

KEY FACTORS TO A DURABLE BRIDGE DECK SLAB MADE WITH HIGH PERFORMANCE CONCRETE IN WASHINGTON STATE

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ABSTRACT

Concrete bridge deck slabs develop signs of deterioration, some at early age right after construction, and some after the bridge has been opened to traffic for a long time. Deck cracking accelerate reinforcement corrosion, reduces the service life of the structure and increases maintenance and rehabilitation costs.

High performance concrete with low permeability is known to improve the durability and to extend the service life of bridge deck slabs. Appropriate construction practice, reinforcing detailing, pouring sequence, and curing, among other things is important factors to achieve durable bridge deck slabs.

Cast-in-place concrete is the preferred option for WSDOT bridge decks; however, the use of precast prestressed concrete stay-in-place deck panels with some limitations is also allowed in bridge deck construction. This method of construction is provided as an alternative to cast-in-place concrete deck when accelerated construction is desired.

A comprehensive review of causes of cracking and factors affecting the durability of bridge deck slab are discussed in this paper. The current WSDOT practice of concrete deck slab design, detailing, construction, and recommendation to minimize deck cracking and to improve durability of deck slabs are presented.

Keywords: Bridge Deck, Durability, Cracking, HPC, SIP, Curing, Design, Detailing

INTRODUCTION

Development of high performance concrete, HPC capable of resisting chloride diffusion and other environmental distress has been the subject of interest for bridge engineers. HPC has enhanced specific properties, such as workability, durability, strength and dimensional stability, resulting in long lasting structures.

Washington State Department of Transportation (WSDOT) uses Class 4000D High Performance Concrete (HPC) for bridge deck to extend the service life of bridges. This concrete mix design along with the WSDOT extended 14 days wet curing has successfully resulted in a superior performance over the years¹. Class 4000D (28D) concrete is a high performance air-entrained concrete specially designed for low permeability and high resistance to freeze-thaw cycles in severe environmental exposures.

WSDOT has recently developed standard details and specifications for Stay-In-Place (SIP) deck panels to be used for bridge deck construction. This method of construction is provided as alternative to Cast-In-Place (CIP) deck slab on prestressed girder bridges when accelerated construction is desired.

CAUSES OF DECK DETERIORATION

Deck cracking is the main concern for bridge deck deterioration. Cracks in concrete occur when a restraint mass of concrete tends to change volume. Volume change in concrete depends on the properties of its constituents and their proportions as well as environmental conditions such as ambient temperature changes and humidity. This restraint, which is due to composite action of deck and girder, depends on design characteristics of the bridge, and volume changes of concrete mass². Volume change in concrete bridge deck could be categorized as follows:

- Drying shrinkage, described as the change in concrete volume due the change in water content during the time after exposure to atmosphere.
- Thermal shrinkage, due to cooling of concrete after initial hydration.
- Plastic shrinkage, caused by excessive evaporation of surface water. Plastic shrinkage cracks are often attributed to higher evaporation rates than concrete bleeding, where evaporation rates increase with high temperatures, low humidity, and high wind speed.
- Creep strain, volume change of concrete when subjected to sustain loads. Creep strains in some cases tend to counteract the effect of shrinkage.

Drying shrinkage and thermal shrinkage is considered the major cause of concrete deck cracking. Construction practice, curing procedures, pouring sequence, and form type can affect deck cracking.

Precast girders with relatively wide top flange restrain the volume change of CIP concrete deck against precast top flange, and provide the condition for cracking. These cracks are

formed at the bottom of slab perpendicular to girder direction³. The concrete on top of girder flange is restrained while the concrete between girder flanges is free to shrink. This differential shrinkage within the deck slab could be, among other reasons, one of the reasons for transverse cracking. These typical shrinkage cracks may be reduced by adequate distribution of reinforcement, and reducing the ratio of cross sectional area of girder to deck slab. To minimizing transverse deck cracking for beam-slab bridges with main reinforcement perpendicular to traffic, and removable formwork WSDOT requires the following steps⁴:

- The amount of longitudinal reinforcement in the bottom of slabs shall not be less than $220/\sqrt{f'_c} \leq 67$ percent of the primary reinforcement for positive moment as specified in AASHTO LRFD Specifications⁵.
- The maximum bar spacing in transverse and longitudinal directions for the top mat, and transverse direction of the bottom mat shall not exceed 12 in. (305 mm). The maximum bar spacing for bottom longitudinal within the effective length shall not exceed the deck thickness.

The causes of deck deterioration and factors affecting concrete deck slab durability are discussed in the following sections².

