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Extended-Life Concrete Bridge Decks Utilizing Internal Curing to Reduce Cracking—Results from Ohio DOT Field Trial

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PROJECT TITLE

Extended-Life Concrete Bridge Decks Utilizing Internal Curing to Reduce Cracking—Results from Ohio DOT Field Trial

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Introduction

Eliminating or reducing cracking in bridge decks has been a priority goal for DOTs for a number of years. Early-age deck cracking results in making the bridge deck as well as the supporting substructure elements particularly susceptible to moisture and chloride ingress—the cracks provide a direct pathway for the intrusion of water and chlorides. In the worst case, these early-age cracks could lead to reduced deck and substructure service life. Many agencies began taking mitigating measures in the 1980s by using corrosion-resistance coatings for steel reinforcement. But cracks still leave the concrete itself with an increased susceptibility to premature deterioration.

It is generally accepted that the occurrence of early-age deck cracking is mainly due to the restraint of concrete volume change by the girders and supports as the deck concrete cures. It is also thought that the major cause of concrete volume change is a combination of shrinkage and thermal effects (including temperature drop after heat of hydration, autogenous shrinkage, drying shrinkage, and plastic shrinkage due to evaporation of the mix water). The amount of concrete volume change and the degree of restraint are dependent upon many factors that can be generally categorized into three broad categories, with a number of contributing factors within each category. These are summarized below and discussed in more detail in the November 2016 MAP Brief entitled *Causes of Early Cracking in Concrete Bridge Decks* (<https://intrans.iastate.edu/app/uploads/2019/11/MAPbriefNovember2016.pdf>)

- Concrete material properties and proportioning factors
 - Cement type, content, and proportions
 - Aggregate contents, type

- Air content
- Other admixtures
- Water content

- Structural design attributes of the bridge associated with the structural interaction between the deck and other components
 - Concrete strength
 - Span type
 - Girder type
 - End restraint condition
 - Top transverse bars size
 - Girder depth/spacing
 - Cross-frame location
 - Expansion joints
 - Reinforcement mesh
 - Concrete cover
- Construction environment and techniques
 - Ambient conditions
 - Mechanical vibration
 - Finishing practices
 - Curing
 - Placement time period
 - Wind speed
 - Construction sequence

All together these three categories and associated factors result in a complex matrix of variables that need to be considered in reducing or eliminating deck cracking. With this understanding however, there is broad consensus that focusing on reducing the volume change of the concrete mixture itself during the curing process will significantly help in reducing the risk of undesirable deck cracking.

One of the promising technologies for accomplishing this is has been the use of light weight fine aggregate (LWFA) to provide internal curing for the deck concrete. Using LWFA to provide internal curing has been subject of research for the past two decades

and in the last few years has transitioned to field trials for bridge deck concrete and patching applications in a number of states including Illinois, Indiana, Iowa, Kansas, Michigan, New York, Ohio, Texas, and Utah. The number of states evaluating this technology is growing rapidly.

This MAP Brief will discuss the recent efforts of the Ohio Department of Transportation to place and monitor the performance of a bridge deck using LWFA for providing internal curing.

What is Internal Curing?

According to the American Concrete Institute (ACI), “[i]nternally cured concrete uses pre-wetted absorptive materials that contain moisture. The absorbed moisture is released as the internal humidity of the concrete drops below 100 percent to enhance and maximize the hydration of cement” (ACI 308 2013). The provision of additional water at the surface after setting may be an inadequate approach to hydration because the water is unlikely to penetrate far enough into the concrete, leaving most of the volume untreated (Bentz 2007).

The material used to provide the absorbed moisture is normally LWFA; however, research is ongoing to evaluate other material options. Common U.S. practice currently is using LWFA for internal curing.

