Bridge Views

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Wisconsin's Experience with HPC Bridge Decks

James M. Parry, Wisconsin Department of Transportation

The third generation of HPC specifications was used on I-94.

The first development by the Wisconsin Department of Transportation (WisDOT) toward what could be considered high performance concrete (HPC) for bridge decks came in the mid to late 1990s with the development of the first Quality Management Program (QMP) specifications. It was not called HPC at that time, but certainly led toward improvement in concrete properties. The principal motivation for these changes was to improve concrete quality and durability and decrease bridge deck cracking. The air content used in all QMP and HPC specifications described below has been 6 ± 1.5%. Components of the early QMP specifications and the associated benefits were as follows:

Introduced percent within limits (PWL) requirements for compressive strength with incentive/disincentive payments. This solved an age-old problem of excessive water addition (retempering) of concrete mixes in the field. It also rewarded uniformity of production for producers with good quality control. Reduced water content also led to reduced shrinkage.

- Reduced the minimum cementitious materials content from 610 to 565 lb/yd3 (362 to 335 kg/m3). This reduced shrinkage.
- Increased maximum nominal size of aggregate from ¾ to 1½ in. (19 to 38 mm). This also reduced shrinkage.
- Required 7-day continuous wet cure with burlap cover. This decreased concrete permeability and cracking potential.

First Generation of HPC Specifications

In 1998 and 1999, WisDOT programmed the use of an HPC specification as a pilot program on 22 bridge decks across the state. WisDOT followed a traditional approach to HPC that equated high performance concrete with high strength concrete and low water-cementitious materials ratio (w/cm), with the following mix requirements supplementing the QMP mix requirements listed previously.

- 5000 psi (34 MPa) compressive strength requirement at 28 days
- High-range water-reducing admixture required
- Maximum w/cm of 0.40

This approach resulted in mixes that generated high temperatures, very high early strength gain, and an extremely large amount of deck cracking on several structures. This cracking problem was judged to be of sufficient severity that this specification was removed from several of the projects scheduled for the second construction season.

Second Generation of HPC Specifications

- The Marquette Interchange in downtown Milwaukee, constructed from 2004 to 2008, was the first of several megaprojects scheduled for reconstruction of aging interstate highways in southeastern Wisconsin. The Federal Highway Administration was pushing for a 75-year service life for the structures; so the use of HPC was essential in the harsh Wisconsin environmental conditions. A holistic approach was taken to address all properties of the HPC. This included the following: Aggregate quality specifications tightened to allow only the best of locally available materials
- Crushed limestone with 100% fractured faces and low coefficient of thermal expansion
- Mandatory use of supplementary cementitious materials (SCM's)
- Cementitious materials content between 565 and 660 lbs/yd³ (335 and 392 kg/m³)
- Central mixed concrete
- 5000 psi (34 MPa) minimum compressive strength at 28 days
- Rapid chloride permeability (RCP) of 2000 coulombs maximum using standard 28-day curing
- 80°F (27°C) maximum concrete temperature at placement
- 0.15 lb/ft²/hr (0.73 kg/m²/hr) maximum evaporation rate during deck placements
- 10-day continuous wet curing using soaker hoses and two layers of burlap
- Wet burlap placed within 10 minutes of strike-off by finishing machine
- Longitudinal grooving texture applied later to the hardened concrete
- Silane sealer applied to the final textured deck

Third Generation of HPC Specifications

The 5000 psi (34 MPa) concrete compressive strength on the Marquette Interchange was required for structural reasons and was not considered to be optimum for minimization of deck cracking. Many decks turned out well on that project, but a few had excessive cracking. It was decided at the conclusion of the project to use a 4000 psi (28 MPa) compressive strength requirement for future HPC bridge decks. Contractors also commented that it was difficult to meet the 28-day RCP requirement using fly ash as the locally preferred SCM. The fly ash did not have sufficient time to impart benefits to the concrete in 28 days at the standard curing temperature. However, it was desired not to extend the curing period beyond 28 days because the test was being used for acceptance and monitoring during construction of projects with very tight schedules. It was decided to adopt the accelerated curing method developed by the Virginia Transportation Research Council* (VTRC), in which the specimens are cured at 73°F (23°C) for the first 7 days and 100°F (38°C) for the last 21 days. This method is reported to give an equivalent test result to a 90-day standard curing period.(1)