Effect of Materials and Concrete Mix-design

Concrete properties are affected by the type, size, volume and properties of aggregate. In general, concrete mixes with good quality, clean, low shrinkage aggregate with high aggregate to paste ratio perform better. Higher amount of cement in the concrete mix may have adverse effect on concrete properties. The adverse effect of higher cement content is usually related to higher drying shrinkage, higher temperature rises during hydration and higher early modulus of elasticity of concrete⁶.

Reducing water cementitious ratio is believed to reduce shrinkage of concrete. The use of retarders reduces rate of early temperature rise and early gain of modulus of elasticity would reduce deck cracking. Air content is usually used to increase freeze thaw durability of concrete. It is believed that increase in air content at about 6% improves deck durability.

High strength concrete shall be avoided in bridge deck concrete. Increased strength, which is usually accompanied by an increase in cement content, increase in paste volume and higher hydration temperatures, is blamed to cause more cracking in concrete decks.

Effect of Construction Practice

Hot and cold weather conditions may result in poor quality concrete. Thermal stresses developed at early age in concrete deck depend greatly on concrete temperature and weather conditions. Concrete temperature rises because of hydration heat sometimes beyond the limit allowed by specifications and causes thermal stresses in the section. To minimize the

adverse effect of temperature on deck durability the following concrete temperatures during placement of concrete deck slabs are proposed²:

- Maximum concrete placement temperature of 80^{oF} (26^{oC})
- Minimum and maximum ambient temperature of 40 and 90^{oF} (4 and 32^{oC})
- Concrete temperature of at least 10-20^{oF} (5 - 11^{oC}) cooler than ambient temperature
- Girder temperature of 55-75^{oF} (12 - 23^{oC}) should be maintained in cold weather
- Temperature difference of at least 22^{oF} (12^{oC}) for at least 24 hours is recommended

Effect of Curing

Curing has an imminent effect on the properties of hardened concrete such as durability, and mechanical properties. Adequate and timely curing is a key factor in reducing cracking. The following recommendations should be considered for bridge deck curing.

- Use of fog nozzle water spray in hot weather to cool reinforcing steel and forms immediately ahead of concrete placement
- Application of water spray immediately after strike-off or early finishing.
- Application of two coats of curing compound as soon as bleed water diminishes.
- Application of presoaked heavy quilted blankets or burlap as soon as concrete resists indentation. The presoaked heavy quilted blankets or burlap must be kept continuously wet by continuous sprinkling or by covering the burlap with plastic sheeting and periodic sprinkling.
- Continuation of wet curing for a minimum of 14 days. Curing should be extended in cold weather until the concrete has gained adequate strength.

Curing is one of the most important factors in achieving a superior and durable concrete. Proper curing of concretes should commence immediately after finishing. WSDOT requires an extended wet curing with two coats of curing compound in accordance with the AASHTO M 148, and continuous wet cure using heavy quilted blankets or burlap for 14 days.

After placement of concrete, two coats of liquid membrane-forming curing compound should be applied immediately after finishing or as soon as the visible bleed water has evaporated. The surface should be covered with presoaked heavy quilted blankets or burlap as soon as the concrete has set enough to allow covering without damaging the finish.

Fly ash will generally slow the setting time of concrete and increases the water requirement. The degree of slowing depends on factors such as amount of Portland cement, water requirement, the type mineral admixtures, and the temperature of the concrete.

Use of mineral admixtures may require longer effective curing time; this effect should be considered when proportioning the concrete mix. The effects of temperature and moisture conditions on setting properties and strength developments of concretes containing mineral admixtures are very important.

Effect of Pour length and Sequence of Construction

Pour length, sequence, and rate of pouring may have some effects on deck cracking. It is recommended to specify pouring sequence as described below and to avoid pouring irregularities in deck slab construction. To minimize deck cracking the following recommendations should be considered²:

- Cast complete deck at one time whenever feasible within the limitation of the maximum placement length based on drying shrinkage consideration.
- If multiple placements must be made and the bridge is composed of simple spans, then place each span in one placement.
- If the bridge is simple span and single placement cannot be made over full span length, then place the center of span segment first and make this placement as large as possible.
- Place deck slab concrete in daytime.
- If multiple placements must be made and the bridge is continuous span, then place concrete in the center of positive moment region first and maintain a 72-hour delay between placements.
- Placing concrete first in positive moment regions first

It should be mentioned that traffic vibrations during the period of setting and early strength development do not adversely affect concrete deck slabs. WSDOT bridge deck construction sequence for multiple span prestressed girder bridges made continuous for live load is shown in Appendix A.

