 day curing period.

(a) Street Deck Placement Court (b) Interstate 190/290 Interchange

Figure 5. Pump Trucks Placing HPIC Bridge Decks [29]

Kansas DOT [2009] [30]

Kansas University conducted laboratory experiments on evaluation of internal curing mixture designs including fourteen batches between two testing programs. Program 1 evaluated the performance of differing amounts of internal curing replacement. Program 2 evaluated the use of LWA with ground granulated blast furnace slag. Both consisted of two control mixes: limestone to compare reducing shrinkage between limestone and LWA, and granite to evaluate its performance with the addition of LWA.

After attempted to soak aggregate in a bucket failed, a vacuum saturation method was incorporated, which lowered the time to achieve total moisture content (MC) from 16 hours to 1 hour. After achieving total MC, the aggregate was dried to saturated surface dried (SSD) condition, which was defined as no longer having shine on particles. The method defined in ASTM C70: Standard Test Method for Surface Moisture in Fine Aggregate, was not used because the blow dryer would scatter aggregate and lose particles.

Accounting for lost particles presented problems. The research team noted that many fine particles were lost when draining aggregates in the No. 50 sieve. Aggregate loss also occurred when allowing the aggregate to dry on newspaper. The mix design used was Low-Cracking High-Performance Concrete (LC-HPC) with the goal of minimizing bridge deck cracking. This mix utilized a lower w/c ratio, low slump, low evaporation rates and better construction methods/materials.

Indiana DOT [2013] [26]

For the four mixes, a trial batch was held for a minimum of 28 days before the beginning of bridge construction to identify and solve potential production difficulties. Preceding batching, the LWA pile was soaked for a minimum of 48 hours and drained for a minimum of 12 hours, shown in Figure 6.

Additional training for the batch plant operators was recommended by the research team. This training ensured operators avoided issues and understood how to make moisture adjustments and change scale jog rates when mixing batches with LWFA.

(a) Paper Towel Method (b) Centrifuge Method

Figure 6. Methods to Determine Moisture Adjustments [26]

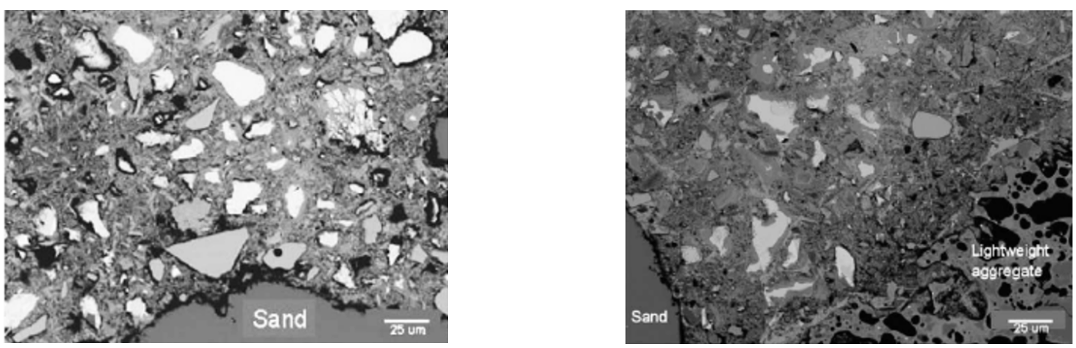
The batching plants had a shortage of aggregate bins for LWFA, leading to producers having to refill LWFA hopper throughout the production process (Figure 7). During construction, low air content was observed. It was later determined that the free fall to the point of placement was excessive due to pump geometry. The research team noted the pumping issues would exist regardless of operators training. All four bridge decks were constructed successfully and are currently in service.

Figure 7. LWA Piles being Pre-wetted and Drained before Batching [26]

Oregon DOT [2013] [31]

In 2013, Oregon DOT in conjunction with Oregon State University explored the use of internal curing in HPC concrete. The mix included a local siliceous river gravel and natural siliceous sand as aggregates, then used three shale types, two clay types, and one Shale+SRA as LWFA. Mixtures were proportioned with 633 lb/yd^3 of LWA. The mixes used LWFA replacement levels of 9 percent and 20 percent for clay-1 and shale-1, respectively. Clay-2, Shale-2, and Shale+SRA used replacement levels with FLWA of 12 percent, 25 percent and 25 percent, respectively. Shale-3 mix was a 100 percent replacement of normal weight fine aggregate with LWFA. Clay exhibited a higher potential absorption capacity than shale but required a longer time to reach maximum absorption capacity. Both FLWA materials are indicated to readily give off absorbed water when internal RH of concrete begins to drop due to hydration and drying. Figure 8 shows the micrographs of LWFA mortar.

Higher replacement levels of LWFA showed an increase in compression strength at 28-day strength. However, the reported strength increases were lower than previous research, which may indicate that including a LWA in high strength concrete may have a less significant impact than in normal strength concrete. The research group concluded that the incorporation of SRA with pre-wetted LWFA proved to be the most effective method to reduce drying shrinkage. LWFA was shown to be the least effective at reducing drying shrinkage, although, the long-term strength gains could reduce cracking potential.



(a) NW sand (b) pre-wetted FLWA

Figure 8. Micrograph Pictures of Mortars using Different Fine Aggregates [31]

It was concluded that the pre-soaked LWFA and the SRA were effective at reducing the long-term drying shrinkage, but the combination of SRAs and pre-wetted LWFA was the most effective method to reduce long-term drying shrinkage for all curing durations (at days 1, 7, and 14). It was found that the use of SRAs performed the best in freeze-thaw, chloride permeability and restrained shrinkage. It was recommended to start at 25 percent LWFA replacement and 2 percent SRA addition by cement mass for HPC.

Colorado DOT [2014] [32]

In 2014, Colorado DOT along with Purdue University examined the replacement of normal-weight aggregate with varying amounts of pre-wetted LWA and the freeze-thaw resistance of internal curing concrete. HPC mixtures used in this study were required to meet CDOT specifications Class H and Class D bridge deck concretes. The research team used nine different mixtures consisting of Class D and H deck mixtures. They differed on replacing either the coarse or fine aggregate, the amount of replacement water desired, and which LWA aggregate supplier was being used. Class H and D mixtures are required to have 5-8 percent air content, while there is no range for desired slump. All mixtures except 1 met air content specification with slump increasing for mixtures with LWFA and CLWA. Class H mixtures exceeded the CDOT specification for compressive strength of 4500 lbf/in^2 at 56-day. Class D IC mixtures met required 4500 lbf/in^2 at 28-day.

For freeze-thaw, beam samples were wet-cured for 14 days, then immediately underwent the freeze-thaw testing. It was mentioned that it is detrimental for the three internal curing beams to not experience a drying period before a free-thaw cycle, therefore, the results are a "worst case scenario." After undergoing 195 cycles, the 100 percent LWCA replacement failed, which shows that excessive dosages of Light Weight Coarse Aggregate materials can lead to poor performance in freeze-thaw (see Figure 9).

In terms of shrinkage, it was found that internal curing concrete prevents autogenous shrinkage and causes expansion in a sealed system, which relaxes over time as hydration reduces. For water absorption, a vacuum saturation system similar to the one used in the Kansas investigation was used. It was found that porosity increased in class H mixtures as LWA increased. It was also determined that the critical degree of saturation was about 86 percent, where excessive freeze-thaw damage could begin. None of the mixtures for class H or D reached this critical number. The research team concluded that about 20 percent replacement of the normal-weight concrete was desirable to combat chemical shrinkage. A reasonable w/c ratio to combat freeze-thaw was concluded to be 0.48, as increases in excessive water in pre-wetted LWA can lead to freeze-thaw damage.

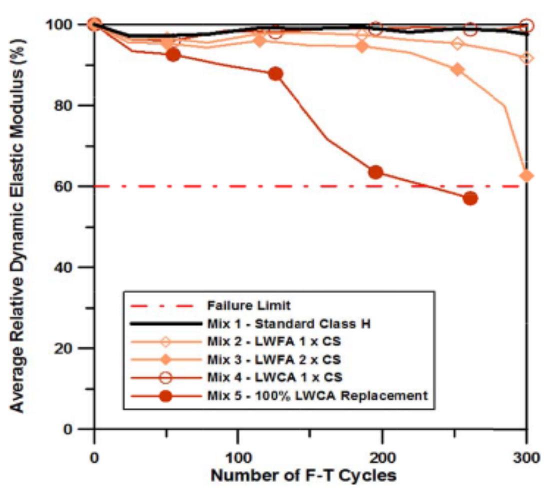


Figure 9. Freeze-Thaw Performance by LWCA/LWFA Level [32]

Utah DOT [2014] [33]

In 2014, Utah DOT along with Brigham Young University published a field study comparing two ICC bridge decks alongside two conventional bridge decks poured in the Mountain View Corridor Project. Testing was conducted to determine differences in in-situ moisture and diffusivity, as well as early age cracking, compressive strength, and chloride ingress. Laboratory testing was also conducted on field cast samples for additional mechanical and durability property testing. Field in-situ testing showed the average volumetric moisture content of ICC was maintained 2-4 percentage points higher than the conventional for the first year but stabilized at 2 percent higher at two years. Electrical conductivity of the internally cured concrete was tested at 38-50 percent greater than of the conventionally cast decks after 6 months. In field Schmid rebound hammer testing showed similar strengths at 1 year but a slight increase in strength in conventional decks after 2 years. This field testing was confirmed in lab with conventional samples displaying 13 percent greater strength when tested at 1 year. Rapid chloride permeability testing showed a 13-17.5 percent decrease in current passed in ICC as compared to conventional concrete. A slight decrease in modulus of elasticity of 4 percent was observed in ICC.

Table 4 – Total Crack Lengths Observed during Distress Surveys [33]

Location	Total Cracking Length (in.)			
	5-month	8-month	1-year	2-year
Dannon Way SB Conventional	175	1045	6353	11953
Dannon Way NB Internally Cured	24	463	7106	18280
8200 South NB Conventional	257	3442	16774	25143
8200 South SB Internally Cured	66	221	2231	9352

The mix tested used a replacement of fine aggregate with 30 percent LWFA by volume, which accounted for 7 lb of absorbed water per 100 lb of cementitious material. LWFA was prewetted for a minimum of two days at the batch plant with a sprinkler system to achieve a moisture content of 15 percent, and excess water was allowed to drain for two additional days (Figure 10). The same batch plant and contractor were used for all mixes, with no reported concerns with mixing or casting. Significant differences in cracking severity were observed during all distress surveys, with conventional concrete displaying 4.8, 6.6, 2.5 and 1.3 times more cracking at 5 months, 8 months, 1 year, and 2 years respectively when compared to internally cured concrete (Table 4).

Figure 10. Stockpile of LWFA Displaying Water Sprinkling System [33]

Florida DOT [2015] [34]

In 2015, Florida DOT in collaboration with the University of Florida published their findings of their field testing of ICC and NC mixtures which included slabs loaded with a Heavy Vehicle Simulator (HVS). Testing was done to determine mechanical and cracking properties of ICC compared to conventional approved bridge deck materials. Six mix designs were evaluated, being the Florida DOT Class II, Class IV, and Class V as well as three ICC mix designs based on the approved standard mixtures. ICC mixtures contained a replacement fine aggregate with LWFA such that a supply of 7lb of absorbed water per 100 lb of cementitious material would be available for internal curing. LWFA material for this study was prepared by submerging for a minimum of 48 hours and brought to SSD.

Testing showed comparable workability, with slightly less water reducing admixture required for ICC mixes to achieve the same workability. Comparing the average results of the ICC mixes to the average results of approved DOT mixtures, the compressive strength, flexural strength, and elastic modulus decreased by 11 percent, 6 percent and 18 percent respectively. The ICC mixes displayed a significant increase in resistance to shrinkage cracking with an average cracking age of 2.7 times that of standard mixes on the restrained ring test. ICC field cast slabs loaded by the Heavy Vehicle Simulator displayed improved stress to strength ratios, with an average value of 0.57 to the standard slabs 0.62. Additionally, cracking was observed along the wheel path of the HVS in the standard slab after loading (see Figure 11).

(a) (b) (c)

Figure 11. Crack Patterns: (a) Standard, (b) ICC-1 and (c) ICC-2 mixes after HVS loading [34]

Pennsylvania DOT [2015] [35]

In 2015, Penn DOT published an exhaustive general literature review with the Thomas D. Larson Pennsylvania Transportation Institute on bridge deck cracking. The focus of this report isn't specifically on lightweight aggregate but it notable references internal curing as a prospective solution to mitigate bridge deterioration in the literature review.

Tennessee DOT [2015] [36]

In 2015, Tennessee DOT and the University of Tennessee conducted a study assessing the corrosion potential due to chloride penetration in Light Weight Concrete (LWC) bridge decks. While the study did not include LWFA for the purpose of internal curing, expanded slate coarse aggregate was used as specified by TDOT approved mix designs. This study primarily conducted testing on surface resistivity and rapid chloride permeability and assessed material and curing effects. Mechanical properties and fresh properties of LWC and standard concrete were reported to be comparable. The study indicated the primary quality control concern as proper saturation of LWC for consistency with pumpability.

In the study, five existing LWC bridge decks were surveyed with only minor cracking reported. The main concern observed in the survey is the exposure of the porous lightweight aggregates when surface grinding is used for reprofiling, potentially leading to a mechanism of chloride ingress into the bridge deck.

North Carolina DOT [2016] [37]

In 2016, North Carolina DOT led a study with the University of North Carolina to assess internal curing for bridge deck and pavement applications. In this study, eighteen mixtures containing normal weight (control), slate expanded aggregate (LWFA 1) and shale expanded (LWFA 2) were analyzed. Ten mixtures meeting bridge deck Class AA specifications, five latex modified concrete overlay mixtures, two very high early strength, and two pavements' mixtures were tested. The relationship developed by Bentz et al. [38] was used to determine the proportion of LWFA based on the water demand of the cementitious materials and the internal reservoirs of LWFA.

ICA mixes showed similar workability and required the same placing and finishing operations as conventional concrete. Quality assurance testing, such as air content and slump, was also performed in the same manner for both ICA and conventional mixtures. Specifications were outlined based on this study and other DOT experience, noting that the bulk of successful field implementation relies on proper preparation of the internally curing material by the concrete supplier. Proper stockpile saturation (Figure 12), handling, and measurement of surface moisture were critical to consistent batching. A minimum of 48 hours of prewetting with 12–15 hours of drainage is specified, with the additional requirement of turning and mixing before batching to homogenize surface moisture. Specifications using the brown paper towel method are outlined, along with a recommendation for the centrifuge method to rapidly determine LWFA surface water content for batching. Researchers emphasized the need for a producer with space and technical knowledge to maintain consistency, which may be challenging in rural or low-production plants.

Laboratory testing showed a reduction in cracking for all ICA mixtures when compared to their conventional counterparts, and in many cases a reduction in permeability. A pilot project bridge deck containing NC and ICA sections was instrumented and assessed as part of this study and showed no substantial differences between the performance of standard and internally cured sections (Figure 13). This was assumed due to the relatively low absorption of the internal curing aggregate preferred by the NCDOT and the lower replacement value used, which may not have provided significant enough internal water to make significant differences in the highly restrained conditions of the bridge deck tested. A pump hose with a minimum of 5 in diameter was specified to reduce pumping pressures that may prematurely draw water out of the LWFA.

Figure 12. Stockpile of LWFA Draining in Saturated Condition [37]

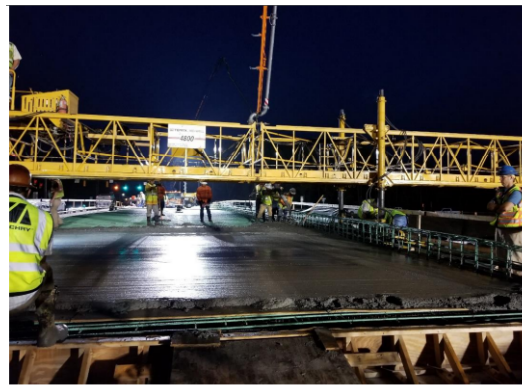


Figure 13. ICA Field Bridge Deck Placement [37]

Louisiana DOTD [2016] [39]

In 2016, Louisiana DOTD funded a study with the Louisiana Transportation Research Center to assess ICC for bridge applications. Laboratory testing determined mechanical properties of mix designs with 0.35 and 0.4 w/c, as well as 0, 5, 10, 15, 20, and 25 percent replacement of fine aggregate with LWFA. Results of all mixes were in compliance with all Louisiana DOT specifications. A slight decrease in flexure strength was reported as replacement with LWFA increased. No statistical difference in strength or elastic modulus was reported with an increase in LWFA in any curing conditions observed.

Two pairs of ICC and NC bridge deck replacements were incorporated into the study. The bridge deck at Western Lafayette Parish (Figure 14) incorporated two placements of ICC with 285 lb/yd^3 of expanded clay LWFA. The ready-mix plant operator stated the mix containing LWFA behaved comparable to the control mix, and the contractor noted easier finishability characteristics and made the statement, "ICC is just like normal concrete" in terms of placing. A crack survey conducted 9 months after the bridge was brought into service showed minimal cracking, with two longitudinal cracks in the control slab measuring 6 ft and 16 in. average 0.013 in. US 80 near Ada (Figure 15) incorporated two formulations of ICC with 150 and 300 lb/yd^3 of expanded clay LWFA, as well as a control mixture containing only normal weight aggregates. A similar lack of problems regarding mixing and placing were reported. Crack analysis revealed both ICC portions displayed a decrease in cracking and crack severity compared to the control sections.

Figure 14. West Congress Bridge Looking East into Lafayette Parish [39]

Figure 15. Aerial View of the U.S. 80 KCS Railroad Crossing [39]

Virginia DOT [2016] [40]

In 2016, VDOT investigated the effectiveness of LWC in reducing cracks in seven bridges. The bridges are located in Northern Virginia, Staunton, Lynchburg, Culpeper, Richmond, and Fredericksburg districts. Three decks were constructed in 2012 and 2013 for each bridge, and one deck was constructed for each in 2014. The study concluded that LWC with a maximum cementitious content of 650 lb/yd^3 is recommended to be used in VDOT bridge deck concrete mixtures.

VDOT also noted that they inspected a Route 269 bridge over the Cowpasture River. This bridge was constructed in 1979 with LWC that had coarse aggregate with a very high absorption of 18 percent. A visual inspection in 2013 showed no transverse or other visible cracks, and limited wear. The only issue found was shallow popouts exposing the coarse aggregate, shown in Figure 16.

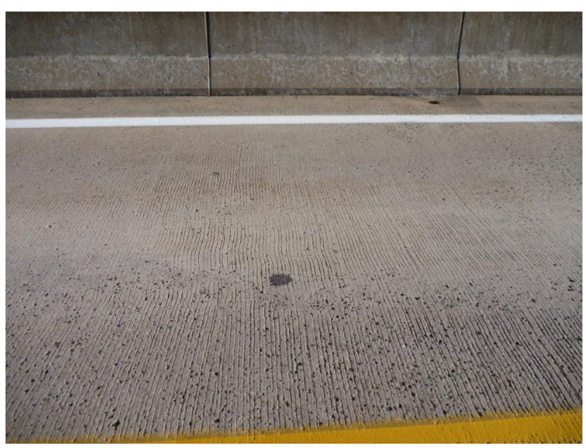


Figure 16. 1979 LWC Bridge Deck at Route 269 [40]

The bridge decks were constructed with mixtures containing differing cementitious contents) 635 to 705 lb/yd^3), fine aggregates, and mineral admixtures. Expanded slate lightweight coarse aggregate and commercially available air-entraining, water-reducing, and retarding admixtures were used in all mixtures. Decks were placed via pumping in multiple pours and concrete properties met VDOT specifications. During construction, VDOT requires an evaporation rate below 0.1 lb/ft^2/hr to reduce water loss and avoid plastic shrinkage. All three cases reported that evaporation rate remained below the maximum allowed.

VDOT noted in their hardened concrete samples that had a higher cementitious content led to a higher drying shrinkage, so lower cement, water and paste contents are desirable to decrease cracking. The average strength values found were different, which was attributed to a lack of proper saturations of lightweight aggregates.

Only the Route 646 Nokesville Bridge reported severe cracking in the LWC concrete section with crack densities of 0.15 ft/ft^2 and 0.13 ft/ft^2. The cracking was attributed to a lack of pre-saturation of the LWA prior to mixing, which resulted in varying concrete quality and strengths. The cracks can be shown in Figure 17.

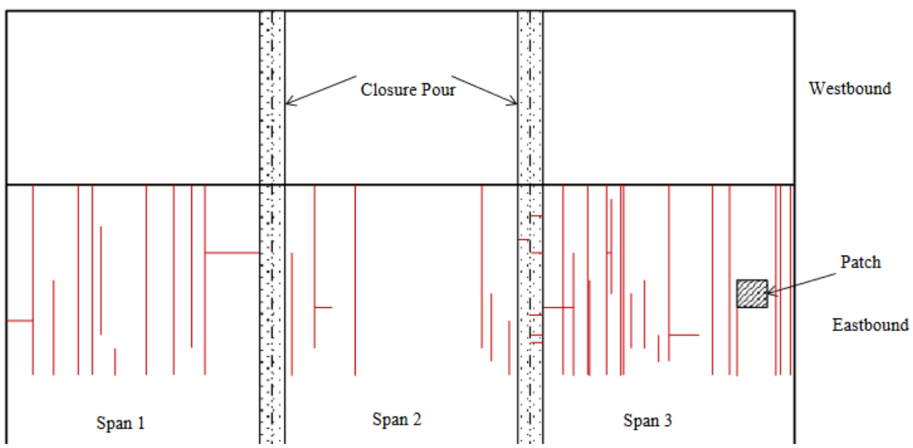


Figure 17. Cracking Plot for Route 646 Nokesville [40]

Nebraska DOT [2020] [41]

In 2020, Nebraska DOT with the University of Nebraska-Lincoln and Texas A&M University investigated the application of internal curing for bridge decks by compiling a literature review as well as laboratory testing on four different LWFA materials. Efforts were made to optimize a mix using different replacements of LWFA and aggregate distributions to improve workability and reduce admixture dosage. Mix designs were calculated in this study using the formula proposed by Bentz et al. [31] and modified by Castro [36] using a time dependent parameter. LWFA was saturated by submerging for 24 hours and batched in SSD condition.

Results from optimized mixes met Nebraska DOT specifications for use in bridge decks while greatly reducing autogenous shrinkage as well as delaying restrained ring cracking in all mixtures containing LWFA. Slight decreases in flexural strength, tensile strength, and elastic modulus were observed in most mixes while an increase in compressive strength was observed. Electrical resistance testing showed a reduction in early age results for ICC that caught up with standard mixes as the internal curing agents water desorbed.

Iowa DOT [2021] [42]

In 2021, Iowa DOT investigated the impacts of internal curing concrete on warping in test pavements, both in the field and in the lab. Two field sites were used, both being overlays under construction: CR W-61/Riverside Road in Washington County, and CR W-34 in Winneshiek County. Iowa did not expect high structural benefits, so the study was focused on potential reductions in maintenance and life-cycle costs. Control mixtures were those typical of the respective county. Internal curing mixtures were about 25 percent replacement of fine aggregate with LWFA, to produce 7 percent internal curing water by mass of Cementitious materials. Lab results showed mixed slump results and a decrease of 0.5 percent in internal curing concrete, however field samples showed mixed results in both metrics. There was also an increase in long-term compressive and splitting tensile strength in both field and lab results. Internal curing concrete showed a decrease in modulus of elasticity, but an increase in surface resistivity. Figure 18 shows the cracking results.

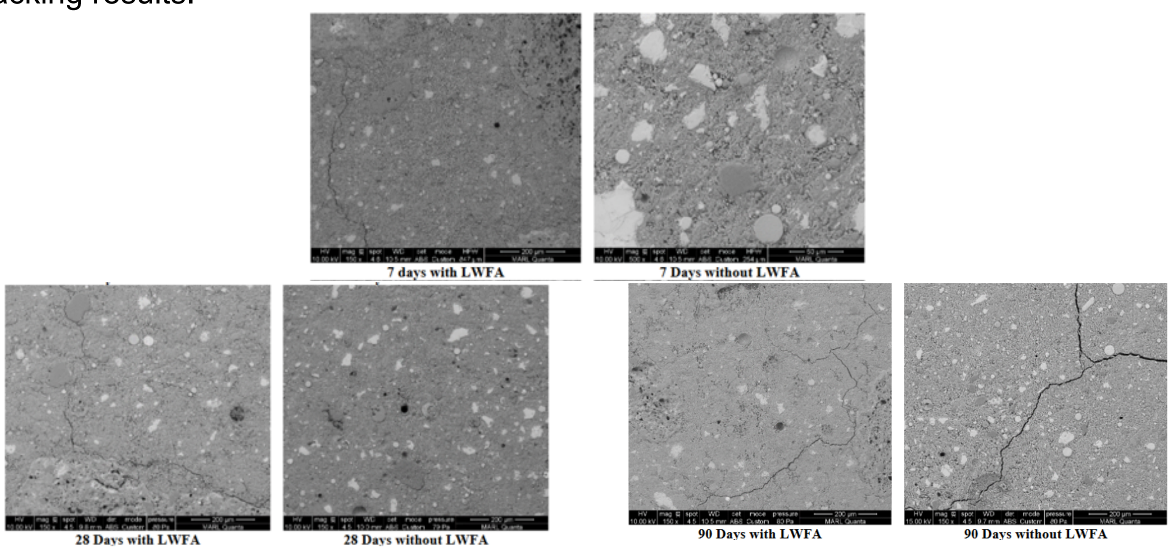


Figure 18. Comparisons of Cracking of LWFA and non-LWFA Concrete [42]

The research team concluded that internal curing improves the degree of hydration over time does not affect maturity, reduces temperature and moisture differentials, decreased deck warping and curling, and improved permeability resistance. In terms of LCA, internal curing indicated a long-term financial benefit based on maintenance work and extended life.

