The Use of Corrosion Resistant Reinforcement as a Sustainable Technology for Bridge Deck Construction

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ABSTRACT

As part of the Innovative Bridge Research and Construction Program (IBRCP), this study used the full-scale construction project of the Route 123 Bridge over the Occoquan River in Northern Virginia to identify differences in the installation practices and comprehensive placement costs of epoxy-coated reinforcing steel (ECR) and corrosion-resistant reinforcing steel (CRR), specifically an ASTM A1035 steel.

Two bridge decks were constructed separately with a raised median covering the longitudinal joint between them. The southbound and northbound decks were reinforced with ECR and CRR respectively.

Internal VDOT construction records provided construction costs specifically associated with one of the two reinforcement materials. For this project, the cost advantage of ECR at the time of contract award was not preserved after inclusion of unanticipated construction costs directly related to ECR. Specifically, adding the cost of deck sealing operations to the bid cost of ECR produced an in-place cost estimate of $.804/lb compared to $.780/lb for CRR. Inclusion of the indirect costs of the sealing operations, however, more than quadrupled the unit cost of ECR over bid, predominantly because of road user costs to the public. Moreover, it is expected that this structure will experience dramatic traffic growth in the future.

CRR was ultimately cost-competitive with ECR in this project when costs of common VDOT practices related to ECR were included, but CRR potentially possesses superior longevity benefits as a sustainable choice for deck reinforcement, especially since significant traffic growth is expected on this new structure.
INTRODUCTION

This paper is based on a study that documents the installation procedures and costs of two types of deck reinforcement, specifically ECR and CRR (in this case an ASTM A1035 steel rebar), used in a bridge deck in Northern Virginia (1). Completed in late 2007, a six-lane bridge replaced a two-lane structure on State Route 123 over the Occoquan River in the Town of Occoquan in Northern Virginia. The bridge now has two continuously reinforced decks of three lanes each, a 15-ft median, 10-ft shoulders on each side, and a pedestrian walkway adjacent to the southbound shoulder. This new structure was completed in two stages with the southbound deck constructed in Stage I and the northbound deck constructed in Stage II.

The reinforcing steel in a bridge deck often determines the operational life of the structure through corrosion-induced spalling of the concrete which can lead to a diminished rideability of the deck surface and eventually to structural insufficiency. Both ECR and CRR are considered to be more resistant to corrosion than traditional black steel (2). ECR relies on a flexible epoxy coating to impede chloride ions from reaching the black steel, whereas CRR is alloyed to improve the corrosion-resistance of the steel itself. Research indicates that the use of CRR could result in a service life that far exceeds the service life of black steel, with some research indicating as much as 100 years (2). As part of the Innovative Bridge Research and Construction Program (IBRCP), modified bridge plans called for CRR to be installed on a 1:1 basis replacing the ECR originally planned for the northbound deck.

The structure was a good candidate for trial of a CRR with the goal of sustainability in concrete construction in a transportation infrastructure application. CRR is expected to yield benefits to both VDOT and the public through its material longevity in resisting corrosion and its high reclamation and recycling characteristics (3). The use of deicing salts in Northern Virginia makes corrosion of susceptible deck reinforcement likely along with spall-related maintenance operations on the decks. Consequently, expected short-term benefits to VDOT from long-lived concrete reinforcement derive from avoided maintenance expenditures over the 50-year design life of the Rt 123 structure. In the long term, expected VDOT gains from CRR would consist of delayed replacement costs due to prolongation of the structure’s service life.

Public benefits will be gained in two areas. First, more durable concrete reinforcement implies less frequent disruption of traffic for maintenance of the deck surface, with collateral related benefits of less idling of vehicle engines and lower quantities of unproductive emissions over the service life of the structure. When the completed bridge was opened to traffic in 2007, traffic demand was about 32,000 vehicles per day. Projections indicate quadrupled traffic volumes by 2020 with far higher implied social and economic costs for maintenance activities that delay travel. To summarize, public benefits from avoided maintenance operations will grow directly with future traffic volumes on the structure.

