100-YEAR SERVICE-LIFE BRIDGE DECKS USING LOW-SHRINKAGE HIGH-PERFORMANCE CONCRETE

Daniel Cusson, Ph.D., P.Eng.
National Research Council Canada, Ottawa, Ontario, Canada

Abstract: Highway bridges and parking structures, subject to coupled effects of mechanical loads and corrosion, often show early signs of distress such as concrete cracking and rebar corrosion leading to reduced structural performance and shortened service life. One possible solution is to use low-shrinkage low-permeability high-performance concrete (HPC) for bridge decks exposed to de-icing salts and severe loading conditions. A new HPC has been formulated to achieve low shrinkage and low permeability, high early-strength, and 28-day compressive strength of up to 70 MPa. Its mechanical performance and durability have been tested both in the lab and field under severe test conditions, including restrained shrinkage, cycling loading, freezing and thawing cycles, and application of de-icing salts. Prediction models have been developed and calibrated to predict structural performance and service life of concrete bridge decks under severe exposure conditions. Prediction models indicate that bridge decks designed with low-shrinkage HPC can achieve service lives exceeding 100 years. Compared to normal concrete decks, short-to-medium span bridge decks using low-shrinkage HPC could be built at a comparable initial construction cost, but at less than 40% of the life-cycle cost over a 100-year period.

INTRODUCTION

The use of high-performance concrete (HPC) for the construction of bridges and buildings has increased significantly in the past decades. Typical high-performance concrete, however, is prone to early-age cracking when shrinkage is restrained in concrete structures. This tendency to crack is mainly due to the low water-cement ratio (w/c) used in HPC to achieve low permeability and/or high strength. This low w/c often results in self-desiccation, leading to autogenous shrinkage. Although this type of shrinkage is typically negligible in normal-strength concrete, the high water-cement ratio often results in undesired performance such as high permeability, low strength and high drying shrinkage, all leading to short service lives of concrete structures.

MATERIALS

To develop HPC with low shrinkage, low permeability, high strength and long-term durability, different materials were evaluated: (i) supplementary cementing materials (SCM: slag & silica fume); (ii) lightweight aggregate for internal curing (LWA: expanded shale); (iii) shrinkage-reducing admixture (SRA: glycol ether); and (iv) corrosion inhibitor (CI: calcium nitrite).

HPC formulations have been developed based on the same basic proportions, such as: (i) effective water-cement ratio of 0.35; (ii) Type 10 blended cement content of 450 kg/m^3; (iii) cement/sand/stone mass ratio of 1:2:2; and (iv) maximum aggregate size of 10 mm. Superplasticizer and air entraining admixtures were used to achieve adequate workability (near 200 mm slump) and high resistance to salt scaling (4-6% air). The tested HPC formulations are:

- HPC-2 with saturated LWA for internal curing (IC)
- HPC-3 with shrinkage-reducing admixture (SRA)
- HPC-4 with combined IC and SRA (IC/SRA)
- HPC-5 with combined IC, SRA, and corrosion inhibitor (IC/SRA/CI)
- HPC-6 (control mix)

EXPERIMENTAL PROGRAM

Laboratory testing

The above HPC formulations have been developed and first tested in the laboratory under controlled environments. Several concrete material and mechanical properties developing over time have been measured: cement hydration rate, heat of hydration, strength, stiffness, thermal expansion, and free shrinkage, as well as several other properties related to durability, including water permeability, chloride diffusion, freeze-thaw resistance, and salt-scaling resistance. Test results can be found in Cusson & Margeson (2010) and will not be discussed herein.

Field testing

Large-size HPC slabs were made using the above concrete formulations and have been tested in the field under realistic loading and environmental conditions, including: cyclic loading and restrained movement, as well as exposure to de-icing salts, ambient temperature, relative humidity, solar radiation, wind, and rain. Series of slabs were tested for (i) restrained shrinkage, tensile creep, and modulus of elasticity; (ii) free shrinkage; and (iii) corrosion of various types of embedded steel rebars, including: carbon steel, galvanised steel, chromium steel, and stainless-clad steel. The results obtained from the corrosion slabs, however, will not be presented herein.