Recent research has reported the benefits of using LWFA in concrete mixtures to provide internal curing (IC). These benefits include reduced risk of early-age cracking and improved durability. The theory behind using LWFA is that the pre-soaked fine particles act as reservoirs to provide water for hydration without influencing the water-to-cementitious materials (w/cm) ratio. Uniformly distributed LWFA particles in a mixture provide a benefit to the whole volume of the element rather than only the surface, as is the case with conventional curing. This improvement in uniformity and hydration is intended to improve durability while reducing the effects of dimensional change, such as shrinkage. These benefits are most useful in bridge decks that are exposed to aggressive environments and are at a high risk of cracking (Taylor et al. 2016).

The amount of LWFA required for IC is based on the need to provide about 7 lb of water for every 100 lb of cementitious material content (Bentz 2007). This equates to about 20% to 30% replacement of fine aggregate by volume. Figure 1 conceptually illustrates the volumetric components of a conventional and internally cured mixture.

The example in Figure 1 considers an aggregate with approximately 20% absorption that is intended to provide a volume of internal curing water equivalent to the volume of chemical shrinkage of a typical cement. This corresponds to replacing

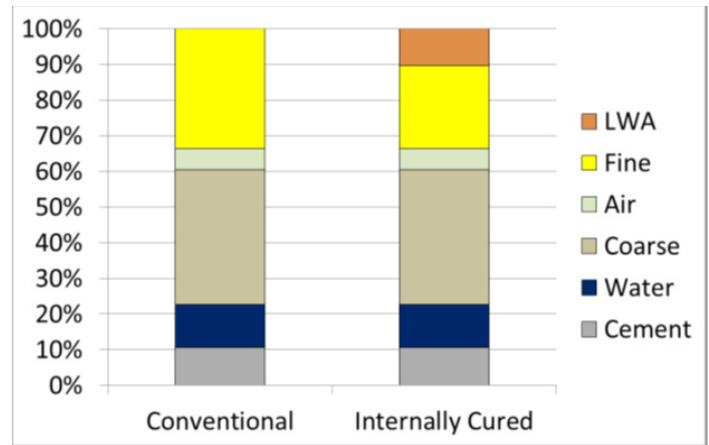


Figure 1. Conceptual illustration of volumetric components in a plain and internally cured mixture

approximately 30% of the volume of the fine aggregate (approximately 460 lb/yd³) for this mixture with a fine lightweight aggregate.

Mixture Considerations

Because a significant contributor to the risk of cracking is the amount of thermal- and moisture-related shrinkage occurring in the mixture, careful proportioning of mixtures with well-graded aggregates that help minimize the paste content along with a selection of supplementary cementitious materials (SCMs) will help reduce cracking. The following guidelines are likely to minimize the risk of cracking (Darwin et al. 2011, Taylor and Wang 2014, Taylor et al. 2012):

- Maximum paste content below 25% (by volume), achieved by requiring an optimized aggregate gradation and a maximum cement content of 540 lb/yd³
- Maximum w/cm ratio of 0.44 to 0.45
- Moderate (~4,000 psi) rather than high compressive strength
- Air content in the range of 6.5% to 9.5%
- Use of slag cement
- Use of internal curing
- Maximum aggregate size of 1 in.

Ohio Field Trials

Ohio DOT (ODOT) has seen newly constructed bridge decks cracking prematurely, and previous research has shown that the use of highly absorptive materials can improve internal curing of low permeability concrete. The Department had completed other installations in the past with some success; however, specification changes were not made to incorporate internal curing. Based on other completed research, ODOT was interested in evaluating internal curing in a state highway application.

In working with ODOT Central Office Research and the Ohio FHWA, statewide planning and research funds were used to set the project in motion. ODOT District and Office of Materials Management staff determined a project that would be of benefit for the research.

The project selected was a pair of twin bridges, carrying Interstate 271 in Mayfield Heights, Ohio, with construction occurring in summer 2017. The bridges were two-span, with total lengths of 193 feet. The southbound bridge deck was cast using traditional mix designs and was deemed the control deck, while the northbound bridge deck was cast using the recommended internal curing mix design.