A second major public benefit would be the long-term conservation of an array of valuable resources, from materials to energy to time, resulting from the increased service
longevity of the reinforcement. Longer useful life of black steel through alloying (Table 1) will permit greater reductions in the quantities of energy and other resources required to maintain a structure over its service life. Primary steel production can easily consume 20-30 GJ per ton of crude steel output while secondary steel production, using recycled steel, consumes 9-12 GJ per ton of crude steel output (4). Furthermore, work by Johnson et al. indicated that 48 GJ of energy is required and 3.6 tons of CO₂ are generated to produce 1 ton of 304 stainless steel, based on current global operations (5). Even for the best-case scenario, 100% recycling, 24 GJ of energy is required and 1.6 tons of CO₂ are generated to produce 1 ton of 304 stainless steel (5). Therefore, it is clear that steel production requires significant quantities of energy and, for 304 stainless steels, generates more tons of waste CO₂ than tons of steel even when recycling. Increasing the life of a bridge through longer-lasting reinforcement will conserve resources that will otherwise be absorbed in earlier rehabilitation or replacement of the structure.

**TABLE 1 Examples of Currently Available Carbon Steel and Corrosion-Resistant Reinforcement Alloys and Their Corrosion Resistance Based on the Work of Clemeña (6)**

<table>
<thead>
<tr>
<th>Common Name</th>
<th>Steel Type</th>
<th>UNS</th>
<th>Corrosion Resistance Range&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical carbon steel&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Ferritic-pearlitic carbon steel</td>
<td>ASTM A615</td>
<td>1.0</td>
</tr>
<tr>
<td>2101 LDX</td>
<td>Ferritic and austenitic stainless steel</td>
<td>S32101</td>
<td>2.6 - 3.7</td>
</tr>
<tr>
<td>MMFX-2</td>
<td>Austenitic-martensitic alloyed steel</td>
<td>ASTM A1035</td>
<td>4.6 - 6.4</td>
</tr>
<tr>
<td>Clad Bar 316L&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Carbon steel core with an austenitic cladding</td>
<td>---</td>
<td>6.5 - 8.8</td>
</tr>
<tr>
<td>Clad Bar 316L&lt;sup&gt;d&lt;/sup&gt;</td>
<td>Carbon steel core with austenitic cladding</td>
<td>---</td>
<td>&gt;10.4&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td>316 LN</td>
<td>Austenitic stainless steel</td>
<td>S31653</td>
<td>&gt;10.4&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

UNS = Unified Numbering System

<sup>a</sup>Ratio of the Cl⁻ threshold for alloy listed to Cl⁻ threshold for carbon steel

<sup>b</sup>Plus Cu.

<sup>c</sup>Clad bar with damaged cladding

<sup>d</sup>Clad bar with intact cladding

<sup>e</sup>Testing ongoing at time of report; value is probably underestimated here

The Route 123 Bridge project presented yet another opportunity for quantitative comparison of ECR and CRR. In other studies, reinforcement materials with different qualities and lifetime maintenance requirements are usually compared using life cycle cost analysis based on a simplifying assumption that placement costs are nearly identical (7). This project provided sufficient documentation to examine this assumption and ultimately to reverse the actual in-place cost differential between ECR and CRR from the cost differential at bid.

As a side-by-side comparison of ECR and CRR beginning at the time of construction and continuing over the structure’s design life, the Route 123 Bridge project allows a comparison over time in a scenario where virtually all environmental and manmade influences other than the deck reinforcement itself are the same.
PURPOSE AND SCOPE

The purpose of this study was to document a full-scale construction project and to compare final in-place costs of competing deck reinforcing steels which differ primarily in length of useful material life.

The objectives of this study were to record the construction and initial condition of the two decks and to conduct a cost analysis of the ECR and CRR used to reinforce the concrete bridge decks.

The scope of the study was restricted to the Route 123 Bridge.

METHODS

The Route 123 Bridge over the Occoquan River has two continuously reinforced decks with an expansion joint located near Pier 4. The bridge decks were constructed using both plywood deck forms and stay-in-place (SIP) forms. Spans A, B, and C were constructed using plywood deck forms, and the remaining spans were built using SIP forms. A plan view drawing of the bridge is shown in Figure 1.

