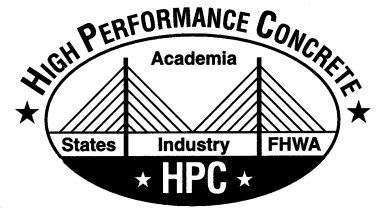




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May/June 2000

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HIGH PERFORMANCE CONCRETE BRIDGES: NOT JUST FOR STATES ANYMORE

Edward Binseel, Prince George's County, Maryland

Prince George's County, Maryland, plans to build 12 new bridges in the next three years. Some of the bridges will be designed and built using high performance concrete (HPC). All bridges will have simple spans ranging from 24 to 80 ft (7.3 to 24.4 m) in length.

The move toward HPC began several years ago, when the County's bridge inventory grew to more than 170 structures. Financial demands related to the maintenance and repair of the bridges grew to a level that was in excess of the available resources. Several of the fundamental decisions that had been guiding the design of new bridges in the County were changed. At the expense of higher initial costs, the County would now design its bridges to be more durable with extended longevity, while also decreasing each structure's long-term maintenance and repair costs. Decreasing the life-cycle costs associated with each bridge became a priority. We believe HPC will give us durability and longevity at a lower overall cost.

The lack of familiarity with HPC within the design community and the construction industry poses a potential barrier to our use of HPC. It's one thing to design specifying the use of HPC and it's another to build with it. These barriers can be overcome by recognizing the education and resources of the consulting engineers that we use for design, construction management, and inspection, and then by facilitating their training. Since we intend to require designs utilizing HPC, the consultants will have to learn what's necessary to prepare the design and specifications accordingly.

Five years ago, the County began restricting the water-cementitious materials ratio for all bridge-related concrete. By specifying a maximum ratio of 0.40, we are achieving denser, less porous concrete that is also stronger. The low ratio, which implies an additional amount of cement, appears to be giving us the longevity and durability that we need. If one consequence of the design is added strength,

we'll accept that—although we're not seeking that result directly or depending on it in the way a traditional design would.

Curing of the decks has been an important factor in reducing concrete shrinkage cracking. In winter, decks have been wet cured under burlap and plastic sheeting with flooding of the deck several times a day. In summer, burlap without plastic sheeting is used since we do not wish to retain the heat. Sprinklers are used on the deck to keep the deck flooded for seven days.

We are prepared to pay higher initial costs for HPC, but this has not been necessary. In recent projects, where we have restricted the water-cementitious materials ratio and increased the minimum concrete cover over all steel reinforcement to 2 or 2-1/2 in. (50 or 65 mm), we have not experienced higher bid prices or driven up the overall construction cost. We have also seen fewer construction-related problems than were expected using the stiffer mix, and there have not been any change orders as a result of surprises or any difficulties encountered. Each of the design changes that we have incorporated has also been directed toward decreasing the porosity of the concrete to prevent chloride ions from reaching the reinforcement.

HPC may also offer economic advantages because it results in greater strength and requires fewer structural members. We will be exploring this benefit as we become more familiar with the material. With dwindling resources, we are determined to achieve the best value for our construction dollar.

The State and the other counties have been slower to move and adopt these design changes. We have decided to lead, having determined that we cannot afford to wait for the local design community or for the local construction industry to mature and become proficient in the use of HPC. We believe in the benefits of HPC, and will help lead the local industry in its use by putting contracts on the street for construction.

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CORROSION MODELING FOR HPC SPECIFICATIONS IN NORTH CAROLINA

Rodger D. Rochelle, North Carolina Department of Transportation

HPC is rapidly gaining prominence in highway bridge construction because of the advantages of higher strength and greater durability. Unfortunately, the concept of designing for durability is more elusive than the quest for high strength. Bridge designs often include the 100-year flood, a 475-year seismic event return-period, or perhaps a Method II vessel impact analysis, all of which target a probabilistic service life. Similarly, the design should satisfy a 100-year service life when concrete is exposed to a chloride environment.