Figure 1 illustrates the outdoor loading frames designed for testing restrained shrinkage, tensile creep and elastic modulus. Each HPC slab was loaded in tension by using two hydraulic jacks to pull on five reinforcing bars going through each test frame. Gauges were used to monitor strains in the middle of the concrete slab and on the loaded steel bars outside the slab. The target ultimate load applied on each reinforced concrete slab was 150 kN. Figure 2 presents the forms used to cast the companion HPC slabs for free shrinkage testing at the outdoor test site. Sensors were used to monitor strain, temperature, and relative humidity in the free concrete slabs.

All restrained and free concrete slabs were moist cured for 7 days with wet burlap and tarpaulin, and then exposed to drying from the top surface. The mean ambient temperature measured during the first 28 days was 20°C (10-35°C range) and the mean ambient relative humidity during the corresponding drying period was 77% (30-100% range) in August/September 2010.

Fig. 1: Restrained shrinkage loading frames (slab dimensions: 2000 × 500 × 100 mm)

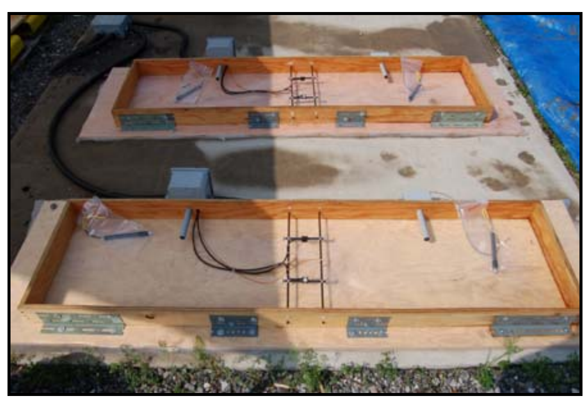

Fig. 2: Wood forms for free shrinkage slabs (slab dimensions: 2000 × 500 × 100 mm)

SELECTED TEST RESULTS

Fresh and hardened concrete properties

Table 1 presents some of the fresh and hardened concrete properties measured for the different concretes. Compressive strengths over 40 MPa were measured at 7 days, over 50 MPa at 28 days, and up to 67 MPa for HPC-2 and HPC-5 with internal curing. The target air content in HPC-3 had been exceeded, which resulted in a lower than expected strength of 53 MPa at 28d.

Table 1: Properties of concrete for field shrinkage slabs

Property	**Number of replicates**	**HPC-2 (IC)**	**HPC-3 (SRA)**	**HPC-4 (IC/SRA)**	**HPC-5 (IC/SRA/CI)**	**HPC-6 (CTRL)**
Slump (mm)	2	210	175	210	225	105
Air content (%)	2	4.3	8.5	4.4	4.9	5.4
Fresh density (kg/m^3)	2	2238	2213	2257	2220	2311
7d compressive strength (MPa)	3	54	41	43	50	57
28d compressive strength (MPa)	3	67	53	57	67	65

Autogenous shrinkage and cracking

The free shrinkage strain was determined by subtracting the thermal strain from the measured total strain in the unrestrained concrete slabs. As shown in Fig. 3, HPC-6 (CTRL) with no shrinkage control measure rapidly developed a high shrinkage strain of 200×10^{-6} in only 7 days. HPC-3 with the SRA developed moderate shrinkage, while HPC-2,4,5 with internal curing developed initial expansion followed by very small shrinkage. External drying shrinkage from 7 days to 28 days was found negligible for all HPCs due to their low permeability, as expected.