Control of Cracking by Distribution of Reinforcement

Reinforcing detail, bar size, type, spacing, and distribution affects cracking tendency of concrete deck slabs. Concrete cover over reinforcement is the most important factor affecting crack formation. Increased cover depth reduces risk of cracking. However, excessive increase in cover depth increases probability of settlement cracks over reinforcement. Increase in deck thickness reduces deck cracking.

The control of cracking by distribution of reinforcement has been a subject of discussion in recent years. The ACI 318-02 (7) and the AASHTO LRFD Specifications have different requirements for the distribution of the reinforcement. The ACI method does not include the effect of environmental exposures and requires bar spacing is less restricting than the AASHTO LRFD Specifications. The proposed WSDOT method shown Equation 1 is based on the ACI 318-02 with added multiplier factor to account for the effect of environmental exposures in distribution of reinforcement. The maximum reinforcement spacing is taken as shown in equation 2.

$$s = \frac{Z}{170} \left(\frac{540}{f_{sa}} - 2.5 d_c \right) \quad (1)$$

$$s = 12 \left(\frac{36}{f_{sa}} \right) \leq 12 \text{ in } (25 \text{ mm}) \quad (2)$$

Where:

- Z Exposure factor, Z=170 kips/in for moderate exposure, and Z=130 kips/in for severe exposure⁵.
- f_{sa} Stress in reinforcement at service limit state, ksi
- d_c Concrete cover, in.

Table 1 shows the numerical comparison between different methods. It should be mentioned that the WSDOT proposed equation and the ACI 318-02 equation result in identical bar spacing for moderate exposure. However, for severe exposure WSDOT proposed equation results in more conservative bar spacing than the ACI 318-02 equation.

Table 1: Maximum bar spacing required by different method

	Moderate, Z= 170 kips/in			Severe, Z= 130 kips/in		
	Concrete Cover in.			Concrete Cover in.		
	1	2	3	1	2	3
LRFD	18.00	13.16	5.85	18.00	5.89	2.62
ACI 318-02	12.00	10.00	7.50	12.00	10.00	7.50
WSDOT	12.00	10.00	7.50	9.56	7.65	5.74

In. = 25.4 mm

WSDOT Recommendations for Concrete Deck Slab Detailing

These recommendations are primarily for beam-slab bridges with main reinforcement perpendicular to traffic⁴.

- The minimum slab thickness including 0.5 in. (12 mm) wearing surface shall be 7.5 in. (190 mm) for concrete bridges and 8.0 in. (203 mm) for steel bridges, and 8.5 in. (216 mm) for concrete decks with SIP deck panels.
- Minimum cover over the top layer of reinforcements shall be 2.5 in. (65 mm) including 0.5 in. (12 mm) wearing surface. The minimum cover over the bottom layer reinforcement shall be 1.0 in. (25 mm).
- Maximum bare size of #5 is preferred for all longitudinal and transverse reinforcements in deck slab except maximum bar size of #7 may be used for longitudinal reinforcements at intermediate piers.
- The minimum amount of reinforcement shall be 0.18 in.²/ft (0.38 mm²/m) of steel for top layer and 0.27 in.²/ft (.57 mm²/m) of steel for bottom layer.
- Top and bottom reinforcement in both longitudinal and transverse direction of deck slab shall be staggered to allow better flow of concrete between bars. Reversing lying transverse and longitudinal rebars in the top mat and staggering top and bottom rebars so as not to create significant plane of weakness and using higher percentage of longitudinal steel.

- For bridges with skew angle less than 25 degrees, the primary reinforcement shall be placed parallel to the skew direction.
- For bridges with skew angle exceeding 25 degrees, the primary reinforcement shall be placed perpendicular to the girder direction.
- For bridges with skew angle exceeding 25 degrees, the amount of reinforcement in both primary and secondary direction shall be increased in the end zones.
- The construction joint with roughened surface in the slab at the intermediate pier diaphragm shall be specified instead of construction joint with shear key.
- Both, top and bottom layer reinforcement shall be considered when designing for negative moment at the intermediate piers.
- Using reinforcement ratio of 0.002 for top mat longitudinal steel and using the same for bottom mat and trying to use No. 4 bars
- Reduce splices if possible
- Extend deck transverse steel full width if possible