The decks were placed on haunched prestressed concrete beams that were spliced using post-tensioning. To construct the decks, 572,121 lb of ECR was used in the southbound deck and 674,447 lb of CRR was used in the northbound deck; an additional 4,702 lb of ECR was used for the bolster in the northbound Span A deck.
To accomplish the objectives of this study, three tasks were performed:

1. **Documentation of the construction of the decks.**
   - Conduct site visits during construction.
   - Review the design specifications, construction specifications, and construction reports and photographs after completion of construction.

2. **Performance of an initial condition survey.**
3. Comparison of the final in-place costs of the ECR and CRR used in the decks.

Documentation of Deck Construction

Site visits were made during deck construction to document storage and placement of deck reinforcing bars, tying of deck reinforcing bars, preparation for concrete placement, and concrete placement. The majority of these activities occurred simultaneously; therefore, a single visit captured multiple events. Other events such as concrete placement necessitated a specific visit. Since it was not possible to monitor the construction site on a daily basis, construction diaries and reports were used to augment on-site visits.

Review of Design Specifications, Construction Specifications, and Construction Reports

To document the work required to place the ECR and CRR, design specifications, construction specifications, and construction reports and photographs were reviewed. Key points of interest were special handling requirements, material availability, construction repairs, and any indications of difficulties attributable to the reinforcing steel itself.

The design specifications for this project were the 1996 American Association of State Highway and Transportation Officials (AASHTO) Standard Specifications for Highway Bridges (8); the AASHTO 1997 and 1998 Interim Revisions (9,10); and VDOT Modifications to AASHTO Standard Specifications for Highway Bridges, Sixteenth Edition (1996, Interim 1997 and 1998) (11).

The construction specifications included VDOT’s 1997 Road and Bridge Specifications (12) and VDOT’s 1996 Road and Bridge Standards (13).

The construction reports included site plans, photographs, inspection and daily work reports, including work item reports and materials invoices.

Initial Condition Survey

Visual Survey of Deck Surfaces

The visual survey was performed by visiting the construction site and observing the construction of the decks. Photographs taken by inspectors were also examined. The completed deck was again visually evaluated.
Cost Comparison

To compare final in-place costs of the ECR and CRR used in the bridge, the researchers (1) combined estimated direct costs and unanticipated costs reported in inspectors’ construction records for each material and (2) estimated and added major indirect construction costs based on inspectors’ records to direct costs. To break unit bid costs into labor and material components, labor costs estimated from construction records were subtracted from in-place bid costs, resulting in estimated material costs as a residual for each material.

Inspectors for VDOT and the prime contractor kept daily records of subcontractor labor crews engaged in placing deck reinforcement. Only ironworker reimbursement was considered in labor costs. However, when ironworker crew supervisor or crane operator person-hours were identified in daily records as present specifically for the purpose of deck reinforcement activities, those hours were counted in combined person-hours spent on placing one of the two reinforcement materials.

The cost comparison is reported in terms of both dollar costs and person-hours to show differences between the materials in terms of final expense and the labor required to place them.

Dollar Cost Comparison  The dollar cost comparison estimated direct and indirect costs of activities related to deck reinforcement at the time of construction as comprehensively as project documentation and simple modeling allowed.

Direct costs were defined as estimated labor costs associated with specific deck reinforcement, estimated material costs as a residual of bid costs and labor costs, and unanticipated construction costs for which VDOT paid the prime contractor. Unanticipated construction costs included the expense of extra CRR bolster for the northbound (CRR) deck and the expense of sealing the southbound (ECR) deck discussed below.

Indirect costs were defined as (1) costs effectively transferred to VDOT that were incurred in the course of tasks for which a contractor was paid, and (2) costs effectively transferred to the public—i.e., road user costs (RUCs)—which in this study are limited to those resulting from traffic disruption caused by work zones. All indirect costs (and some direct costs) considered in this report resulted from unanticipated construction costs described below.

Person-Hour Comparison  Subcontractor ironworker hours attributed to placement and tying of deck reinforcing steel in each span were tabulated from construction records and summed across spans in the same deck. In northbound Span A, surplus ECR for added bolster was installed along with the planned CRR by the subcontractor but the labor hours were not identified by reinforcement type. Therefore, person-hours to place this
comparatively small intrusion of ECR into a deck otherwise reinforced with CRR were unavoidably attributed to placement of CRR.