Mixture Designs

After extensive laboratory testing and mixture evaluation by the National Concrete Pavement Technology Center, the mixture design was selected for the IC mixture; see Table 1. The control concrete proportions are based on the ODOT's standard mixture requirements.

Construction Placement

Documentation of the deck placement was performed via on-site visual observations, as well as a series of embedded gages placed in the deck to monitor both early-age and long-term comparative performance. Table 2 details the fresh properties of both mixes, while Figure 2 shows the bridge prior to deck placement.

On the day of deck placement, wet burlap was placed after finishing, with curing compound applied after 7 days.

Prior to placement of the deck, several gages were placed for embedding in the bridge deck. The instrumentation plan included the following:

- 5TE Decagon sensors to measure temperature, bulk electrical conductivity, and relative permittivity (material property performance)



Figure 2. Bridge prior to deck placement, with wet burlap ready to be placed

- Vibrating wire strain gages: to determine comparative performance in load carrying characteristics (structural performance)

Properties of the mixtures used in the two sections were monitored during and after construction.

The mixture proportions and fresh properties were consistent with the mixture designs. Both mixtures had the same w/cm ratio of 0.45 and target air content, while the IC mixture had a higher slag cement content and about 20% (by mass) of the fine aggregate was replaced with lightweight fine material that was saturated before batching.

Semi-adiabatic calorimetry (Figure 3) of the two mixtures indicated that setting time was similar for both mixtures, but the peak temperature was significantly lower in the IC mixture, likely because of the additional slag cement. This may be considered beneficial because it reduces stresses due to temperature differentials through the thickness of the slab.

The temperatures of the mixtures were recorded using sensors embedded in the deck, as mentioned previously. Figure 4 illustrates that despite similar environmental temperatures, the

IC mixture showed generally higher internal temperatures and smaller daily fluctuations for the first week. This supports the contention that the internal curing is promoting extended hydration, thus leading to higher mechanical performance in the long term, while damping temperature profiles, both of which will reduce the risk of cracking. Mechanical properties of the mixtures are shown in Table 3.

The increased strength of the test mixture would also contribute to reduced cracking risk in the long term. Increased resistivity is a measure of the improved hydration and

Table 1. Bridge deck mix designs

	Cement (lb/yd ³)	Slag (lb/ yd ³)	Water (lb/ yd ³)	Sand (lb/ yd ³)	LWFA (lb/ yd ³)	Coarse agg. (lb/ yd ³)	Coarse agg. (lb/ yd ³)
Control concrete	410	160	256.5	1305	-	1360	355
IC concrete	282	282	253.8	940	220	1380	345

Table 2. Fresh properties of both mixes

	Unit weight (lb/ft ³)	Air content (%)	Slump (in.)
Control concrete	143.5	5.7	6
IC concrete	140.6	6.0	5