DURABILITY OF BRIDGE DECK CONCRETE

The durability of concrete exposed to the environment depends primarily on its ability to resist the penetration of water and other harmful solutions. Air-entrained concretes with low permeability are required to resist the penetration of the aggressive compounds into the concrete. Permeability of concrete is defined as concrete resistance to chloride ion penetration⁶. The permeability of concrete depends on numerous factors including water cementitious ratio, degree of consolidation and adequacy of curing. Low-permeability can be accomplished by the addition of pozzolanic additives such as fly ash and micro silica. These admixtures increase the density of concrete resulting in transformation of large pores into fine pores or pore refinement. Fly Ash is the most commonly mineral admixture used in bridge deck slab concrete. Concretes using fly ash generally show less segregation and bleeding than plain concretes. In class 4000D (28D) concrete, the use of fly ash reduces the amount of heat built up in a concrete because of lower heat hydration. Fly ash will generally retard the setting time of concrete. The best ways to achieve a superior resistance to chloride diffusion is to incorporate a combination of fly ash and micro silica into high performance concrete mixes. The 5 to 10 percent addition of micro silica into the concrete containing 25 percent fly ash by weight of cement improves the mixes resistance to chloride diffusion⁸.

Concrete mixes containing fly ash generally require less water than concrete containing only Portland cement. However mixes containing micro silica require more water for a given slump, unless a water reducer or super plasticizer is used⁹.

Mineral admixtures generally improve the workability of concretes of equal slump and strength. Water reducer is usually added to concrete containing micro silica to maintain workability. The use of mineral admixtures generally aids the pumpability of concrete. Concretes containing mineral admixtures generally show less segregation and bleeding than ordinary concretes. Mineral admixtures because of incorporation of finely divided particles will generally improve Finishability of concrete when compared to similar concrete without

mineral admixtures⁶. However, high percentage of mineral admixtures in fresh concrete makes the mix sticky and difficult to finish.

As the water in moist concrete freezes, it produces hydraulic pressures in the capillaries and pores of the cement paste and aggregate. If the pressure exceeds the tensile strength of the paste or aggregate, the cavity will dilate and rupture. Air-entrained concretes with low permeability have been successfully used in bridge decks to resist the penetration of harmful solutions and to provide the necessary durability when exposed to the harsh environmental conditions.

WSDOT HPC Deck Mix-Design

Class 4000D (28D) concrete is typically used for CIP concrete decks in Washington State. Class 4000D (28D) concrete is a high performance air-entrained concrete specially designed for low permeability and high resistance to freeze-thaw in severe environmental exposures. This concrete mix design along with WSDOT extended wet curing with two coats of curing compounds, and continuous wet curing for 14 days results in more durable concrete. The WSDOT wet curing has successfully resulted in a superior performance over the years.

The following recommendations based on the WSDOT deck construction practice can be made as positive steps to improve the durability of bridge deck and to reduce the potential of deck cracking:

- Reduce cement content to 660 lb/yd³ (389 kg/m³). Consider using fly ash.
- When early strength is not an issue, consider using low early strength concrete.
- Use Types I or II cement for bridge deck construction because of its reduced early thermal gradient and shrinkage.
- Limit the water cementitious ratio to 0.4. Make use of water reducers to reduce water content.
- Maximize aggregate content and use largest possible aggregate size. Use crushed stone for coarse aggregate if possible.
- If practical, consider shoring for simply supported girders during construction.
- Use air-entrainment at a rate of 6% to improve the workability of fresh concrete and to increase the freeze-thaw resistance of hardened concrete.
- Specify extended wet curing with two coats of curing compounds and heavy quilted blankets or burlap for 14 days to achieve a superior deck slab concrete.

The concrete mix-design for class 4000D (28D) used for cast-in-place deck slab is shown in Table 2.

Table 2, WSDOT class 4000D (28D) Concrete mix design for deck slab

Class 4000D (28D) Mix Design	
Materials	Quantities
Cement, pcy	660
Fly Ash, pcy	75
Fine Aggregate, pcy	1100
Coarse Aggregate, pcy	1700
Water, pcy	290
Water Cementitious Material Ratio	0.39
Air Entrainment	6%
Water Reducer Type A	Required

$$Pcy = 0.5933 \text{ kg/m}^3$$

The absorption resistance tests have been conducted in accordance with ASTM C-944-95 on 6 inches diameter concrete test cylinders from deck slab¹⁰. The test results indicates a weight loss ranged from 0.11 to 0.13 oz. (3.1 to 3.7 grams) for test cylinders from surface whereas the concrete test cylinders at midpoint cut surface had abrasion weight loss from 0.04 to 0.06 oz. (1.1 to 1.7 grams). Class 4000D (28D) concrete indicates very good absorption resistance.

