High Performance Concrete Overlays for Bridges

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ABSTRACT

Hydraulic cement concrete overlays are usually placed on bridges to reduce the infiltration of water and chloride ions and to improve skid resistance, ride quality, and surface appearance. Some overlays have performed well for more than 30 years while others have cracked and delaminated before the overlay was opened to traffic. High performance concrete overlays have high bond strengths and minimal cracks and should perform well for more than 30 years. Obtaining a high performance concrete overlay requires that appropriate decisions be made with respect to the selection and use of surface preparation equipment and procedures, mixture proportions, and placement and curing procedures. The paper relates construction procedures and equipment and concrete mixtures to bond strength and cracking in overlays.

KEYWORDS

Overlay, Repair, Rehabilitation, Bridge, High Performance Concrete, Construction Techniques and Experiences, Quality Control and Assurance.

INTRODUCTION

Hydraulic Cement Concrete (HCC) overlays are usually placed on bridge decks to reduce the infiltration of water and chloride ions and to improve the skid resistance, ride quality, drainage, and appearance of the surface. The service life of an overlay is usually controlled by a loss of bond to the deck. The service life of a well bonded overlay is usually controlled by the time it takes for it to become saturated with chlorides or to allow chlorides to reach the reinforcement in the deck and cause corrosion induced spalling. It is rare that loss of skid resistance controls the life of a hydraulic cement concrete overlay. It is reasonable to expect that the service life of overlays will increase with an increase in bond strength and with a decrease in permeability and incidence of cracking. High performance concrete overlays should be designed to have high bond strength, low permeability to chloride ion, minimal cracks and good surface characteristics.

Experience has shown that obtaining overlays with high bond strengths is often a problem. Some major overlays have delaminated over large areas before ever being opened to traffic. Others have delaminated prematurely under traffic because of low bond strengths.

In addition, minimizing or eliminating cracks in overlays is often a problem. Low permeability concretes bleed very little and are very prone to plastic shrinkage cracking. Good concrete placement practices and curing practices must be exercised to minimize plastic shrinkage cracks. Autogenous shrinkage and drying shrinkage can also contribute to the incidence and severity of cracking in overlays. Creep and shrinkage in new bridges and reflective cracking in older bridges can also cause cracks in the overlay. It is rare for an overlay to be constructed that does not have some cracks.

On the other hand, obtaining overlays with low permeability concrete is typically not a problem. Use of pozzolans and slag as supplemental cementitious materials and good concreting practices easily provides for overlay concretes with a low permeability.

Finally, obtaining overlays with good skid resistance, ride quality, drainage, and surface appearance is typically not a problem. These factors are easily achieved with good construction practices and the grooves that are saw cut into the hardened concrete surface insure good skid resistance.

OBJECTIVE

The objective of this paper is to describe the materials and construction procedures that can be used to provide high performance concrete overlays.

HIGH BOND STRENGTH

Obtaining overlays with high bond strengths is often a problem because any one of a number of factors can cause low bond strength. Bond strength is a function of the strength of the deck concrete, surface preparation, placement of the overlay concrete, curing of the overlay concrete, and the strength of the overlay concrete.

Given the many factors that control bond strength and the cost to achieve high bond strengths, it may be more practical on many projects to settle for a lower but adequate bond strength. Adequate bond strength is the bond strength necessary for performance and typically insures that the bond strength is greater than the bond stress. Adequate bond strength is difficult if not impossible to generalize and most certainly varies with the design and service of the bridge structure. Knowledge of the causes and levels of bond stress in the overlay enables the designer to make more practical decisions as to the bond strength to specify in a given situation.

BOND STRESS

Bond stress is caused by a combination of factors which may include plastic shrinkage, autogenous shrinkage, drying shrinkage, thermal shrinkage, superstructure creep and shrinkage, live loads, cracks in the overlay and the deck, and overlay thickness.

Shrinkage of the overlay, regardless of the type of shrinkage, stresses the bond interface because the overlay is trying to shorten relative to the deck. The stresses are the highest around the perimeter of the overlay and along cracks in the overlay. Superstructure creep and shrinkage stresses the bond interface because the overlay is trying to restrain the movement of the deck. Live loads stress the bond interface because the overlay maintains composite action with the deck and contributes to its stiffness. Cracks in the deck can be expected to cause reflective cracks in the overlay. Cracks in the overlay stress the bond interface because bond stresses are the highest along cracks that intersect the bond interface. Overlay thickness contributes to stress at the bond interface because bond stresses increase as the thickness of the overlay increases.