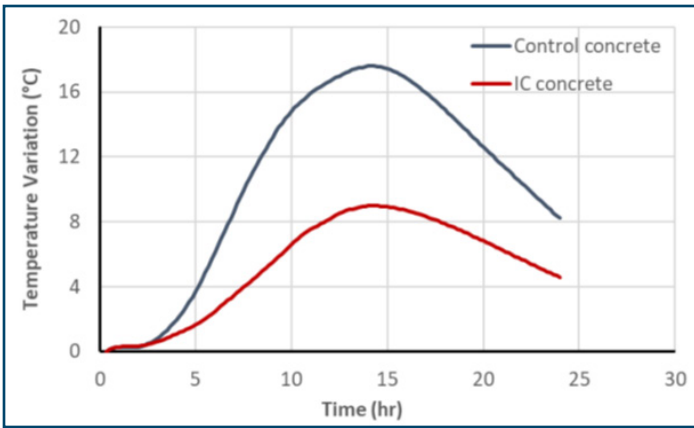


Figure 3. Semi-adiabatic calorimetry temperature rise

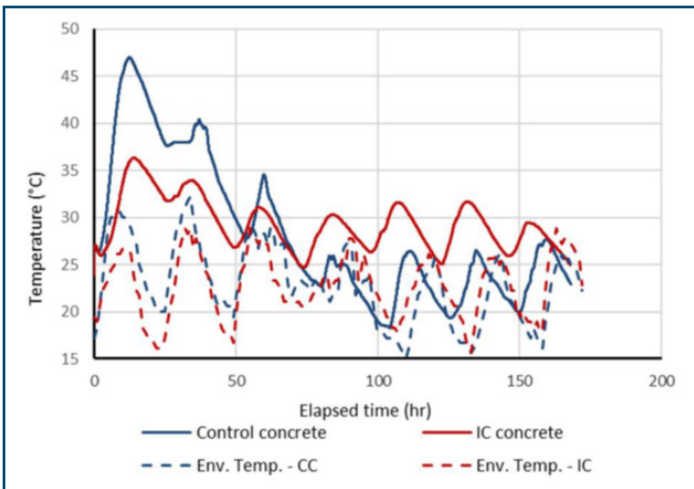


Figure 4. Temperature data

Table 3. Hardened properties of the two mixtures

	Compressive strength, psi			Split tensile strength, psi		Resistivity, k ohm. cm	Relative permittivity
	7 day	14 day	28 day	7 day	28 day	42 day	42 day
Control concrete	3980	4570	6030	355	385	18	15
IC concrete	4910	6570	6640	390	550	40	18

impermeability of the mixture, potentially contributing to an increased lifetime because of an improved resistance to ingress of aggressive chemicals.

The higher relative permittivity of the test mixture near the bottom of the uncured, exposed surface of the slab is an indication that the moisture content of the system is higher, leading to the increased hydration, and thus the improved long-term properties that were measured. Little difference was observed between the top faces of the test and control

slabs. This was likely due to the conventional curing applied to the decks.

Drying shrinkage of the mixtures was also assessed on field samples transported to the University of Ohio laboratory after 1 day (Figure 5). The test mixture shows less shrinkage than the control, again reducing the risk of cracking.

Structural Testing

To assess the structural performance of both bridges, six vibrating wire strain gages were embedded in the bridge deck. The data from the strain gages was collected, and are seen in Figure 6 and Figure 7 for the first ~2 weeks after placement for each bridge. As can be seen from these figures, the two bridges performed very similarly, with daily variations in strain due to temperature changes. Overall, the IC concrete bridge deck experienced slightly lower strains, with behavior similar to that of the normal concrete bridge, although the enveloped strain profile of the IC concrete was less than that of the normal concrete.