In 2009, construction began on two additional megaproject corridors. These were the north-south stretch of I-94 between Milwaukee and the Illinois state line, and the U.S. Highway 41 corridor south of Green Bay. This construction is still ongoing. The HPC for these corridors has utilized the Marquette HPC specifications with the following modifications:

- Maximum cementitious materials content of 610 lb/yd³ (362 kg/m³)

- 4000 psi (38 MPa) minimum compressive strength at 28 days
- RCP of 1500 coulombs maximum at 28 days using VTRC accelerated curing procedure
- 14-day continuous wet curing

WisDOT will continue to move forward with refinements to our HPC specifications.

Reference

1. Ozyildirim, C., "Permeability Specifications for High-Performance Concrete Decks," Transportation Research Record No. 1610, Concrete in Construction, Transportation Research Board, Washington, DC, 1998, pp. 1-5.

Further Information

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* VTRC is now the Virginia Center for Transportation Innovation and Research (VCTIR).

HSC for Route 22 Bridge over the Kentucky River

Steve Schweitzer, Prestress Services Industries, LLC.

High strength concrete was used for the precast, prestressed concrete beams.
Photo: Aerial Innovations of Tennessee, Inc.

Route 22 Bridge over the Kentucky River near Gratz, KY, has the longest span for a post-tensioned, spliced, precast, prestressed concrete girder bridge in the United States. That honor was achieved by spanning 325 ft (99.1 m) across the Kentucky River. The other three spans that make up the bridge are one at 175 ft (53.3 m) and two at 200 ft (61.0 m).

The bridge did not start out being precast concrete but was originally designed to use steel plate girders. Prestress Services Industries, LLC (PSI) asked to submit a precast concrete alternate that saved the state of Kentucky over $800,000. PSI employed the design firm of Janssen & Spaans Engineering, Inc. to perform the redesign of the bridge.

Bridge Design

The bridge was redesigned to use four precast, prestressed concrete girder lines and four spans. Six girder segments and two pier segments were used to make up each girder line for a total of 32 pieces. Span 1, 175 ft (53.3 m) long, comprised two segments with lengths of 90 ft 9 in. and 84 ft 3 in. (27.7 m and 25.7 m) that were spliced together. Span 2, 200 ft (61.0 m) long, comprised one end of the 138-ft (42.1-m) long cantilevered pier segment and a 131-ft (39.9-m) long drop-in girder segment. Span 3, 325 ft (99.1 m) long, utilized one end of each of the 138-ft (42.1-m) long cantilevered pier segments and a 185-ft (56.4 m) long drop-in girder segment. Span 4, 200 ft (61.0 m) long, utilized one end of the 138-ft (42.1-m) long cantilevered pier segment and two girder segments with lengths of 57 ft 6 in. and 73 ft 6 in. (17.5 and 22.4 m) that were spliced together.

The girder segments were modified bulb-tee beams with a 3-ft 4-in. (1.02-m) wide bottom flange and a 5-ft 1-in. (1.55-m) wide top flange. The cantilever pier segments varied in depth from 16 ft (4.88 m) over the piers to 9 ft (2.74 m) at the ends of the cantilever. The girder segments had a constant depth of 9 ft (2.74 m). The web was 8 in. (200 mm) thick and contained four post-tensioning ducts. All segments were pretensioned in the plant and then post-tensioned in the field.