The rapid determination of chloride permeability of concrete, in accordance with AASHTO T277 was performed on the specimens cast with concrete from deck. The test results for the cylinders made from the concrete used to cast deck fall in moderate chloride ion permeability as defined by FHWA/HPC performance grades. In the permeability test, concrete slab is subjected to the infiltration of sodium Chloride solution for definite time usually 56 days. The test results of class 4000D (28D) concrete are shown in Table 3.

Table 3. Test results of class 4000D (28D) Concrete from HPC Showcase Bridge

	FHWA Requirement	Test Result
Min. 28 days Concrete Compressive Strength, psi (Mpa)	4000 (28)	4800 to 5800 (33 to 40)
Max. Abrasion	4% to 8%	0.03% to 0.06%
Max. Permeability, Coulombs	2000 to 3000	2338 / 2164 / 3434
Max. Water cementitious Ratio	0.35	0.39
Entrained-Air	6%	4.6% to 6.8%

PRECAST STAY-IN-PLACE DECK PANELS

The CIP bridge deck is the preferred option for WSDOT bridge deck slabs. However, speed of construction in some cases requires the use of SIP deck panels for bridge deck construction.

SIP Deck Panel Design, Detailing, and Construction Limitations

WSDOT has recently developed standard details for precast concrete SIP deck panels to be used on prestressed concrete girders. These standard details can be inserted into the bridge plans when the SIP deck panels alternative to CIP concrete deck slabs can be allowed. The WSDOT SIP deck panels are 3.5 in. (90 mm) thick minimum and 8.0 ft (2.44 m) wide maximum. The SIP deck panels are made with high performance concrete with maximum release strength of 7.0 ksi (48 Mpa) and final strength of 8.0 ksi (55 Mpa) with either 3/8 in. (9.1 mm) or 7/16 in. (11.1 mm) diameter uncoated prestressing strands. The standard details for WSDOT SIP deck panels are shown Appendix B.

The design of SIP deck panels follows the AASHTO LRFD Bridge Design Specifications⁵ and the PCI Bridge Design Manual¹². The design philosophy of SIP deck panels is identical to simple span prestressed girders. They are designed for Service Limit State and checked for Strength Limit State. The precast panels support the dead load of deck panels and CIP topping, and the composite SIP deck panel and CIP cross-section resists the live load. The tensile stress at the bottom of the panel is limited to zero per WSDOT design practice⁴.

There have been some negative consequences in the form of deck cracking where SIP deck panels are used. Transverse cracking at the joint between adjacent panels and longitudinal cracks along the length of the girder at the edge of SIP deck panels have been observed¹¹. Longitudinal cracking is probably the most significant problem associated with the use of SIP deck panels because it can result in a reduction in deck stiffness over the girders that could compromise the deck's load-transfer mechanism. In many cases, early users of the system experienced significant longitudinal cracking along the panel edges over the girders. In most cases, these cracks can be attributed to insufficient bearing under the panels for live load. The causes of transverse cracking are shrinkage of the concrete, restraint provided by the panels, and the gap between adjacent panels. These cracks do not affect the structural performance of the composite deck. To minimize the negative consequences of using SIP deck panels for WSDOT bridge decks, the following limitations are considered:

- Simple span precast prestressed I-shaped and trapezoidal Tub bridge girders.
- Positive moment region of continuous spans.
- Continuous spans with longitudinal post-tensioning.
- In bridge widening and staged construction, the SIP deck panels are not allowed in the bay adjacent to the existing structure because of the requirement for CIP concrete closure. The SIP deck panels can be used on the other girders when the widening involves multiple girders.
- SIP deck panel shall not be used on steel girders.

CONCLUSION

1. Air-entrainment at a rate of 6% improves the workability of fresh concrete and increases the freeze-thaw resistance of hardened concrete.
2. The WSDOT extended wet curing with two coats of curing compounds for 14 days results in more durable concrete deck slabs.

3. Resistance of high performance concrete to chloride diffusion improves greatly with the incorporation of fly ash into the concrete mix.
4. The 5 to 10 percent addition of micro silica into the concrete mix containing fly ash improves the mixes resistance to chloride diffusion. Water reducer or super plasticizer shall be specified in mixes containing fly ash and micro silica.
5. In mixes containing fly ash and micro silica, water shall be immediately applied to the concrete surface, otherwise concrete cracking may occur immediately after finishing.
6. The SIP deck panels bridge deck allows accelerated construction, however limitations to the use of this system shall be imposed to minimize some negative deck cracking consequences.

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