ADEQUATE STRENGTH IN THE DECK CONCRETE

Overlay bond strength cannot be higher than the strength of the concrete in the deck. Virginia Department of Transportation (VDOT) Class A4 concrete has a design minimum 28-day compressive strength of 4000 lb/in^2 [1]. Properly prepared A4 concrete surfaces can provide tensile bond strengths of approximately 280 lb/in^2. VDOT Class A4 bridge deck concrete in good condition has adequate strength for good bond in most situations.

PROPER SURFACE PREPARATION

To achieve high bond strengths clean the deck surface by shot blasting and other approved cleaning practices to remove asphalt, oils, dirt, rubber, curing compounds, paint, carbonation, laitance, weak surface mortar, and other detrimental materials that may interfere with the bonding or curing of the overlay. Use the test method prescribed in ACI 503R and VTM-92 to determine the cleaning practice necessary to provide tensile bond strengths greater than or equal to 250 lb/in^2 or a failure area at a depth of 0.25 in. or more into the base concrete over greater than 50 percent of the test area[2, 3]. Tests can be conducted on the prepared surface or on HCC overlay test patches. A bond strength test result is usually based on the average of three individual tests.

Testing The Prepared Surface

In situations where it is not practical to place and cure HCC overlay test patches, the prepared surface can be tested for bond strength. Metal disks or plates can be bonded to the prepared surface and pulled in tension to provide an indication of the tensile strength of the prepared surface (Fig. 1). A rapid setting acrylic adhesive can be used to bond the test discs or plates to the surface. If disks are used the test area is cored prior to bonding the disk. If plates are used, a saw cut is made around the perimeter of the plate after the adhesive has cured to isolate the test area (Fig. 2). The advantage of testing the prepared surface is that results are obtained in approximately one hour and surface preparation activities can be adjusted as needed with negligible delay to the project. The disadvantage is that the bond strength of the HCC overlay is likely to be less than that of the acrylic adhesive used to bond the disks or plates and bond problems that come from the overlay mixture and placement are not identified ahead of time.

HCC Overlay Test Patches

On larger jobs it is practical to construct HCC overlay test patches with one or more overlay mixtures and different surface preparation conditions (Fig. 3). Once the patches have achieved their design compressive strength they can be tested for tensile bond strength (Fig. 4). Surface preparation procedures and overlay mixtures that give the desired results can be specified for the overlay project. Although days or weeks may be required for the overlay concrete to cure sufficiently to get results, any problems associated with the deck concrete, surface preparation and placement and curing of the overlay can be identified ahead of time and appropriate adjustments made prior to placing the overlay. On real large jobs and where time permits, a full bridge deck width test section can be placed and tested with the concrete mixture and procedures that gave good results for the test patch.

Quality Control of the Surface Preparation

Once the surface preparation procedures that provide adequate bond strength is determined from tests on the prepared surfaces, test patches or test sections, the contractor can use these surface preparation procedures on the entire deck surface. However, it is necessary to insure that the same procedures are used over the entire deck surface. This is accomplished by

Fig. 1 Tensile Adhesion Tests on Prepared Surface Using 2-in and 4-in Square Plates