High Strength Concrete

The concrete specified for girder segments in Spans 1, 2, and 4 was normal weight concrete with a 28-day compressive strength of 7,500 psi (52.MPa). The actual final strengths ranged from 7,800 to 11,000 psi (53.8 to 75.8 MPa) with most cylinders breaking close to 10,000 psi (69.0 MPa). The prestressing strands were cut and the girders released from the forms at a minimum compressive strength of 5,500 psi (38 MPa) after 14 hours of curing. This was achieved by adding 105 fl oz/yd³ (4.06 L/m³) of high-range water-reducing admixture to the mix and using 752 lb/yd³ (446 kg/m³) of Type III cement. The same normal weight concrete mix used on the girder segments was also used for the pier segments. The girders were cured at concrete temperatures up to 140°F (60°C) with steam heat to ensure the release strength would be achieved overnight. The prestressing strands were 0.6-in. (15.2-mm) diameter Grade 270 and the non-prestressed reinforcement was standard Grade 60, epoxy-coated bars.

At 185 ft (56.4 m) long, the drop-in girder segments for Span 3 (over the river) needed to be braced together in pairs for stability during transportation and erection. PSI used a semi-lightweight concrete mix, consisting of normal weight fine aggregate, 42% normal weight coarse aggregate, and 58% lightweight coarse aggregate to reduce the unit weight to 125 lb/ft³ (2001 kg/m³). Even with the reduced concrete unit weight, the beams still weighed 129 tons (1150 kN) each, or 258 tons (2300 kN) for the pair. The concrete compressive strengths specified for the semi-lightweight concrete were the same as those for the normal weight concrete. Actual strengths averaged 6,450 psi (44.5 MPa) at 14 hours and 8,570 psi (59.1 MPa) at about 14 days.

Special forms had to be constructed to cast the pier segments. The formwork height of 16 ft (4.88 m) necessitated the use of concrete pump trucks. At 169 tons (1500 kN) each, these were the heaviest individual pieces on the project. Since these pier segments were cantilevered, the prestressing strand was located in the top flange of the segment with minimal prestressing in the bottom flange.

Transportation

Transportation of the girder segments proved to be a challenge in itself. The girder segments for the approach spans could be transported by truck using 13- and 15-axle trailers. The pier segments and drop-in segments over the river were too large and heavy to transport by road. Therefore, they were placed on barges and transported on the river. Unfortunately, the locks along the waterway were not operating. Even though the girders were not needed for a few months, they were shipped by barge during the high water of spring 2009 so they could float over the locks. The pier segments and drop-in girders over the river were erected by C.J. Mahan Construction Co. during the summer and fall 2009 with the balance of the girders for the approach spans erected during the 2010 winter. The bridge was finished by Haydon Bridge Co., the prime contractor, on schedule in the fall of 2010.

Further Information

For further information about this bridge, see ASPIRE, Winter 2011 or contact the author at sschweitzer@prestressservices.

Concrete being placed in the pier segments

Erected pier segments.
Photo: Haydon Bridge Co. & ASPIRE™ Magazine

Benefits of Metakaolin in HPC

Kimberly E. Kurtis, Georgia Institute of Technology

Metakaolin
Photo: Portland Cement Association

Self-consolidating concrete using metakaolin

Metakaolin is produced by heat-treating kaolin, a natural, finely divided, aluminosiliceous mineral, which is found in abundance in North America in Georgia, South Carolina, and Saskatchewan. Heating to 1200 to 1650°F (650-900°C) alters its structure, producing a highly reactive supplementary cementitious material (SCM) that is widely available for use in concrete construction. ASTM C618 and AASHTO M 295 classify metakaolin as a Class N (or natural) pozzolan.

Because it is produced under controlled conditions, its composition (typically 50 to 55% SiO_2 and 40 to 45% Al_2O_3), white appearance, and performance are relatively consistent. Due its high surface area and high reactivity, relatively small addition rates of metakaolin—typically 10% or less by weight of cement—produce relatively large increases in strength, impermeability, and durability, while its light color gives it an aesthetic advantage over other SCMs.