Visco-elastic properties for each HPC were also determined from the restrained shrinkage tests on the loaded slabs. For full restrained and isothermal conditions, the tensile stress was then determined for each concrete and compared to its respective tensile strength measured over time. Figure 4 presents the stress-strength ratio determined for each concrete. Under these conditions, HPC-6 (CTRL) was found to crack after 5 days, while all other concretes with shrinkage control measures did not crack. HPC-3 (SRA) had a moderate stress-strength ratio of 40% at 7 days, while HPC-4 (IC/SRA) and HPC-5 (IC/SRA/CI) obtained a low stress-strength ratio of 25% at 10 days. Note that the visco-elastic properties of HPC-2 could not be obtained due to equipment problems, explaining its absence in Fig. 4. It would likely behave almost as well as HPC-4.

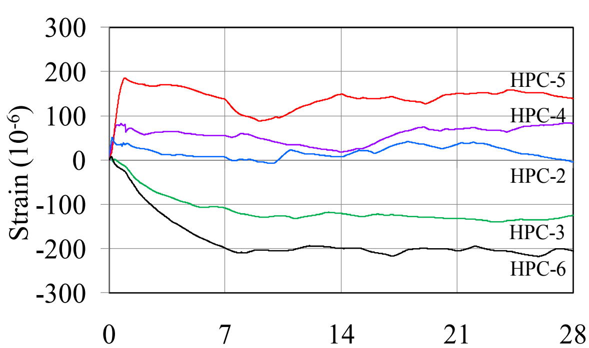

Fig. 3: Measured free shrinkage

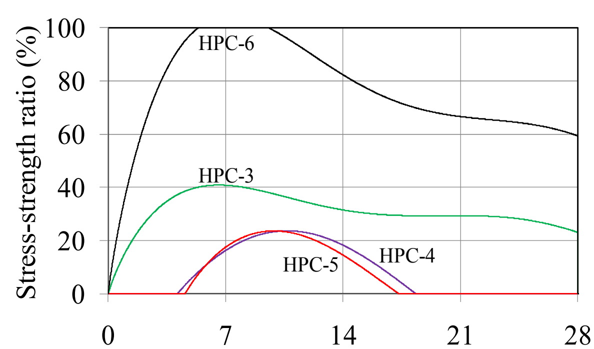

Fig. 4: Stress-strength ratio under full

restraint

Chloride diffusion

The concentration of chloride ions along penetration depth was measured after 28d, 56d, and 90d of chloride ponding (3.5% NaCl) on concrete specimens. Figure 5 shows one set of total chloride measurements expressed as percent of concrete weight for HPC-6 after 90 days of ponding. Each profile was best-fitted with Crank (1975) solution of Fick's 2nd law of diffusion to determine the apparent chloride diffusion coefficient (D_c). The obtained values of D_c (Fig. 6) are considered very small (still decreasing over time). The use of internal curing appears to slow down chloride diffusion in HPC-2,4,5 compared to HPC-6 (CTRL), which may be due to enhanced cement hydration resulting in reduced concrete permeability. The lowest value of D_c was found for HPC-3 (SRA) with a 90-day value of 0.15 cm^2/year, which is only 30% of the control value of 0.5 cm^2/year. These trends are confirmed by previous test results for water permeability, chloride ion penetrability, and salt scaling weight change (Cusson & Margeson 2010).