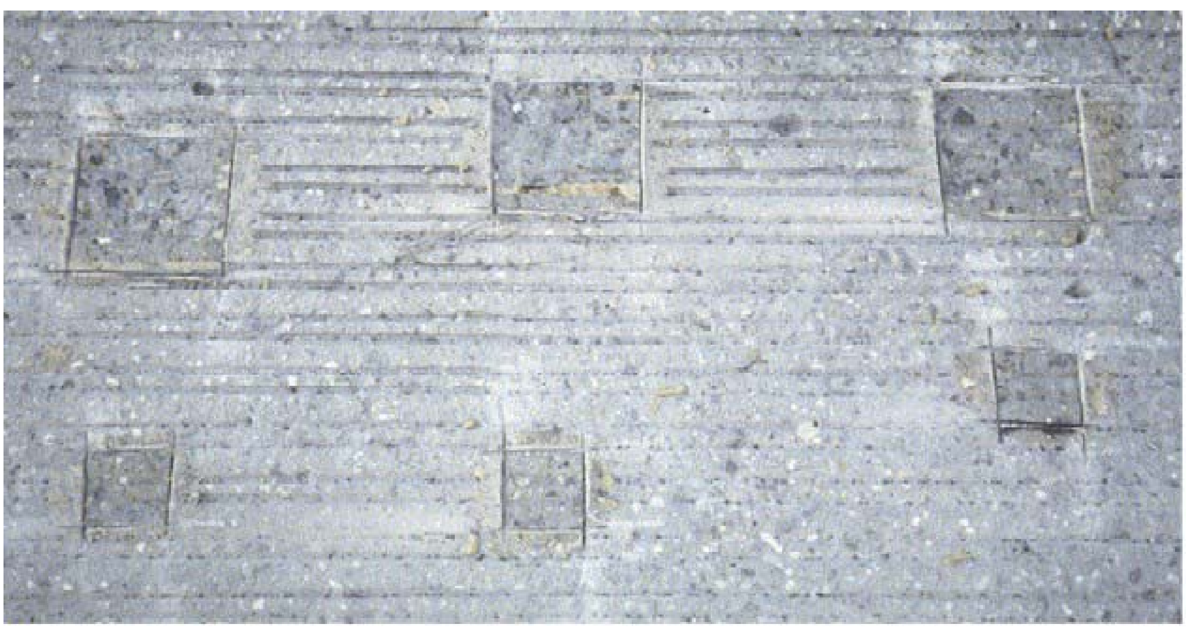

Fig. 2 Failed Surfaces Using 2-in and 4-in Square Plates

Fig. 3 HCC Overlay Test Patches with One or More Overlay Mixtures and One or More Surface Preparation Conditions

Fig. 4 Test Patch Being Tested for Tensile Bond Strength

determining the macrotexture of the surfaces upon which the bond tests were done (macrotexture is usually determined prior to the construction of the test patches or test sections) and monitoring the macrotexture of the prepared deck surface to ensure that the surface macrotexture is the same or heavier than that on which the bond tests were done[4].

Monitoring The Macrotexture Of The Prepared Surface

One of two methods can be used to monitor the macrotexture of the prepared deck surface. Macrotexture depth measurements (ASTM E 965) are made on the prepared surface or the prepared surface is compared to one of the International Concrete Repair Institute (ICRI) molded standards that represent 9 concrete surface profiles [5, 6].

Macrotexture Depth Measurements To Insure Surface Preparation, ASTM E965

The procedure includes placing sand on the prepared surface; spreading sand into a circle and leveling the sand to one grain thickness at high points; measuring the diameter of the circle; using a chart to determine the macrotexture indicated by the diameter of the circle; and using the average of 10 tests as the macrotexture value (Fig 5). The macrotexture measurements are easy to perform and results are quantitative. The surface texture is either acceptable or unacceptable.

ICRI Molded Standards To Insure Surface Preparation

The procedure includes selecting one of the 9 molded standards as the most representative of the macrotexture of the surfaces upon which the bond tests were done and comparing the macrotexture of the selected molded standard to the macrotexture of the prepared deck surface to ensure that the surface macrotexture is the same or heavier than that of the molded standard (Fig. 6).

Use of the molded standards requires less effort than the ASTM E965 procedure but results are qualitative and therefore subject to opinion. However, disputes as to texture that arise using the molded standards can be resolved by using the ASTM E965 procedure. Recent research indicates a strong correlation between laser surface macrotexture measurements and the ASTM E965 procedure [7]. Use of laser measurements to monitor surface preparation is a third option that should be considered.

Concrete Removal By Milling

Adequate surface preparation is usually achieved by cleaning the surface to remove anything that can interfere with the bonding of the overlay. It is not usually necessary to remove a considerable depth of concrete to get adequate bond strengths. Concrete is sometimes removed to improve the grade or surface profile prior to placing the overlay or to allow for a thicker overlay to be placed. On older bridge decks concrete may be deteriorated to the point that major concrete removal is required.