Improved Strength

Metakaolin's reaction rate is rapid, significantly increasing compressive strength, even at early ages, which can allow for earlier release of formwork. Mixes with metakaolin at 8% of the total cementitious materials have produced concrete compressive strength increases of more than 20% at 1 day and 40% at 28 days.(1) Early age flexural strengths can also be increased by as much as 60%, potentially allowing for early opening of concrete pavements to traffic. Strengths of up to 35,000 psi (240 MPa) have been achieved in ultra-high strength concrete, formulated with 25% metakaolin and a water-to-binder ratio of 0.22.(2)

Improved Durability

In addition to increasing strength, the densification of the microstructure that results from the pozzolanic and hydraulic reactions of metakaolin also leads to greater impermeability. Very low and low 28-day rapid chloride permeability test (RCPT) results per AASHTO T 277 have been reported for concretes containing 8% metakaolin at water-to-binder ratios of 0.40 and 0.50, with the metakaolin concrete achieving remarkably lower RCPT values than other comparable mixes.(3) In concretes containing metakaolin at 8 to 12% of the total cementitious materials, 50-60% decreases in chloride diffusion coefficient suggest that significant improvements in service life can be achieved through metakaolin utilization in chloride environments.(4) In addition, metakaolin has been shown to be highly effective in mitigating expansion due to alkali-silica reaction (ASR) and sulfate attack.(5,6)

Improved Early Age Behavior

The relative fineness of metakaolin can result in decreased slump, but the use of water reducing admixtures or use in combination with fly ash in ternary mixes can compensate for this.(7) Slumps of 5 to 7 in. (125 to 180 mm) have been achieved with metakaolin at water-cementitious materials ratios (w/cm) of 0.36 to 0.38, using 25-35% less high-range water-reducing admixture than comparable mixes.(8)

Metakaolin concrete tends to exhibit a creamy texture, resulting in better finishability compared to other finely divided SCMs. This quality also improves pumpability and can be used to impart detailed surface textures to cast surfaces. In addition, the cohesiveness provided by the metakaolin allows for relatively simple formulation of self-consolidating concrete, when using an appropriate dosage of polycarboxylate water reducer as shown in the photograph at the beginning of this article.

Data on the potential contributions of metakaolin to chemical, autogenous, and drying shrinkage are inconsistent, with authors reporting both decreases and increases in each form at various ages and at various addition rates. For applications with restrictions on shrinkage, additional testing, including the assessment of shrinkage-reducing admixtures and fiber reinforcement, may be advised.

Contributions to Sustainability

Because of the lower processing temperature compared to cement clinker, use of metakaolin can contribute to sustainability through energy savings, as well as reductions in greenhouse gas emissions. After examining various SCMs alone and in combination and considering performance, economic, and environmental criteria, metakaolin concrete was identified as a “very promising solution” for the precast industry for reducing clinker content in concrete.(9)

In ternary blends with 25% fly ash and 8% metakaolin, concrete achieved equivalent strength to other concrete at just 3 days, while reducing cementitious materials content by more than 350 lb/yd^3 (208 kg/m^3). Combinations of 25% fly ash and 3% metakaolin achieved strength equivalence by 28 days, at a w/cm of 0.30.(7)

Alkali-activation of metakaolin, alone and in combination with slag or fly ash, has produced good quality geopolymers. Compressive strengths exceeding those of comparable portland cement concrete have been demonstrated, suggesting that metakaolin may be commercially viable as an alternative binder, in addition to its currently more common use as an SCM.