**Unanticipated Costs** Two events directly related to deck steel reinforcement resulted in unanticipated costs to VDOT and the public.

1. Although the plans called for a 1:1 exchange of CRR for ECR in the northbound deck, the bid quantity of CRR was augmented during construction by the reinforcement of unexpected high bolster above the beams in that deck.

2. The concrete in the southbound (ECR) lanes exhibited cracking soon after the concrete was placed in late 2005. VDOT followed established practice in sealing the southbound lanes but did not seal similar cracked concrete in the northbound lanes because research suggests that corrosion-resistant reinforcement such as CRR can be exposed to chlorides and moisture for up to 100 years without corroding (2).

**Road User Costs** Lane closures were required during the southbound (ECR) deck seal operation in November 2006. Resulting RUCs were estimated as a function of the value of a vehicle-hour of travel, the travel delay caused by the specific lane closures given the highway capacity, the segment length, the free flow speed and work zone speed, and vehicle operating costs.

\[
\text{Total road user cost} = \text{Travel time cost} + \text{Vehicle operating cost} \quad \text{[Eq. 1]}
\]

\[
\text{Travel time cost} = \text{total delay} \times [($/\text{Passenger car-hour}) \times \text{Passenger car occupancy rate} \times (% \text{ Passenger cars in traffic stream}) + ($/\text{Truck-hour}) \times (% \text{Trucks in traffic stream})] \quad \text{[Eq. 2]}
\]

\[
\text{Total delay (vehicle-hours)} = \text{Queue delay} + \text{Travel delay} \quad \text{[Eq. 3]}
\]

The estimated total delay to the public from the lane closures is the output of a set of linear and quadratic equations adapted from highway capacity principles by Gillespie (14,15). Queue delay and travel delay were calculated as functions of the queue 1 hr earlier, the current queue, current excess capacity, free flow speed, work zone speed, and segment length of lane closure.

The deck sealing operation occurred during construction of the northbound lanes after the old bridge had undergone demolition. All traffic had been routed to the southbound deck by then, with two lanes each for northbound and southbound traffic including travel in the shoulder lane. Based on recommendations in the *Highway Capacity Manual* for multilane highways (16), it was assumed that the capacity was
1,400 vehicles per lane per hour, that free flow speed for the four undivided lanes was 45 mph, and that work zone speeds fell to 30 mph during periods of lane closures.

Several deficiencies existed in the traffic data used to estimate the cost to the public of the lane closures:

1. **Traffic data for the Route 123 Bridge was lacking for the specific period around bridge construction (2003-2007).** Similar (adjacent) link traffic data was provided by VDOT’s Traffic Engineering Division.

2. **The 2004 adjacent link data were gathered over weekdays, but the deck seal occurred intermittently over a 10-day period spanning two weekends.**

3. **Traffic counts were recorded by number of axles rather than number of vehicles.**

4. **The percentage of trucks in the traffic stream was unavailable in the 2004 adjacent link data.**

5. **Pronounced directional (southbound-SB and northbound-NB) flows are evident in the 2004 adjacent link data for the Route 123 Bridge (Figure 2). If these flows were not representative of the actual bridge traffic at the time of the sealing activity, use of this data would introduce error to estimates of RUCs.**

![FIGURE 2 Directional Traffic Flows for VDOT 2004 Similar Link Data for Route 123 Bridge, 2004](image)

**RESULTS AND DISCUSSION**

**Documentation of Construction**
**Stage I: Construction of Southbound (ECR) Deck**

**Overview**  ECR was used as the reinforcement for the southbound deck. The placement of the concrete for the construction of the Stage I deck began on October 6, 2005, with the placement of the Span A deck concrete. Upon completion of construction, approximately 572,121 lb of ECR reinforcement had been used to construct the southbound deck.