Fig. 5 Macrotexture Depth Measurement to Insure Surface Preparation, ASTM E965

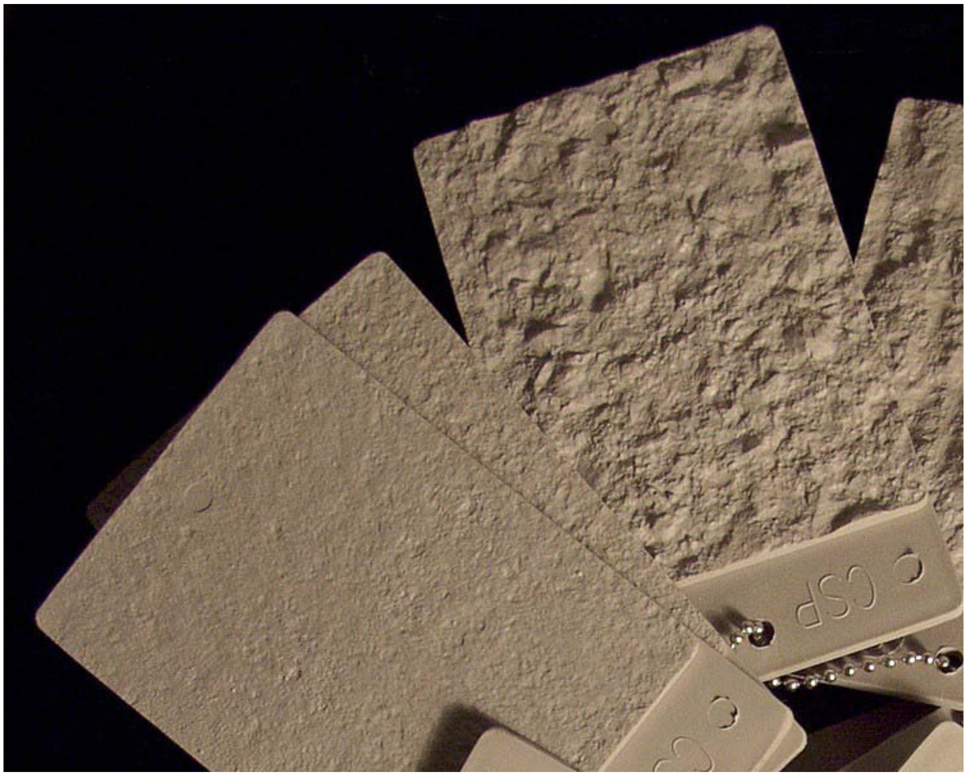

Fig. 6 ICRI Molded Standards To Insure Surface Preparation

Milling is the most economical way to remove concrete down to the level of the reinforcement (Fig. 7). Unfortunately the impact heads on the milling machines typically fracture the surface left in place (Fig. 8). When concrete decks are milled prior to placing an overlay the bond strength of the overlay is usually controlled by the fractured concrete surface (Fig. 9). The milled surface can be shot blasted or hydro blasted to remove some of the damaged concrete. Bond strengths increase as the damaged concrete is removed but it is usually not practical to remove all the damaged concrete. A variety of types and sizes of milling machines are available and research needs to be done to relate the equipment and procedural aspects of milling to damage so that equipment and procedures can be identified or developed that will do minimal damage. Smaller impact heads may cause less fractures.

Fig. 7 Milling is the Most Economical Way to Remove Concrete

Fig. 8 Impact Heads on the Milling Machines Typically Fracture the Surface Left in Place

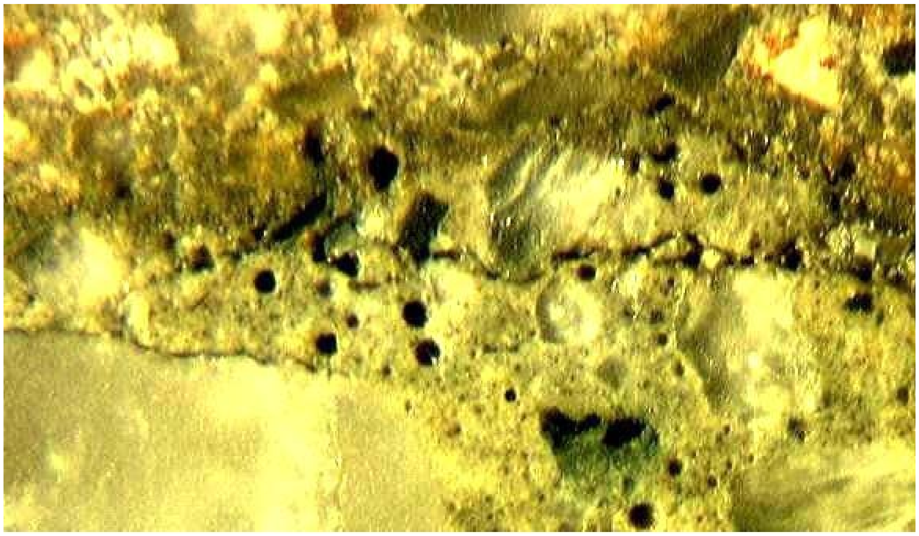

Fig. 9 Fractures in Deck Surface Caused by Impact Heads on the Milling Machine

Surface Preparation By Shot Blasting

Shot blasting is one of the practical ways to prepare concrete surfaces to achieve high bond strengths (Fig. 10). The shot blaster abrades the deck surface with shot and vacuums up the shot and concrete cuttings. The shot does not leave fractures in the prepared concrete surface. The speed and number of passes of the shot blaster that provides for adequate bond strength is determined with bond tests. By monitoring the speed and number of passes of the shot blaster the cleaning operation is controlled. The shot blaster typically removes up to 1/8-in of the surface and larger shot blasters can remove up to ¼-in of the surface.