This approach has broadened the bridge corrosion protection policy in North Carolina. Unfortunately, due to the heterogeneity of concrete, arduous numerical analyses are required to predict the rate of chloride ingress within a concrete structure. In practice, such analyses are not feasible. Instead, comparative studies serve to evaluate the array of corrosion mitigation measures available with HPC. Such an investigation is conducted for North Carolina's major coastal structures, targeting a service life of 100 years. Fick's Second Law of Diffusion is modeled to optimize the durability design by examining each structural element independently. Various applications of this law are used to predict the service life provided by different protection measures.

Protection measures may be categorized in three ways. Physical systems enhance durability with tangible, physical barriers to chloride penetration. They commonly include increased concrete cover and epoxy-coated reinforcing steel. Passive systems act to slow down chloride ingress by decreasing the concrete's permeability and typically include the use of fly ash, microsilica, or ground granulated blast furnace slag (GGBFS). Finally, active systems, in the form of corrosion inhibitors, strive to chemically elevate the corrosion threshold of the reinforcing steel. Fick's Law encompasses each of these systems, albeit with varying degrees of convenience. The model also differentiates the chloride load and loading rate among structural elements. For instance, the splash zone piles may be subjected to a direct, immediate 20 lb/cu yd (12 kg/cu m) chloride load whereas a bridge deck may experience a maxi-

mum chloride load of 5 lb/cu yd (3 kg/cu m) deposited over several years.

Chloride loads are first determined by generating chloride profiles from neighboring structures. In coastal regions of North Carolina, surface chloride concentrations range from 5 to 23 lb/cu yd (3 to 14 kg/cu m). A preliminary durability model is then created incorporating concrete cover, water-cementitious materials ratio, and epoxy-coated reinforcing steel. Next, the model is expanded to include passive and active corrosion mitigation systems as necessary. The threshold chloride concentration is incrementally adjusted to reflect the presence of corrosion inhibitors while the concrete permeability is reduced according to the presence of mineral admixtures. A reduction in concrete permeability is based on a combination of results from AASHTO T277* testing, existing chloride profiles, and literature review.

The first structure designed using this procedure was the 5-mile (8-km), \$94 million bridge to the Outer Banks over the Croatan Sound, estimated to be completed in December 2001. The highly corrosive environment of the Sound has a variable chloride content in the water ranging up to 13,000 ppm. The structure contains approximately 190,000 cu yd (145,000 cu m) of concrete, the vast majority of which includes three levels of corrosion protection. Each type of structural element was ana-

lyzed independently such that, theoretically, all members begin to corrode simultaneously. Numerous levels of calcium nitrite, chloride load, and levels of concrete permeability were considered. Hundreds of possible options were pared down to the most cost-effective treatment schemes for each element. Among these options, constructibility requirements were addressed to further refine the schedule for corrosion mitigation techniques, resulting in the prescription for corrosion mitigation measures summarized below.

Calcium nitrite is used throughout the structure to elevate the corrosion threshold of all members. Microsilica is mandated in elements in which low permeability is required at an early age. Class F fly ash is used to reduce permeability in both the substructure and superstructure. Higher amounts of fly ash are incorporated into the pile caps to reduce the heat of hydration in these mass concrete elements. GGBFS is allowed as an alternate to fly ash in all precast members. Epoxy-coated reinforcing steel is used throughout the structure and concrete cover is greater in all substructure elements. The water-cementitious materials ratio is limited to 0.40 and 0.43 for precast, prestressed concrete and cast-in-place concrete, respectively, and all precast, prestressed concrete members are designed for zero tensile stress under full service loads.