Wisconsin DOT [2021] [36]

In 2021 Wisconsin DOT published a study with Construction Technology Laboratories, Inc. to evaluate the performance of internally cured concrete with the aim of reducing volumetric changes, cracking, and warping. A distress survey was conducted on 12 ICC bridge decks of the Illinois Tollway system. The survey showcased a decrease in cracking in all structures using expanded slag LWFA, with most of the cracking being structural related cracking observed continuing from the precast approach slabs. From 12 ICC bridge decks, only single crack was observed that is suspected to be associated with volumetric changes.

Twelve concrete mixtures were tested in a laboratory setting to assess IC agents, with four testing LWFA and four testing SAP. Each IC agent was tested in a mixture with slag and fly ash as well as with a w/c ratio of 0.45 and 0.36. This study concluded that the replacement level suggested by Bentz and Snyder [31] resulted in optimal performance of the mixture. Mechanical properties were largely improved, especially regarding shrinkage mitigation and improved durability. Significant improvement was observed in ICC regarding resistance to cracking in restrained conditions. Total shrinkage in free conditions was comparable to control mixtures in free conditions. Overall, LWFA were reported to produce more consistent results than SAP mixes, and recommendations were made for verification through trial mixes for SAP mixes due to increased variance in fresh properties. Life-cost analysis showed an increase in initial costs, with a reduction in costs once rehabilitation is factored in.

Summary of Specifications and DOT Study Results

Table 5 describes the outcomes of the reports that investigated the use of LWA for internal curing as well as their performance enhancement compared to HPC without internal curing agents. Performances shown are compared only if the study included a control mix with the same proportions to an HPIC modification with the only difference being its LWA content. Table 6 shows the mix design that provided the best performance in the studies described in Table 5.

Table 5 – DOT Field Study Results of LWA for Internal Curing

DOT	Application	ICA		Performance Change from HPC (28 Days)				
		Material	Product	f_c'	f_t	MOE	MOR	SHRKG
OH [28]	Pilot study	LWFA	Hydrocure	+6%	+15%	-	+4%	-100%
NY [29]	Bridge Deck	LWFA	Norlite	*	-	-	-	-5%
KS [30]	Bridge Deck	LWFA	Haydite	+7%	-4%	-	-	-15%
IN [26]	Bridge Deck	LWFA	Stalite	+10%	+10%	*	-	-80%
OR [31]	Lab Testing	LWFA	Multiple	+26%	+7%	-29%	-	-25%
CO [32]	Pilot study	LWFA	Haydite	+10%	-	-20%	*	-30%
UT [33]	Bridge Deck	LWFA	Utelite	+2%	-	-7%	-	-
FL [34]	Pavement	LWFA	Riverlite	-11%	-4%	-19%	-	+20%
PA [35]	Pilot Study	LWFA	Multiple	-	-	-	-	-23%
TN [36]	Bridge Decks	LWCA	Stalite	-	-	-	-	-
NC [37]	Bridge Deck	LWFA	Stalite,	-33%	-			-50%
LA [39]	Bridge Deck/Pavement	LWFA	Riverlite	+30%	-	-22%	*	-
VA [40]	Bridge Deck	LWCA	Stalite	-	-	-	-	-
NB [41]	Bridge Deck	LWFA	Haydite	+22%	-	-17%	-27%	-39%
IA [42]	Pavement	LWFA	Riverlite	+28%	+19%	+2%	-	-
WI [43]	Pilot study	LWFA	Tru Lite	+8%	-			-45%

* Values remain largely unaffected
MOR = Modulus of Rupture; MOE = Modulus of Elasticity; SHRKG = Free Shrinkage

Table 6 – DOT Study Mixtures using LWA [lb/yd^3]

DOT	Cement	Slag	Fly Ash	SF	Sand	LWFA	CA	LWCA	Water	Material
OH [28]	480	0	150	30	1012	227	1480	0	264	Shale
	440	190	0	30	1041	227	1490	0	264	Shale
NY [29]	473	100 - 135	0	41 - 68	779	334	1800	0	258	Shale
	540	0	100 - 135	41 - 68	779	334	1800	0	258	Shale
KS [30]	540	0	0	0	1057	243	1515	0	237	Shale
IN [26]	435	0	115	25	825	340	1740	0	228	Shale
OR [31]	455	130	0	25	654	385	1796	0	257	Shale
	419	0	189	25	812	130	1810	0	234	Clay
	419	0	189	25	761	277	1810	0	234	Shale
NC [37]	572	0	172	0	890	139	1720	0	266	Shale
LA [39]	600	0	114	0	819	291	2031	0	210	Clay
VA [40]	480 – 680	0	120 - 170	0	0	1300*	0	875*	270	Slate
	360 – 510	240 – 340	0	0	0	1300*	0	875*	270	Slate
	360 - 480	240	0	0	1300*	0	1804	0	270	Slate
NB [41]	457	0	114	0	942	200	1698	0	257	Clay
IA [42]	457	0	114	0	861	330	1672	0	246	Clay
	474	0	119	0	998	363	1539	0	255	Clay
WI [43]	364	0	156	0	843	238	1892	0	234	Slag
	432	108	0	0	855	247	1892	0	243	Slag

* VDOT mixes are from a study of 23 mixtures [40], all with varying amounts of LWCA, LWFA, and cementitious. The values shown are typical mixtures based on the mixtures studied

Mix designs typically include a maximum replacement of 30 percent, with some DOTs allowing a lower replacement depending on the required performance. It is recommended to use SCMs that increase density and react with the alkali content of the cementitious matrix to help mitigate ASR reactivity enabled by the internal curing process. Therefore, each mixture must include a percentage of pozzolanic material such as fly ash or slag cement. Silica fume is also typically dosed for use in high-performance concrete (HPC) elements; however, it is not required for all proposed mix designs.

Currently, LWFA are the only accepted material for internal curing, while SAPs, SFs, and LWCA are not. LWCA is typically used to reduce the weight of concrete but is generally not approved for internal curing. LWFA is preferred over LWCA due to its improved particle distribution and absorption capacity, allowing for greater retention of internal moisture in concrete and resulting in enhanced internal curing performance [28]. SAPs and SFs remain unapproved largely due to a lack of material availability and studies on their performance in concrete elements. Moreover, they are not as readily available as LWFA. Key takeaways from previous work are presented, along with a culmination of current HPIC specifications shown in Table 7.

LWA preparations: To achieve the optimum benefits of HPIC, LWA should be at or near SSD condition when utilized. Most DOTs specify uniform periodic sprinkling for approximately 24 hours prior to use. NYSDOT, Indiana DOT, and the National Concrete Pavement Technology Center agree that pre-wetting is required. Large-scale preparation is conducted using LWA stockpiles, which are soaked prior to use. Stockpiles are mixed periodically to ensure uniform moisture distribution. It is also noted that stockpiles may pose challenges for certain facilities that lack the space to create them.

Cement limits: Minimum cement content is specified to be 715, 658, and 700 lb/yd³ for NC, DC, and MD, respectively. The cement limit is intended to maintain the strength properties of the concrete (compressive strength, flexural strength, tensile strength) while reducing shrinkage.

External curing periods: It can be reduced compared to conventional concrete. NYSDOT specifies 7 days of external wet curing with 30 percent LWA, which is 50 percent less than the curing period specified for conventional concrete. This reduces labor, cost, and construction time and is possible because the internal moisture content of the LWA compensates for the reduced external curing.

Maximum average density: A 118-120 lb/ft³ of maximum average density is specified by Maryland and Virginia DOTs, respectively. This requirement is intended to reduce dead load; however, it may have little impact on internal curing properties.

Although LWA is primarily used to mitigate shrinkage and cracking for all DOTs, shrinkage limits are not specified by any of them. Studies that have inspected HPIC deck pours compared to control HPC deck pours on the same bridge report differences in cracking performance through deck crack mapping, but no quantifiable values are provided for in-lab or in-situ testing to directly correlate with deck performance.

LWA internal moisture: A 8 lb of LWA internal moisture per 100 lb of total cementitious materials is required by Mississippi DOT for bridge deck applications. This moisture content is specified to achieve long-term hydration and internal curing of the concrete. Florida DOT specifies 7 lb of absorbed water per 100 lb of total cementitious material. This difference is likely due to variations in the materials used, as the absorption rate, specific gravity, and desorption rate can vary greatly depending on the LWA material and its source.

Casting processes and curing: North Carolina DOT observed the potential for water to be removed from the LWA due to pumping pressure and recommends a minimum 5-inch diameter pump line to reduce pressure. For curing, conventional methodologies and durations are recommended. However, while it is possible to reduce curing time due to internal curing mechanisms, according to NYSDOT and LADOTD, any reduction in curing time should be validated during a mockup.

Table 7 – Available Specifications of LWFA in US DOTs.

DOT (Year)	Applications permitted
DC (2013)	For structural concrete; Min. Cement = 658 lb/yd^3, Max w/c allowed = 0.44; absorption value of LWCA not exceed 10 % in 24 hours; min. 28-day f_c' = 4000 lbf/in^2, Max. permeability = 1500 coulombs
MS (2017)	Bridge deck: LWA should contain 8 lb of water per 100 lb of total cementitious materials
WV (2017)	Lightweight fine/coarse aggregate for structural concrete
NC (2018)	Min cement content for LWC = 715 lb/yd^3
VA (2020)	Max Cement content = 650 lb/yd^3 max of cement Maximum density of freshly HPIC shall be 120 lb/yd^3
MD (2021)	Superstructure concrete, Min Cement content = 700 lb/yd^3, f'_c = 4500 @ 28 days, the maximum average Density of Cured Concrete shall be 118 lb/ ft^3.
OR (2021)	Concrete designed to utilize lightweight fine aggregate to mitigate shrinkage
NY (2022)	Substitute 30% of Standard Fine aggregates with LWFA; Max w/c allowed = 0.4; Curing Period = 7 days (-50% compared to standard curing period)
IL (2022)	LWA shall be in a moist condition achieved by periodic sprinkling
FL (2022)	LWFA suitable for internal curing shall meet the requirements of ASTM C1761.

Survey of Concrete Suppliers and Industry Partners on Internal Curing

In order to assess the readiness of concrete providers in the state of New Jersey, two premier concrete suppliers servicing New Jersey and the surrounding region shared their experience with internal curing concrete, lightweight aggregate usage, and their thoughts on readiness for large-scale internal curing implementation for DOT bridge deck and pavement projects. Their responses are assessed alongside lessons from the literature review and laboratory testing.

Clayton Concrete, herein referred to as Concrete Supplier 1, and Silvi Concrete, referred to as Concrete Supplier 2, provided full responses. Questions were placed into two categories: 1) previous experience with IC or lightweight concrete (LWC) and 2) questions to determine readiness and the steps needed for implementation.

1) Experience
Have you produced internal curing concrete?
Response: Yes, using Light Weight Aggregate #57 & #8

If so, how often and since when?
Response: Approximately 25,000 yards per year

What type of lightweight aggregate have you used? Supplier?
Response: Solite (Only Coarse aggregate, not light weight sand)

Which agencies have you worked with for internal curing concrete?
Response: NJDOT used Clayton LTWT HPC on Rt 280 project on bridge decks in 2015. HPC failed Freeze/Thaw during verification "due to high absorption, 18 to 20%" using the coarse expanded aggregate

What type of structures (building, bridge, etc) have you supplied with internal curing/lightweight concrete?
Response: Mainly Slab on deck for buildings and bridge decks

2) Readiness
Do you have additional compartments or silos to accommodate lightweight aggregate? If not, do you have plans?
Response: We do have bins for light weight coarse aggregates but not for fine aggregates. Temporary stockpiles can be used for IC material.

Have you ever provided training for the ready-mix truck drivers and batch operators about internal curing concrete?
Response: Internal curing concrete batching was done in coordination with RIME for field testing

Concrete supplier 2 also has extensive experience with LWC and currently stockpiles and uses expanded clay coarse aggregate. Survey was completed verbally by the head of Technical Services and paraphrased.

1) Experience Have you produced internal curing concrete? *Response: Yes, Arcosa lightweight aggregate specifically for light weight concrete in 3/8th* If so, how often and since when? *Response:* Since widespread implementation What type of lightweight aggregate have you used? Supplier? *Response: Arcosa lightweight materials, shipped by train from expanded clay plant in Alabama to the primary Ready-mix plant in PA* Which agencies have you worked with for internal curing concrete? *Response: Approved provider for NJDOT, PENNDOT, and NCDOT* What type of structures (building, bridge, etc) have you supplied with internal curing concrete? *Response: Lightweight concrete for building slabs and bridge decks* 2) Readiness Do you have additional compartments or silos to accommodate lightweight aggregate? If not, do you have plans? *Response: Material is submerged in basins to ensure complete saturation. Additional temporary bin space can be made per request for lightweight fine aggregates at satellite plants when required.* Have you ever provided training to the ready-mix truck drivers and batch operators about internal curing concrete? *Response: Plant and batch operators are well experienced producing LWC*

Overall, producers have some knowledge of the requirements for IC concrete implementation due to the similarities to lightweight concrete production. Lightweight aggregate and its use in concrete is a mature industry with widespread application, specifically in urban and developed regions where use in high-rise buildings and bridge decks is commonplace. Testing requirements for lightweight concrete are given in ASTM C330. Parallels and differences between the two material classifications were assessed to evaluate the applicability of concrete producers' current experience and considerations for applying that experience to internal curing concrete production.

The base material of expanded shale, clay, or slate aggregate is functionally the same for internal curing and lightweight concrete use and requires proper prewetting, stockpiling, preparation, sampling, and batching procedures.

Expanded aggregate for lightweight concrete has been intentionally relegated to coarse aggregate to reach the targeted unit weight of 90 to 135 lb/ft³ as specified by ASTM C330. A large portion or all of the normal-weight coarse aggregate is replaced by lightweight expanded coarse aggregate to meet the required unit weight of concrete to be considered lightweight. According to Concrete Supplier 1, lightweight coarse aggregate is often blended using precalculated volumes of #8 and #57 to simplify batching and reduce the burden of requiring multiple stockpiles to be set up and prepared.

Internal curing materials, typically classified as lightweight fine aggregate, have a higher degree of fines to achieve higher absorption and desorption capacity, as well as a more homogeneous distribution in the concrete matrix, as specified in ASTM C1761. Additionally, ensuring a high degree of saturation of the LWFA is more critical for IC concrete [26,33] compared to lightweight coarse aggregate when used in lightweight concrete, which emphasizes the need for proper preparation, batching, and sampling. Notably, a much smaller proportion of the concrete formulation is replaced by lightweight material, typically 30–50 percent of normal-weight sand depending on the material and dosage requirements. Concrete Supplier 1 stressed challenges with lightweight aggregate and freeze-thaw testing using coarse aggregate. These challenges were highlighted in the literature review, where pop-out defects were found a year after production in a bridge deck using lightweight coarse aggregate, raising concerns for the implementation of IC concretes. Freeze-thaw testing during in-lab complete evaluation and in other DOT pilot programs has not shown significant concern, which is attributed to the fine particle size of LWFA negating deleterious effects of freezing and thawing, with similar results shown when compared to a control HPC.

Concrete Supplier 1 partnered in batching and delivering a converted control for field testing of HPIC. Follow-up questions were addressed onsite during the demonstration with the head of QC and a lead technician with extensive experience. The use of HPIC, aside from the additional effort required for batching, showed no significant difference in fresh properties or finishability. Both representatives deemed the implementation feasible for NJ.

LABORATORY-BASED RESEARCH PROGRAM

The project integrated lessons learned from the literature review into both laboratory and field testing of HPIC. Upon completion of the literature review, a framework for the work plan was developed to build upon the existing knowledge base of this material technology. Specifically, successful implementation strategies identified in the literature were replicated in the laboratory to simulate large-scale production, strengthen correlation with field testing, and enhance readiness for institutional adoption.

The primary objectives of the laboratory and field testing were to evaluate and recommend a cost-effective HPIC for bridge deck and pavement applications and, through this process, to assist NJDOT in developing detailed specifications for institutional adoption.

Selection and Characterization of Internal Curing Agent

Internal curing materials were sourced for testing with consideration for availability and economic feasibility in New Jersey and the Northeast in general. Primary considerations were materials already approved for use in New Jersey through the NJDOT Qualified Materials Engineering List. Products or variants specifically intended for internal curing from Stalite and Northeast Solite were used. Products that were available and economically feasible for use in the Northeast, such as those from Arcosa, which can be delivered by train from its plant in Alabama, were also tested. A superabsorbent polymer (SAP) product was selected based on widespread industry usage and its use in numerous concrete research programs. A Superfine Particle (SP) product was also sourced for feasibility testing. These materials are summarized in Table 8.

Table 8 – Selected Materials and Their Properties per Supplier

Company	Product Name	Material Descrip.	Plant Location	Absorption (72h submersion)	S.G. at SSD	NJ QPL
Northeast Solite	Hydrocure	Exp. Shale	Saugerties, NY	18%	1.8	Yes
Northeast Solite	Greenlite	Exp. Shale	Saugerties, NY	10%	1.8	Yes
Stalite	Washed MS-16	Exp. Slate	Salisbury, NC	12.1%	1.9	Yes
Arcosa	Riverlite	Exp. Clay	Livingston, LA	32%	1.43	No
BASF	HySorb – Tro C	Polymer (SAP)	Florham Park, NJ	>5,000%	~1	No
Agrilectric	Maxflo	Rice hull ash (SP)	Lake Charles, LA	50-60%	~2.3	No

Preliminary selection resulted in the exclusion of the SP material. Because it is a superfine particle, it would drastically affect the fresh properties of a mixture if used as a replacement for fine aggregate. A powder replacement or a full mix formulation rework would have been required, and the focus was placed instead on materials compatible with current practices in the USA.

The remaining materials underwent characterization for their physical properties, namely their absorption properties using both the centrifuge method and the paper towel method, as well as their desorption behavior over time. An accurate absorption calculation ensures that the correct amount of adhered water is accounted for during batching, and that a proper dosage of internal curing material is used to replace normal-weight sand to ensure proper internal curing. Desorption behavior can be used to assess how rapidly an internal curing material releases its stored water to aid in hydrating the surrounding concrete matrix.

Absorption Testing and Analysis

Lightweight material characterization as per ASTM C1761 allows for both centrifuge and paper towel methods to be used. The paper towel method involves taking a measured sample and placing it on paper towels in a well-ventilated area, then patting the aggregate pile with fresh paper towels until they remain dry after patting, as shown in Figure 19. By removing adhered water, a state at or approximating SSD is achieved and then weighed. Once weighed, the samples can be oven dried to determine the absorption of the sample.

One demerit of the paper towel method is its visual nature, as it leaves the decision up to the tester to determine when the SSD condition is satisfied. Care must be taken to ensure that minimal fine particulate is removed along with the adhered water. For industry use, it is likely that multiple operators will need to be trained, which can introduce operator error.

The centrifuge method is largely independent of operator error when done consistently. The major demerit is the requirement for a centrifuge extractor device, as shown in Figure 19, which in 2025 can be sourced for 3-5 thousand dollars depending on the model selected. This upfront cost and the additional testing requirements may be a consideration for concrete suppliers.

With the centrifuge method outlined in ASTM C1761, soaked lightweight aggregate of approximately 600 grams is taken from a thoroughly mixed stockpile, loaded into the bowl, and weighed. It is then spun at 2000 ± 20 rpm for 4 ± 1 min, removed, and weighed to determine the mass of adhered water that was spun off. The sample is now effectively in a saturated surface-dry (SSD) condition and can be oven dried to determine the absorbed water capacity at the time of testing. Care must be taken to ensure a new filter is properly applied to minimize the loss of fine material and accurately determine the percentage of adhered water. Additional care must be taken by the operator to ensure proper fitment of the centrifuge components so that no material is lost, and experience shows that fine aggregate should be brushed off the filter and retained for measurement accuracy.

Figure 19. Centrifuge and Paper Towel Testing used for This Project

With the centrifuge method, water adhering to the surface of soaked aggregate is mechanically expressed using a centrifuge, allowing for an accurate calculation of saturation percentage and additional free-water content. An alternative when a centrifuge device is unavailable is the paper towel method, where water adhering to the surface of soaked aggregate is manually removed using paper towels, allowing for a reasonable prediction of saturation percentage and additional free-water content with minimal equipment.

Absorption testing showed the varying capacities of each material to act as a water reservoir for internal curing. The experimental absorption results at 72 hours were compared to the manufacturers' listed 72-hour absorption capacities in Table 9. The expanded clay product had the highest absorption capacity at over 30 percent after 3 days of soaking. The expanded clay also showed similar 1- and 3-day absorption, demonstrating its capacity to rapidly achieve a soaked state due to its lightweight and highly porous structure. The expanded shale product specifically developed for internal curing had an absorption capacity of 17-19 percent at 72 hours, with a lower absorption of 15.5 percent after one day of wetting. This difference between 24- and 72-hour absorption highlights the importance of proper soaking of material stockpiles to ensure optimal usage of the internal curing material. The expanded slate product specifically developed for internal curing had the lowest absorption at approximately 11-11.5 percent, and, similar to the expanded shale, showed a need for proper preparation to ensure its absorption capacity is fully achieved.

Table 9 – Absorption Properties using Paper Towel and Centrifuge Methods

Supplier	**ICA**	**Absorption (72 hr)**	**Absorption (24 hr)**		**Absorption (72 hr)**	
			Paper towel	**Centrifuge**	**Paper towel**	**Centrifuge**
Northeast Solite	Hydrocure	18%	15.6%	15.4%	17.5% **(-3%)**	18.8% **(+4%)**
Northeast Solite	Greenlite	10.2%	13.8%	13.7%	15.4% **(+40%)**	15.6% **(+42%)**
Stalite	Washed MS-16	12.1%	10.1%	9.4%	10.9% **(-10%)**	11.5% **(-5%)**
Arcosa	Riverlite	32%	27.3%	30.2%	34.1% **(+6%)**	30.7% **(-4%)**

Castro [44] showed comparable results, with 24-hour absorption for Hydrocure and Livlite, a previous branding of a comparable expanded clay product produced by the same plant, at 15 percent and 30.5 percent, respectively. A previous iteration of Stalite showed 6 percent absorption, illustrating the importance of using their IC-specific product, Washed MS-16, which showed a 33 percent increase in absorption with a 24-hour value of 9.4 percent. The paper towel method was used as specified by NYSDOT. Figure 20 shows the aggregates selected with LWFA images from the manufacturer to show coloration.

This testing was used to assess the differences between the two ASTM C1761-approved methods of testing absorption, namely the centrifuge method and the paper towel method. Results were comparable, but up to 1 percent variance was observed for expanded shale and slate materials, while up to 4 percent variance was observed for the expanded clay material.

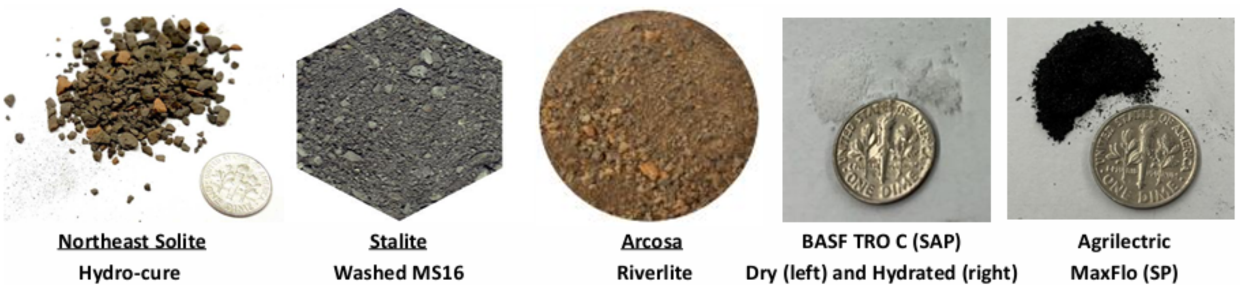


Figure 20. Materials Selected for Review

Aggregate Desorption Testing and Analysis

Desorption and the rate of desorption are important for IC material selection. As the process of hydration depletes the available pore water, the IC material desorbs the internally stored water and acts as a water reservoir for continued hydration. This is particularly important for low-porosity concretes such as HPC, where externally applied curing water may not effectively or consistently reach the interior of a cast cross section. Low water–cement ratio concretes like HPC reach a final internal relative humidity of 85–95 percent, after which hydration slows to a negligible rate. Desorption testing is done at 94 percent RH to predict how much water has been released during the curing stage (Lura, 2003) [45].

Desorption testing was undertaken according to ASTM C1761 to determine the capacity of the selected internal curing aggregate materials to release stored water as shown in Figure 21. Presoaked aggregate at SSD was maintained at 94 percent RH and 21 ± 2°C environment using a potassium nitrate solution in an airtight bag. Each sample consisted of 5 grams of fine aggregate in SSD condition after 72 hours of soaking. Calibrated temperature and humidity sensors were included in the test to ensure environmental conditions were maintained for the duration of testing. A scale capable of measuring 0.0001 grams was used to determine the water lost from saturated SSD samples over the duration of testing. Testing was undertaken on the same samples to determine the dry weights and initial absorption values. Once the rate of desorption decrease was deemed negligible, specified in ASTM C1761 as 0.01 grams in 24 hours (Figure 22), the test was considered complete and desorption values were calculated (Table 10).