References

1. Justice, J. M. and Kurtis, K. E., “Influence of Metakaolin Surface Area on Properties of Cement-based Materials”, ASCE Journal of Materials in Civil Engineering, September 2007, Vol. 19 No. 9, pp. 762-771.
2. Tafraoui, A. et al., “Metakaolin in the Formulation of UHPC,” Construction and Building Materials, Vol. 23, 2009, pp.669-674.
3. Justice, J. M. et al., “Comparison of Two Metakaolins and Silica Fume Used as Supplementary Cementitious Materials,” Seventh International Symposium on Utilization of High-Strength/High Performance Concrete, Ed. Russell, H. G., Publication SP-228, Vol. 1, American Concrete Institute, Farmington Hills, MI, 2005, pp.213-236. Also on Compact Disc.
4. Gruber, K. A. et al., “Increasing Concrete Durability with High-Reactivity Metakaolin,” Cement and Concrete Composites, Vol. 23, 2001, pp. 479-484.
5. Khatib, J. M. and Wild, S., “Sulphate Resistance of Metakaolin Mortar,” Cement and Concrete Research, Vol. 28, No. 1, 1998, pp. 83-92.
6. Ramlochan, T., Thomas, M., and Gruber, K. A., “The Effect of Metakaolin on Alkali-Silica Reaction in Concrete,” Cement and Concrete Research, Vol. 30, 2000, pp. 339-344.
7. Garas, V. Y. and Kurtis, K. E., “Assessment of Methods for Optimising Ternary Blended Concrete Containing Metakaolin,” Magazine of Concrete Research, September 2008, Vol. 60, No. 7, pp. 499-510.
8. Caldarone, M. A., Gruber, K. A., and Burg, R. G., “High-Reactivity Metakaolin: A New Generation Mineral Admixture,” Concrete International, November, Vol. 16, No. 11, 1994, pp. 37-40.
9. Cassagnabere, F. et al., “Metakaolin, A Solution for the Precast Industry to Limit the Clinker Content in Concrete: Mechanical Aspects,” Construction and Building Materials, Vol. 24, 2010, pp. 1109-1118.

(articles continue on next page)

Curing, Shrinkage, and Cracking of Ternary Concrete Mixes

Tommy E. Nantung, Indiana Department of Transportation

SR 23 bridge under construction using a ternary concrete mix.

Many state transportation agencies are exploring ways to increase the service life of concrete bridge decks. In many cases, bridge deck replacement is needed while the pavement leading to the bridge is still in good condition. With more and more restrictions on closing road sections to traffic, there is an initiative to "match" the life of the concrete bridge deck with the life of the pavement.

Cracking of concrete bridge decks is not a new issue with bridge engineers. It is one of the most important issues to be resolved because of its relationship with deterioration of the bridge deck. Many experts in the bridge community already put significant effort into reducing bridge deck cracking by way of improving construction practices and improving the appurtenances in bridge deck components, from anchoring the reinforcement to the formwork to improving the lips of the stay-in-place deck forms. While the use of admixtures and supplementary cementitious materials (SCMs) in concrete has been practiced for a long time, little attention has been given to the issue of shrinkage behavior and the cracking susceptibility of concrete ternary mixes containing fly ash and silica fume.

Research Project

The Indiana Department of Transportation (INDOT) initiated a research project to explore the issue of shrinkage cracking and its relationship to ternary mixes and curing conditions. The objective is to minimize the cracking tendency of concrete bridge decks and to achieve a 50-year service life with a "manageable" maintenance effort from the Department. The research project was conducted in cooperation with the Joint Transportation Research Program at Purdue University.

The ternary concrete mixes were proportioned based on the INDOT Class C structural concrete for bridge decks. The INDOT Class C structural concrete typically contains 658 lb/yd³ (391 kg/m³) of cementitious materials and a maximum water-cementitious materials ratio of 0.443 with a paste content of 29%. Mix designs were based on using a maximum cementitious materials reduction of 20% with the cement content held constant at 389 lb/yd³ (231 kg/m³). In this study, INDOT Class C concrete without fly ash and silica fume was used as a control.

Four ternary mixes were included in the experiment with either 20 or 30% fly ash (FA) by weight of the total cementitious materials in combination with 5 or 7% silica fume (SF). The mixes were designated as 20FA/5SF, 20FA/7SF, 30FA/5SF, and 30FA/7SF. The paste contents were 23, 24, 27, and 28%, respectively. The mixes had a 0.41 water-cementitious materials ratio, 6.5 ± 1.0% air content, and a 4.0 to 7.5 in. (100 to 190 mm) slump.

Four curing conditions were used for the prepared samples. They were: (a) air drying immediately after casting, (b) three-day curing using wet burlap, (c) seven-day curing using wet burlap, and (d) curing with a white pigmented compound for seven days after which it was removed with a stiff wire brush.