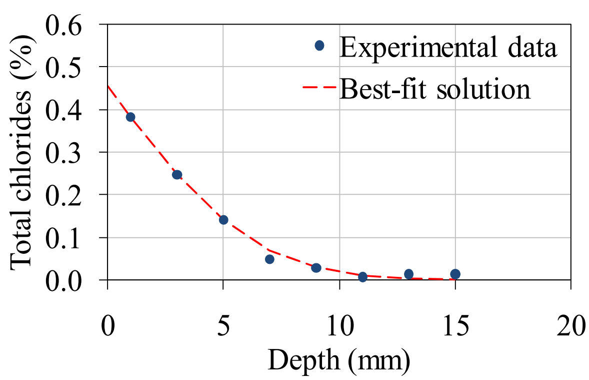

Fig. 5: Chloride profile for HPC-6 at 90d

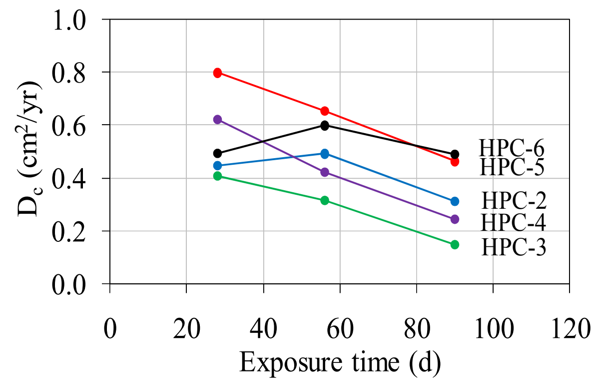

Fig. 6: Chloride diffusion coefficient

SERVICE LIFE OF BRIDGE DECKS MADE WITH LOW-SHRINKAGE HPC

The goal of this section is to demonstrate the performance and cost benefits of using low-shrinkage high-performance concrete (HPC) as opposed to normal concrete (NC) for the design and construction of common bridge decks. In this case study, the two types of concrete will be assumed to have similarly-low shrinkage, but different levels of strength and permeability.

Design and construction of HPC decks

As a case study, the Canal Bridge to be built in 2011-2012 in Cornwall, Ontario, was used for the analysis. Figure 7 presents the original design of the bridge deck made with normal-strength concrete (f'_c = 30 MPa) and normal steel reinforcement (f_y = 400 MPa).

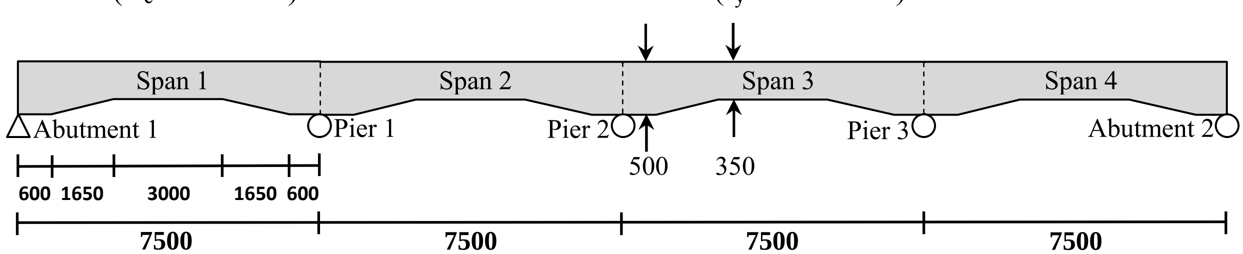

Fig. 7: Elevation view of Canal Bridge, Cornwall – Original design with normal concrete (mm)

The deck of the Canal Bridge consists of a continuous reinforced concrete haunched slab, carrying 3 lanes of traffic over 4 continuous spans. The slab width is 21.75 m. In this comparative analysis, the 2004 AASHTO LRFD specifications were used to determine the slab thickness and reinforcement schedules. Four limit states were verified: Strength 1, Strength 2, Service, and Fatigue. Typical dead loads were assumed for self-weight, wearing surface, utilities, railings and curbs, and live loads were set according to the HL-93 truck live load specification. For the alternative design with HPC, two properties were taken advantage of, namely: its higher strength and its lower permeability. As a result, the minimum slab thickness could be reduced from 350 mm to 200 mm, and the concrete cover was slightly reduced from 75 mm to 60 mm in order to increase the effective slab depth, thus providing higher bending strength. Table 2 presents the reinforcement schedules calculated for the two deck designs, as well as the approximate material quantities and costs required to build the bridge deck.