Figure 21. Expanded Aggregate Desorption Testing Setup

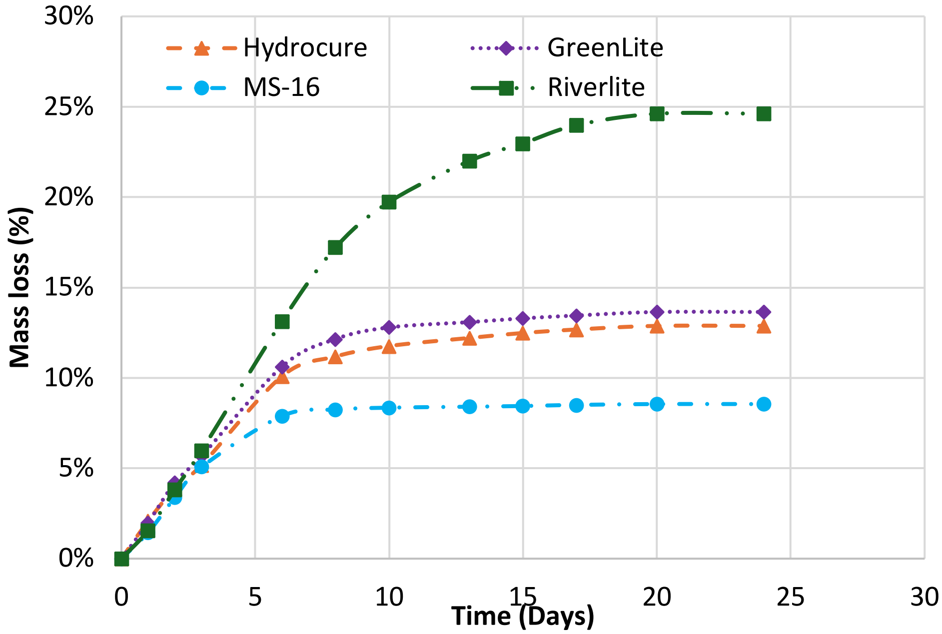


Figure 22. LWFA Mass Lost Through Desorption

Table 10 – Desorption Testing Overview

Company	Material	Desorption*	Casto 2011 et. al.
Northeast Solite	Hydrocure	93.2%	95.1%
Northeast Solite	Greenlite	93.8%	n/a
Stalite	Washed MS-16	95.7%	96.7%
Arcosa	Riverlite	91.9%	92.2%
BASF	HySorb	~86%**	n/a

* tested at 94% Relative Humidity (Mass Oven Dry sample/Final mass at 94% RH)
** SAP was shown in literature to desorb approximately 86% when tested according to ASTM C1761-17 at 94% RH (Montanari 2018).

Results from material characterization were used to aid in ICA selection and dosage. The expanded shale, slate, and clay products specifically designed for internal curing were selected for expanded testing. The SAP product was also selected for evaluation. All the LWFA materials tested displayed a similar desorption profile.

The “green” variant of expanded shale was excluded due to its redundancy, its higher variability in absorption caused by its higher fine content, its lower availability, and its use in a different industry. The Superfine Particle ash product was excluded because it is a powder, specifically a fine powder with a particle profile similar to fly ash and silica fume. The SP, being a fine powder rather than a fine aggregate, would require significant modification to the formulation and replacement of cementitious powders to retain fresh properties, due to the increased water demand associated with the increased fine material.

Laboratory-Based Experimental Program

An initial evaluation was conducted to test the provided NJDOT HPC formulation as a control and four NJDOT HPC-modified formulations with dosages of the three down-selected LWFAs and one SAP as IC carriers. A target of 7.5 ± 0.2 lb of internally trapped water per 100 lb of cementitious material was selected to conservatively ensure the minimum of 7 lb of internal water per 100 lb of cementitious material, and this target was exceeded as the material testing and laboratory batching procedure was developed.

A focus was placed on fresh-property testing to assess any differences in workability, slump, unit weight, and air content of HPIC compared to the control HPC. Strength testing was done to assess compressive, tensile, and flexural strengths, as well as stiffness through elastic-modulus testing. Durability was assessed with free-shrinkage testing and internal humidity. Autogenous (sealed) shrinkage testing was conducted during the complete evaluation. Additional preliminary testing was done with surface resistivity and rapid-chloride-penetration testing. LWFA types, characteristics, dosages, and evaluation of HPIC under different wetting and curing scenarios were assessed after the initial testing was complete, and materials were selected for continued testing.

Since the primary focus of this testing was to assess dosages and curing conditions rather than the materials themselves, one mixture containing the most commonly used LWFA, expanded shale, was selected for all testing. Wet-curing testing incorporated different regimes to assess the standard dosage of 7 lb of water per 100 lb of cementitious material. Four methods were selected, from most to least optimal: first, 14 days of wet curing, which is the standard NJDOT requirement; second, 7 days of wet curing followed by application of curing compound, a regime used for NYSDOT HPIC bridge decks; third, 7 days of wet curing; and fourth, no wet curing at all. Post-curing conditions were maintained at 50 percent relative humidity in a laboratory setting.

Testing consisting of shrinkage testing (ASTM C157), compressive-strength testing (ASTM C39), internal-humidity testing (ASTM F2170), and surface-resistivity testing (AASHTO T358) was conducted at days 1, 7, 28, and 56 to assess the effectiveness of the different curing regimes.

Complete-evaluation testing primarily expanded the scope of the testing done initially. No materials were down-selected, since each IC product, expanded shale, slate, clay, and SAP, had benefits that warranted continued investigation under the expanded testing. The control HPC and expanded-shale HPIC underwent complete evaluation with no omitted testing.

Control Mix Design

A typical NJDOT mix was selected for use and was modified based on the current practices for Internal Curing HPC in the US that were investigated in the literature review. Laboratory testing was conducted on the concrete mixture provided by the NJDOT, and field testing was done using an NJDOT approved mixture provided by our industry partner and delivered via ready mix truck. Both formulations are NJDOT HPCs and can be used interchangeably. Formulations are detailed in Table 11.

Table 11 – Control Mix Design for Laboratory and Field Testing (lb/yd^3)

NJDOT HPC	Cement	Slag	Silica Fume	w/c ratio	Total Binder	Rock	Sand
Lab	450	200	25	0.382	675	1810	1113
Field	370	263	25	.385	658	1800	1233

All testing incorporated control mixtures of the unmodified HPC formulation alongside the modified HPIC variants. Internal Curing materials were added in as a substitute for fine aggregate, normal weight sand.

Laboratory-Based Testing Procedure

To establish consistency and best replicate field stockpile conditions, LWFA material was soaked underwater for 72 hours and drained 24 hours before mixing. LWFA material was placed in a pile and covered with plastic to retain humidity while still allowing free water to drain via gravity as shown in Figure 23. The waterlogged material on the bottom was excluded. Collected material was well mixed and samples centrifuged to calculate adhered external water. SSD samples oven dried to confirm absorbed internal water.

Batched aggregate and powder materials were weighed out to 0.02 lb while chemical admixtures were measured to 1 ml accuracy. Trial batches consisted of 1 ft^3, while initial testing batches consisted of 4 ft^3 mixtures and complete evaluation batches were 6 ft^3. The working capacity of the mixer was approximately 6.5 ft^3 depending on the workability of the mix.

Figure 23. Batching Procedure

Mixing procedure remained consistent for all laboratory testing and was developed during the initial trial mix. Half the conventional aggregate was added initially along with half of the batch water. The aggregate was run until well wetted and mixed for approximately 2 minutes. The air entrainer dosage and 75 percent of the High Range Water Reducer were added to the remaining batch water and set aside. Half of the batched powder component was added next on top of the wetted aggregate and covered with a quarter of the batched conventional aggregate. A bit more than half of the remaining water with the chemical dosage was added into the mix and allowed to run until well mixed for approximately 5 minutes. The remaining conventional aggregate and half of the LWFA was added. The remaining portion of the water was added, and the mix was allowed to run while the remaining LWFA was finely spread into the running mixer. For HPIC SAP, saturated SAP was hand dosed at this stage. If required to modify slump for casting purposes, more of the batched HRWR dosage was added and the dose was recorded. The mix was allowed to run for a period of 10 minutes and was sampled for fresh properties. If air content was deemed suitable the casting of samples was begun.

Casting conformed to ASTM C192 with rodding and mallet tapping of samples at the specified lifts. Vibrating tables providing external vibration were used briefly after each lift to ensure consolidation of shrinkage and flexural prisms. Samples were removed from molds 22 ± 2 hours after casting and tested 24 hours ± 30 minutes after casting for Day 1 testing. Typical cylinder and flexural sample prisms were wet cured in a misting room conforming to ASTM C192 and maintained at 73.5 ± 3.5°F and above 95 percent RH. Samples were maintained with a continuously saturated surface.

Initial Evaluation

Initial evaluation testing began with reduced 1 ft^3 volume trial mixes of each respective formulation to gauge chemical admixture dosages and to dial in the fresh properties of slump, air content, and unit weight. Compression and elastic modulus cylinder samples were cast for day 1, 7, 28, and 56 testing. The testing plan is summarized in Table 12. Once deemed satisfactory, the full 3-4 ft^3 mixture was mixed, and samples were cast for the full Initial evaluation testing regime. This process was done to increase consistency and to conserve LWFA material sampled from the producers. A total of 12 mixes consisting of 6 trials and 6 full testing regimes were mixed and cast as summarized in Table 13.

Table 12 – Testing plan for Initial Evaluation

Characterization	Standard	Test Method	Age (Days)	Units (#)
Strength	AASHTO T22	Compressive Strength	1,7,28,56	3
	ASTM C496	Tensile Strength	1,7,28,56	3
	AASHTO T97	Flexural Strength	1,7,28,56	2
	ASTM C469	Modulus of Elasticity	1,7,28,56	2
Durability	ASTM C157	Free Shrinkage	1,7,28,56	3
	ASTM F2170	Internal Humidity	1,7,28,56	2
	AASHTO T277	Chloride Permeability	28,56	2
	AASHTO T358	Surface Resistivity	28,56	2
Fresh Properties	AASHTO T119	Slump	-	1
	AASHTO T152	Air Content (Pressure)	-	1
	ASTM C173	Air Content (Volumetric)	-	1
	ASTM C138	Unit Weight	-	1

Initial Evaluation Testing Results

Testing was done in a concrete rotary drum mixer with a capacity of 6-7 ft^3. Mix size was deemed to be a factor comparing trial mixes to initial evaluation mixes. A higher mixing energy imparted (power and duration) over a similar mixing duration is likely to result in a lower air percent and more homogenous mixture resulting in consistently higher unit weight and slightly higher compressive strengths for mixtures at 1 ft^3 (17 percent capacity) compared to 4 ft^3 (67 percent capacity). Chemical admixtures were adjusted with a reduced air entrainer dosage being used once the relationship was established.

Regarding fresh properties, the air content pressure method showed similar results to the volumetric pressure method. Initial reported variance was corrected with a recalibration of the faulty Pressure Air meter by the manufacturer. Slump was largely determined unaffected by the inclusion of IC material, and any difference was primarily associated with variation in high range water reducer used to fine tune the slump for casting purposes.

Table 13 – Initial Evaluation Fresh Property Testing

Mix formulation	**HPC**	**HPIC Clay**	**HPIC Clay**	**HPIC Clay**	**HPIC Clay**	**HPIC Shale**	**HPIC Shale**	**HPIC Slate**	**HPIC Slate**	**HPIC Shale**	**HPIC SAP**	**HPIC SAP**
Air content Pressure method (%) *	5.75*	6.25*	9.5*	5.5*	9*	3.5*	7.5*	5*	6*	5.5*	6	7.5
Air content Volumetric method (%)	n/a	5	9.5	5	9	3.5	7.5	4.5	5.75	5	6	7.5
Slump (in)	4	6	6.5	4.5	5.5	6	7.5	5.25	4.25	3.75	4.5	5.75
Unit weight (lb/ft^3)	144.8	140.4	132.4	141.6	134.6	144.2	136.6	143.1	139.1	141.4	144	139.7
Absorption at testing (%)	n/a	27.65	27.75	26.5	26.5	16.25	16.4	12	12	19.1	n/a	n/a
Air entrainer (fl oz/100lb cem)	.3	.3	.3	.2	.2	.3	.3	.2	.2	.2	.2	.2
Mix size (ft^3)	4	1	4	1	4	1	4	1	4	1	1	4

* Initial results offset by 1% after recalibration of the Air Meter

Table 14-17 summarize compressive strength, splitting tensile strength, flexural strength and modulus of elasticity, respectively. The percentage difference for HPIC results were compared to the control HPC. Initial evaluation testing showed largely consistent results between HPC and the three HPICs with LWFA for compressive strength, tensile strength, modulus of elasticity, and flexural strength. HPIC with SAP showed a reduction in strength compared to HPC for all respective tests and follows trends supported by literature (Xu et al. 2021) [46]. The cause of strength reduction is the resulting void space left as the absorbent material desorbs.

Durability testing setups for RCPT and SR are shown in Figure 24. HPC/HPIC did not show considerable differences between formulations between standard and extended test periods. AASTHO 277 Guidelines for RCPT show coulombs passing 1000-2000 are classified as “Low permeability” and are typical of “low w/c ratio < 0.4” mixes. HPC and HPIC formulations had results between 989 and 1615, typical of a base mixture with 0.385 w/c. SR testing showed similar results.

Table 14 – Compression Strength AASHTO T22 (psi)

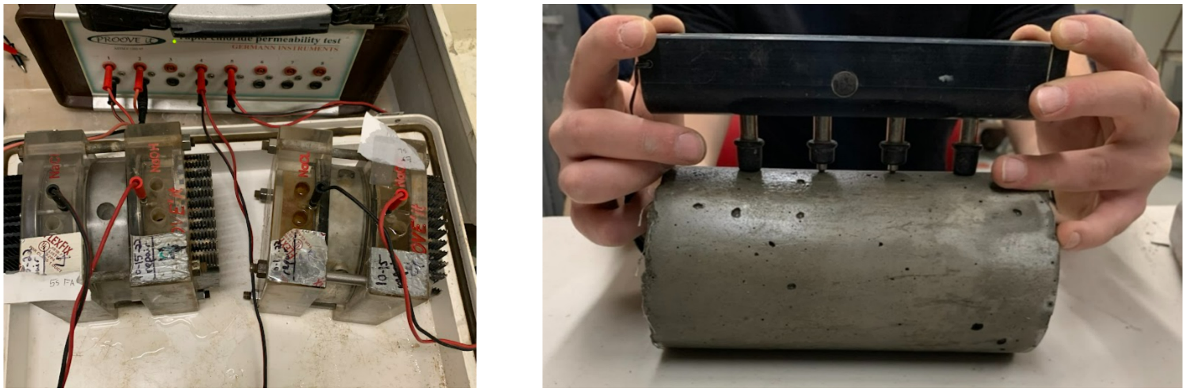
Time (Days)	HPC	HPIC Shale	HPIC Clay	HPIC Slate	HPIC SAP
1	2783	2642 (-5%)	2905 (4%)	2427 (-15%)	1561 (-78%)
7	5354	4953 (-8%)	5093 (-5%)	4973 (-8%)	3720 (-44%)
28 (Standard)	6409	7400 (13%)	7282 (12%)	6843 (6%)	5709 (-12%)
56 (Extended)	7325	7619 (4%)	7341 (0%)	7301 (0%)	6207 (-18%)

Table 15 – Splitting Tension ASTM C496 (psi)

Time (Days)	HPC	HPIC Shale	HPIC Clay	HPIC Slate	HPIC SAP
1	279	269 (-4%)	307 (9%)	249 (-12%)	189 (-48%)
7	368	289 (-28%)	433 (15%)	299 (-23%)	279 (-32%)
28 (Standard)	464	537 (14%)	458 (-1%)	478 (3%)	413 (-12%)
56 (Extended)	487	582 (16%)	468 (-4%)	438 (-11%)	418 (-17%)

Table 16 – Flexural Strength AASHTO T97 (psi)

Time (Days)	HPC	HPIC Shale	HPIC Clay	HPIC Slate	HPIC SAP
1	535	503 (-6%)	558 (4%)	547 (2%)	438 (-22%)
7	687	700 (2%)	788 (13%)	831 (17%)	755 (9%)
28 (Standard)	907	897 (-1%)	886 (-2%)	941 (4%)	831 (-9%)
56 (Extended)	920	875 (-5%)	963 (4%)	842 (-9%)	820 (-12%)



(a) Rapid Chloride Penetration Testing Apparatus

(b) Surface Resistivity Testing Apparatus

Figure 24. Testing Overview of RCPT and SRT

Table 17 – Modulus of Elasticity ASTM C469 (ksi)

Time (Days)	HPC	HPIC Shale	HPIC Clay	HPIC Slate	HPIC SAP
1	3442	3620 (5%)	3136 (-10%)	2676 (-29%)	2700 (-27%)
7	4615	4038 (-14%)	3793 (-22%)	3756 (-23%)	4042 (-14%)
28 (Standard)	4528	4803 (6%)	4575 (1%)	4390 (-3%)	4390 (-3%)
56 (Extended)	4472	4967 (10%)	4873 (8%)	4541 (2%)	4440 (-2%)

Table 18 – RCPT AASHTO T277 (Coulombs) and SR AASHTO T358 (kΩcm)

Time (Days)	HPC	HPIC Shale	HPIC Clay	HPIC Slate	HPIC SAP
RCPT 28 (Coulombs)	1374	1504	1426	1448	1546
RCPT 56 (Coulombs)	1251	989	1456	1615	1294
SR 28 (kΩcm)	39.7	30.0	31.7	26.9	30.9
SR 56 (kΩcm)	40.2	39.4	42.5	31.8	44.4

All HPIC mixtures showed a reduction in observed shrinkage compared to the control. This is summarized in Table 19. The three HPICS formulations containing LWFA had a higher reduction in shrinkage than the control and SAP HPIC.

Table 19 – Free Shrinkage Properties (με)

Time (Days)	HPC	HPIC Shale	HPIC Clay	HPIC Slate	HPIC SAP
7	326	217 (-50%)	194 (-67%)	140 (-133%)	269 (-21%)
14	496	367 (-35%)	287 (-73%)	224 (-121%)	417 (-19%)
21	544	440 (-24%)	362 (-50%)	271 (-101%)	479 (-14%)
28 (Standard)	588	447 (-32%)	431 (-36%)	338 (-74%)	567 (-4%)
56 (Extended)	632	530 (-19%)	496 (-28%)	402 (-57%)	622 (-2%)

Table 20 – Internal Humidity (%)

Time (Days)	HPC	HPIC Shale	HPIC Clay	HPIC Slate	HPIC SAP
0	100	100	100	100	100
3	94.5	95.0	99.0	99.5	99.5
7	88.1	92.7	97.3	99.0	97.7
14	82.7	87.7	88.5	95.0	92.6
28	78.0	79.5	78.9	87.7	85.6
42	75.9	76.7	75.4	86.0	81.3
56	74.2	75.6	72.0	82.2	78.0
140	67.6	68.8	-	-	-
210	67.5	68.5	-	-	-

Internal Relative humidity was increased by all HPIC mixtures at early ages as summarized in Table 20. Past day 28, the difference between HPC and HPIC became less consistent and pronounced. Over a long duration in a 50 percent relative humidity environment, both HPC and HPIC desiccate and stabilized at approximately 68 ± 1 percent internal relative humidity.

As outlined in literature, once internal RH reaches 85-95 percent, the pore water is largely exhausted, and the hydration reaction slows to a negligible rate. At 50 percent RH and dry conditions, the upper limit of this range was reached in 3-14 days by all formulations. This highlights the critical importance of standard wet curing in addition to any curing benefits Internal curing agents provide, especially in periods of challenging environmental conditions such as limited rainfall and low humidity.
The HPIC formulations based on the control NJDOT HPC retained their fresh properties, strength properties, and durability properties while decreasing shrinkage and maintaining a higher internal relative humidity for a longer period of time.

HPIC with SAP showed the largest reduction in strength and the smallest decrease in shrinkage but was by far the easiest material to prepare and batch. SAP required no dedicated prewetted stockpile and was batched by weighing the desired internal curing water and pouring the plastic granules until the water was sufficiently absorbed and appeared to approximate SSD conditions after dabbing with a paper towel.

For this reason, all materials were deemed worth continuing testing, with the control HPC and HPIC with shale being selected for undergoing the complete testing regime and continuation to Field Demonstration testing.

An optimization study on varying LWFA dosages and curing regime evaluation intended to assess HPIC curing methods and their effect on the hydration process. Internal curing via stored water as well as external curing were both investigated. Varying dosages of Internal curing agent also were tested to determine the effect of different amounts of internally stored water on strength, shrinkage, and durability. HPIC was tested under different wet curing regimes to determine the effect of traditional external curing methods.

To determine the effect IC carrier dosage has on curing, four different dosages were tested for compressive strength to assess strength gain, Surface resistivity was used to assess durability, and prism samples to assess shrinkage via ASTM C157/C157M. The four dosages tested were none (HPC), 50 percent the standard dosage (3.5lb absorbed water/100lb cement), the standard dosage (7lb/100lb cement), and 150 percent the standard dosage (10.5lb/100lb cement). Herein the mixes are referred to as Control HPC, 50 percent dose HPIC, standard dose HPIC, and 150 percent dose HPIC. The ICA for all testing was the expanded shale product selected for complete evaluation and field testing.

Four curing regimes were assessed. Typical 14-day wet curing was tested, along with 7 days wet curing and application of curing compound, 7 days of wet curing, and lastly no wet curing. All samples were placed in an environmental chamber at 50 percent relative humidity post wet curing.

Internal Curing Material HPC Dosage

Results from material characterization testing were used to calculate the dosage of LWFA in lb/yd^3 of concrete in Figure 25 in accordance with ACI 308-213-13(22). In order to simplify calculations, ACI 308-213-13(22) provides a graph method in addition to equations to quickly calculate carrier dose.

If a known concrete formulation is to be modified by replacement of normal sand with LWFA, the graph provided by ACI 308-213-13(22) *Report on Internally Cured Concrete Using Prewetted Absorptive Lightweight Aggregate* allows for a rapid and confident calculation of the required material dosage while equations can be used to get an exact dosage.
308-213-13(22) instructions for the dosing nomograph are summarized in Figure 25. It states that:

> *"Starting with the cement content in the graph on the upper right, find the chemical shrinkage of the mixture (a good default value is 0.07). Proceed to the value on*

the y-axis and starting with this same value in the graph on the upper left, find the line for the mixture's w/c ratio. Note that there is a single (thick) line for all w/c ratios greater than or equal to 0.36 as for these w/c ratio values, it is assumed that complete hydration of the cement powder can be achieved. Proceed to the value on the x-axis and starting with this same value in the graph on the lower left, find the line for the absorption (dry mass of aggregate basis) of the lightweight aggregate. Finally, proceed to the value on the y-axis to obtain the recommended level of lightweight aggregate (dry mass basis) to be added to the concrete mixture. This replacement should then be conducted on a volumetric basis, replacing an equal volume of normal weight aggregates with pre-wetted (SSD) lightweight aggregates."

The inputs required are

1) Cement content in lb/yd^3;
2) CS value. The value corresponds to lb stored water per 100 lb of cementitious material;
3) Water/cement ratio (w/c ratio); and,
4) absorption capacity of the IC material in percent (abs).

An example is outlined below using the NJDOT HPC selected for laboratory testing

Inputs used are

1) Cement content = 675 lb/yd^3;
2) CS = 0.07 (referred as a "good default value" and corresponds to 7 lb stored water /100 lb of cementitious material in typical usage);
3) w/c ratio = 0.385 (Since 0.385 is above 0.36, 0.36 is selected); and,
4) abs = 18 percent (when using the selected prewetted expanded shale).

Starting at the upper right corner with 675 lb/yd^3 cement, and making turns 90 counterclockwise at CS = 0.07, w/c = 0.36, and abs = 18 percent, a final resulting LWFA dosage of *just over* 300 lb/yd^3 is estimated using the graph, which matches the hand calculations of 310 lb/yd^3.

Table 21 shows the IC carrier dosages and replacement of normal weight sand for the laboratory NJDOT typical bridge deck HPC providing a CS of 0.07, with 675 lb of cementitious material, and 1113 lb/yd^3 normal weight concrete at 2.62 S.G. for the down selected materials.