Fig. 10 Shot Blaster Cleans a 20-year Old Concrete Pavement to Provide an Excellent Surface Upon Which to Place a Concrete Overlay

Surface Preparation By Hydro Blasting

Hydro blasting is another practical way to prepare concrete surfaces to achieve high bond strengths. The hydro blaster abrades the deck surface with water with nozzle pressures of over 20,000 lb/in^2. The cuttings and water are usually collected and vacuumed from the surface. A low-pressure water blast is used to do the final cleaning of the surface prior to placing the concrete overlay. The water does not leave fractures in the prepared concrete surface. The blasted texture that provides for adequate bond strength is determined with bond tests. By monitoring the surface texture the cleaning operation is controlled. The hydro blasting equipment shown in Fig. 11 typically removes up to 1/8-in of the surface. Large self-contained units are used to remove concrete to depths greater than 1/8 inch. The saturated concrete deck that results from the hydro blasting provides for a good cure of the overlay concrete. High bond strengths are obtained with hydro blasted surfaces.

Fig. 11 Hydro Blasting Equipment Removes Approximately 1/8-in of the Deck Surface

Tensile Bond Strength Test Results

Fig. 12 shows the results of tensile bond strength tests conducted on HCC overlays placed on concrete deck and pavement surfaces prepared in three different ways. Tensile bond strengths are the lowest for surfaces that were milled and subsequently shot or grit blasted. Overlays placed on grit blasted, shot blasted and hydro blasted surfaces typically have high bond strengths. The low bond strengths obtained for the overlays placed on the milled surfaces is attributed to the fractures caused by milling. The higher bond strengths were likely obtained by use of milling machines that did minimal damage and follow up abrasive blasting that removed many of the fractures. The lower values obtained for overlays placed on shot or grit blasted surfaces is like due to the strength of the old deck or pavement concretes. Concretes with a compressive strength of only 3000 lb/in^2 will not provide bond strengths much greater than 210 lb/in^2. The higher bond strengths are likely due to placement of the overlays on concrete decks with compressive strengths approaching 7000 lb/in^2.

Good Surface Preparation

A properly prepared surface is clean and free of any materials that may interfere with the bonding or curing of the overlay. Also, the surface is soaked with water and covered with polyethylene within 24 hours of final pass of shot blaster or other final cleaning equipment. Finally, the surface is maintained in a wet and covered condition until the overlay is placed.