Images collected during construction, shown in Figure 3, demonstrate various possible sources for coating damage during construction. In Figure 3(a), ECR was cut and required repair of the end before the concrete could be placed. In Figure 3(b), grit from the bottom of shoes could abrade the coating. In Figure 3(c), the impact from concrete aggregate as it leaves the hose and contacts the ECR mat could abrade the coating. When the deck was inspected for proper tying of the steel and repair of coating as shown in Figure 3(d), however, the ECR was in an acceptable condition and ready for the concrete placement. No further evaluation of the epoxy coating was performed after placement of the concrete.
FIGURE 3 Potential Sources of Coating Damage During Construction. (a) Cutting of bar ends, (b) Abrasion from bottom of shoes, (c) Impact of concrete as it leaves hose and strikes ECR, and (d) Example of ECR Showing Wire Ties and Bar Surfaces.
Stage II: Construction of Northbound (CRR) Deck

Although the majority of the steel in the northbound deck was CRR, some ECR was inserted as supplemental reinforcement in Span A. Stage II deck construction began with Span A on October 20, 2006. Upon completion of construction, approximately 674,447 lb of CRR had been used to construct the northbound deck, supplemented by 4,702 lb of surplus ECR used for the unanticipated high bolster in Span A.

Initial Condition Survey

At the time of this study, the southbound (ECR) deck appeared to be in good condition. The deck had a grooved surface finish and the epoxy sealant applied to the cracks appeared to be in fair shape. Photographs in Figure 4 (a) shows the deck surface before applying the epoxy sealant in late 2006, and Figure 4(b) shows the sealed deck surface in 2008.
FIGURE 4  Cracks in Concrete on Stage I Southbound (ECR) Deck.  (a) Cracks perpendicular to expansion joint, (b) Close-up of surface after crack repair.
Although the epoxy sealant was observed to seal the cracks shortly after the sealing operation was completed, immediately following a rainstorm on August 28, 2008, water was evident on the underside of both decks (Seung-Kyoung Lee, unpublished data). This indicates that the cracks are providing a pathway for the water on the surface to penetrate through the structure on both decks.

A visual survey of the northbound (CRR) deck indicated the deck is in fairly good condition although the deck did exhibit some cracking. As discussed above, it was decided in this case that an epoxy sealant would not be applied because the deck was constructed using CRR.

Visual analysis of the underside of both decks was also performed. The majority of the cracks observed on the underside of both decks were oriented in the transverse direction. Based on Spans A, B, and C, both southbound and northbound decks each contained an average of 9 transverse cracks per span. Cracks observed in this region are not continuous from one deck to the other since the southbound and northbound decks have a longitudinal joint located between Girders 7 and 8.

Cost Estimation and Comparison

Although the Route 123 Bridge was one of seven parts of the total construction project, as the focal point of the project it comprised 77.1% of the total project cost at bid. Planned bridge deck reinforcement costs formed only 4.13% of the bridge portion cost at bid. Ultimately, the total bridge deck reinforcement including the unanticipated reinforcement of high bolster in the northbound lanes still accounted for only 4.24% of the bridge portion of the project. Yet it is expected that deck reinforcement will eventually be a major determinant of the nearly $25 million project’s service life.

Dollar Costs

Direct Dollar Costs  Unit bid prices for deck reinforcement steel included materials, fabrication and installation costs. Direct dollar costs were composed of the following: (1) the estimated cost of the reinforcing steel placed in the bridge decks, including that for bolster reinforcement; (2) the estimated cost of the ironworker labor to fabricate, handle, transport, and install the reinforcement; and (3) the invoice amount for the southbound deck seal operation, payable to the prime contractor. As discussed previously, although sealing of cracked concrete above ECR is a common VDOT practice, cracked concrete above the CRR was not sealed in this project consistent with research that indicates that CRR will prove over time to be less sensitive than ECR to chlorides and moisture.

At bid, unit prices for planned quantities of ECR and CRR were $0.51/lb and $0.78/lb, respectively. Ironworker hours were valued at the rate of $31.20 and fringe benefits were paid in cash, as reported by the subcontractor (17). Table 3 shows the quantities and costs of deck reinforcement materials as determined from summary
contract line item category reports, contract staffing reports, and estimating procedures used in this study.

Higher labor costs per pound of ECR placed, as found here, are consistent with restrictive handling requirements recommended for the material. The lower material costs of ECR are consistent with a mature manufacturing sector with many competitive producers. CRR, which lacks a vulnerable polymer coating, can be less carefully handled without damage, and material costs can be expected to decline as producers become more numerous and competitive.