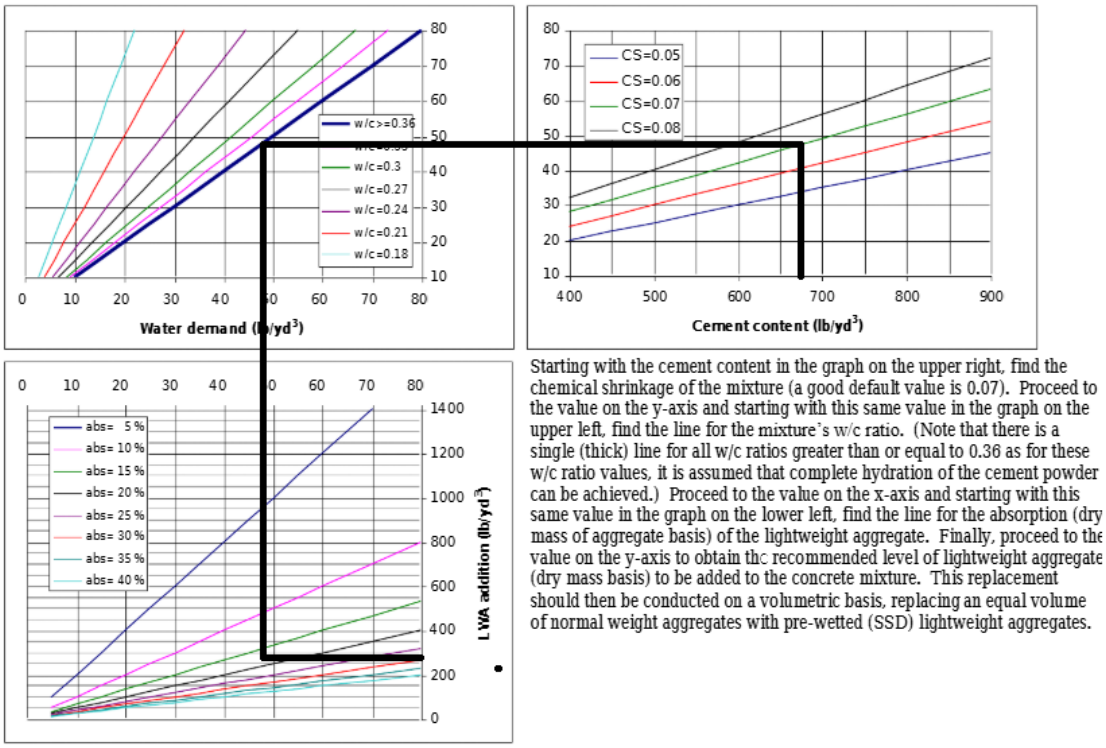


Figure 25. 308-213-13(22) Nomograph Used for Calculating LWFA Dosage and Example

Table 21 – Dosage to Achieve 7 lb Stored Water per 100 lb Cementitious

Material	Absorption (72hr)	S.G. (SSD)	ICA Weight (lb/yd^3)	Normal weight sand % by vol.
Hydrocure	18%	1.8	310	41%
Stalite	12.1%	1.9	438	54%
Arcosa	32%	1.43	195	32%
TRO C (SAP)	> 5,000%	1	47.5	12%

In Bentz (2005), which forms the basis for 308-213-13(22), the water demanded is represented in the left hand side of the top form of Eq. 1. Cf represents the cement content, CS is the chemical shrinkage of the cement, αmax is the expected maximum degree of reaction for the binder.

The right side of the top form represents the water supply. M(LWA) is the mass of dry aggregate dosage required, Φ(LWA) is absorption, and S is saturation from 0 to 1.

$$C_f*CS*\alpha_{max}=S*\Phi_{LWA}*M_{LWA}$$

$$M_{LWA}=(C_f*CS*\alpha_{max})/(S*\Phi_{LWA}). \qquad \text{(Eq. 1)}$$

Using the inputs used in 308-213-13(22) nomograph for the bottom form of the above equation,

- C_f= 675 lb/yd^3
- CS= 0.07
- α_{max}= 1
- S= 1
- Φ(LWA)= 0.18

M(LWA) is calculated to be 262.5 lb/yd^3, which when fully saturated at 18 percent results in a dosage of 310 lb/yd^3, identical to the graphic method.

While 7 lb stored water/100 lb cementitious material or CS =0.07, is known to provide good results and allows for simplified dosing, dosing methodology exists to compensate for the increased water demand of Supplementary Cementitious Materials (SCMs) and to modify the supplied water based on the desorption properties of the IC material.

With only 93 percent of the absorbed water being released during desorption on average, Φ(LWA) can be reduced from 0.18 to 0.167 (Castro 2011) [36].

Modification of CS can be done to compensate for the increased water draw of blended cement. Ground Granulated Blast Furnace Slag (GGBFS or Slag cement), fly ash, and silica fume have a higher water draw than Portland cement. The water demands for of the blend can be calculated as a summation of the individual binder components, as shown in Eq. 2 (Bentz 2005) [47].

$$\text{Water\_demand} = \sum_i C_f^i * CS^i * \alpha^i_{max} \quad \text{(Eq. 2)}$$

Bentz 2005 states Portland cements water demand can be taken as 0.07, slag and fly ash 0.14-0.21, and silica fume 0.22 (Jensen et al. 2001) [48]. Using the NJDOT HPC formulation tested in lab with 400 lb/yd^3 Portland cement, 200 lb/yd^3 slag cement, and 25 lb/yd^3 silica fume and 0.07, 0.014, and 0.22 respectively a water demand of 0.096 is calculated based on equation 2.

An example calculation for M(LWA) using modified coefficients for the previous example

- C_f= 675 lb/yd^3
- CS= 0.096
- α_{max}= 1
- S= 1
- Φ(LWA)= 0.167

M(LWA) is calculated to be 388 lb/yd^3, which when fully saturated at 18 percent results in a dosage of 458 lb/yd^3.

This methodology requires a significant increase in LWFA dosage. This increased dosage of approximately 150 percent of the normal dosage is investigated in the variable dosage study portion of this report. A minimum of 7lb stored water per 100lb cementitious material was selected for the majority of testing due to its prevalence and success in DOT usage.

Optimization for LWFA Dosages

While 7 lb internally stored water per 100 lb of cement is a standard dosage in common usage, alternative dosages have pros and cons associated with them that warrant investigation. A reduced dosage of LWFA has a reduced overall material cost due to the higher price of LWFA compared to normal weight sand while still reducing shrinkage. An increased LWFA dosage carries a cost penalty, a potential for strength and durability to be degraded, and a further beneficial decrease in shrinkage. The relationship between shrinkage, strength, and durability are not linear, and necessitate testing multiple dosages to attempt to predict behavior.

The testing regime of 0, 3.5, 7, 10.5 lb stored water/100lb cement intended to investigate the effect of LWFA dosage and to create a graphical tool that can be used to predict the degree of shrinkage expected at a specific LWFA dosage. This opens the potential for optimization for specific project needs with more sensitive applications warranting a higher customized dosage. All formulations were tested in 1 ft^3 batches, and all HPIC formulations contained expanded shale LWFA for IC applications.

Figure 26 and Table 22 summarize compressive strength testing performed in accordance with ASTM C39 to assess strength properties. The results showed HPIC formulations performing better than the control HPC formulation. The standard dosage HPIC (7lb) consistently performed well, with a 56 day strength 29 percent higher than the HPC. The next best performance was by the 150 percent dosage HPIC (10.5lb) with an improvement of 21 percent, and lastly the 50 percent dosage HPIC (3.5lb) at 15 percent.

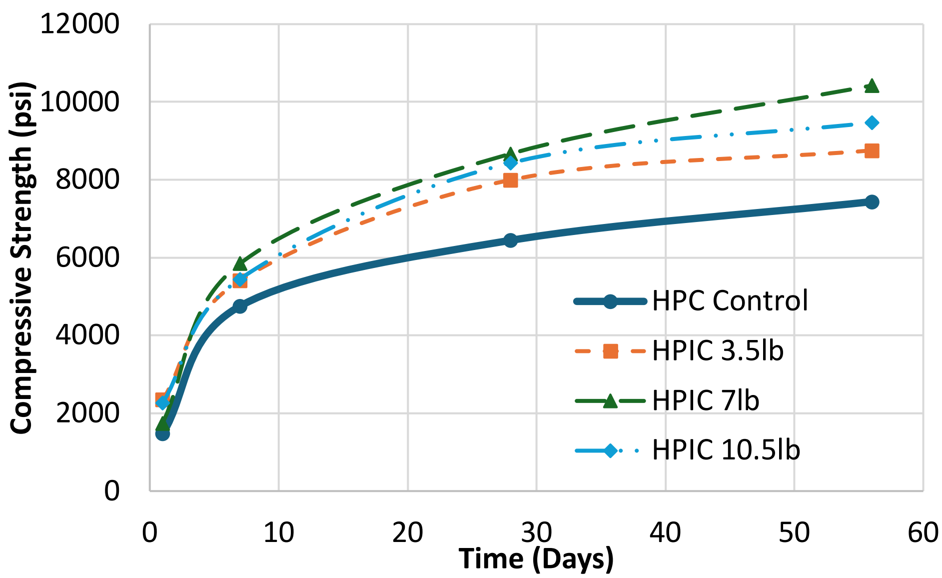


Figure 26. Compressive Strength of Alternative LWFA Dosages

Table 22 – Compressive Strength Incorporating Varying LWFA Dosages (lbf/in^2)

Time (Days)	HPC Control	HPIC 3.5lb	HPIC 7lb	HPIC 10.5lb
1	1472	2348 (37%)	1750 (16%)	2268 (35%)
7	4753	5411 (12%)	5847 (19%)	5451 (13%)
28	6444	7998 (19%)	8671 (26%)	8435 (24%)
56	7438	8754 (15%)	10422 (29%)	9470 (21%)

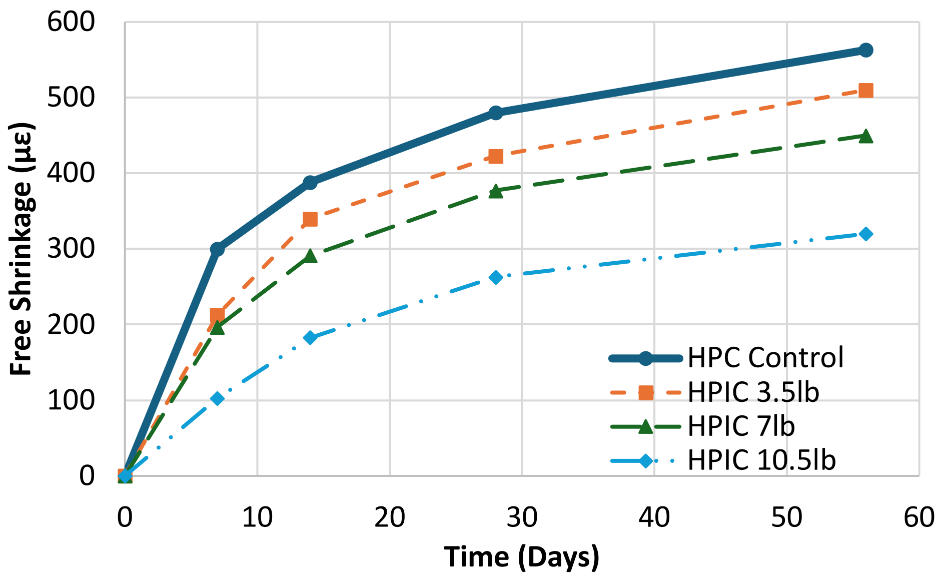


Figure 27. Free Shrinkage Incorporating Varying LWFA Dosages

Table 23 – Variable LWFA Dosage Effect on Shrinkage

Time (Days)	HPC Control	HPIC 3.5lb	HPIC 7lb	HPIC 10.5lb
7	300	213 (-41%)	197 (-53%)	103 (-191%)
14	388	340 (-14%)	291 (-33%)	183 (-112%)
28	480	423 (-13%)	377 (-27%)	263 (-83%)
56	563	510 (-10%)	450 (-25%)	320 (-76%)

Figure 27 and Table 23 summarize shrinkage testing conforming to ASTM C157 \to assess the effect of variable LWFA dosage on shrinkage. A relationship was shown to exist with an increasing reduction in shrinkage for a given increase in LWFA. The percent reduction of shrinkage was most pronounced at early ages, which is highly advantageous to reduce early age cracking.

An overview of the percentage difference of shrinkage at different times is summarized in Table 24, along with the respective dosages and percent replacement of sand by volume. While the 10.5 lb/100lb cement dosage showed an excellent reduction of shrinkage, the 62 percent replacement of normal weight sand by volume is likely excessive for traditional IC applications.

Table 24 – Overview of Results of Variable Dosage Shrinkage Study

Mix		**HPC Control**	**HPIC 3.5lb**	**HPIC 7lb**	**HPIC 10.5lb**
lb/yd^3 of LWFA		0	155	310	465
% replacement of sand by volume		n/a	20%	41%	62%
Percent difference of shrinkage	7 days	n/a	-41%	-73%	-191%
	14 days	n/a	-14%	-33%	-112%
	28 days	n/a	-13%	-33%	-83%
	56 days	n/a	-10%	-25%	-75%

The four formulations and four testing dates were used to compile a graphical representation of the percent reduction in shrinkage the HPIC experiences compared to the control HPC. By selecting a dosage of LWFA, a predicted reduction in shrinkage can be assumed. Since the relationship changes over time, four test dates are included in order to accurately assess shrinkage reduction over the initial curing phase.

Figure 28 shows an example of the shrinkage prediction curve being used. If a 30 percent replacement by volume is selected and the material has an absorption capacity of 18 percent, the LWFA dosage provides 5.25lb internal water. This dosage is predicted to produce a reduction in shrinkage of 52 percent at day 7, 21 percent at day 14 and 28, and 15 percent at day 56. When compared to the HPC shrinkage values, the corresponding shrinkage is predicted in Table 25. In this way, other commonly specified dosage methods can be evaluated, such as 25 and 30 percent replacement by volume, 8lb per 100lb cement, etc.

Table 25 – Shrinkage of HPIC with 5.25 lb Internally Stored Water/100 lb Cement

Day	**Strain (με)**
1	0
7	147
14	307
28	379
56	479

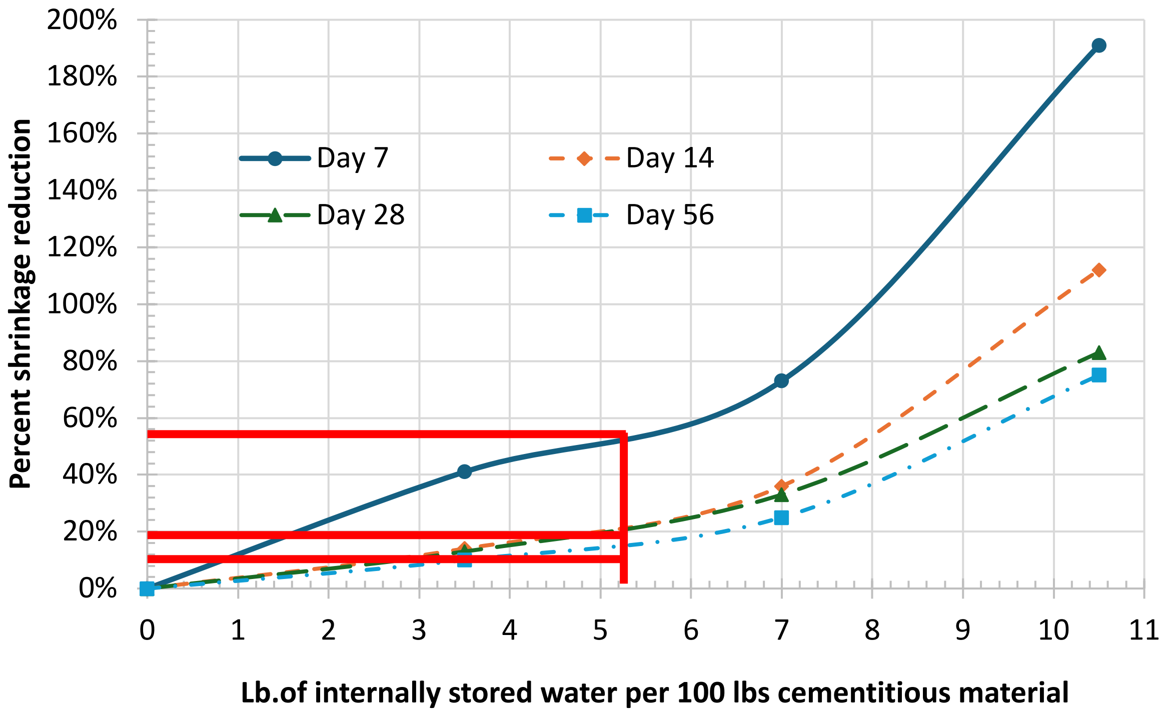


Figure 28. Example of Shrinkage Reduction per lb of Absorbed Water over Time

Effect of HPIC Curing Regime

Curing regimes for HPIC were evaluated to assess their effects and to better understand the relationship between externally applied water using traditional wet curing methods and water released from internal reservoirs for the purpose of internal curing.

Curing methods consisted of conventional curing with 14 days of wet curing, modified curing with 7 days wet curing and application of curing compound, 7 days of wet curing, and no curing applied, herein referred to as W14, W7cc, W7, and Dry, respectively.

Strength properties were assessed through compressive strength testing, and durability properties through surface resistivity testing. Notably, surface resistivity is likely a strong indicator of curing effectiveness, as traditional wet curing primarily densifies the surface of HPC like materials as shown in Figure 2 in the literature review as well as Table 26-27.

Figure 29 summarizes compressive strength testing in accordance with ASTM C39. The results showed that all curing methods gave similar results, with uncured samples experiencing a significant decrease in strength, approaching 20 percent at day 56.

Interestingly, W7cc showed continuing improvements in strength past even W14 at day 56, likely due to the significant reduction in water lost to the environment due to the curing compound sealing in moisture. This benefit may not be as pronounced in field settings because the curing compound is typically specified to flake off over time from degradation from sun exposure as well as friction from vehicle traffic.

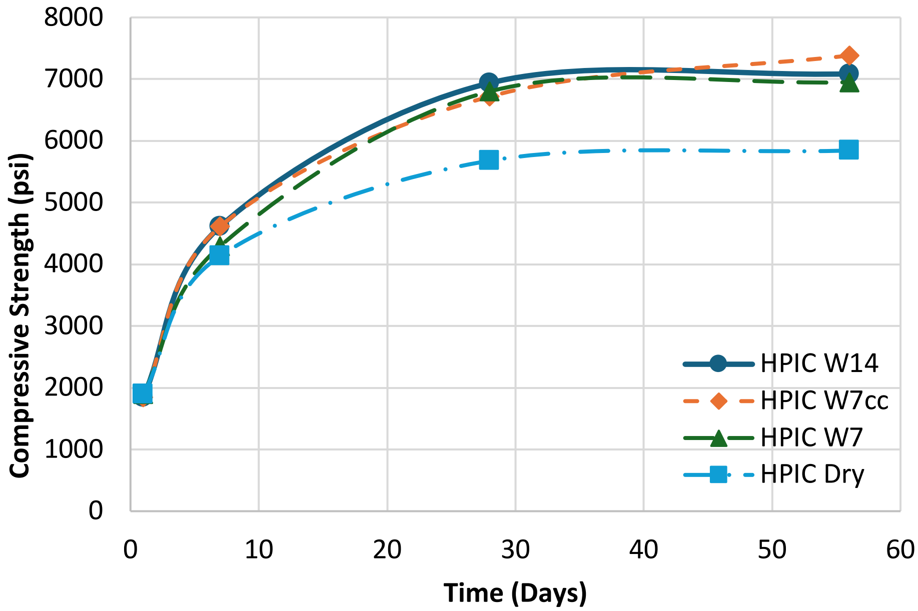


Figure 29. Compressive Strength of Curing Series

Table 26 – Surface Resistivity of Curing Series

	HPIC W14	HPIC W7cc	HPIC W7	HPIC Dry
Day 28	21	22	21	19
Day 56	44	42	39	33

Table 27 – Surface Resistivity of HPICs Compared to HPC

	HPC	HPIC-H	HPIC-A	HPIC-S	HPIC-SAP
Day 7	15	9	10	11	10
Day 28	31	33	32	27	22
Day 56	40	38	42	32	31

Figure 30 illustrates the effect of wet curing on HPIC for mixtures W14, W7cc, and W7. The primary objective of the curing regime testing was to evaluate differences in shrinkage behavior. Results include HPIC with four curing regimes and HPC subjected to dry curing. A pronounced difference was observed between HPC and HPIC under dry curing, with the inclusion of LWFA IC material significantly altering early-age shrinkage behavior. W7cc and W7 exhibited similar shrinkage trends, while W14 showed notable improvement and a substantial reduction in total shrinkage by day 56. Under wet curing, length change was negligible and, in several cases, slightly negative due to swelling from pore saturation. Dry curing resulted in a noticeable decrease in surface density, corresponding to lower kΩ·cm readings. Based on the complete SR testing series, it can be inferred that although HPC initially exhibits higher density, by day 56 the densities of HPIC and HPC become comparable.

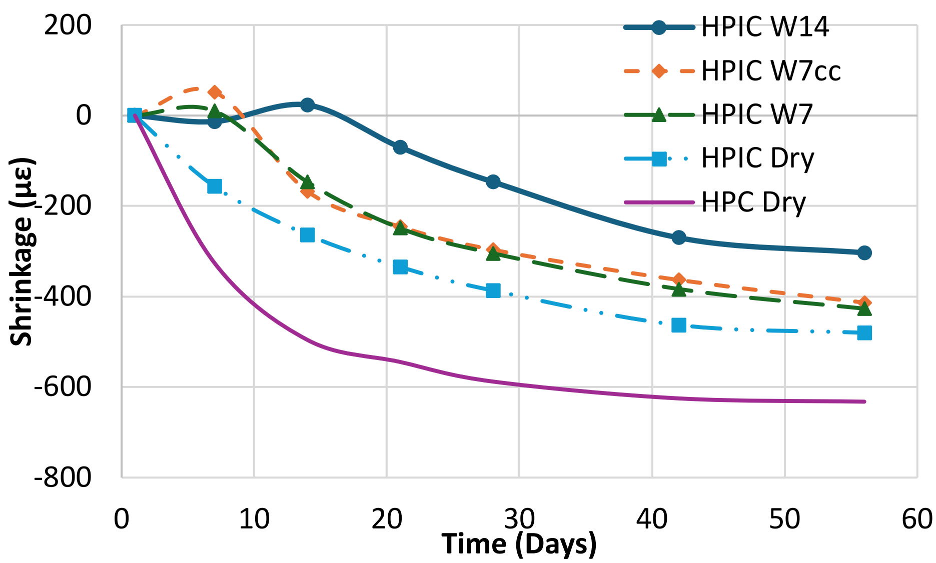


Figure 30. Shrinkage of HPICs Compared to HPC

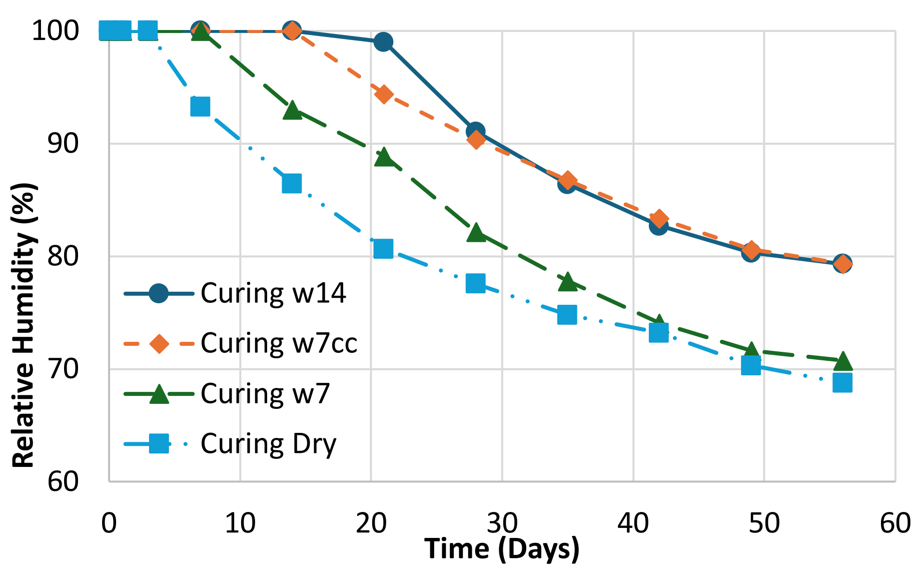


Figure 31. Curing Regime Effect on Internal Humidity of HPIC

Figure 31 summarizes internal humidity testing results. It confirmed the assumptions made with shrinkage testing and shows that during wet curing, the internal humidity is maintained at 100 percent. Once the curing is lifted and samples are exposed to a desiccating environment of 50 percent RH, a rapid reduction of internal humidity was observed. W14 and W7cc samples showed the most significant benefit. According to Figure 2 in the literature review, when exposed to proper wet curing, HPC undergoes densification of the surface, which aids in locking moisture in the material. W7cc has a similar effect with the inclusion of a non-permeable curing compound, sealing in original and wet curing moisture.

Comprehensive Evaluation of Selected HPIC Formulations

Using the down selected materials from initial testing and recommended IC carrier dosage from the optimal dosage investigation, a complete evaluation of the selected materials with a specific focus being placed on the Expanded Shale IC carrier and the control. Testing is summarized Table 28 and is largely a repeat of initial testing with the addition of freeze thaw testing, autogenous shrinkage testing, rapid chloride permeability testing, and restrained shrinkage testing.

Table 28 – Complete Evaluation Testing Regime

Characterization	Standard	Test Method	Age (Days)	Units (#)
Strength	AASHTO T22	Compressive Strength	1,7,28,56	3
	ASTM C496	Tensile Strength	1,7,28,56	3
	AASHTO T97	Flexural Strength	1,7,28,56	2
	ASTM C469	Modulus of Elasticity	1,7,28,56	2
Durability	ASTM C157	Free Shrinkage	1,7,28,56	3
	ASTM C157	Autogenous Shrinkage	1,7,28,56	3
	AASHTO T334	Restrained Shrinkage	-	1
	ASTM C666 Proc. A	Freeze-Thaw Durability	-	6
	ASTM F2170	Internal Humidity	1,7,28,56	2
	AASHTO T277	Chloride Permeability	28,56	2
Fresh	AASHTO T358	Surface Resistivity	28,56	2
	AASHTO T119	Slump	-	1
	AASHTO T152	Air Content (Pressure)	-	1
	ASTM C173	Air Content (Volumetric)	-	1
	ASTM C138	Unit Weight	-	1

The control HPC formulation and the HPIC formulation containing expanded shale underwent all tests. Expanded clay was excluded from restrained shrinkage testing because it did not exhibit significantly different shrinkage properties at the same stored water dosage. Expanded shale and SAP were also excluded from restrained shrinkage testing for the same reason and did not undergo freeze-thaw testing due to the limited number of sample replicates that could be tested concurrently.