Table 2: Comparison of slab deck designs for the Canal Bridge in Cornwall

Design details	**NC deck design**	**HPC deck design**
Concrete compressive strength	30 MPa	70 MPa
Minimum slab thickness	350 mm	200 mm
Clear concrete cover	75 mm	60 mm
Bottom longitudinal reinforcement (M+)	25M @ 160 mm	35M @ 180 mm
Top longitudinal reinforcement (M+)	20M @ 160 mm	25M @ 160 mm
Bottom longitudinal reinforcement (M−)	25M @ 160 mm	30M @ 180 mm
Top longitudinal reinforcement (M−)	25M @ 160 mm	30M @ 160 mm
Bottom transverse reinforcement	15M @ 300 mm	15M @ 160 mm
Top transverse reinforcement	15M @ 300 mm	15M @ 300 mm
Volume of concrete	266 m^3 (\$450/m^3)	173 m^3 (\$600/m^3)
Mass of steel	35 tons (\$2/kg)	52 tons (\$2/kg)
Approximate cost	\$189,000	\$207,000

Based on the above assumptions and suggested unit costs, the approximate cost of concrete and steel would be \$189,000 for the NC bridge deck, and \$207,000 for the HPC bridge deck, which is only 10% higher in comparison. If HPC was used in the original design (i.e. original deck geometry and reinforcement) the cost of concrete and steel would amount to \$230,000, which would represent a 22% increase compared to the normal concrete deck design. It will be shown later that this cost increase in deck construction (from 10%, at best, to 22%, at worst) is negligible when compared to the considerable savings offered by HPC decks over the life cycle.

Service life prediction of HPC decks

Figure 8 presents the conceptual model used to determine the service life of the Canal Bridge deck. The corrosion initiation stage included effects of cracking and apparent chloride diffusion coefficient on chloride penetration in the deck. Direct exposure to de-icing salts was assumed with a high surface chloride concentration of 9 kg/m^3 (Weyers 1998). A chloride corrosion threshold of 0.2% by mass of cement in concrete was assumed for the steel rebars (CEB 1992), which was increased by 50% for HPC-5 with the corrosion inhibitor. For the damage accumulation stage, a corrosion rate of 0.5 $\mu A/cm^2$ was assumed, which was increased by 30% for HPC-6 (control) due to early cracking. The stress build-up in concrete due to rust formation around the steel bars was considered along with concrete tensile strength to determine damage accumulation. The full set of prediction models used can be found in Lounis and Daigle (2008).