Each of the concrete mixes had three 3x3x11 in. (75x75x285 mm) free shrinkage specimens subjected to the above curing conditions. The samples were demolded at final set and cured. The shrinkage initial reading was taken immediately after demolding. At the end of the curing period, the samples were subjected to drying at 73°F (23°C) and 50% relative humidity.

Shrinkage Results

Figure 1 shows that if no curing is provided (air drying only), the free shrinkage at 450 days was almost identical (about 550 millionths) for all four ternary mixes. However, the free shrinkage for all the ternary mixes in the air dry condition was significantly lower than that of the INDOT Class C mix without fly ash or silica fume. After adjusting for aggregate content relative to the INDOT Class C mix, the free shrinkage appeared to be a function of SCM content, the larger the SCM content, the smaller the free shrinkage.

As shown in Fig. 2, the wet burlap curing generally resulted in less free shrinkage than air-dried specimens. This phenomenon is mainly due to the initial expansion that occurred during the first few days of wet burlap curing. However, the 30% FA specimens gave higher free shrinkage values in all curing conditions compared to the air drying condition. This phenomenon may be due to the dry conditioning of the specimens at an early age when a significant amount of water evaporates from the specimens due to its fairly open pore structure.

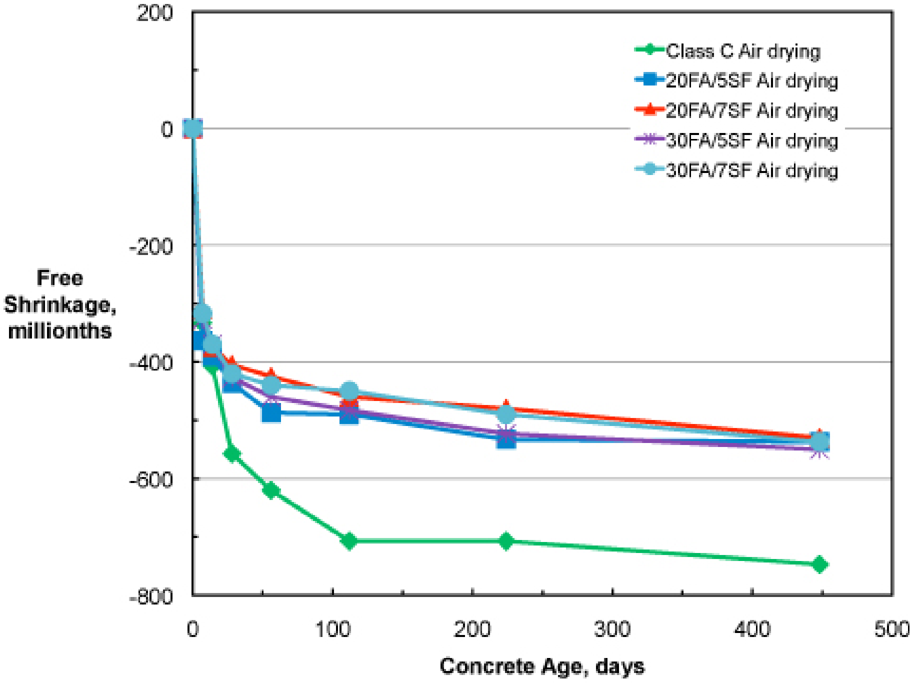


Fig. 1. Air drying results

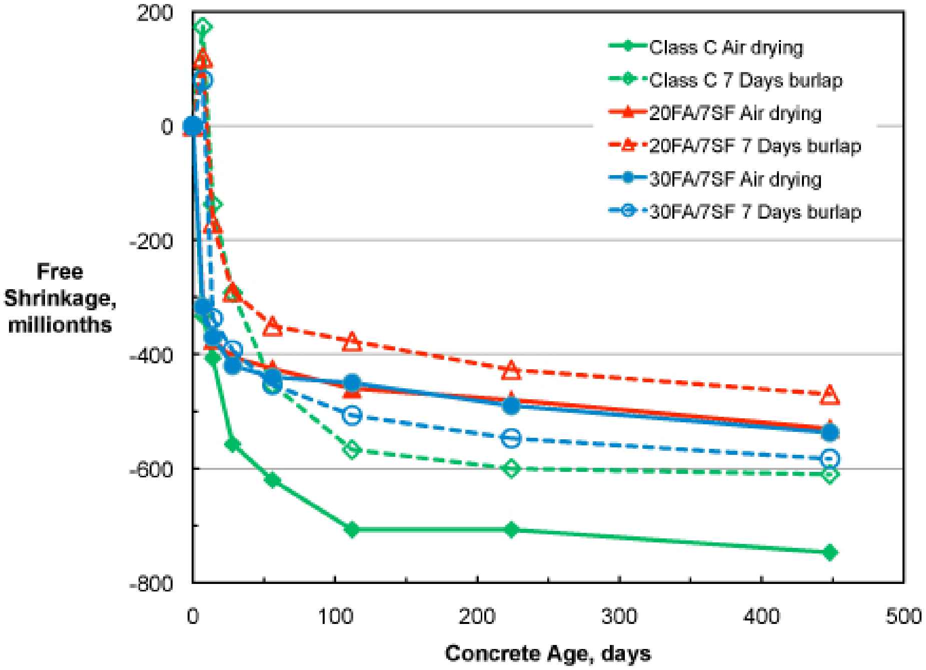
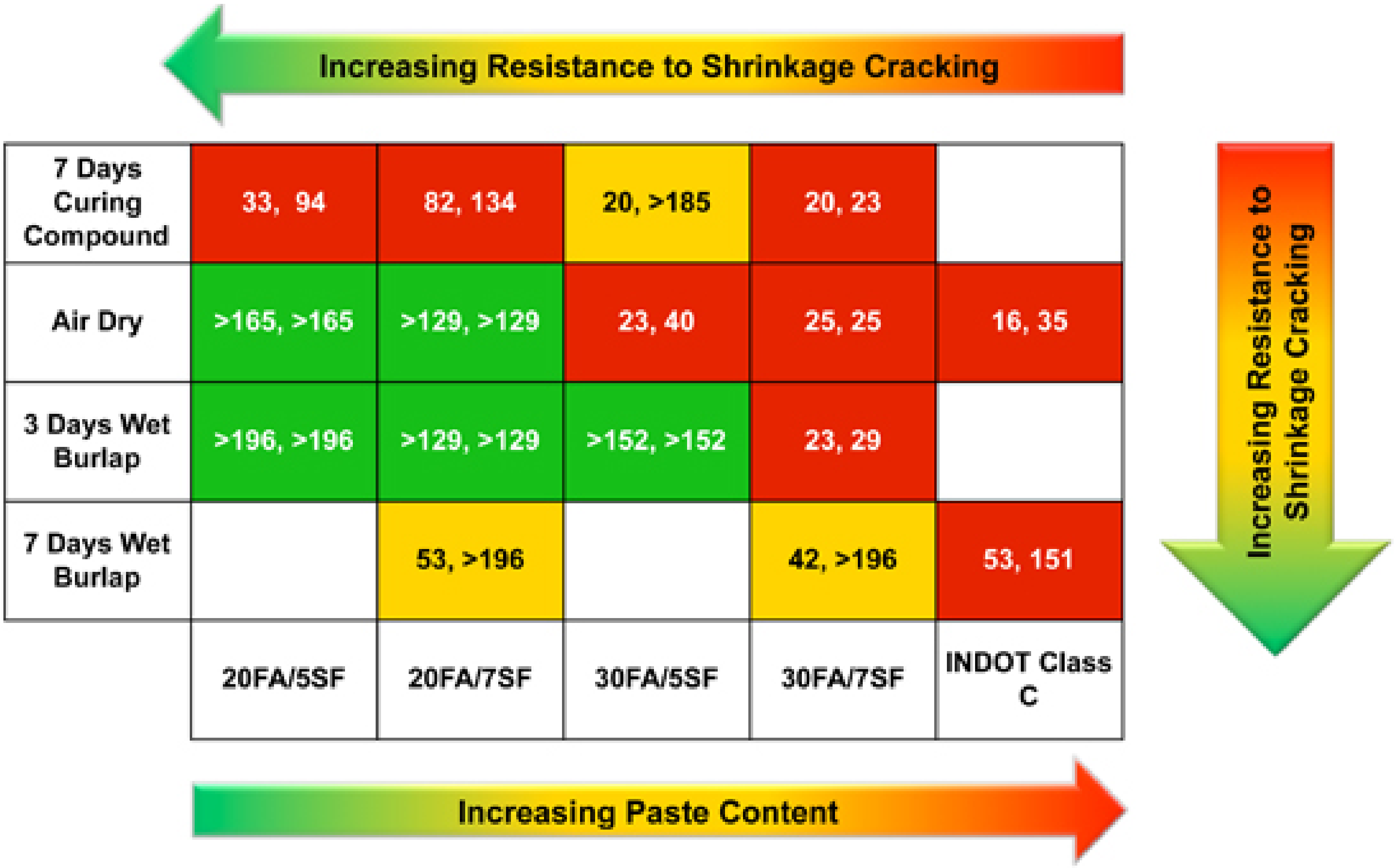