For brevity, results from the complete evaluation are combined with the initial evaluation because both used an identical dosage of 7 lb internally stored water per 100 lb of cement. This combined presentation benefits from a larger dataset with more mixes and samples. By presenting the data in this format, relationships show stronger statistical results and clearer trends.

Table 29 – Fresh Properties

Mix ID	HPC-C	HPIC-H	HPIC-A	HPIC-S	HPIC-SAP
Formulation	HPC Control	HPIC Shale	HPIC Clay	HPIC Slate	HPIC SAP
Product used	n/a	Hydrocure	Riverlite	Stalite	SAP
Air content (pressure)	8.75%	8%	6.5%	5.75%	6.25%
Air content (volumetric)	9%	8%	6.5%	6%	6.25%
Slump (6 ± 2 in)	7	6.5	6.5	5	5
Unit weight (lb/ft^3)	138.1	138.1	139.5	140.0	142.4
Absorption	n/a	15.8%	29.7%	10.8%	n/a
IC Dose (lb/yd^3)	0	310	165	445	49
Internal water/ 100 lb cementitious material	0	7.26	7.26	7.15	7.26

Fresh property testing during the complete evaluation showed similar behavior to the initial evaluation, as summarized in Table 29. HPIC showed negligible differences in workability and maintained a similar slump to the control HPC based on the dosed water-reducing admixture. Comparing volumetric and pressure testing methods, all tests for each formulation recorded within 0.25 percent and averaged 0.1 percent. A recalibrated and repaired air pressure meter was used for the complete evaluation series, which likely caused the smaller range between test methods compared to the initial evaluation. HPIC showed negligible differences in workability and maintained similar slump behavior to the control HPC. Unit weight varied due to air content and LWFA dosage, which was adjusted based on absorbed water to provide 7.15-7.25 lb per 100 lb of cementitious material.

Figure 32-36 depict the compressive strength, splitting tensile strength, modulus of elasticity, and flexural strength, respectively. Strength properties exhibited the same trends across all lab testing, with LWFA HPIC showing improved compressive strength, tensile strength, and a slight increase in elastic modulus. HPIC with SAP showed a reduction in strength compared to HPC for all respective tests, consistent with trends reported in the literature (Xu et al., 2021) [46]. The reduction in strength is attributed to the void space left as the absorbent material desorbs. Flexural strength for HPIC and HPC samples ranged between approximately 800 and 1000 psi for day 28 and 56 testing. A slightly higher variation was observed in the strength gain curve for each respective series. According to ASTM C78 and AASHTO T97, this variation falls well within the coefficient of variation for high-strength 4-in. samples at 11.4 percent.

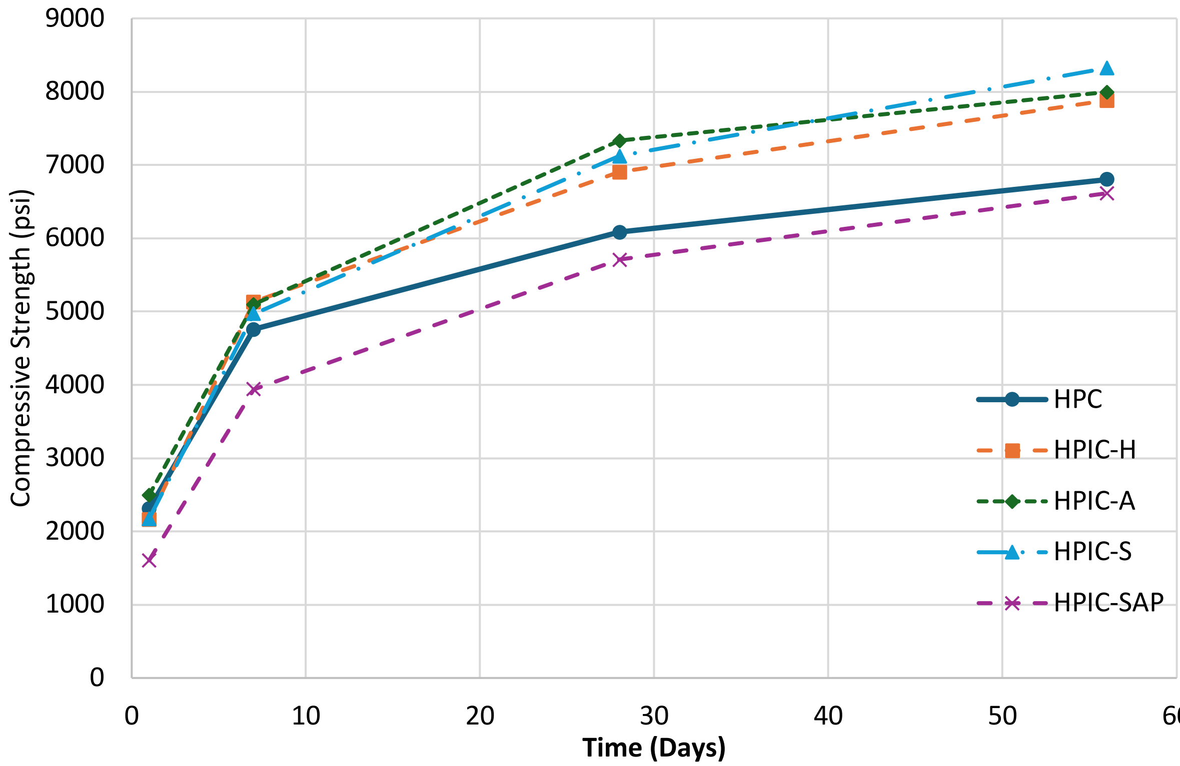


Figure 32. Compressive Strength of HPIC and HPC

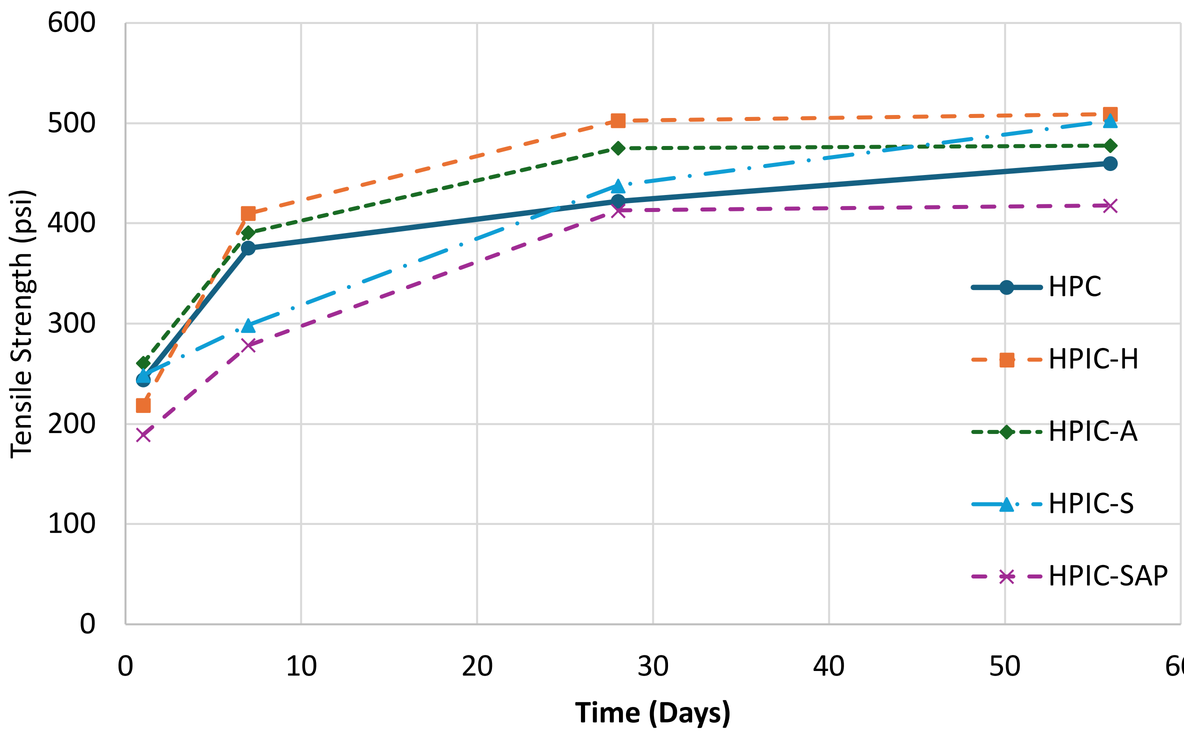


Figure 33. Tensile Strength of HPIC and HPC

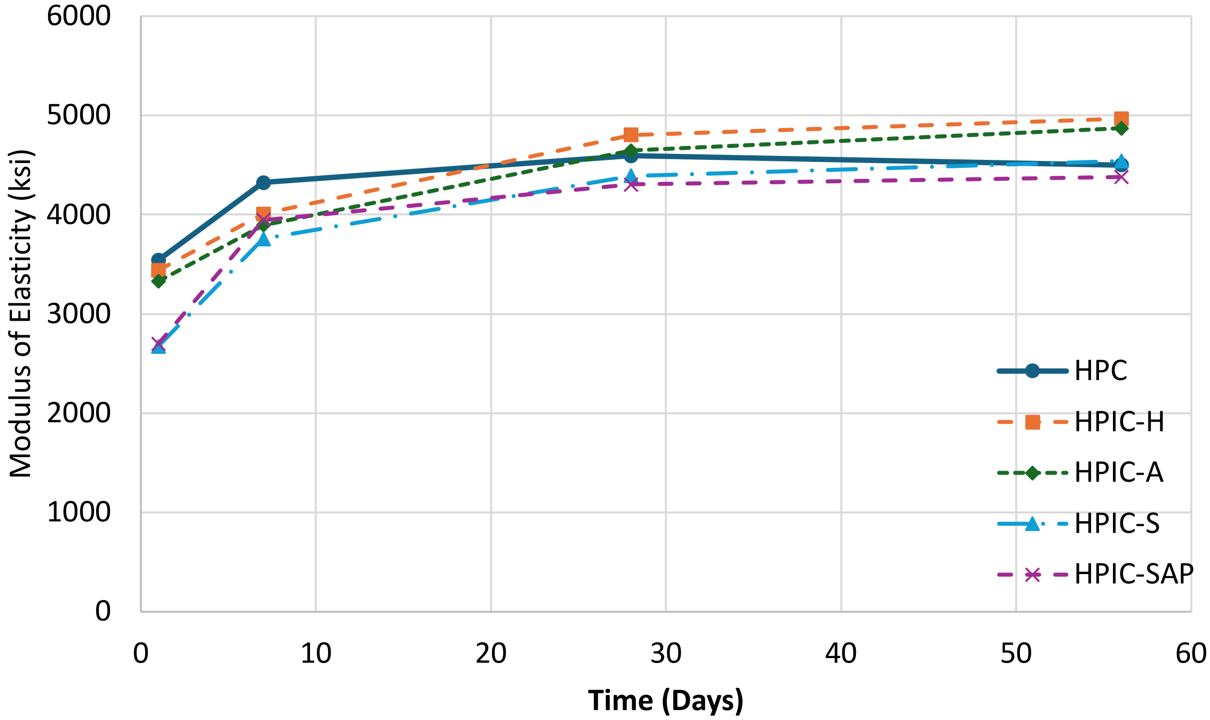


Figure 34. Elastic Modulus of HPIC and HPC

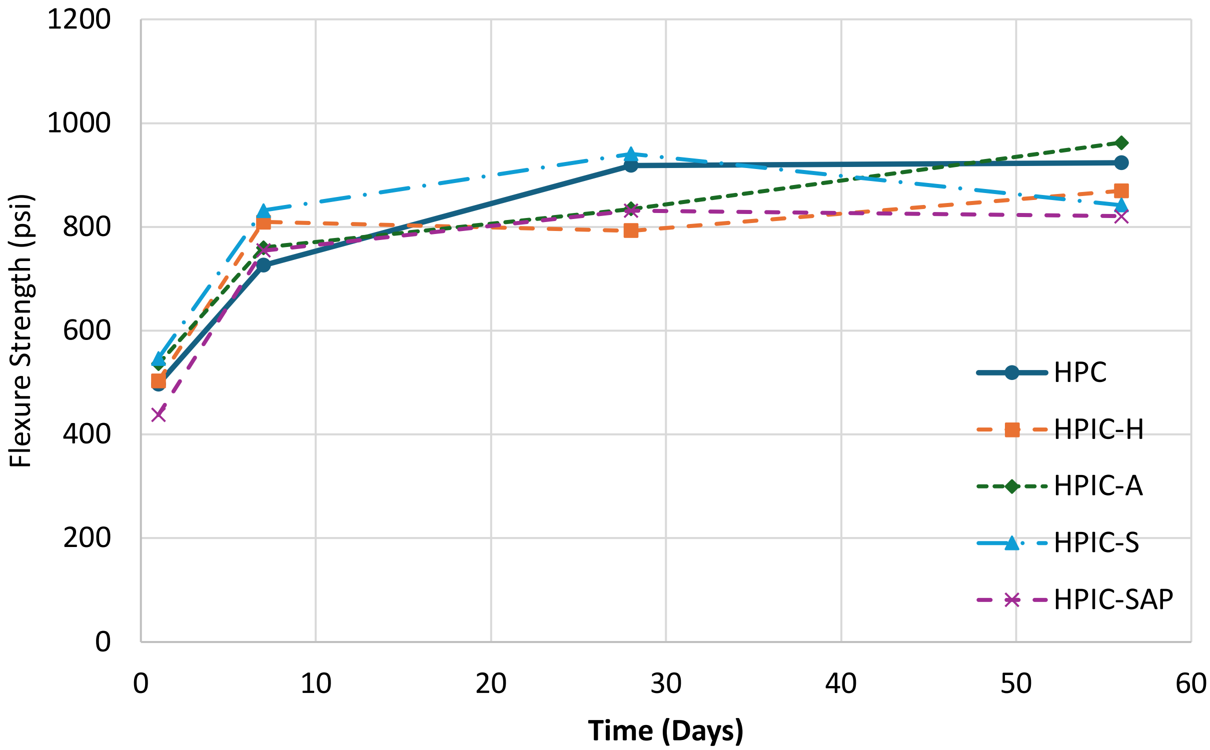


Figure 35. Flexural Strength of HPIC and HPC

Table 30 – Surface Resistivity Testing Results

	HPC-C	HPIC-H	HPIC-A	HPIC-S	HPIC-SAP
Day 7	14.8	10.1	11.2	11.0	10.8
Day 28	30.7	34.8	27.8	27.1	29.0
Day 56	40.2	39.1	42.5	35.9	42.0

Table 31 – Rapid Chloride Permeability Testing Results

	HPC-C	HPIC-H	HPIC-A	HPIC-S	HPIC-SAP
Day 28	1485	1605	1426	1617	1881
Day 56	1328	1037	1457	1574	1480

Table 32 – RCPT AASHTO T277 Guidelines

Coulombs	Permeability	Typical of
>4000	High	High W/C ratio >0.6
2000-4000	Moderate	Moderate W/C ratio 0.4-0.6
1000-2000	Low	Low W/C ratio < 0.4
100-1000	Very low	Latex modified concrete
<100	Negligible	Polymer Impregnated concrete

Rapid Chloride Penetration Testing and Surface Resistivity reflected the typical highly dense microstructure found in HPC as a class of concrete. SR results in Table 30 showed similar behavior between HPC and HPIC, with results ranging from 36-42.5 at day 56. RCPT in Table 31 showed low permeability, 1000-2000 according to AASHTO T277 guidelines (see Table 32), for all samples tested on day 28 for standard testing and day 56 for extended testing. This range is typical of Low water cement ratio concretes <0.4, which corresponds to the selected NJDOT mix for lab testing with a w/c ratio of 0.38.

Internal humidity testing showed formulations with IC materials maintained a higher Internal relative humidity for longer, specifically at early ages (Figure 36). Over time both mixtures continue to desiccate and stabilize at approximately 68 percent RH (Figure 37). Testing conditions were intentionally harsh with no wet curing and in a stable environment of 50 percent relative humidity.

Because of this, laboratory humidity testing is not indicative of real world results, as conditions tend to be more forgiving in New Jersey with an average annual humidity of approximately 55 percent and averaging 47 in of rain (NOAA National Centers for Environmental Information Climate Normals) [49]. Exposed concrete surfaces such as a bridge deck receiving periodic wetting would stabilize at a higher internal humidity.

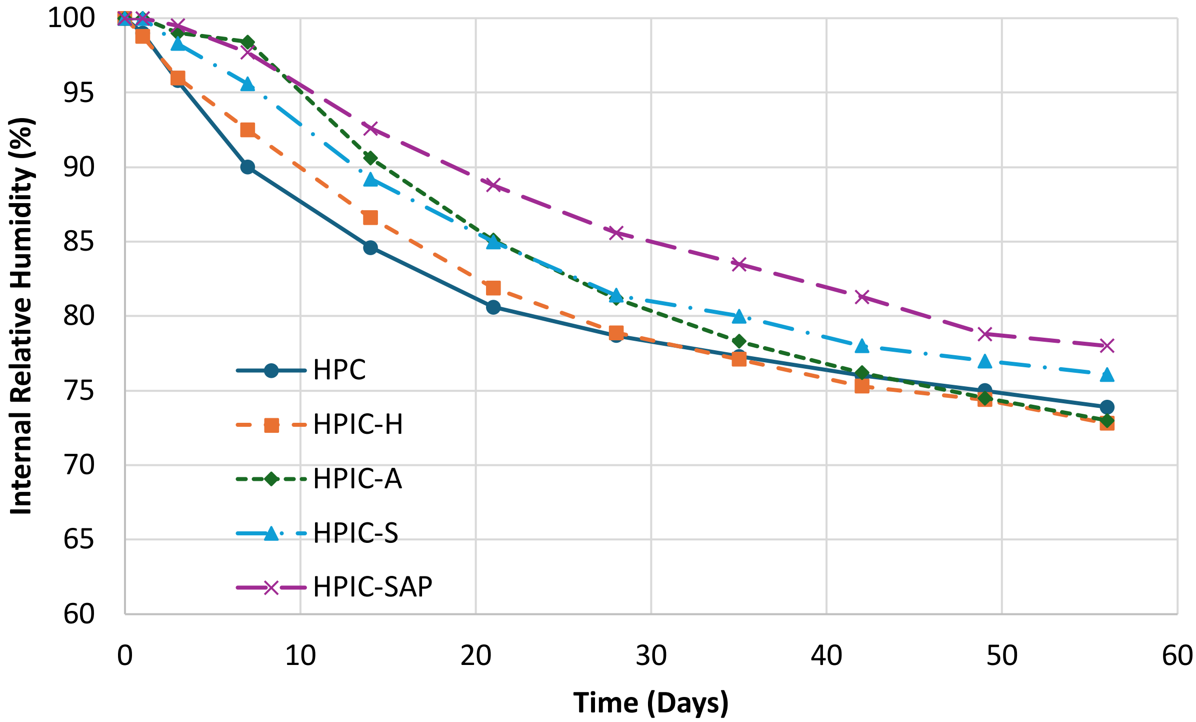


Figure 36. Internal humidity testing results for HPIC and HPC

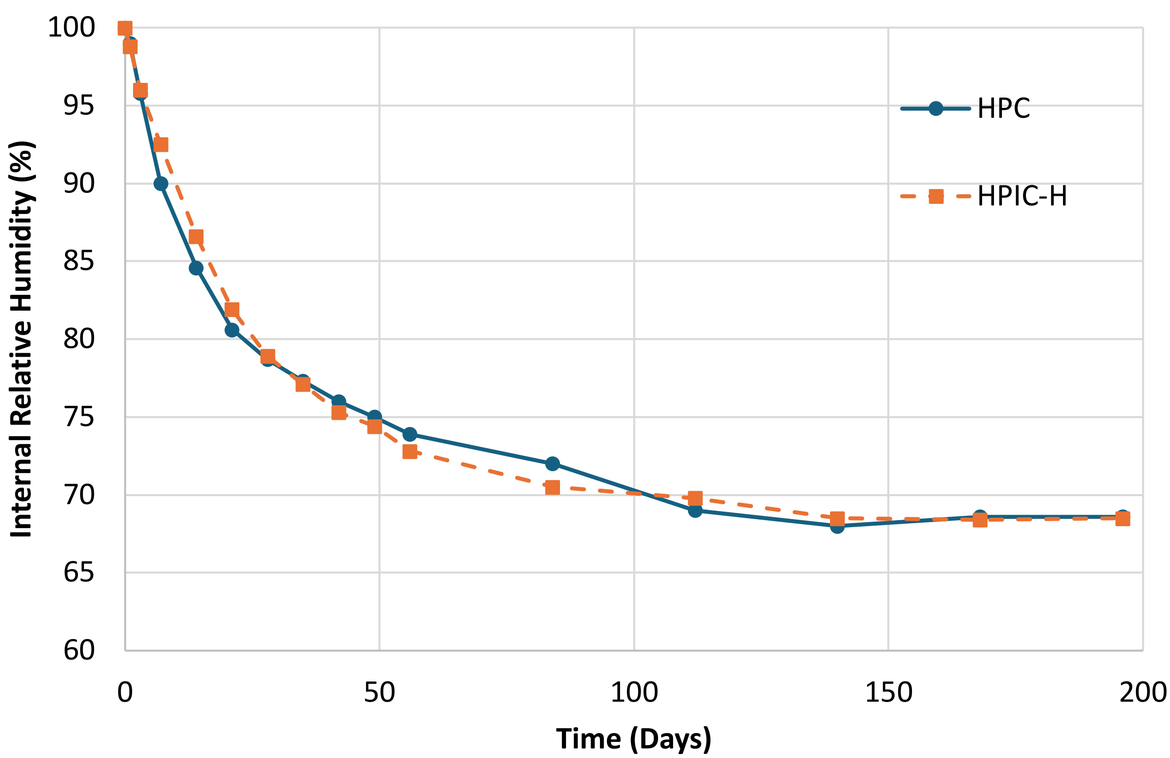


Figure 37. Long term Internal humidity testing results for HPIC and HPC

Freeze-thaw testing was conducted on six replicates of HPC, HPIC with expanded shale, and HPIC with expanded clay. Testing conformed to ASTM C666/C666M-15 Procedure A and was compared to the NJDOT requirement for HPC, which specifies a durability factor exceeding 80 percent over 300 freeze-thaw cycles. Results are reported in Table 33, Table 34, and Figure 38, with a summarized comparison in Table 35.

Table 33 – Freeze Thaw Report Overview for HPIC Expanded Shale

Client:	NJIT	**Project:**	ATC Lab Sample
Material:	HPIC	**Project Number:**	130116
Source:	NJIT	**Lab Number:**	25-0751A-F
Date Sampled:	2/19/2025	**Sampled By:**	Client
Date Tested:	6/18/2025 - 8/29/2025	**Tested By:**	Isabella Pollina

Report of Resistance of Concrete to Rapid Freezing and Thawing

Test Method: AASHTO T161 Method A/ASTM C666 Method A

Concrete Mixture Data		
Fine Aggregate	Not Provided	Not Provided
Coarse Aggregate	Not Provided	Not Provided
Cement:	Not Provided	Not Provided
Admixture:	Not Provided	Not Provided
Water:	Not Provided	Not Provided
Mix Properties - Not Provided		

Specimen Characteristics (0 Cycles of Freezing and Thawing)					
Sample ID	Mass	Length (in)	Width (in)	Height (in)	Gauge Length
1	7268.2	16.062	2.975	4.012	N/A
2	7354.8	16	3.006	4	N/A
3	7334.4	16.062	3.009	3.985	N/A
4	7233.6	16.062	2.984	3.987	N/A
5	7294.7	16.125	3.035	3.967	N/A
6	7330.7	16	3.015	3.99	N/A

Sample ID	**Cycles**	**Original Mass (g)**	**Final Mass (g)**	**Mass Change (%)**	**Relative Dynamic Modulus of Elasticity**	**Durability Factor**
1	300	7268.2	7281.7	-0.19	93.99378	93.9938
2	300	7354.8	7348.4	0.09	96.11173	96.1117
3	300	7334.4	7315.5	0.26	96.07357	96.0736
4	300	7233.6	7234.7	-0.02	96.11173	96.1117
5	300	7294.7	7301.6	-0.09	97.89624	97.8962
6	300	7330.7	7333.7	-0.04	96.07357	96.0736
Average				**0.05**	**95.4**	96.0

Notes: Three 3x3x11.25-inch prisms were fabricated and finished. Specimens were cured in a saturated lime water bath at 73.4 ± 3.0°F for 14 days.

Visual observations of the specimens revealed no signs of cracking with minor deterioration of flaking and scaling on the exposed surfaces.