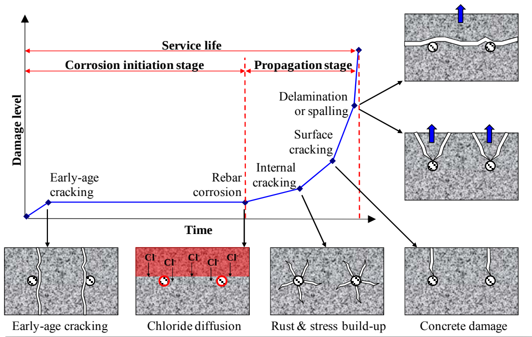

Fig. 8: Service-life model for RC decks

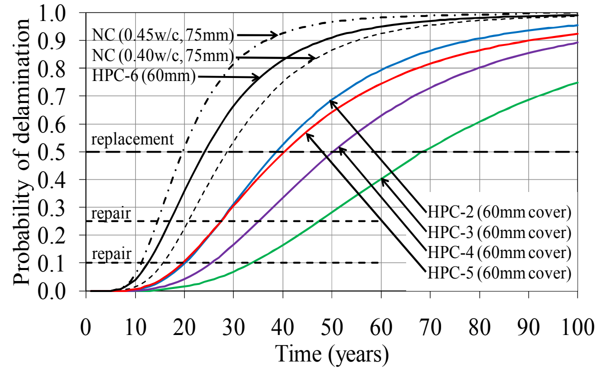

Fig. 9: Probability of deck delamination

A probabilistic analysis using carefully-selected values for the mean and coefficient of variation of the input parameters was conducted to determine the probability of delamination of the bridge deck, as shown in Fig. 9. Taking the 50% probability of delamination as the end of service life and the time for a deck replacement (AASHTO 2002), service lives ranging from 20 years to 70 years were found depending on selected deck designs. For example, the use of HPC-6 (CTRL) with a 60 mm concrete cover and premature cracking would provide an estimated service life of only 24 years. On the other hand, the use of HPC-2 (IC), HPC-5 (IC/SRA/CI), HPC-4 (IC/SRA), and HPC-3 (SRA) would provide significantly longer service lives of 38 years, 40 years, 50 years, and 68 years, respectively. Not shown in this paper, if a full cover thickness of 75 mm was used for all high-performance concretes, the service lives would become 36 years for HPC-6, 58 years for HPC-2, 61 years for HPC-5, 76 years for HPC-4, and 105 years for HPC-3. Compared to a normal-strength concrete deck with a 0.45 w/c and 75-mm cover, the use of HPC-3 in an aggressive environment could increase the service life by a factor of 5.

Life-cycle cost of HPC decks

In this study, the analysis period was set to 100 years, using a discount rate of 3% to calculate the present value life cycle cost (Grant et al. 1990). The direct costs incurred by the bridge owner usually include the initial construction cost and other costs associated with the maintenance activities, and ultimately deck replacement. Various maintenance activities were assumed to take place on the bridge deck over its life cycle. For example, routine inspections were scheduled at two-year intervals with a unit cost of $2/m^2, while non-destructive evaluation (NDE) and protection activities were scheduled to occur every 5 years for normal concrete decks and every 10 years for HPC decks, each with a unit cost of $20/m^2, assuming more frequent interventions required for normal concrete decks due to drying shrinkage, freeze-thaw damage, etc. Major patch repairs at a unit cost of $200/m^2 (including concrete removal, surface preparation, patching, and traffic control) were scheduled to take place when 10% and 25% of the deck surface has delaminated, as indicated in Fig. 9. Deck replacement ($350/m^2) was deemed necessary when 50% of the deck surface has delaminated. After replacement, it was assumed that the bridge deck would be rebuilt with a similar type of deck at a similar initial construction cost. Figure 10 presents the maintenance schedule assumed for HPC-3 with the 75-mm cover. Based on the above assumptions, the present value life cycle cost (PVLCC) was calculated for each deck design. Figure 11 shows the present value cumulative expenditures for most possible combinations of concretes and cover thicknesses (60 mm vs. 75 mm).

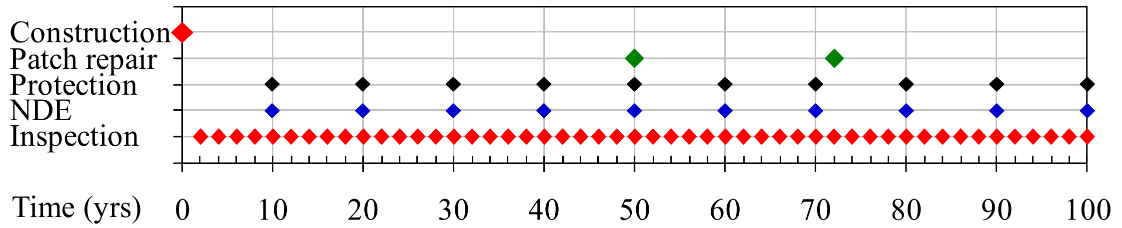

Fig. 10: Maintenance schedule assumed for bridge deck made with HPC-3 (75 mm cover)