*Standard Method of Test for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration.

| Structural Element | Calcium Nitrite gal/yd ³ | Class F Fly Ash ⁽¹⁾ % | Silica Fume ⁽¹⁾ % |
|------------------------------|-------------------------------------|----------------------------------|------------------------------|
| Barrier Rail | 2.0 | 20 | - |
| Deck Slab | 2.0 | 20 | - |
| Diaphragms | 2.0 | 20 | - |
| Prestressed Concrete Girders | 2.0 | 20 ⁽²⁾ | - |
| Bent Caps | 3.0 | 20 | 5 |
| Columns | 3.0 | 20 | 5 |
| Pile caps | 3.0 | 30 | 5 |
| Prestressed Concrete Piles | 3.0 | 20 | 5 |

1 gal/yd³ = 4.951 L/m³

(1) Percentage of total cementitious materials content

(2) Contractor option for fly ash or GGBFS

(continued from pg. 2)

The durability design procedure culminates in a simple and direct two page prescriptive specification. This specification is a notable departure from the original intent for specifying HPC in North Carolina bridges. In fact, AASHTO T277 research was initiated to generate criteria for a performance-based specification. However, the research was remarkably conclusive, rendering the performance specification obsolete. Furthermore, the prescriptive speci-

fication arguably avoids surcharges buried within the bid to cover the unknown cost of developing and testing mixes to satisfy a strict performance criterion, and eliminates concerns about the variability of the AASHTO T277 test method.

Further Information

For further information, contact the author at rdrochelle@dot.state.nc.us or 919-250-4048. For a discussion of Fick's

Law, see Amey, S. L., Johnson, D. A., Miltenberger, M. A., and Farzam, H., "Predicting the Service Life of Concrete Marine Structures: An Environmental Methodology," *ACI Structural Journal*, Vol. 95, No. 2, March-April 1998, pp. 205 - 214.

CONCRETE SPECIFICATION REQUIREMENTS FOR ALABAMA'S HPC BRIDGE

Sergio Rodriguez, Alabama Department of Transportation

The Alabama Department of Transportation's (ALDOT) first high performance concrete (HPC) bridge was let in April 1998. There was a lot of excitement in Alabama because we were going to play in the majors. We wanted to win the World Series title for the best HPC bridge. Two years before the letting, we started revising the plan of those who played the game before us. In Alabama, everybody played the game; there was no bench. ALDOT, FHWA, academia, contractors, and suppliers all played an important role in drafting what later became our first specification for HPC bridges.

For conventional concrete, ALDOT provides a master proportions table for all mixes used in a project. The responsibility for the HPC mix design fell to the contractor. The only parameters specified were the materials, water-cementitious materials ratio, temperature of the concrete, air content, slump, and compressive strength. The contractor was permitted to use Class C fly ash at 20 to 30 percent, Class F fly ash at 15 to 25 percent, or microsilica at 7 to 15 percent by weight of the total cementitious materials. A combination of one of the fly ashes with microsilica was allowed provided that the microsilica percentage was considered as additive. Crushed limestone was specified for the coarse aggregate and natural sand for the fine aggregate. Chemical admixtures were allowed based on the manufacturer's recommended dosages.

The maximum specified water-cementitious materials ratios were 0.40 and 0.32 for cast-in-place concrete and precast, prestressed concrete, respectively. The minimum temperature of the concrete at time of placement was set at 50°F (10°C) and

the maximum at 95°F (35°C). The range of air content allowed was from 3.5 to 6 percent. There were three criteria for slump of the concrete: for non-prestressed concrete, the maximum slump was set at 5 in. (125 mm) for superstructure concrete and 8 in. (200 mm) for substructure concrete. For the 54-in. (1.37-m) deep bulb-tees, the maximum slump was set at 9 in. (230 mm). The compressive strength was specified at 6000 psi (41 MPa) at 28 days for non-prestressed concrete. For precast, prestressed concrete, compressive strengths of 10,000 psi (69 MPa) at 28 days and 8,000 psi (55 MPa) at release of the strands were specified.

Additionally, for acceptance of the concrete mix, test pours were required to provide evidence of the contractor's ability to mix, transport, place, consolidate, finish, and cure the concrete properly. For the bridge deck, the test pour required a minimum slab area of 400 sq ft (37 sq m) with a minimum thickness of 4 in. (100 mm). The test pour for the precast, prestressed concrete girders consisted of a full cross-section of a girder at least 10-ft (3.1-m) long and using the planned casting bed.