Table 34 – Freeze Thaw Report Overview for HPIC Expanded Clay

Client:	NJIT	**Project:**	ATC Lab Sample
Material:	HPIC	**Project Number:**	130116
Source:	NJIT	**Lab Number:**	25-0752A-F
Date Sampled:	3/6/2025	**Sampled By:**	Client
Date Tested:	6/18/2025 - 8/29/2025	**Tested By:**	Isabella Pollina

Report of Resistance of Concrete to Rapid Freezing and Thawing

Test Method: AASHTO T161 Method A/ASTM C666 Method A

Concrete Mixture Data		
Fine Aggregate	Not Provided	Not Provided
Coarse Aggregate	Not Provided	Not Provided
Cement:	Not Provided	Not Provided
Admixture:	Not Provided	Not Provided
Water:	Not Provided	Not Provided
Mix Properties- Not Provided		

Specimen Characteristics (0 Cycles of Freezing and Thawing)					
Sample ID	Mass	Length (in)	Width (in)	Height (in)	Gauge Length
1	7220.4	16.062	3.006	3.981	N/A
2	7080.5	16	3.01	3.995	N/A
3	6970.4	16.062	2.995	3.99	N/A
4	7042.7	16.125	2.996	3.977	N/A
5	6976.4	16	2.986	3.978	N/A
6	7054.2	16.125	2.979	3.985	N/A

Sample ID	Cycles	Original Mass (g)	Final Mass (g)	Mass Change (%)	Relative Dynamic Modulus of Elasticity	Durability Factor
1	300	7220.4	7218.4	0.03	92.21484	92.2148
2	300	7080.5	7080.5	0.00	88.37186	88.3719
3	300	6970.4	6957.5	0.19	84.4525	84.4525
4	300	7042.7	7031.8	0.15	82.78622	82.7862
5	300	6976.4	6963.5	0.18	82.62206	82.6221
6	300	7054.2	7052	0.03	92.13924	92.1392
Average				**0.07**	**86.7**	86.7

Notes: Three 3x3x11.25-inch prisms were fabricated and finished. Specimens were cured in a saturated lime water bath at 73.4 ± 3.0°F for 14 days.

Visual observations of the specimens revealed no signs of cracking with minor deterioration of flaking and scaling on the exposed surfaces.

Report of Resistance of Concrete to Rapid Freezing and Thawing
Test Method: AASHTO T161 Method A/ASTM C666 Method A

Before: **After:**

Figure 38. Before and After Images of HPIC Expanded Shale Samples

Visual reports revealed "no signs of cracking with minor deterioration of flaking and scaling on the exposed surfaces" for all three formulations.

Table 35 – Freeze thaw summary

	HPC	**HPIC Shale**	**HPIC Clay**
Mass change (%)	0.00^	0.05	0.07
Durability factor	94.9	96	86.7
^HPC weighed using a scale with lower resolution, no mass change reported			

Mass data changes show negligible loss of material for all formulation samples based on visual observations and weighing over the duration of testing. HPIC samples showed a slight increase in mass, likely due to exposure to saturated conditions during freeze-thaw testing. HPC was tested with a less precise scale and showed no mass change. HPIC was subsequently tested with a scale precise to a tenth of a gram to detect any mass changes.

The durability of HPC and HPIC with expanded shale was excellent, at 94.9 and 96, respectively. Expanded clay showed a lower degree of durability at 86.7 but still remained above the 80 percent passing threshold according to ASTM C666. No cracking or significant surface defects were observed during visual inspection.

Figure 39. Isoline Map of Freeze-Thaw Severity Index ASTM D5312

New Jersey falls within the range for consideration of freeze-thaw severity, ranging from 20-30 (Figure 39). Users of LWFA HPIC in regions with more severe freeze-thaw conditions, such as Illinois's IDOT and New York State's NYSDOT, have not reported notable deleterious effects from the inclusion of fine expanded aggregate, although some reports exist of pop-outs with coarse expanded aggregate associated with lightweight concrete. Freeze-thaw testing indicates that shale-based LWFA may exhibit higher durability when exposed to freeze-thaw conditions in the Northeast over the lifetime of the structure.

Shrinkage testing was conducted in accordance with ASTM C157, in both sealed and unsealed configurations, as shown in Figure 40, with results summarized in Figure 41 and Figure 42. Testing showed a similar degree of shrinkage reduction for all three LWFA HPICs in both sealed and unsealed samples. All LWFA samples showed a significant reduction in shrinkage compared to control samples. Due to the identical target dosage and similar desorption capacity, the differences between LWFA IC carriers were minimal. SAP HPIC showed a moderate reduction in shrinkage, with most of the effect occurring at very early ages, within 14 days post-casting. Overall, all HPIC formulations had a measurable effect on shrinkage reduction compared to HPC, with the most pronounced effects observed at early ages.

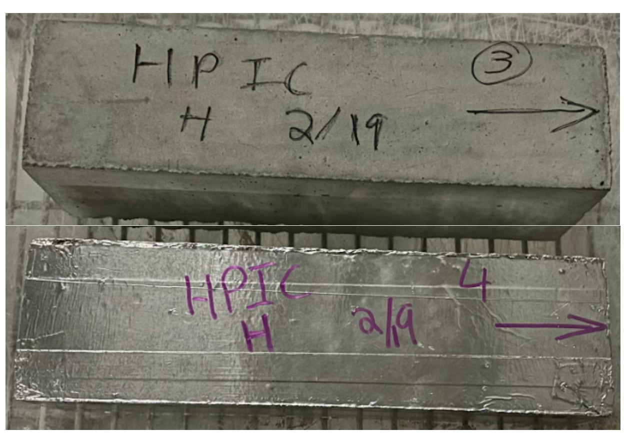


Figure 40. Unsealed and Sealed Samples Conforming to ASTM C157

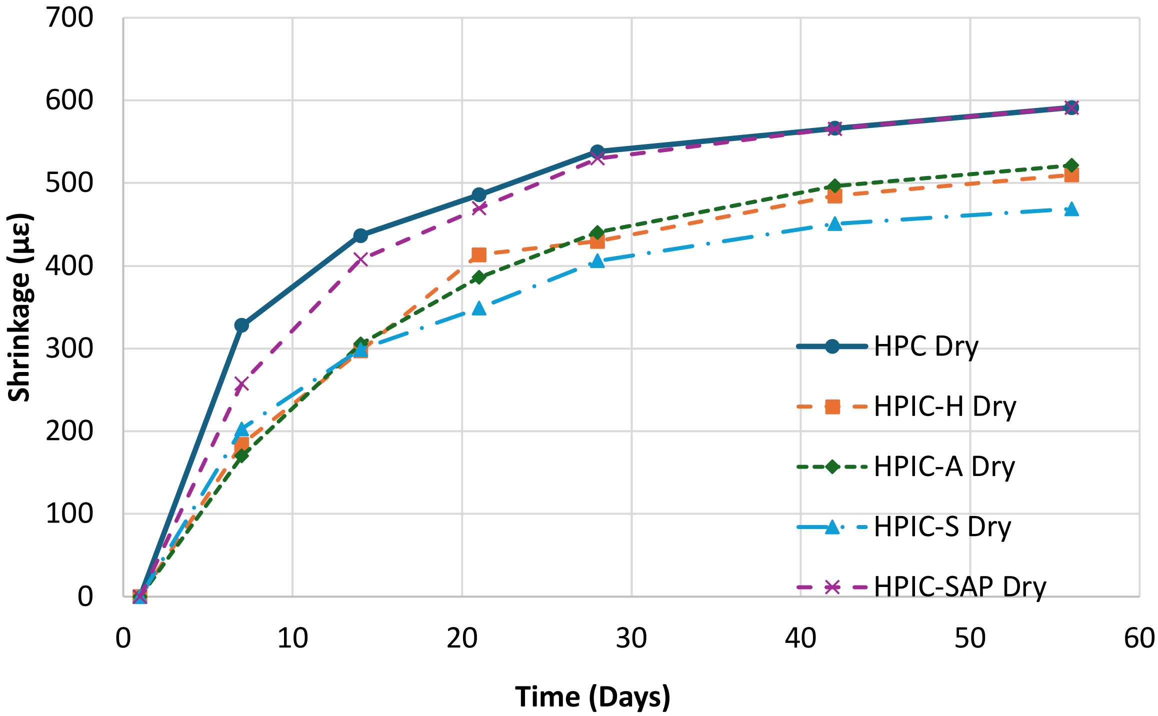


Figure 41. Total and Autogenous Shrinkage of HPC and HPIC

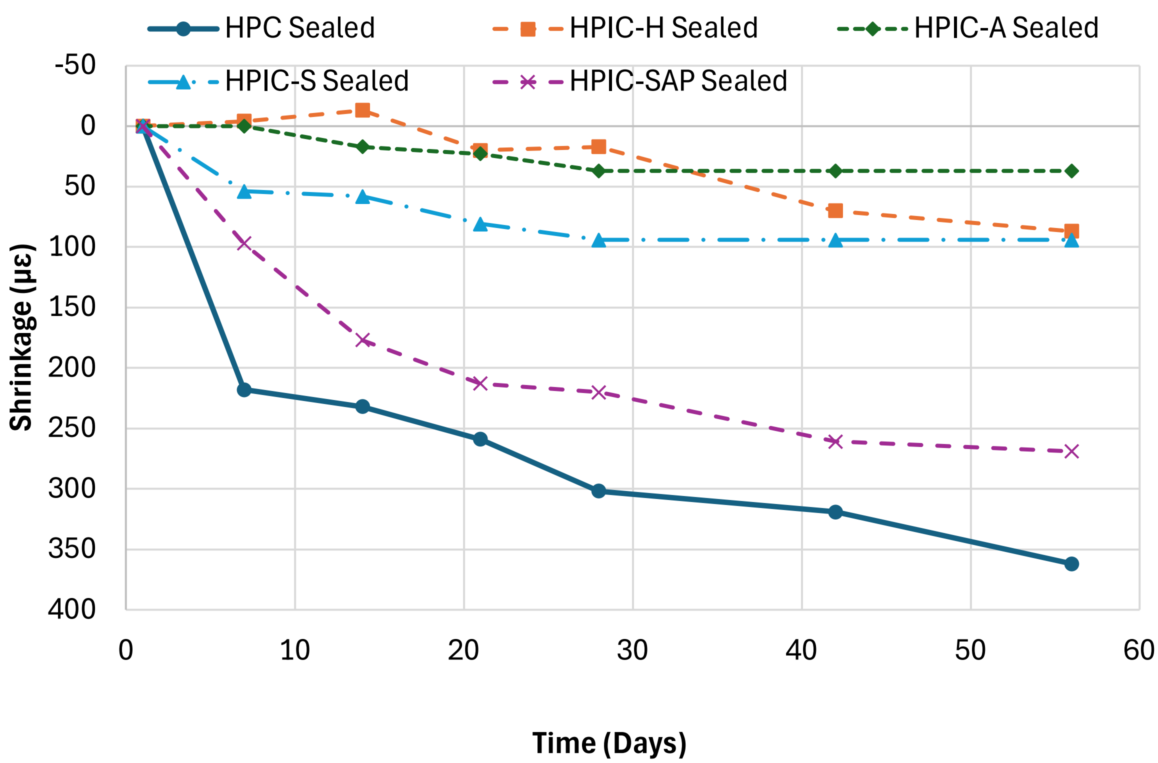


Figure 42. Total and Autogenous Shrinkage of HPC and HPIC (Sealed)

Restrained shrinkage testing was conducted to assess the effect of shrinkage on the development of stress in concrete. One of the primary causes of early-age cracking is concrete cast under highly restrained conditions, such as in bridge deck applications. The test setup is shown in Figure 45.

Typically, bridge decks incorporate a high degree of steel reinforcement, including reinforcement tied into previous adjacent pours, stay-in-place formwork, and shear studs affixed to the rigid superstructure. This high degree of rigidity impedes concrete shrinkage. The resulting interaction causes stress to build, commonly resulting in hairline longitudinal cracking spaced 3–10 ft apart on new bridge decks, as established during the literature review. This effect is especially pronounced in high-performance concrete (HPC) formulations, which have a higher cracking potential than conventional concrete due to their high cementitious content and low w/c ratio, exacerbating autogenous shrinkage as well as differential shrinkage across the cross section from external curing while being a relatively impermeable material.

Testing was conducted according to AASHTO T334 to assess the restrained shrinkage properties of HPC compared to HPIC with a dosage of 7 lb of internally stored water per 100 lb of cement. Results are shown in Figure 43 and Figure 44. Testing showed a significant reduction in the resultant stress at all ages when comparing HPIC to the HPC control (HPC-C) formulation, with a 45–55 percent reduction maintained across the majority of the testing period.

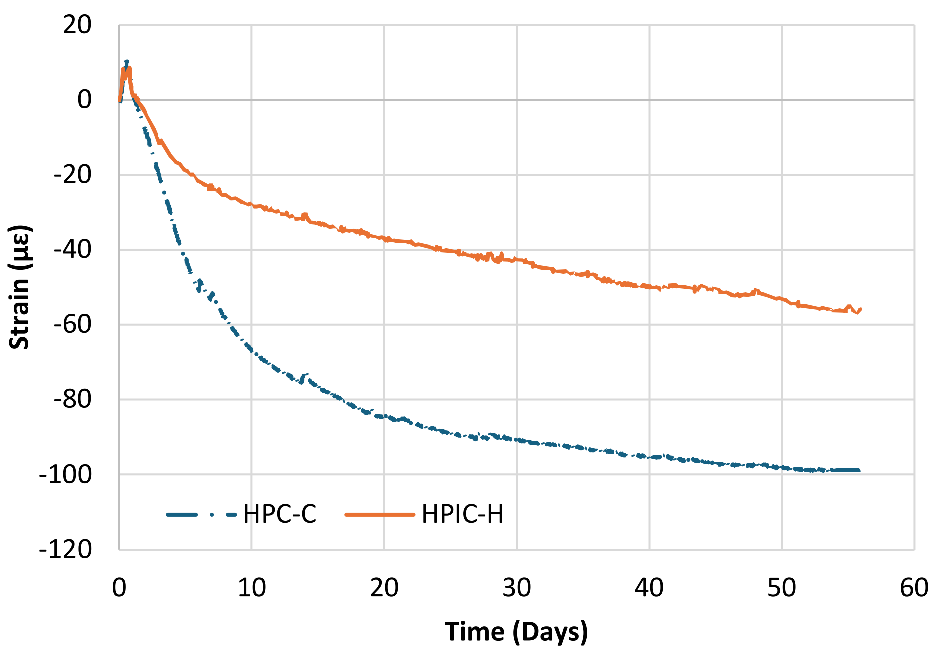


Figure 43. HPC Strain compared to HPIC

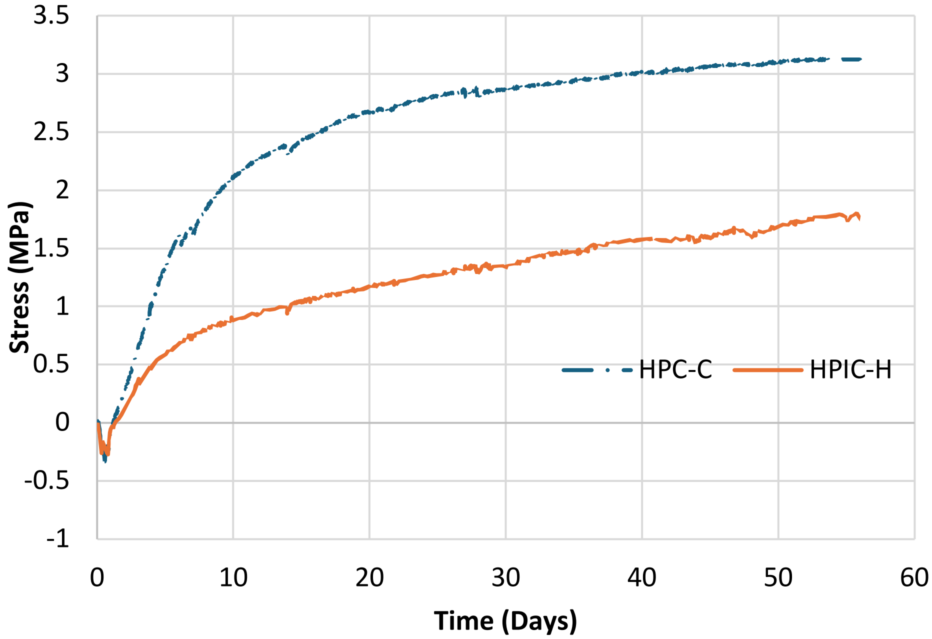


Figure 44. HPC Stress compared to HPIC

Figure 45. AASHTO T334 Testing Arrangement with Inner Steel Ring

Summary and Conclusion of the Laboratory Testing Program

Effect of Curing Regime

The testing conducted in the dosage evaluation showed clear trends in the effect of IC carrier dosage on shrinkage, as well as the critical importance of conventional external wet curing procedures for HPC-class materials regarding shrinkage, strength, and durability.

Findings support a dosage of 7 lb of internally stored water per 100 lb of cement, which showed comparable results to HPC at a replacement of normal-weight sand by LWFA of 41 percent by volume, while achieving a significant improvement in shrinkage behavior. For this reason, this dosage was accepted for further testing in the complete evaluation and field demonstration testing.

Testing of curing regimes highlighted the continued importance of proper wet curing practices and showed that internal curing alone does not provide an effective solution to reduce shrinkage or the potential for early-age cracking. Findings supported the typical recommendation of 14 days of wet curing, while 7 days of wet curing followed by the application of a curing compound showed comparable results for internal humidity, strength, and durability. Regarding shrinkage, the typical 14 days of wet curing produced the lowest degree of shrinkage, especially at early ages when concrete is most susceptible to shrinkage-induced cracking. During wet curing, concrete showed negligible shrinkage and, in many cases, even slight expansion due to the swelling effect commonly observed in saturated concrete.

For best results, 14 days of wet curing is recommended to provide maximum shrinkage reduction for shrinkage-sensitive applications such as bridge deck pours. Seven days of wet curing with the application of a curing compound also showed good results and can be beneficial in accelerated construction schedules, providing associated cost savings. The 14-day wet curing period had a larger effect than the inclusion of LWFA IC material when compared to conventional HPC left uncured. For that reason, internal curing HPC can be seen as an improvement to, but not a replacement for, a well-executed wet curing regime.

Comprehensive Evaluation

The expanded laboratory evaluation provided a more comprehensive assessment of the impact of the selected IC carriers and HPIC performance compared to HPC performance.

Across the majority of tests, HPIC with LWFA at comparable dosages behaved similarly to HPC. Strength results were comparable or slightly improved with the inclusion of LWFA, while durability testing demonstrated the low permeability indicative of a dense HPC matrix. One exception was freeze-thaw testing, where expanded shale LWFA behaved similarly to the HPC control formulation. Expanded shale LWFA HPIC results indicate higher resistance to freeze-thaw conditions than expanded clay, even though both passed ASTM C666 Procedure A.

Significant reductions in shrinkage were observed in all tests comparing HPC to HPIC with LWFA, including sealed and unsealed ASTM C157 testing and restrained shrinkage AASHTO T334 testing. This is especially important at early ages, when HPC is most susceptible to cracking.

HPIC using Super Absorbent Polymer (SAP) showed reductions across all strength properties tested compared to HPC or HPICs with LWFA. HPIC with SAP showed marginal improvements in shrinkage compared to HPC, primarily at early ages. The primary benefit of HPIC with SAP is its ease of use, as the SAP granules can be added to a measured dosage of water until approximately saturated surface dry immediately before inclusion into the concrete mixer and do not require stockpiling.

FIELD IMPLEMENTATION PROGRAM

An upscaled HPIC demonstration was coordinated between a premier concrete supplier for New Jersey and the primary supplier of lightweight aggregate for New York. A ready-mix truck was batched with IC material, mixed, and delivered onsite for sampling and a casting demonstration. Samples for a full range of testing were collected, as well as instrumented bridge deck slab samples. All testing of HPIC was conducted alongside conventional HPC, with a high degree of oversight by quality control representatives to ensure that the w/c ratio, air content, and all cementitious dosages were comparable.

Testing of HPIC and HPC batched and delivered by the concrete supplier conformed to the initial testing regime. Internal humidity testing was attempted on the bridge deck slab samples, but rainwater ingress into the boreholes invalidated the sensor readings.

Demonstration Slab Preparation

Simulated bridge deck slabs were prepared and instrumented as shown in Figure 46. Slabs were 8 in deep in “square” and “elongated” configurations of 4 ft × 4 ft and 2 ft × 8 ft, respectively. Two rebar mats with #4 rebar at 12 in spacing were installed with 2 in of clear cover on the top and bottom. While these slabs contained rebar, they do not have a degree of restraint sufficient to be considered highly restrained and primarily acted as a platform to attach rebar foil strain gauges and suspend high-precision vibrating wire strain gauges in the concrete.

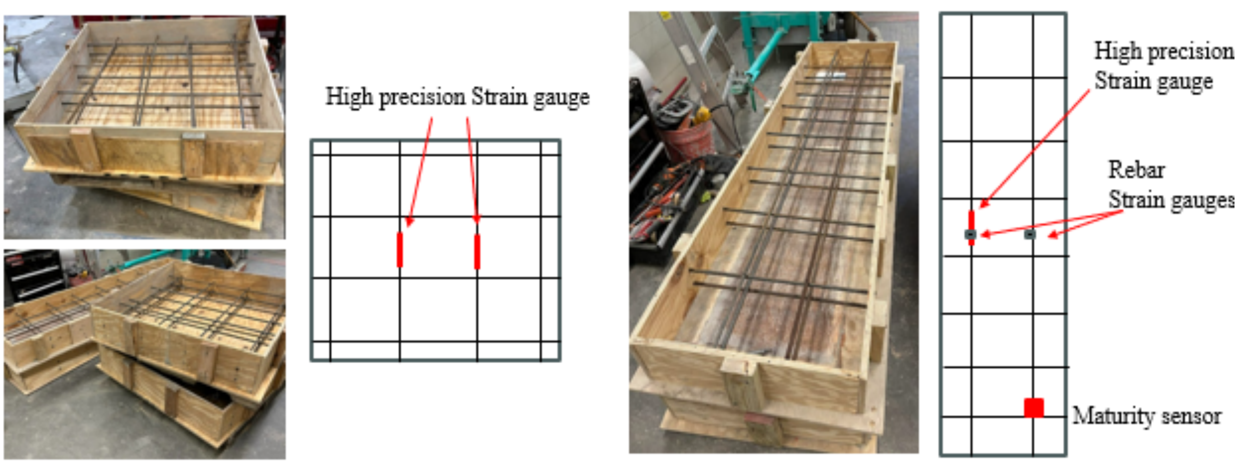


Figure 46. Demonstration Slabs Simulating Bridge Deck Segments

The following NJDOT HPC was used. Batch weight reports for both the NJDOT HPC and the modified HPIC are shown in Table 36.

Table 36 – Batch Weight Sheet Summary

Material (per yd^3)	HPIC	HPC
#57 Coarse Agg (lb)	1350	1350
Sand (lb)	900	1233
LWFA Exp. Shale (lb)	250	0
#8 Coarse Agg (lb)	450	450
Type 2 cement (lb)	370	370
Slag cement (lb)	263	263
Silica Fume	25	25
AEA (oz)	2	2
POLY HRWR (oz)	80	80
RX Retarder (oz)	44	40

Field Demonstration Results

The formulations delivered in Table 36 were ensured by QA/QC representatives present to have a w/c ratio of 0.385. LWFA was batched at SSD with an absorption of 19.5 percent, providing 7.4 lb of internally stored water per 100 lb cement. Fresh properties were deemed comparable (Table 37) and no additional high range water reducer was added onsite.

Table 37 – Field Demonstration Fresh Properties

Fresh properties	HPIC	HPC
Slump (in)	7	5
Air Content	3%	3%
Unit Weight (lb/ ft^3)	146.9	152.0

Figure 47-51 summarize the testing results. Testing showed a very high strength for the HPC and HPIC formulations, with both exceeding 11,000 lbf/in^2 compressive strength at day 56. Differences are unremarkable, with HPC having a consistently higher tensile strength. For compressive strength, flexural strength, and elastic modulus stiffness testing HPIC lagged at early ages but managed to equalize or exceed HPC properties at 56-day testing.

This continued strength gain at later ages can likely be attributed to continued hydration due to the IC carrier desorbing its stored water reserves. Concrete with normal weight aggregate generally displays higher strength than formulations with light weight expanded aggregates (Mohammad et al. 2022) [50], which can be attribute to the reduced mechanical properties at earlier ages.