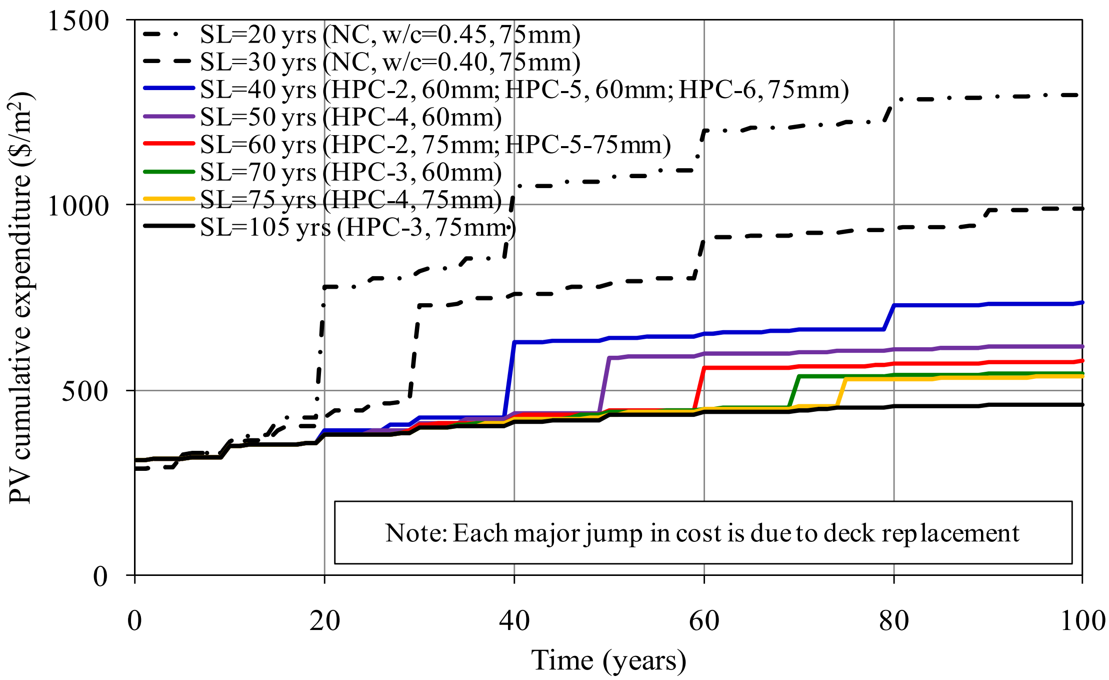

Fig. 11: Present value cumulative expenditure for different concrete deck designs

As expected, the longer the service life the least expensive it is to build and maintain a bridge deck over a given period of 100 years. It is interesting to see that the most durable deck designs provide present value life-cycle costs that are just slightly larger than their corresponding initial construction cost. More specifically, for normal-strength concrete (w/c=0.45, f'_c=30 MPa) with a 75-mm concrete cover, the cost for a square meter of deck area would be $1297/m^2, which is 4.5 times higher than the initial construction cost of $288/m^2. At the other end of the spectrum, using HPC-3 (SRA) with a 75-mm concrete cover, the unit cost would be $460/m^2, which is only 1.5 times higher than the initial construction cost of $312/m^2. It is also shown that the slightly higher initial investment in a HPC deck design, compared to NC deck design, can be offset in only 5 years due to the lower maintenance costs associated with HPC. Compared to a 30 MPa concrete (w/c=0.45), the use of HPC-3, for example, can reduce the life-cycle cost by a factor of 3 over a hundred years. The use of low-shrinkage low-permeability HPC for the construction of a bridge deck under severe exposure conditions is undeniably advantageous over normal strength concrete. Other benefits of low-shrinkage HPC, not calculated herein, are the much lower impact on (i) bridge users, with less traffic disruption, improved safety, higher comfort level; and (ii) environment, with less construction materials used due to fewer deck replacements and thinner deck designs, decreased use of landfills, and reduced transportation cost and pollution.

CONCLUSIONS

Based on the experimental results obtained in both lab and field studies, and the prediction models calibrated with the test results, the following general conclusions are drawn:

- Internal curing and shrinkage-reducing admixture are cost effective measures to reduce the risk of cracking in concrete bridge decks;
- Low-shrinkage high-performance concrete can provide high strength and stiffness, and very low permeability to water and chlorides;
- Construction cost of bridge decks using low-shrinkage HPC may be only 10% higher compared to normal concrete due to the smaller concrete volume required;
- Long service life of bridge decks over 100 years can be achieved with low-shrinkage low-permeability HPC, compared to only 20 years for normal-strength concrete decks;
- Present value life-cycle cost of bridge decks made with low-shrinkage HPC may be only 40% of the life-cycle cost of normal-strength concrete bridge decks over a 100-year period.

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