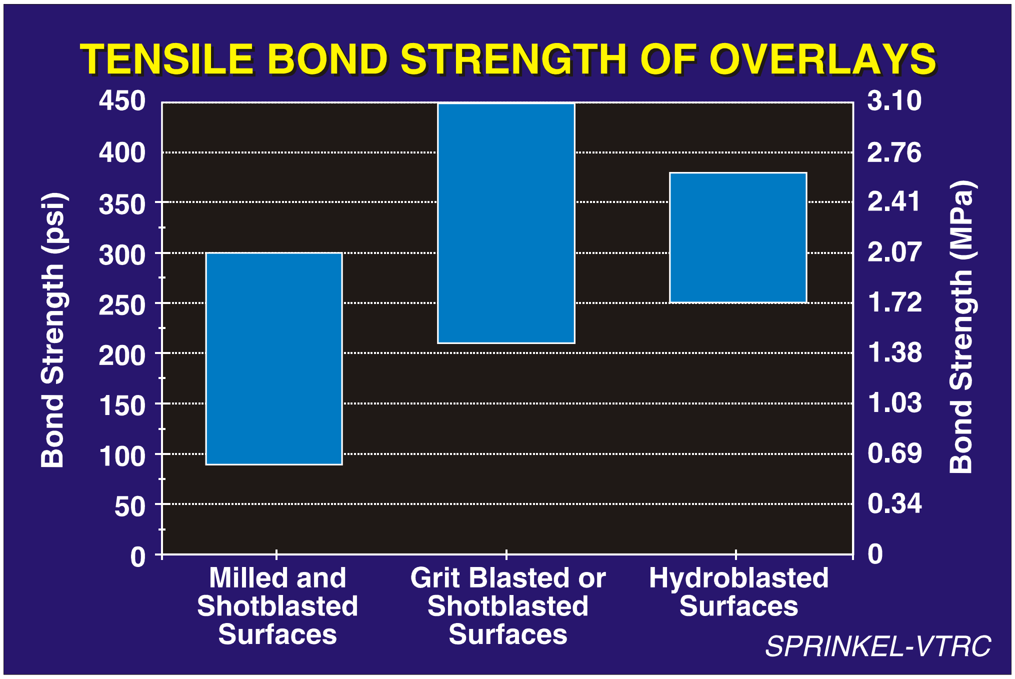

Fig. 12 Results of Tensile Bond Strength Tests Conducted on HCC Overlays Placed on Concrete Deck and Pavement Surfaces Prepared in Three Different Ways

PROPER PLACEMENT OF THE OVERLAY CONCRETE

To obtain high bond strengths good construction practices must be used when placing the overlay concrete. The more important of the practices are those used for the consolidation and curing of the concrete.

Consolidation Of The Overlay Concrete

Good consolidation of the bottom of the overlay is required to achieve good bond to the deck. Since most HCC overlays are 1.25 to 2-in thick a vibrating screed must be used to consolidate the concrete. Fig. 13 shows a vibrating pan attached to the front of a screed consolidating the overlay. The frequency of vibration can be adjusted and care should be taken to ensure that the screed is providing adequate consolidation. The rollers on some screeds and the strike off bar on other screeds consolidate the overlay. The effectiveness of the vibrating screed decreases as the thickness of the overlay increases. Additional internal vibrators should be used to consolidate the overlay when the thickness exceeds 2.5 inches. The vibrating screed failed to properly consolidate the bottom inch of a 3-in thick overlay in Fig. 14. The poor consolidation caused low bond strengths and contributed to the delamination of the overlay within 3 months of its placement.

Fig. 13 The Vibrating Pan Attached to the Front of the Screed Consolidates the Overlay

Fig. 14 The Vibrating Screed Failed to Properly Consolidate the Bottom Inch of a 3-in Thick Overlay

Curing Of The Overlay Concrete

Cracks in the overlay stress the bond interface because bond stresses are the highest along cracks that intersect the bond interface. Plastic shrinkage cracking is caused by water evaporating from the overlay while the concrete is plastic. Cracks often originate because of plastic shrinkage and widen with age because of autogenous and drying shrinkage, temperature change, and bridge loadings.

Timely application of curing materials is necessary to prevent plastic shrinkage cracking in the overlay. Contributing factors include low relative humidity, high concrete temperature, high wind, delay in application of wet burlap, application of dry burlap, delay in application of plastic cover, and failure to secure plastic cover. Special precautions must be followed when evaporation rates exceed 0.1 lb/ft^2/hr. Fig. 15 shows that the wet burlap is placed on the overlay as soon as practical to prevent plastic shrinkage cracking.

Fig. 15 Wet Burlap is Placed on the Overlay as Soon as Practical to Prevent Plastic Shrinkage Cracking

ADEQUATE STRENGTH IN THE OVERLAY CONCRETE

Overlay bond strength cannot be higher than the strength of the concrete in the overlay. VDOT Class A4 post and rail concrete used for thin overlays has a design minimum 28-day compressive strength of 4000 lb/in^2 [1]. A properly placed A4 post and rail concrete can provide tensile bond strengths of approximately 280 lb/in^2. Latex-modified and silica fume concretes typically used in overlays have compressive strengths over 5000 lb/in^2 and are capable of proving bond strengths in excess of 350 lb/in^2. Properly placed VDOT overlay concretes have adequate strength for good bond in most situations.

OVERLAYS WITH LOW PERMEABILITY AND HIGH BOND STRENGTH

The service life of a well bonded overlay is usually controlled by the time it takes for it to become saturated with chlorides or to allow chlorides to reach the reinforcement in the deck and cause corrosion induced spalling. It is reasonable to expect that the service life of overlays will increase with a decrease in permeability and incidence of cracking. High performance concrete overlays should be designed to have low permeability to chloride ion and minimal cracks.

LOW PERMEABILITY OVERLAYS

Obtaining overlays with low permeability concrete is typically not a problem. Use of styrene butadiene latex or pozzolans and slag as supplemental cementitious materials and good concreting practices easily provides for overlay concretes with a low permeability (< 1000 coulombs, AASHTO T277). Low permeability overlays have been constructed with water to cementitious materials ratio < 0.45, 15 % latex admixture by weight of cement, 7 % silica fume, 15 % flyash and 40 % slag[8]. Typical mixture proportions for the most popular low permeability HCC overlays are shown in Table 1.