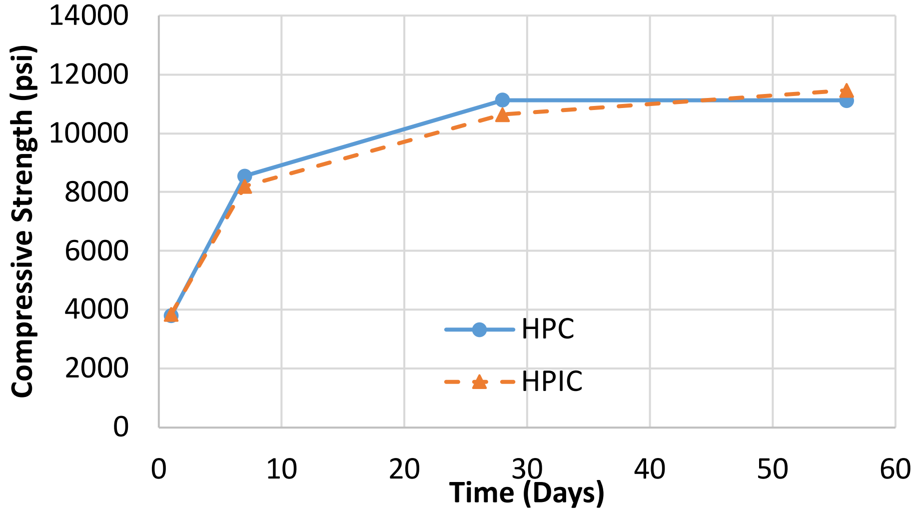


Figure 47. Compressive Strength of HPIC and HPC from Concrete Supplier

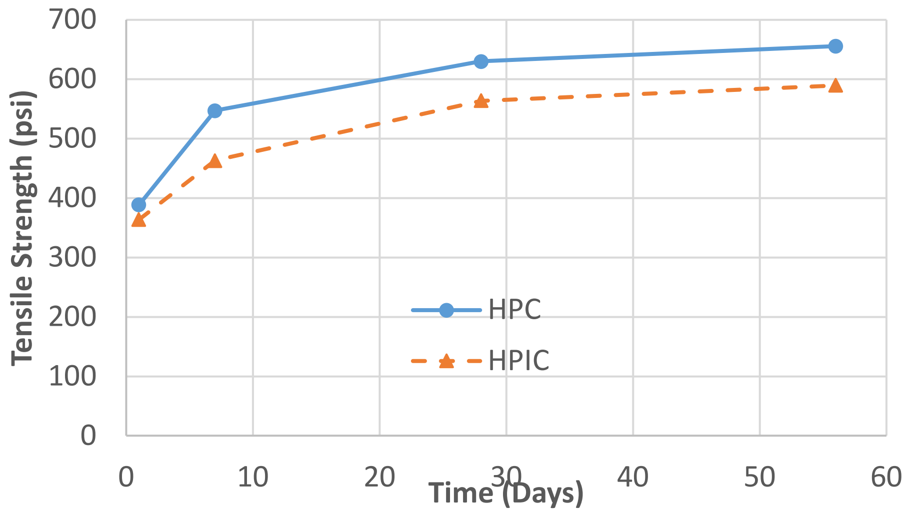


Figure 48. Tensile Strength of HPIC and HPC from Concrete Supplier

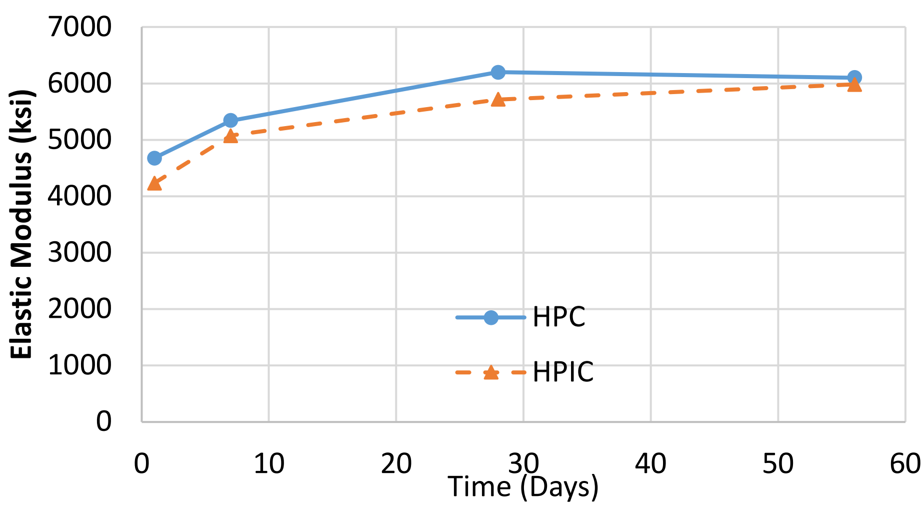


Figure 49. Elastic Modulus of HPIC and HPC from Concrete Supplier

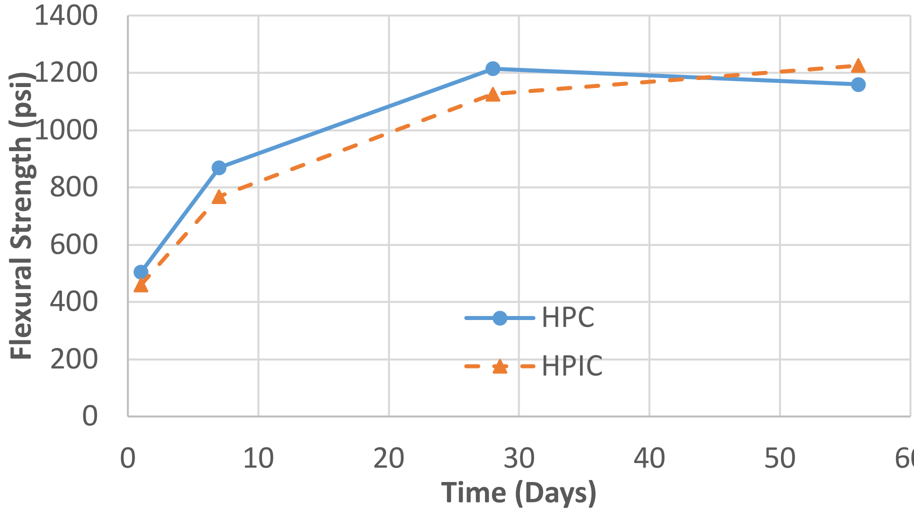


Figure 50. Flexural Strength of HPIC and HPC from Concrete Supplier

Durability results in Table 38 and Table 39 were excellent, showing high mechanical strength properties and indicating a dense matrix for the delivered demonstration formulations. This density can be attributed to the relatively low air content of 3 percent for both mixes and to the homogeneous mixing achieved by the large-scale 2 yd^3 transit mixer. Results for both formulations for SR showed a high degree of surface densification, providing high resistance readings for all test dates. RCPT results were classified as "Very Low," ranging from 100–1000. These readings are typical of latex-modified concrete and are one category lower than typical HPC mixtures with a w/c ratio below 0.4.

Table 38 – Field demonstration Surface Resistivity Test Results

	HPC	**HPIC**
Day 7	12.2	11.9
Day 28	49.7	42.5
Day 56	72.9	63.3

Table 39 – Field demonstration Rapid Chloride Permeability Test Results

	HPC	**HPIC**
Day 28 (Standard)	870	933
Day 56 (Extended)	507	653

ASTM C157 unsealed "dry" shrinkage results largely replicated the laboratory testing results, as shown in Figure 51 and Figure 52. The primary focus of the field demonstration testing was the use of embedded strain sensors to monitor the 8 in deep simulated bridge deck slabs and to replicate real-world curing methodologies and conditions.

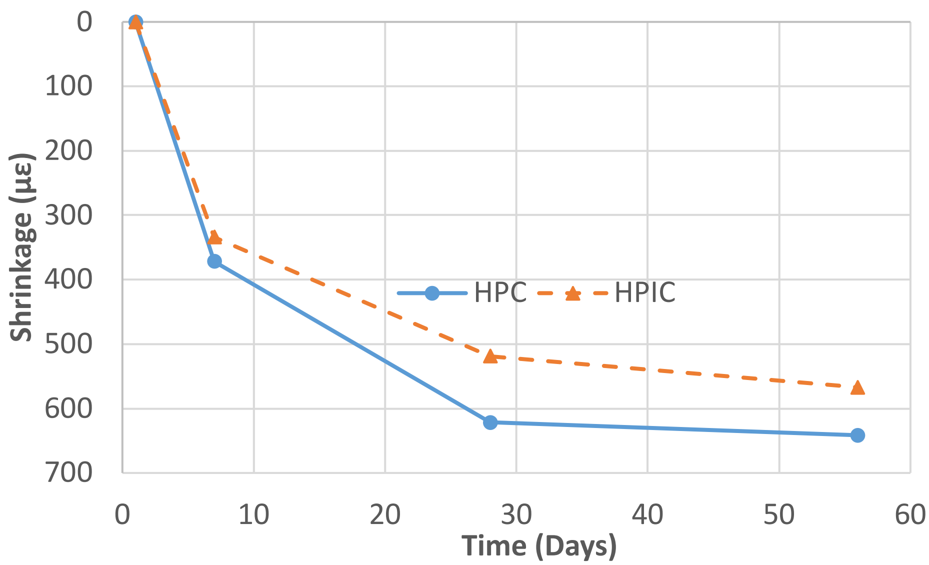


Figure 51. Total Dry Shrinkage of HPIC and HPC from the Field Demonstration

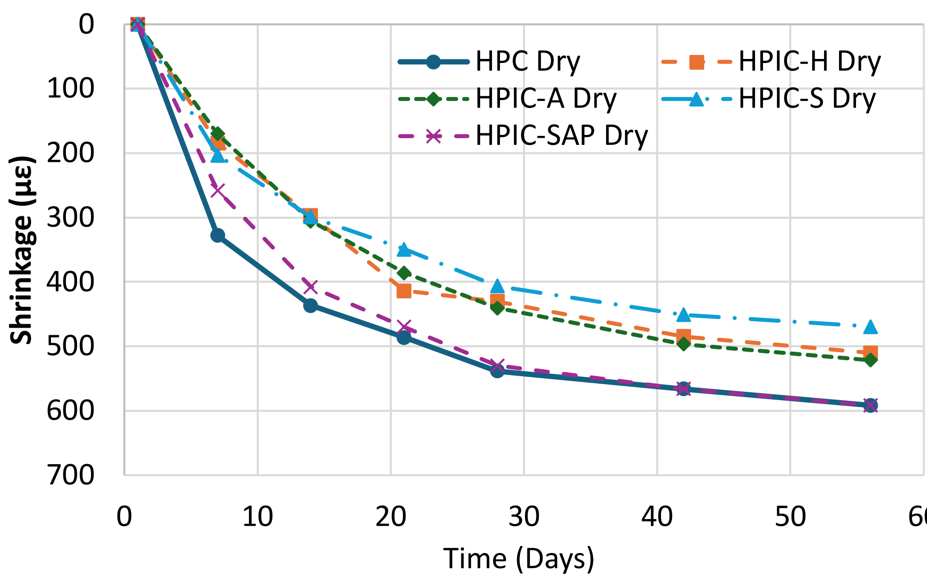


Figure 52. Total Dry Shrinkage of HPIC and HPC from Laboratory Mixes

Slabs underwent 14 days of wet curing, with several cured for 7 days followed by the application of curing compound. All slabs were cast outdoors on May 12th, 2025, and tested under ambient conditions. Shrinkage data between 5/12.25 and 9/25/25 for 136 days from casting to final data collection, is shown in Figure 53. Daily fluctuations of 10-15 με were observed due to thermal expansion and contraction during the day-night cycle. A 24-hour moving average was applied to reduce noise from these thermal fluctuations.

From the evaluation of the 18 high-precision VWSGs over 136 days since set time, a clear trend emerges when comparing the HPIC and HPC formulations under real-world curing conditions. A significant reduction in shrinkage is observed during the wet curing phase (Table 40). At day 3, HPIC exhibits negligible shrinkage, while HPC averages 90 με.

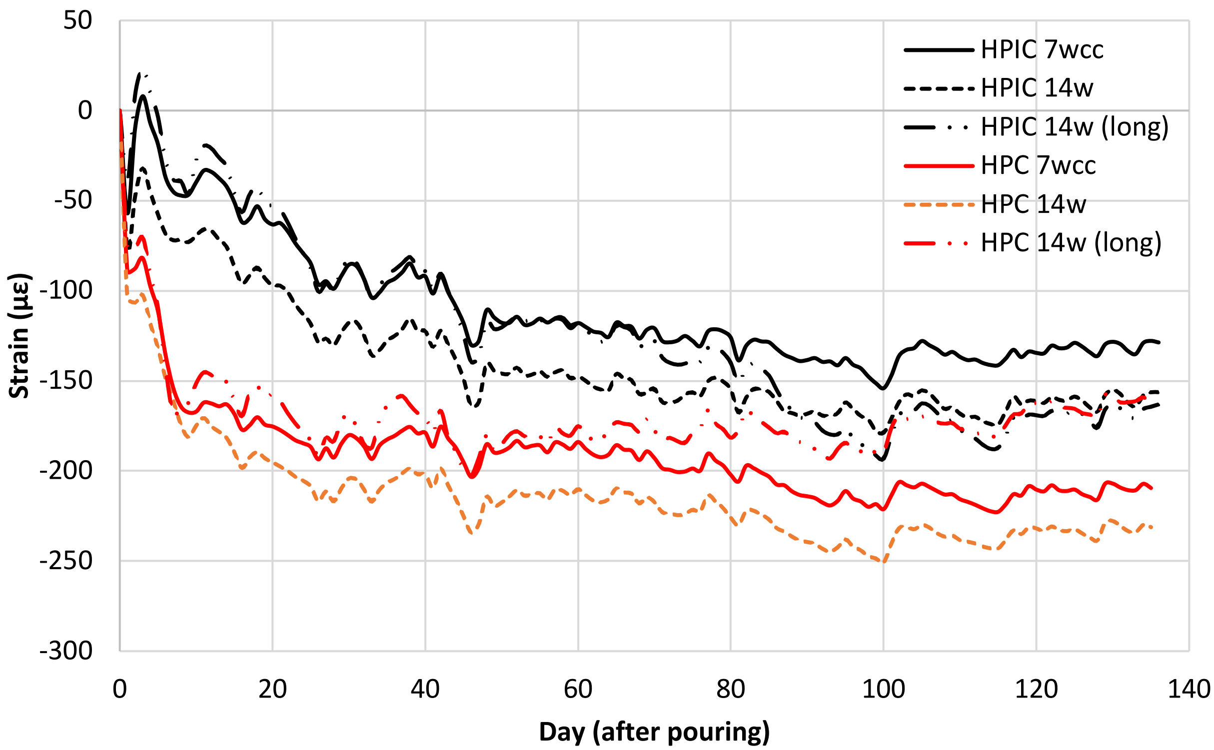


Figure 53. Field Demo Slab Raw Strain Results (24-hour Moving Average)

Table 40 – Percent Difference Comparison between Shrinkage of HPC and HPIC

Age (days)	HPIC Strain (με)	HPC Strain (με)	% diff. HPC to HPIC
3	-5	-89	94%
7	-54	-161	66%
14	-53	-169	68%
28	-111	-203	45%
56	-130	-201	35%
91	-156	-221	29%
136	-146	-207	29%

LIFE-CYCLE COST ANALYSIS (LCCA) OF HPIC IMPLEMENTATION

When evaluating innovative construction materials, it is essential and important to look beyond initial costs and consider the full life-cycle cost of a project, including maintenance, repair, user delays, vehicle operation, and social-economic impact resulting from these activities. Life-Cycle Cost Analysis (LCCA) provides a present value framework to compare material and design alternatives based on total long-term costs. By incorporating direct costs (i.e., agency costs), as well as indirect costs (i.e., road user costs and relevant externalities) across the service life, LCCA enables a more comprehensive comparison of material and design alternatives and quantifies how durability and rehabilitation timing influences cumulative expenditures [51]. In the context of IC-HPC, where enhanced durability aims to reduce shrinkage, cracking, and permeability, LCCA serves as a critical tool to help understand performance benefits into long-term economic value. Considering uncertainties such as service life, discount rate, and unit prices further supports informed, data-driven decision-making.

Inputs were determined in coordination with NJDOT and the industry partners, Clayton Concrete and Northeast Solite. The NJDOT HPC used as control and the modified HPIC using expanded shale in Task 6 was used for all analysis for Life-Cycle Cost. Hearin the formulations will be referred to as “HPC” and “HPIC” exclusively. Rates per yd^3 were determined based on input received from the NJDOT. Unit prices for HPIC were based on the NJDOT bid prices as of November 2025. The cost components considered include the cost of the Internal Curing expanded shale product, transportation to New Jersey from the production plant in New York State and the standard dosage of the IC agent costs. Additional allowances were included to account for additional testing, stockpiling, and additional QA/QC considerations, with IC agents and ensuring proper saturation is achieved. Numbers were verified as acceptable and realistic with the concrete supplier and NJDOT team. Bridge Deck lifespan taken from Federal Highway Administration (FHWA) recommendations [52] (40 years for HPC and 63 years for HPIC) were adjusted to 25 years and 40-50 years, respectively, based on feedback from NJDOT to better reflect NJ conditions. The detailed list of costs and service life considerations based on the feedback is listed in the subsequent analysis section. It’s notable that internal curing pilot programs only began in the late 2000’s and the full proposed lifespan of HPIC bridge decks have not been reached.

Deterministic Analysis

A deterministic LCC analysis was conducted to compare the life-cycle cost of HPC and HPIC using a spreadsheet tool previously developed by the research team to integrate life-cycle costs into agency investment decisions [53, 54]. The tool estimates life-cycle costs for alternative materials by accounting for agency, user, and public costs. Agency cost accounts for direct costs such as construction, maintenance, rehabilitation, replacement, and related engineering and administrative expenses. User and public costs include traffic delay, vehicle operation, and crash risk costs associated with maintenance and rehabilitation activities, as well as other external costs. The LCCA is performed using the net-present value (NPV) method to account for the time value of money over the analysis period.

The cost and service life inputs used are listed as the following:

accounts for direct costs such as construction, maintenance, rehabilitation, replacement, and related engineering and administrative expenses. User and public costs include traffic delay, vehicle operation, and crash risk costs associated with maintenance and rehabilitation activities, as well as other external costs. The LCCA is performed using the net-present value (NPV) method to account for the time value of money over the analysis period.

The cost and service life inputs used are listed as the following:

Unit Cost Inputs Used:

HPC: $1500/CY was used in the analysis based on NJDOT bid prices

HPIC: A set of costs was used to reflect various conditions:

- $1650/CY: A 10 percent increase compared to HPC, based on supplier cost input,
- $1800/CY: Reflects a 20 percent increase in price over HPC per FHWA report [55] and
- $2000/CY: Based on the current higher-end bid prices provided by NJDOT as of November 2025.

It should be noted that the analysis incorporates multiple HPIC unit cost assumptions to account for the current higher-end bid prices (approximately a 30 percent increase, as of Nov 2025) which is likely elevated due to limited market experience. The analysis also considers the anticipated potential future costs (10-20 percent increase) once the material becomes institutionalized and pricing stabilizes.

Service Life Inputs Used:

HPC: 25 years was used to reflect the anticipated service life under NJ conditions

HPIC: Two service life values were used:

- 40 years: Provided by NJDOT to reflect NJ conditions (salt exposure, high usage)
- 50 years: To reflect the minimum improvement threshold (25 years) based on the FHWA report referenced prior

Example input (Figure 54) and output (Figure 55) from the spreadsheet tool using a sample NJ bridge on I-80 are displayed below. The analysis was performed for multiple bridges using a 2.3 percent discount rate based on the OMB rate [56], traffic and bridge information from the National Bridge Inventory (NBI) and NJDOT roadway database [57] (e.g., structure length, width, average daily traffic, truck percentage) over a 75-year analysis period. The updated maintenance schedules were assigned as every 5 years for HPC and every 10 years for HPIC based on NJDOT feedback. Additionally, an initial cost premium for new mix design and verification testing ($25,000) and trial batch and test slab ($25,000) have been added to HPIC calculations based on feedback regarding construction costs.

It should be noted that the weighted sum method is used to calculate the total life cycle cost (LCC), where the user cost is assigned a weight of 0.3, and all other costs are assigned a weight of 1.

INPUT

Project Detail				
Project site:	Interstate-80			
Construction type (Pavement/bridge):	Bridge Deck			
State:	New Jersey			
Milepost from:	61.1901306	To	61.3100552	
Structure Length (feet):	231.9			
Structure Width (feet):	154.8			
Structure Thickness Assumption (inch)	8			
Comments:	Bridge built in 1963			

Analysis Option				
Alternatives:	Alternative A:	HPC		
	Alternative B:	HPIC		
Analysis period (years):	75			
Discount rate (%):	2.3%			
Service Life (years):	Alternative A:	25	Alternative B:	50
Material Unit Price ($/cubic yard):	Alternative A:	1500	Alternative B:	2000
Construction Unit Cost ($/square feet):	Alternative A:	370.37	Alternative B:	493.83

Traffic Data				
Average Daily Traffic (ADT) (veh/day):	114,739			
Trucks as percentage of ADT (%):	1.55%			
Annual Growth Rate of Traffic (%):	0.5%			
Lanes opened under normal condition:	Inbound	4	Outbound	5
Value of time ($/hr):	Passenger cars:	11.58	Trucks:	20.43

Figure 54. Spreadsheet Tool Example Input using I-80 Sample Bridge

OUTPUT

Agency Cost				
Initial Construction Cost ($):	Alternative A:	10,082,497	Alternative B:	13,493,329
Maintenance Cost ($):	Alternative A:	3,334,373	Alternative B:	2,104,491
Rehabilitation Cost:				
(A) Replace the structure (price include demolition&traffic control)($):	Alternative A:	11,795,454	Alternative B:	5,686,761
(B) Approach roadway work (Lump Sum)($):	Alternative A:	589,773	Alternative B:	284,338
(C) Traffic Staging ($):	Alternative A:	2,477,045	Alternative B:	1,194,220
(D) Preliminary Engineering($):	Alternative A:	1,238,523	Alternative B:	597,110
Total Rehabilitation Cost (s):	Alternative A:	16,100,795	Alternative B:	7,762,429
Salvage Value ($):	Alternative A:	0	Alternative B:	-2,198,249
Total Agency Cost ($):	**Alternative A:**	**$29,517,665**	**Alternative B:**	**$21,162,001**

User Cost				
Traffic Delay Cost ($):	Alternative A:	$33,632,357	Alternative B:	$15,547,808
Vehicle Operation Cost ($):	Alternative A:	$2,256,393	Alternative B:	$1,034,130
Crash Risk Cost ($):	Alternative A:	$40,021	Alternative B:	$15,642
Total User Cost ($):	**Alternative A:**	**$35,928,772**	**Alternative B:**	**$16,597,579**

Public Cost				
External Cost ($)	Alternative A:	**$65,757**	**Alternative B:**	**$58,003**
Total Social Cost ($):	**Alternative A:**	**$65,757**	**Alternative B:**	**$58,003**

Total Life Cycle Cost				
Network Present Value ($):	Alternative A:	$40,362,053	Alternative B:	$26,199,277
Recommended Alternative:	Alternative B (New Material)			
Favorite Alternative Benefit:	Agency Cost		28.31%	
	User Cost		53.80%	
	Social Cost		11.79%	
	Total Life Cycle Cost		35.09%	

Figure 55. Spreadsheet Tool Example Output using I-80 Sample Bridge

In addition to the sample I-80 bridge, six additional bridges were selected for the analysis, identified by the following BRKEYs: 1610174, 2116153, 1420151, 1414166, 0225165, and 1610158. The selection was made to capture a representative range of deck sizes across the sample set. The subsequent results were derived from the deterministic analysis.

Deterministic LCCA results: HPIC vs HPC

Deterministic LCCA results demonstrate that HPIC outperforms HPC in all cost categories. Table 41 summarizes the range of benefits associated with implementing HPIC for the selected sample bridge set, relative to HPC. Table 42 and Table 43 present the cost savings for different combinations of service lives and unit costs for a sample bridge on I-80.

Table 41 – Deterministic LCCA Results

	HPIC vs HPC
Agency Cost	15-41%
User Cost	33-58%
Public Cost	7-12%
Total LCC	16-44%

Table 42 – Agency Cost Benefit Range for a Sample Bridge on I-80

Agency Cost Benefits		**HPIC Unit Cost Input ($/CY)**		
		Low	Medium	High
		1650	1800	2000
HPIC Service Life	40 yrs	30.67%	24.39%	16.01%
	50 yrs	40.82%	35.46%	28.31%

Table 43 – Total Cost Benefit Range for a Sample Bridge on I-80

Total Cost Benefits		**HPIC Unit Cost Input ($/CY)**		
		Low	Medium	High
		1650	1800	2000
HPIC Service Life	40 yrs	36.07%	31.48%	25.35%
	50 yrs	44.24%	40.32%	35.09%

An example visualization of these percentage results, along with the NPV of all cost components for the sample I-80 bridge, is shown in Figure 56.

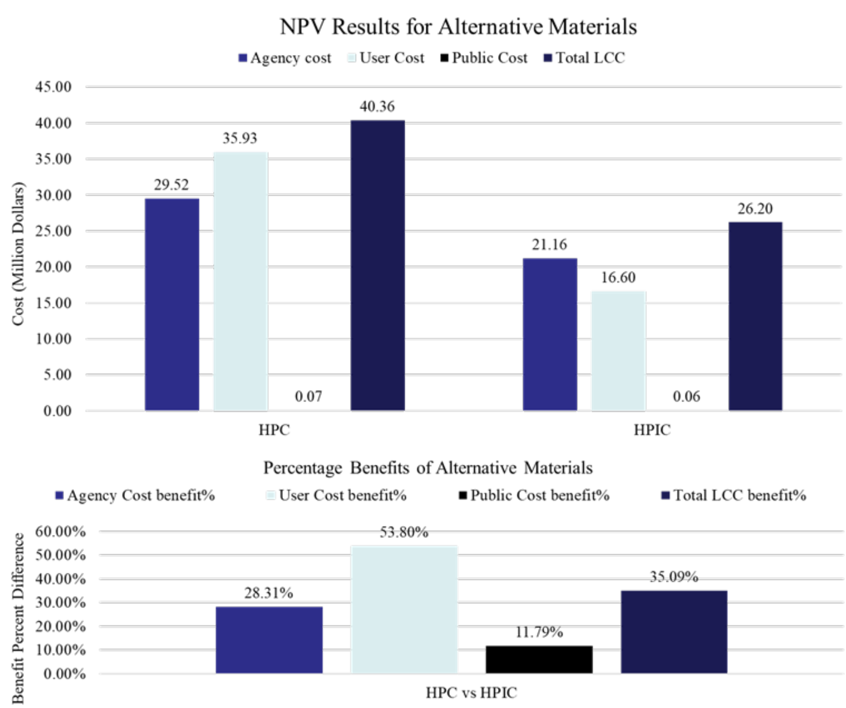


Figure 56. Example Visualization of Benefits and NPVs for I-80 Sample Bridge

Probabilistic LCC Analysis

To account for the uncertainty associated with the new material, a probabilistic LCCA approach was also performed. The uncertainty was evaluated using Monte Carlo simulations, which involve repeated random draws from specified distributions of construction prices, discount rate, and service life over a 75-year analysis period. Each simulation produces an LCCA outcome, and the resulting ensemble provides probability-based cost comparisons. The cost inputs for the probabilistic analysis are listed as the following ranges for both alternatives via triangular distributions ($/CY)

- HPC: [min=1100, mode=1500, max=2000]
- HPIC: [min=1400, mode=1700, max=2000]

The cost range for HPC was based on bidding prices obtained from the NJDOT's Estimation Support and Historical Statistics Report [58]. The HPIC cost range was based on most recent bidding prices provided by NJDOT as of November 2025. Monte Carlo simulations (10,000 runs) were conducted to create a distribution of costs based on the defined distributions for input variables. For each iteration, the model computed agency, user, public, and total NPVs for HPC, and HPIC across the 75-year horizon. The remaining inputs are kept the same as in the deterministic analysis, and two service life estimates of 40 and 50 years are used for HPIC.