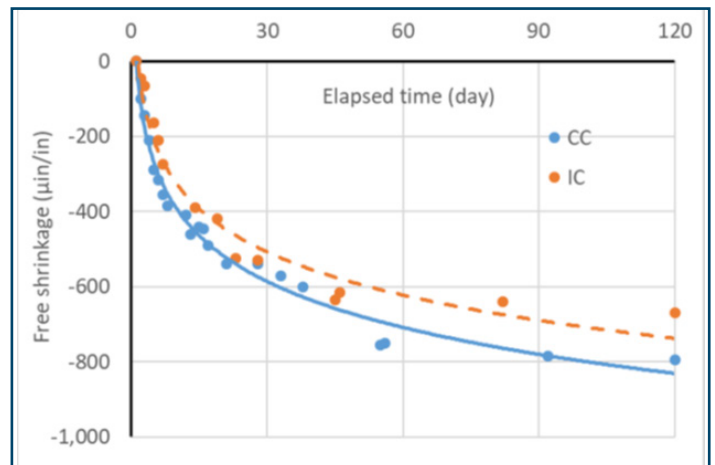


Figure 5. Unrestrained shrinkage

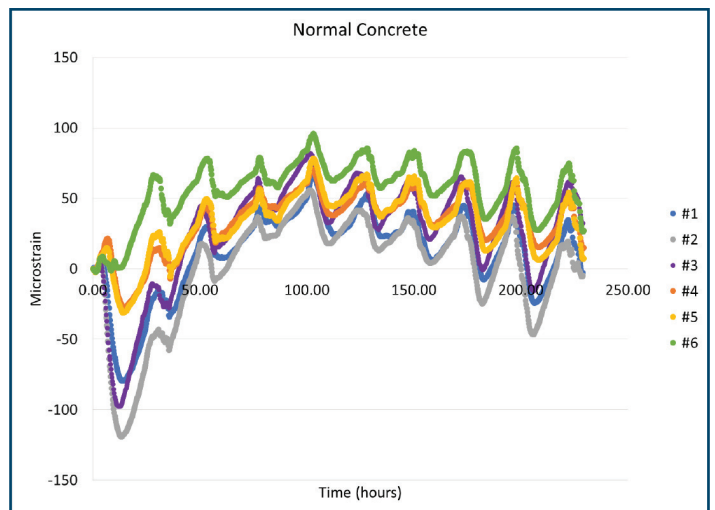


Figure 6. Strain data for normal concrete bridge deck

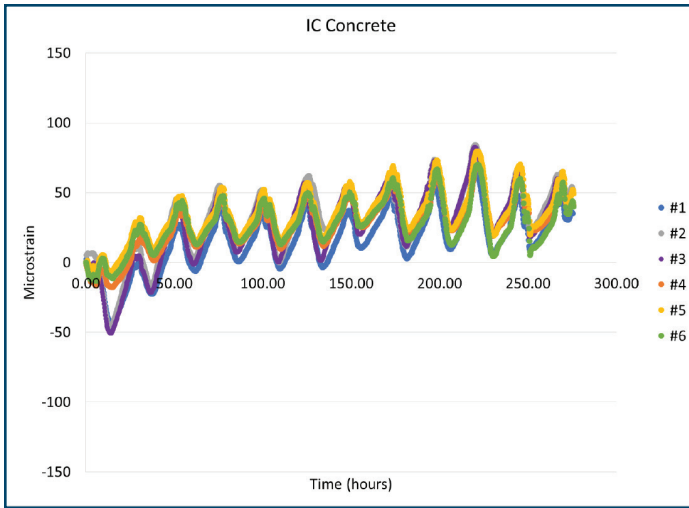


Figure 7. Strain data for IC concrete bridge deck

It was also noted that minor cracking was present on the grooves of the finished concrete surface of the outer lane. According to ACI 201-1R-08, it defined the crack severity as a fine for crack width less than 0.04 and a medium for crack width between 0.04 and 0.08. However, thermal stresses due to temperature variation could cause these cracks to widen over time. As a result, these cracks would provide a pathway of chloride ions to penetrate the deck and corrode the reinforcement. A crack map for the IC deck appears in Figure 10.

Considerably less cracking was present on this bridge, in addition to observations of better condition of the surface grooves. As illustrated by these crack maps, the optimized bridge deck outperformed that of the normal concrete mix in all areas observed by the inspection team.

Performance Monitoring

The initial survey was performed on both bridges approximately two weeks after deck placement. No visible cracks were found in the bridges at that time. Also, approximately one year after deck placement, both bridges were inspected to compare performance and identify any deterioration.

Based upon the strain data obtained from the embedded gages, the southbound bridge (conventional mixture) experienced greater strain and thus would be expected to experience greater cracking levels. The crack map for the southbound, normal concrete, bridge deck is shown in Figure 8, with an image showing an example of the observed cracking in Figure 9.

As can be seen, transverse deck cracks with widths averaging approximately from 0.01 to 0.013, varied in length, were observed at many locations on outer and inner lanes. The middle lane of the bridge was not surveyed because it was kept open to traffic during the survey. Longitudinal cracks were also observed near the bridge approaches, with width ranges from 0.02 to 0.05 in.