Table 1 Mixture Proportions For Latex-modified and Silica Fume HCC Overlays

Mixture	Latex-modified	Silica Fume
Cement, lb/yd^3	658	658
Fine Aggregate, lb/yd^3	1552	1269
Coarse Aggregate, lb/yd^3	1187	1516
Water, lb/yd^3	146	282
Air, percent	5	7
Other Admixtures	24.5 gallons latex	46 lb/yd^3 silica fume and high range water reducer

MINIMAL CRACKS

The effect of cracks on overlay bond stress and ways to minimize cracking were discussed earlier. Cracks in overlays allow chlorides and water to bypass the low permeability overlay concrete and travel directly to the reinforcement. Although cracks compromise the protection provided by the overlay the construction of HCC overlays with few cracks is often a problem. Factors that contribute to minimal cracks in overlays include use of optimum low shrinkage mixture proportions, proper surface preparation, proper placement of concrete, proper cure, few cracks in deck to reflect, and negligible creep and shrinkage in bridge superstructure.

Causes Of Cracks In Overlays

Cracks are typically caused by a combination of factors that include plastic shrinkage, autogenous shrinkage, drying shrinkage, thermal shortening, superstructure creep and shrinkage, live loads, reflective cracks in overlay and deck, overlay thickness, and low bond strength. Cracks in an overlay that originated from plastic shrinkage but were not wide enough to see with the unaided eye until the overlay was approximately 3 months old are shown in Fig. 16. Cracks often originate because of plastic shrinkage and widen with age because of autogenous and drying shrinkage, temperature change, and bridge loadings.

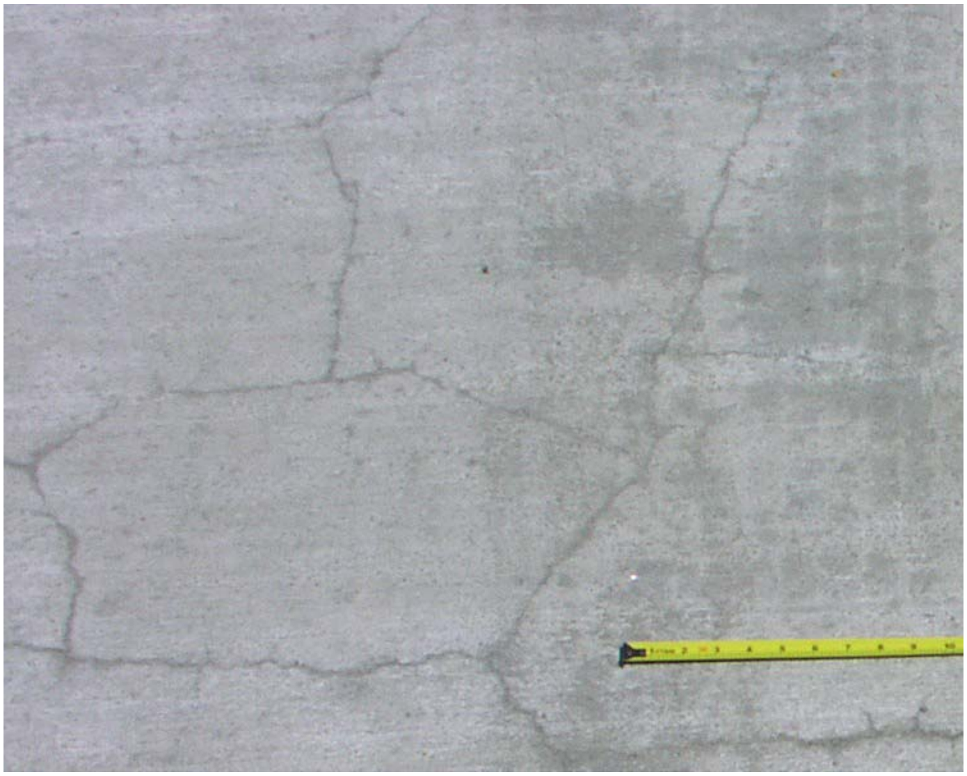

Fig. 16 Shrinkage Cracks in Overlay

Why are Cracks in Overlays a Problem?

A number of questions typically must be addressed when an overlay cracks. What is the significance of the cracks? Do cracks reduce the service level? Do cracks reduce the service life? Should cracks be sealed? How should the cracks be sealed? Should the cracked overlay be replaced? Who is responsible for the cracks?