Probabilistic LCCA Results: HPIC vs HPC

The probabilistic analysis demonstrated that HPIC achieved lower costs than HPC in the majority of simulated outcomes. Based on the probabilistic results, HPIC exhibited an 83.8 percent likelihood of achieving a lower agency cost than HPC (i.e., *P*(HPIC Agency < HPC Agency) =83.8 percent), and 100 percent likelihood of achieving a lower total life-cycle cost than HPC (i.e., *P*(HPIC Total < HPC Total) = 100 percent) when service life is 40 years for HPIC. These results have been displayed in Figure 57 and Figure 58.

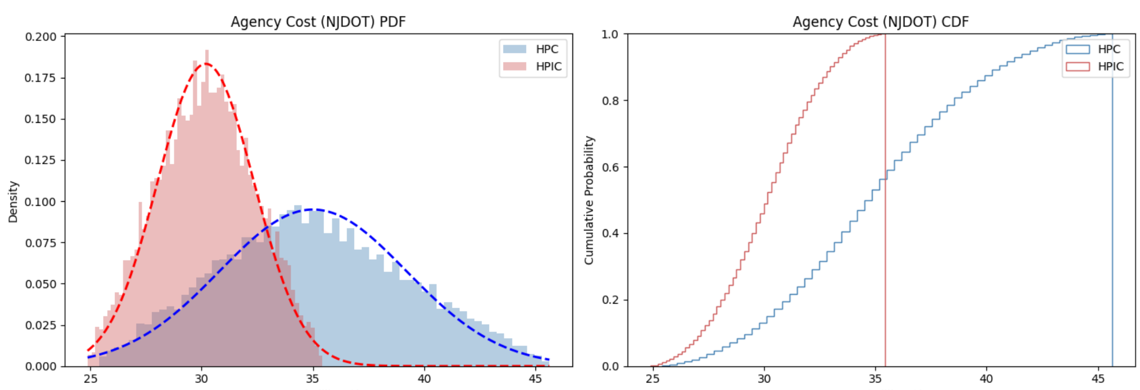


Figure 57. Agency Cost Distribution Comparison: HPIC vs HPC (HPIC Service Life (SL) = 40 Years)

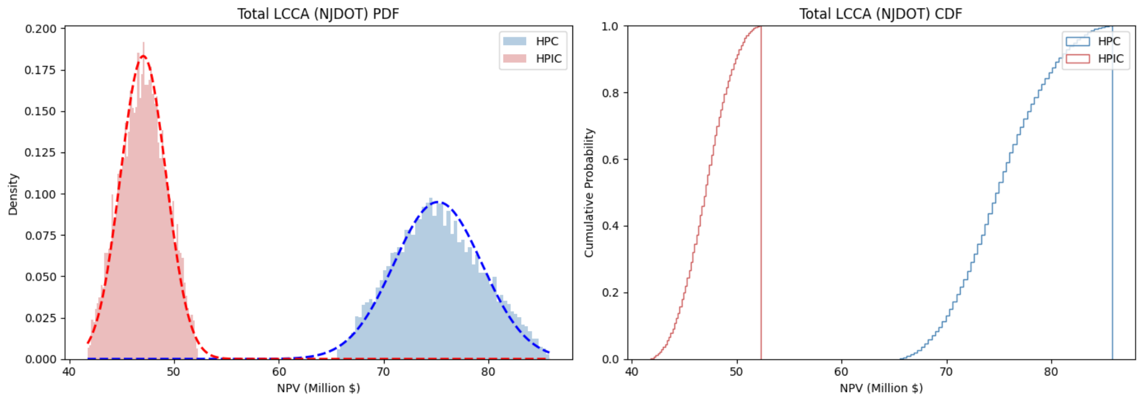


Figure 58. Total Cost Distribution Comparison: HPIC vs HPC (HPIC SL = 40 Years)

When the service life of HPIC was set to be 50 years, HPIC exhibited a 95.9 percent likelihood of achieving a lower agency cost than HPC (i.e., *P*(HPIC Agency < HPC Agency) =95.9 percent), and 100 percent likelihood of achieving a lower total life-cycle cost than HPC (i.e., *P*(HPIC Total < HPC Total) = 100 percent) which are displayed in Figure 59 and Figure 60, respectively. Overall, the HPIC alternative maintained a lower median NPV than HPC for all cost types.

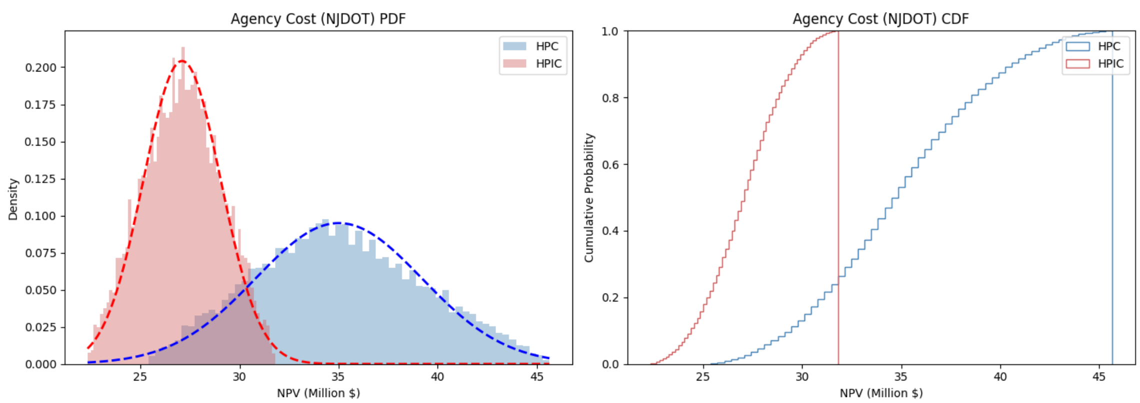


Figure 59. Agency Cost Distribution Comparison: HPIC vs HPC (HPIC SL=50 Years)

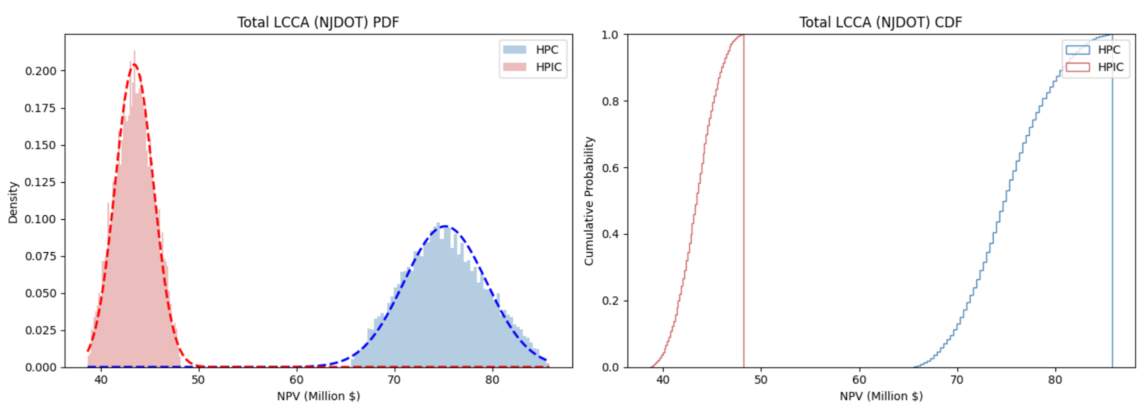


Figure 60. Total Cost Distribution Comparison: HPIC vs HPC (HPIC SL = 50 Years)

CO2 Emission Analysis

Moreover, the public cost among the alternatives was evaluated by comparing their CO_2 emissions using the carbon cost metric reported by Rennert et al. [59], which estimates a mean value of $185/t$CO_2$ and a 5th–95th percentile range of $44–$413/tCO_2. The CO_2 emission factors adopted for the analysis were 404 lb CO_2e/CY for HPC and 444 lb CO_2e/CY for HPIC (Table 44).

Table 44 – Embodied Carbon Values for Alternative Materials

	HPC	**HPIC**	**Embodied carbon (kgCO2e/kg)**	**Source**
Type I cement (kg/m^3)	206.6	206.6	0.941	Holcim Whitehall EPD [60]
Type IL cement (kg/m^3)	0.0	0.0	0.847	Holcim Whitehall EPD [60]
Grade 120 GGBFS (kg/m^3)	20.9	20.9	0.134	Holcim Sparrows Point EPD [61]
Silica fume (kg/m^3)	0.2	0.2	0.014	Norchem EPD 530-R-08-007 [62]
Sand (kg/m^3)	3.7	2.7	0.005	Vulcan Top Sand EPD [63]
Lightweight sand (kg/m^3)	0.0	24.6	0.148	ESCSI Info sheet 2023 [64-68]
ASTM #8 (kg/m^3)	1.6	1.6	0.006	Vulcan EPD [61]
ASTM #57 (kg/m^3)	4.8	4.8	0.006	Vulcan EPD [61]
Water (kg/m^3)	0.0	0.0	0	-
Air Entraining Admixture (kg/m^3)	0.004	0.004	0.15	Euclid EUCON AIR MAC6 EPD [69]
High Range Water Reducer (kg/m^3)	1.5	1.5	1.0	Euclid Plastol 5000 EPD [69]
Set Retarder (kg/m^3)	0.4	0.4	0.6	Euclid EUCON 727 EPD [69]
Embodied carbon (kgCO2e/m^3)	**240**	**263**		
Embodied carbon (lbCO2e/yd^3)	**404**	**444**		

Although HPIC's embodied carbon per yd^3 is slightly higher than that of HPC, its longer service life and reduced rehabilitation frequency result in fewer work-zone activities and associated emissions over the 75-year analysis period. Consequently, the public cost analysis yields a lower NPV for HPIC compared with HPC across tested discount-rate cases, corresponding to emission savings of 11.8 percent and 7.3 percent at 2 percent and 3 percent discount rates, respectively (Table 45 and Figure 61). Overall, HPIC outperforms HPC in terms of life-cycle public cost, despite a modest per-unit CO_2 emission premium.

Table 45 – LCCA Environmental Cost Result Comparison

Discount Rate:	**2%**	**3%**
HPC Emissions (metric tons CO2e):	360.23	320.45
HPIC Emissions (metric tons CO2e):	317.75	297.16
Difference (metric tons CO2e):	42.48	23.29
HPC Public Cost (Mean):	$65,757	$59,621
HPIC Public Cost (Mean):	$58,003	$55,287
HPIC Public Cost Savings Compared to HPC:	11.8%	7.3%

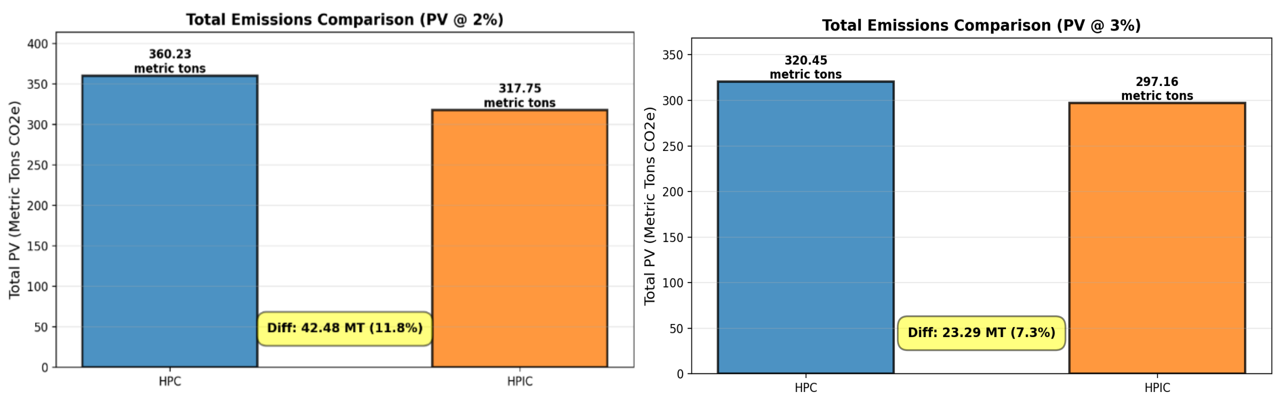


Figure 61. CO_2 Emission Public Cost at Different Discount Rates

Summary

Both deterministic and probabilistic LCCA results confirm that HPIC consistently outperforms HPC in total life-cycle cost across the evaluated bridges. Using NJDOT and supplier-verified inputs and a 75-year analysis horizon, deterministic LCCA results show that HPIC achieves agency cost savings of 15.27-40.90 percent and total cost savings of 15.82-44.24 percent, depending on unit cost assumptions and extended service-life values. Under stabilized HPIC unit-price conditions (10 percent higher than HPC), HPIC can deliver approximately 31-41 percent agency cost savings compared with HPC under typical New Jersey conditions (e.g., high salt usage). Probabilistic LCCA analysis further validates the robustness of this performance. Monte Carlo simulations indicate an 83.8-95.9 percent probability that HPIC yields lower agency costs than HPC and a 100 percent probability that HPIC's total life-cycle cost is lower across all simulated outcomes, regardless of service-life assumptions. The public cost analysis also indicates that, despite HPIC's slightly higher embodied carbon per yd^3 compared with HPC, its extended service life results in lower cumulative CO_2 emissions and, consequently, a lower life-cycle public cost. Overall, the results suggest that HPIC can offer long-term economic advantages despite its higher initial costs compared to HPC.

NJDOT HIGH PERFORMANCE INTERNAL CURING (HPIC) GUIDE SPECIFICATIONS May 2025. Based on experience gained during laboratory testing, the centrifuge method as outlined by ASTM C1761/C1761M was used for modifying NJDOT Test Method A-8 – Determining moisture content of lightweight fine aggregate. Laboratory testing showed improved test consistency, faster test completion, and a significant reduction in operator variance due to the mechanical nature of the centrifuge method when compared to the paper towel method which requires manual drying.

Modifications to the May 2025 iteration (Figure 62) include changing the test description in A. Scope from “Paper Towel Method” to “Centrifuge method”, updating the required B. Apparatus to include a VI. centrifuge and VII. filter rings while omitting disposable paper towels, and updating the C.

Procedure from

> 3. Place Sample #2 on a 2 to 3 ft long sheet of clean, dry paper towel.
> 4. Spread Sample #2 uniformly across the paper towel while patting the sample with another paper towel. Continue patting and spreading the sample, replacing the sheets of paper towel whenever the paper becomes too damp or dirty to absorb moisture. Conduct this process as quickly and carefully as possible. Repeat the patting and spreading of the sample until no further moisture appears on the clean paper towels.

To

> 3. Place Sample #2 in the centrifuge bowl. Place filter ring on top of centrifuge bowl and secure centrifuge bowl in the centrifuge apparatus.
> 4. Set centrifuge speed control to 2000 ± 20 rpm. Testing time of 4 minutes ± 1 minute shall begin when centrifuge speed reaches 2000 rpm ± 20 rpm.

NJDOT TEST METHOD A-8 – DETERMINING MOISTURE CONTENT OF LIGHTWEIGHT FINE AGGREGATE

A. Scope. This test method is used to determine the total, absorbed, and surface (free) moisture content of lightweight fine aggregate to be used for internal curing of Portland cement concrete. The moisture content determination is to be used to verify minimum absorbed water content is provided and for batch adjustments accounting for the surface (free) moisture. The method is commonly referred to as the “Centrifuge method” per ASTM C1761/C1761M.

B. Apparatus.

I. Balance: Having a capacity of at least 4 kg and accurate to at least 0.1 g.
II. Sampling containers: Non-absorbent, sealable, bag or tub with a capacity sufficient for holding approximately 2000 grams of fine aggregate.
III. Scoop, shovel, or large spoon.
IV. Sheets of non-absorbent cloth, canvas, or polyethylene (approximate size: 24” (600 mm) x 24” (600 mm)).
V. Drying apparatus: A ventilated oven capable of maintaining temperature of 230±10°F (110±5°C) for 24 hours. In cases where the aggregate is not altered by overheating, other sources of heat, such as electric or gas hotplates, or electric heat lamps may be used.
VI. Centrifuge extractor: A centrifuge apparatus with a 241 mm [9.5 in.] diameter centrifuge bowl and an apparatus in which the bowl can be revolved at controlled variable 72 speeds up to 377 rad/s [3600 revolutions per minute]. The speed shall be controlled either manually or using a preset speed control. The apparatus shall be provided with a container for catching the surface water thrown from the aggregate particles and a drain for removing the water
VII. Filter rings: Low-ash paper filter rings approximately 1.3 mm [0.05 in.] thick. The ash content of the paper shall not exceed 0.2 % (approximately 0.034 g per ring).
VIII. Metal heat resistant pans: With sufficient capacity to hold a minimum of 500 grams of fine aggregate in an oven or on a hot plate at the specified temperature.

3. Place Sample #2 in the centrifuge bowl. Place filter ring on top of centrifuge bowl and secure centrifuge bowl in the centrifuge apparatus.
4. Set centrifuge speed control to 2000 +/- 20 rpm. Testing time of 4 minutes +/- 1 minute shall begin when centrifuge speed reaches 2000 rpm +/- 20 rpm.
5. Weigh Sample #2 after surface moisture is removed to the nearest 0.1 gram.
6. Record weight of Sample #2 as $W_{WSD,2}$.
7. Dry Sample #2 using the drying apparatus to a constant mass to the nearest 0.1 percent.
8. Record weight of dried Sample #2 as $W_{OD,2}$.

D. Calculations.

1. Calculate the “% Total Moisture (M_T)” Content as follows:

$$M_T = \frac{W_{T,1} - W_{OD,1}}{W_{OD,1}} \, x \, 100\%$$

2. Calculate the “% Absorbed Moisture (M_A)” Content as follows:

$$M_A = \frac{W_{WSD,2} - W_{OD,2}}{W_{OD,2}} \, x \, 100\%$$

3. Calculate the “% Surface Moisture (M_S)” Content as follows:

$$M_S = M_T - M_A$$

4. Calculate the “Wetted Surface Dry (WSD) Specific Gravity” as follows:

$$G_{WSD,1} = G_{OD}(1 + M_A)$$

*G_{OD} (oven-dry specific gravity) shall be obtained from the manufacturer testing data.

E. Report. Report % Total Moisture, % Absorbed Moisture, % Surface Moisture, and Wetted Surface Dry (WSD) Specific Gravity to the nearest 0.1%.

Figure 62. NJDOT Test Method A-8 Modifications

CONCLUSIONS AND RECOMMENDATIONS

The following major conclusions can be drawn from this research based on a comprehensive assessment of existing literature, laboratory testing, field demonstrations, and life-cycle cost analyses. The study evaluated the feasibility and effectiveness of implementing High-Performance Internally Curing Concrete (HPIC) in New Jersey bridge decks and pavements, with a particular focus on mitigating early-age cracking, maintaining mechanical and durability properties, and optimizing agency and public costs over the service life of concrete structures. The conclusions integrate findings from surveys of industry suppliers, evaluation of available internal curing agents, dosage optimization, and revised curing strategies, providing a holistic understanding of the technical and economic implications of adopting HPIC in practice.

Assessment of Existing Work and Feasibility of Implementation

- A comprehensive literature review of 16 state DOT reports indicates that HPIC is a viable and cost-effective technology for bridge decks and pavements where early age cracking is a concern.

- Surveys with leading concrete suppliers in New Jersey indicate readiness and capability to implement HPIC with LWFA, leveraging extensive experience with HPIC with Light Weight Coarse Aggregate.

Laboratory and Field Demonstration Testing

- Numerous internal curing agents available in New Jersey were identified, with expanded shale, slate, clay, and SAP products produced locally selected for extensive testing.

- Existing NJDOT HPC formulations were converted to HPIC using ACI 308-213-13(22). Aggregate absorption testing via ASTM C1761/1761M, using both the paper towel and centrifuge methods, confirmed both methodologies are effective. The centrifuge method provided faster and more consistent results.

- Extensive testing demonstrated that fresh, strength, and durability properties of HPIC with LWFA are comparable to NJDOT HPC. Notably, HPIC with expanded clay LWFA showed reduced freeze-thaw resistance as predicted, whereas HPIC with expanded shale LWFA matched control NJDOT HPC.

- HPIC with SAP exhibited lower strength and stiffness than control NJDOT HPC, with reductions at 56 days of -3 percent compressive strength, -9 percent tensile strength, and -4 percent modulus of elasticity. Early-age strength reductions at 24 hours were more significant: -26 percent compressive strength, -23 percent tensile strength, and -26 percent modulus of elasticity.

- LWFA in the HPIC effectively reduced autogenous shrinkage, while SAP provided a smaller reduction in total and autogenous shrinkage.
- Restrained shrinkage was reduced for HPIC with expanded shale in both

laboratory ring tests and simulated bridge deck slabs per AASHTO T334, with comparable early-age reductions (55 percent in laboratory tests and 65 percent in field-cast slabs).

- Testing with three distinct dosage rates of 3.5 lb, 7 lb, and 10.5 lb of internally stored water per 100 lb of cementitious material (representing 50, 100, and 150 percent of the typical 7 lb dosage) showed negligible effects on compressive strength and durability, while shrinkage reduction was dependent on the dosage rate. The standard 7 lb dosage offered optimal strength with significant shrinkage mitigation.

- Revised curing procedures consisting of 7 days of wet curing followed by application of curing compound were found to increase shrinkage in laboratory tests compared with the standard 14-day wet curing. Field testing, however, showed similar shrinkage rates between the revised and traditional curing methods, likely due to continued curing from rainfall and higher ambient humidity in the field. Therefore, for consistency and to minimize early-age shrinkage risk, the curing procedure should continue to follow the 14-day wet curing protocol.

Life Cycle Cost Analysis (LCCA)

- Deterministic LCCA shows HPIC achieves agency cost savings of 15.27~40.90 percent and total cost savings of 15.82~44.24 percent, depending on unit cost assumptions and service-life extensions.

- Under stabilized HPIC unit-price conditions (10 percent higher than HPC), HPIC can provide approximately 31~41 percent agency cost savings in New Jersey conditions, including high salt usage.

- Monte Carlo simulations indicate an 83.8~95.9 percent probability that HPIC yields lower agency costs than HPC and a 100 percent probability that HPIC's total life-cycle cost is lower across all scenarios.

- Despite slightly higher embodied carbon per yd^3, HPIC's extended service life results in lower cumulative CO_2 emissions and reduced life-cycle public cost.

- Overall, HPIC is a cost-effective solution for extending bridge deck lifespan and offers a high probability of significant agency cost savings over the service life of a bridge or pavement system.

Recommendations for Future Research

The following recommendations should be considered for future research based on the research conducted in this report.

- Explore a revised curing process of 7-day wet curing followed by curing compound under field conditions, as it may be comparable to the standard 14-day wet curing and offer scheduling advantages for rapid bridge construction.

- Refine the alternative dosage rate if 7 lb of internally stored water per 100 lb of cementitious material is insufficient for New Jersey conditions. For reference, Mississippi DOT specifies 8 lb per 100 lb of cementitious material.

- Investigate SAP as an alternative to LWFA, exploring alternative dosing methods to mitigate strength or workability reductions.

- Include shrinkage-reducing admixtures in future testing to achieve further benefits related to reduction in shrinkage. Shrinkage-reducing admixtures have shown additional performance improvements, specifically when used alongside LWFA.

IMPLEMENTATION AND TRAINING

Based on the findings of laboratory testing, field testing, and LCCA, the following recommendations for implementation are proposed.

- The centrifuge method has been shown to provide faster and more consistent absorption testing results compared with the paper towel method. Although the upfront cost for a centrifuge is relatively high, the significant benefits of accurately measuring aggregate absorption make it critical for determining the proper internal curing material dosage.

- To better understand the performance of HPIC under realistic bridge deck conditions, instrumentation of bridge decks using high-precision strain gauges (e.g., vibrating wire strain gages (VWSG)) or other suitable sensors, similar to those employed in simulated bridge deck tests, is recommended. This approach provides enhanced insight into autogenous and restrained shrinkage behavior, and NJDOT pilot studies could implement this technique by directly comparing control HPC segments to HPIC segments.

- Once the market prices for HPIC are stabilized, LCCA predictions can be updated to provide more accurate estimates of cost outcomes. Similarly, observed deterioration rates of HPIC can be incorporated to refine predictions of bridge deck lifespan and service-life extension.

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