Service Life Prediction

The determining parameter in evaluating the service life of a reinforced concrete element is the transport properties of the concrete mixture and its exposure to external chlorides such as deicing salts.

The results of the electrical resistivity test (AASHTO T 358 2017) conducted on the field samples with standard curing (Figure 11), indicated that electrical resistivity of internally cured concrete specimens containing 50 percent slag was 1.88 times higher than control concrete at 28 days. There-

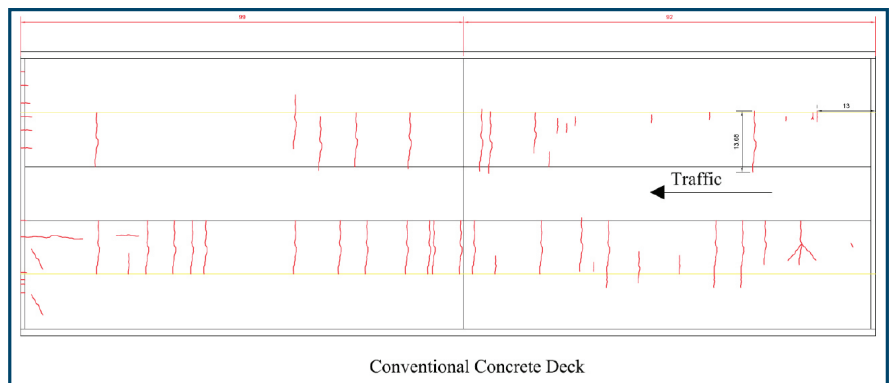


Figure 8. Normal concrete deck (southbound) crack map



Figure 9. Cracking on southbound inner lane of the normal concrete deck

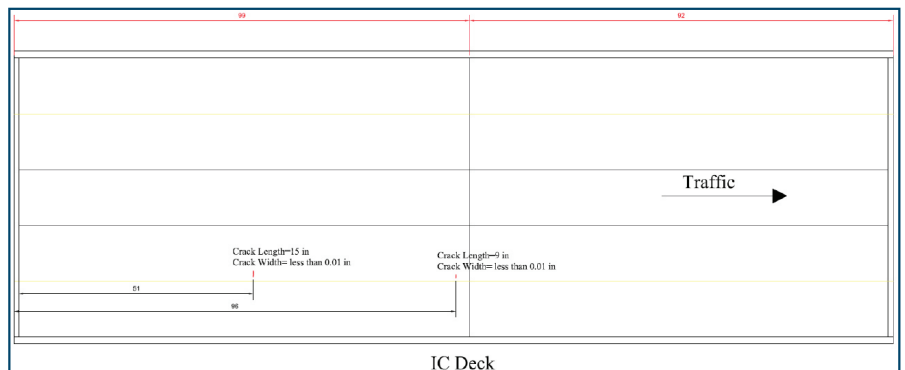


Figure 10. IC concrete deck (northbound) crack map

Table 4. Concrete mixture designs used in field

	OPC (lb/ yd ³)	GGBFS (lb/ yd ³)	W/Cm ratio	Coarse agg (lb/ yd ³)	Intermedi-ate coarse agg (lb/ yd ³)	Fine agg (lb/ yd ³)	LFWA (lb/ yd ³)	Air content (%)
Control concrete	410	160	0.45	1,360	355	1,350	-	6
IC concrete	282	282	0.45	1,380	345	940	220	6

Table 5. Service life prediction of the bridge decks

	D _{ref} (cm ² /sec)	m	C _t	Initiation period (yr)	Propagation period (yr)	Service life prediction (yr)
Control concrete - 30% slag	1.6231E-8	0.37	0.050	18.5	7	25.5
IC concrete - 50% slag	9.7386E-9	0.49	0.050	64.6	7	71.6