**Indirect Dollar Costs**  Indirect dollar costs associated with choice of deck reinforcement consisted of costs of the sealing activities on the southbound deck that were transferred to VDOT or to the public and therefore were not captured in the invoice amount paid to the sealing contractor. All indirect costs were estimated and consisted of the following:

1. *Person-hours of VDOT Inspector Overtime Spent Monitoring Weekend Operations.* This study assumes VDOT inspector overtime is time-and-a-half for pay grades of 3 and 4 for bridge and structure and transportation construction inspectors (T. Mullinax, unpublished data).

2. *Value of Police Presence in Work Zones During Deck Sealing Operations.* The hourly wage rate applied to police hours represents the middle third of the wage distribution determined for police and sheriff’s patrol officers in the Commonwealth of Virginia as of May 2006 (18). The cost range is due to variation in inspectors’ reports of police hours (14.5 to 48 hr).

3. *Travel Delay Cost to Public Caused by Lane Closures Required for Work Zones.* Values in Table 2 are based on the formulas and have the potential shortcomings noted above in the discussion of RUCs.
TABLE 2  Estimated User Costs for Southbound Bridge Lane Closures, Deck Seal, November 2006

<table>
<thead>
<tr>
<th>Date</th>
<th>Lane Configuration</th>
<th>Travel Delay Cost, $</th>
<th>VOC, $\textsuperscript{a}</th>
<th>Low Total RUC, $</th>
<th>High Total RUC, $</th>
</tr>
</thead>
</table>
| 11/03/06  | 2 SBL closed 7 P.M.  \\
|           | 1 NBL redirected to SBL                | 840                  | 58                        | 898              | 1,258            |
| 11/04/06  | 2 SBL closed 24 hr  \\
|           | 1 NBL redirected to SB                 | 295,247              | 24,935                    | 320,182          | 446,943          |
| 11/05/06  | 2 SBL closed until 7 P.M.  \\
|           | 1 NBL redirected to SB until 7 P.M.    | 228,505              | 19,292                    | 247,798          | 345,904          |
| 11/09/06  | 1 SBL closed 9 A.M.-3 P.M.             | 382                  | 19                        | 401              | 565              |
| 11/10/06  | 1 SBL closed 9 A.M.-12 P.M.  \\
|           | 2 NBL closed at 7 P.M.  \\
|           | 1 SBL redirected to NB                 | 908                  | 58                        | 965              | 1,355            |
| 11/11/06  | 2 NBL closed until 7 P.M.  \\
|           | 1 SBL redirected to NB until 7 P.M.    | 228,505              | 19,292                    | 247,798          | 345,904          |
| Total     |                                        | 818,042              | 345,904                   | 1,141,931        |

RUC = road user costs; SBL = southbound lane; NBL = northbound lane; SB = southbound; NB = northbound.

\textsuperscript{a} VOC = vehicle operating costs; all costs rounded.

Lane closure information was available from inspector reports for the period. ADT for this structure in 2006 was estimated by VDOT Traffic Management Systems at 31,582 vehicles (VDOT, unpublished data). On the other hand, numerous assumptions were necessary in modeling traffic disruption for the period of the southbound deck sealing, and they suggest that estimates of RUCs are conjectural at best. Yet the two-lane Route 123 Bridge was considered functionally obsolete when its replacement (six lanes plus shoulders) was built. In fact, after the completed bridge was open to traffic, average annual daily traffic was estimated (using a similar neighboring traffic link) to have risen 51% from 2006 to 2007 (VDOT, Traffic Engineering Division, unpublished data). Considering the growth in traffic volume expected by 2020 cited above, a minimal inference is that RUCs resulting from work zone lane closures would be substantially higher today and in the future than they were prior to the completion of the larger bridge.

The range of the cost increment attributable to lane closure is due to high and low assumptions of the dollar value of a passenger car-hour ($/PC-hr) and a truck-hour ($/TR-hr). The lower cost is based on a Consumer Price Index–adjusted FHWA estimate of $10.34/PC-hr (19) and $34.95/TR-hr (15); the upper cost is based on a more recent Texas Transportation Institute estimate of $15.40/PC-hr and $73.32/TR-hr specifically for Virginia (20). A passenger car occupancy rate of 1.22 was assumed (21).