Fig. 2. Air drying versus 7 days burlap curing

Crack Tendency

The concrete mixtures were also tested for restrained shrinkage cracking using the AASHTO T 334 testing method. Each concrete mix had two specimens for testing. All specimens were subjected to the four curing conditions. While the AASHTO T 334 method doesn’t specify a minimum monitoring period, the test was terminated a few days after cracks occurred. Otherwise, the shrinkage was monitored until the shrinkage values stabilized over time, up to 196 days.

Figure 3 shows the results of the restrained shrinkage testing for all the concrete mixes with their



7 Days Curing Compound	🟥 33, 94	🟥 82, 134	🟨 20, >185	🟥 20, 23	
Air Dry	🟩 >165, >165	🟩 >129, >129	🟥 23, 40	🟥 25, 25	🟥 16, 35
3 Days Wet Burlap	🟩 >196, >196	🟩 >129, >129	🟩 >152, >152	🟥 23, 29	
7 Days Wet Burlap		🟨 53, >196		🟨 42, >196	🟥 53, 151
	20FA/5SF	20FA/7SF	30FA/5SF	30FA/7SF	INDOT Class C

Fig. 3. Age at cracking, days, for the restrained shrinkage cracking test (Green is best performance, red is poorest performance, and yellow is in between)

associated curing conditions. In general, the cracking potential of the ternary concrete mixes increased with the increase in paste content of the mixes. The paste content, in this case, includes the supplementary SCMs of fly ash and silica fume. The curing conditions also influenced the resistance to shrinkage cracking. In most cases, curing of the mixes using wet burlap had a positive effect in reducing the potential for shrinkage cracking of ternary mixes. In addition, the INDOT Class C concrete without SCMs had a significant effect from the wet burlap curing. Mixes with lower paste content also exhibited better resistance to shrinkage cracking. The specimens made with 20% fly ash mixes did not have any shrinkage cracking even when air dried. However, this does not mean that concrete in the field does not require wet curing. The significant benefit of curing on shrinkage cracking potential is clearly demonstrated in this study.

Implementation

At the conclusion of this study, INDOT implemented the research results in actual construction in the field. Beginning in 2004, INDOT constructed a few bridge decks using the ternary mix formula of 20 FA/5SF from this study. The first bridge was the concrete deck on SR 23 in South Bend, IN. A few more bridge decks have been constructed using ternary concrete mixes with the wet burlap curing extended to 10 days to ensure adequate wet curing.

More Information

More details about this research, including the concrete mix proportions and additional test results, are available in ACI's Concrete International, Vol. 33, No. 1, January 2011, pp. 49-55.