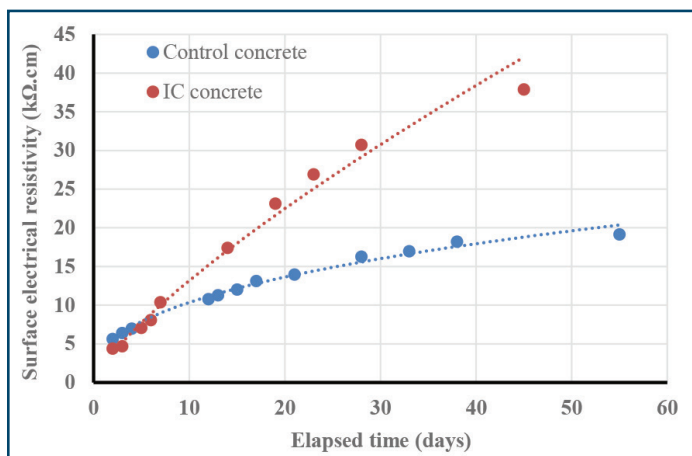


Figure 11. Effect of internal curing on concrete surface electrical resistivity

fore, it can be conservatively estimated that the diffusion coefficient of internally cured concrete slab is decreased to 60% of that of the control concrete at 28 days.

The Service Life Prediction Model presented in ACI 365.1R-17 helps to evaluate time to initiation (t_i) and the time for propagation (t_p) to reach unacceptable levels of risk. Based on these parameters, it is possible to calculate the repair schedule and perform a life-cycle cost analysis using Life-365 software developed based on ACI 365.1 (ACI Committee 365 2017).

The results of the service life prediction analysis, using Life-365 v 2.2.3, are presented in Table 5.

The results indicated that increasing the slag substitution percentage from 30% to 50% and using internal curing significantly increased the service life from 25.5 to 71.6 years.

LCCA Analysis

The base year was assumed as 2017, inflation rate at 1.8%, and discount rate at 2%. The results of the LCCA including initial construction cost (\$), repair cost (\$), and total lifecycle cost (\$) are indicated in Table 5 for both alternatives.

As demonstrated, the total life-cycle cost of internally cured concrete incorporating 50% slag is around 29% less than the original concrete.

Ohio’s Future Plans Regarding Using LWFA for Internal Curing

ODOT bridge inspections occur annually and the two bridges will be monitored and compared throughout their life expectancy. The internally cured deck is currently showing no signs of distress or cracking on the top and bottom surfaces, while the normal concrete deck is showing signs of transverse cracking, as shown in Figure 12.

Based on this information, a second project has been selected and will be cast in late spring 2020 in Miami county, Ohio, on Interstate 75. More installations will follow the Miami county project after it has been completed. Specifications are in the drafting stages for the lightweight aggregate along with a specified mix design for use on bridge decks and other concrete elements. A supplemental document will be developed for the certification of lightweight aggregates for ODOT.

Conclusions and Recommendations

The successful results of this study can be replicated to other bridge decks. The key is to perform a good mixture design analysis with the local materials that are available to the contractor.

The following are suggested as target parameters when seeking to balance the need to achieve low permeability with minimum cracking:

- w/cm ratio range of 0.42 to 0.45
- Combinations of up to four SCMs (and limestone) based on the following:
 - 50% portland cement clinker minimum
 - 25% Class F fly ash maximum
 - 35% Class C fly ash maximum
 - 50% slag cement maximum
 - 8% silica fume maximum
 - 15% interground limestone maximum
- Paste content maximum of 25% by volume
- IC to be included to deliver 7 lb. water per 100 lb. of cementitious materials in a mixture
- Air content range of 6.5% to 9.5%
- 1-in. maximum sized aggregate
- Maximum concrete temperature of 70°F
- External curing of 14 days minimum
- Finishing activities to be kept to a minimum

For More Information

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Figure 12. I-271 NB (internally cured deck) and I-271 SB (normal concrete deck)

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