We made it through spring training. Then, we had to prepare ourselves for those unexpected injuries during the season. To prevent plastic shrinkage cracking of the bridge deck concrete, the maximum evaporation rate was specified not to exceed 0.1 lb/sq ft/hr (0.5 kg/sq m/hr) as determined by an "Evaporation Rate of Surface Moisture" chart. Moist curing was the only curing method allowed for bridge decks. Match curing of the quality control cylinders was required for the precast, prestressed concrete bridge members. The

contractor was responsible for providing a protected environment for field curing of concrete cylinders. This protected environment consisted of a curing box equipped with heating and cooling capabilities, and high/low temperature readout. Concrete testing was required on the first load of concrete delivered every day and then on every 50 cu yd (38 cu m). Concrete samples were obtained for testing of slump, air content, temperature, unit weight, and compressive strength.

As simple as it sounds, that was our game plan. We were ready to play ball! We had a few bad innings, but also hit a few home runs. We found out that playing in the majors is no different than playing minor league. The stakes may be higher but the game is played the same way. Yes, we won the World Series title for the best HPC bridge, but so does everybody else who plays. We are all winners in this game. The experience is great and the challenge so intense that our learning is enriched and we can hardly wait for the next game.

I don't want to end this article without some words of advice for those who are about to bat for HPC. Make sure that everybody is involved (no bench allowed), keep your specifications as simple as possible, specify only what is needed but make sure your goals are attainable. Then, don't settle for less. Remember that the ultimate goal is to produce a structure that is safe for the public, durable, and as economical as possible.

Further Information

A complete copy of ALDOT's game plan is available from the author at 334-206-2410 or at rodriguez@dot.state.al.us.

LETTERS TO THE EDITOR

The following letter was received from Doug Hooton of the University of Toronto concerning the Q & A about the Rapid Chloride Permeability Test that appeared in Issue No. 6, November/December 1999.

As Chairman of ASTM C 09.66 on Concrete Resistance to Fluid Penetration, I have examined a number of rapid tests, and ASTM C 1202 deserves to be seen more positively as a rapid index test of concrete quality. The five "Cons" that were raised in the article merit comment.

1. "The test has poor correlation with ponding tests when different mixes are compared." The reason for poor correlation with the AASHTO T259 test is largely due to insufficient data collection and poor analysis techniques specified in AASHTO T259.^(1,2) When more appropriate analysis procedures are used on T259 results (using depth of chloride penetration rather than integrated chloride values), the results agree fairly well with ASTM C 1202 results (corrected for temperature rise).
2. "The test is not a direct measure of chloride permeability. It only measures electrical conductivity of the concrete." While true, conductivity or its reciprocal—resistivity—is a useful index of the connected pore structure in the concrete. One could argue that there are easier ways of determining this property.
3. "Chloride ions only carry a small proportion of the current during the test, so the test is not specific to chloride." This is also true. The current is carried by all the ions in the concrete's pore solution. However, except in the case of admixtures such as calcium nitrite that leave conductive ions in pore solution, this is not a real concern for most concretes since, after 28 days, most pore solutions are mainly alkali hydroxides. ASTM C 1202 has a warning statement with respect to calcium nitrite.
4. "It has been claimed that the test yields erroneous results when applied to silica fume concrete." This claim⁽³⁾ is based on AASHTO T259 data which when re-analysed (See Item 1), does not bear out in fact.^(1,2) As well, other ponding (chloride bulk diffusion) tests and migration test results have

also been found to relate very well to ASTM C 1202 results, regardless of silica fume's presence.^(4,5) In fact, the relative effect of silica fume addition on concrete's chloride penetration resistance is predicted by ASTM C 1202 with as much accuracy as can be expected with any rapid test.

5. "Self-heating of the specimen during the test affects test results." While true for specimens that have charges in excess of about 2000 coulombs, this is above the values typically required for good quality concrete in bridge structures. A solution proposed for this problem of temperature-affected increases in conductivity is to take the 30-minute charge passed (before temperature rises) and multiply it by 12 to approximate the six-hour value.^(1,4)

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