The protection provided by an overlay affects the service level and the service life of the overlay and the deck. Cracks increase the permeability of the overlay. Cracks increase the rate at which chloride and water penetrate the overlay. Cracks typically reduce the time to corrosion of reinforcement in the deck.

Bond failures affect the service life of the overlay. Cracks increase the shear stress at the bond interface on each side of crack. Cracks increase the probability of the shear stress exceeding the bond strength of the overlay. Cracks increase the probability of delamination of the overlay in vicinity of cracks. Cracks increase the probability that delaminations will spread to other areas.

Determining who is responsible for the cracks is not easily done since the cracks are often caused by a combination of factors. The design of the structure, the construction specification, the surface preparation, the materials, the placement and curing of the overlay and traffic loads can influence the cracking.

Design for Thick Overlays

To minimize cracking the overlay design should be changed as the thickness of the overlay increases. As the thickness increases consider using larger stone, less cement, reinforcement and internal vibrators. On a recent project in Virginia # 57 stone, 6.5 bags per cubic yard of cement and internal vibration were specified for overlays greater than 3 in. thick. Table 2 shows that the mixture proportions for the thicker overlay reduced the 28-day length change (ASTM C157) by 20 percent. On the same project welded wire fabric was specified for overlays greater than 4 in. thick. The welded wire fabric was placed on runners to provide 2-in cover. The 5 ft by 10 ft fabric was positioned immediately following the application of the scrub coat, and lapped at least 6 in. in the 5 ft direction and at least 12 in. in the 6 ft direction.

Table 2. LMC Mixture Proportions

Thickness, inches	1.25	> 3
Cement, lb/yd^3	658	611
Fine Aggregate, lb/yd^3	1552	1451
Coarse Aggregate, lb/yd^3	1187	1451
Water, lb/yd^3	146	144
Air, percent	5	5
Latex, gallons	24.5 gallons latex	22.75
Length change, percent	0.05	0.04

Materials Considerations to Reduce Cracking

Materials considerations to reduce cracking include use of Portland cement with history of less cracking; use of fine and coarse aggregates with good combined gradation and good particle shape and low water demand; substitution of mineral admixtures such as fly ash and slag for some of the Portland cement; use of chemical admixtures that reduce shrinkage; addition of plastic fibers; and use of other cements such as calcium sulfoaluminate and dicalcium silicate, which has been successfully used for very early strength latex-modified concrete overlays[9].

Sealing Cracks

Gravity fill polymers can be broomed into shrinkage cracks to help seal them. Products that have been successfully used include high molecular weight methacrylate, epoxy and urethane. Typically the overlay surface is flooded with the monomer and brooms are used to work the liquid into the cracks. Cracks that are not close enough to justify flooding the surface can be treated individually. While an overlay with sealed cracks cannot be expected to perform as well as an overlay with no cracks, the application of the gravity fill polymer is the only practical way to reduce the penetration of chlorides and water through the cracks.

OVERLAYS WITH GOOD SKID RESISTANCE, RIDE QUALITY, DRAINAGE, AND SURFACE APPEARANCE

Obtaining overlays with good skid resistance, ride quality, drainage, and surface appearance is typically not a problem. These factors are easily achieved with good construction practices. The screed profile and concrete placement procedures control ride quality. The concrete placement and curing procedures control surface appearance. The saw cut grooves ensure good skid resistance. It is rare that loss of skid resistance controls the life of a hydraulic cement concrete overlay.

SUMMARY

The probability that a successful high performance concrete overlay will be constructed increases with the use of low shrinkage concrete mixtures; the use of cements with a record of negligible cracking; the use of good surface preparation procedures; proper consolidation of the overlay; placement of overlays when evaporation rates are low; good curing of the overlay; the construction of 1.25 to 2.5-in thick overlays; and the construction of overlays on bridges that are rigid and subject to low creep.

The probability that a concrete overlay with a short service life will be constructed increases with the use of high shrinkage concrete mixtures; the use of cements with a record of much cracking; the use of milling and poor surface preparation procedures; poor consolidation of the overlay; placement of overlays when evaporation rates are high; inadequate curing of the overlay; the construction of overlays > 3-in thick; and the construction of overlays on bridges that are flexible and subject to high creep.

CONCLUSIONS

Successful high performance concrete overlays require proper design for thickness, reinforcement, and bridge superstructure movements; good surface preparation that provides high bond strength; quality mixture proportions that provide low shrinkage and low permeability; proper placement that includes adequate consolidation low evaporation rates; good curing that minimizes cracking; and contractors capable of delivering the above.

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