**Total Dollar Costs**  Table 3 presents the six components of dollar costs that were reported in or estimated from VDOT project management records.

Table 3 lists direct and indirect costs as increments of final unit cost for each reinforcement type. The summation of all direct costs associated with each reinforcement material reversed the differential between their unit bid costs and showed that ECR was about 4% more costly per pound to use than CRR by the end of the construction phase of this project (and nearly 7% more costly in terms of the value of...
ironworker hours alone). However, when *indirect* costs are included, notably travel delays (RUCs) to the public deriving from the southbound deck sealing, which were attributable specifically to the use of ECR, the estimated final cost of ECR rises to the general range of $2.20-$2.80 per pound as compared to $0.78 per pound for CRR.
### TABLE 3 Direct and Indirect Costs of ECE and CRR Deck Reinforcement, by Components

<table>
<thead>
<tr>
<th>Bar</th>
<th>Deck Reinforcement, (lb)</th>
<th>Cost at unit bid prices, $ ($/lb)</th>
<th>Direct Costs, $ ($/lb)</th>
<th>Indirect Costs, $ ($/lb)</th>
<th>Total Unit Costs, ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Deck</td>
<td>Bolster</td>
<td>Labor&lt;sup&gt;a,b&lt;/sup&gt;</td>
<td>Material&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Deck Seal</td>
</tr>
<tr>
<td>ECR</td>
<td>572,121</td>
<td>(4,702)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>293,040 (.51)</td>
<td>54,101 (.094)</td>
<td>238,939 (.414)</td>
</tr>
<tr>
<td>CRR</td>
<td>631,089</td>
<td>43,358&lt;sup&gt;d&lt;/sup&gt;</td>
<td>526,069 (.78)</td>
<td>59,062 (.088)</td>
<td>467,007 (.692)</td>
</tr>
</tbody>
</table>

<sup>a</sup> Ironworkers only

<sup>b</sup> Estimated

<sup>c</sup> Placed in northbound Span A

<sup>d</sup> Excludes quantity of ECR placed in northbound Span A

<sup>e</sup> Includes placement of ECR in northbound Span A

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Person-Hour Costs

Table 4 lists the labor categories and hours directly related to placing reinforcement for the decks as reported in inspectors’ records. The results indicate that almost 12% more CRR than ECR was placed per combined (supervisor, ironworker, and crane operator) person-hour and that ironworkers were nearly 9% more productive in each hour spent placing CRR than in placing ECR. This average ironworker productivity advantage for CRR over ECR slightly exceeds the nearly 7% average ironworker cost advantage implied for CRR in Table 3 but is of the same order of magnitude although determined from different project management records (which is a credit to inspectors’ record-keeping in such a large and complex undertaking).

It should be emphasized that since the person-hours counted toward CRR installation included about 4,700 lb of ECR (nearly 6% of the CRR in Span A by weight) for additional bolster in northbound Span A, the overall labor productivity advantage for CRR was probably understated in these estimates. Further, it is reasonable to expect labor productivity with respect to CRR to rise relative to the estimates in this study as familiarity with the material grows in the future.

Records show that supervisors of ironworker crews were reimbursed for 15% more hours for placement of only about 91% as much ECR by weight as compared to CRR, a result that suggests due diligence among crew supervisors for the special requirements of ECR. Based on the notes in inspectors’ records on occasions when unsatisfactory handling and storage of ECR were cited, the special handling recommendations for ECR were of considerable importance during Stage I construction. The discrepancy in deck-reinforcement-related crane hours is also consistent with the restrictive handling recommendations for ECR. Uncoated corrosion-resistant reinforcing bars such as CRR have few if any requirements that complicate transport by crane.

To summarize the principal person-hour findings, construction management records show that (1) nearly 9% more CRR than ECR was placed in an ironworker hour, and (2) nearly 12% more CRR than ECR was placed in a combined (supervisor, ironworker, and crane operator) person-hour.

<table>
<thead>
<tr>
<th>Type</th>
<th>Quantity Placed, lb</th>
<th>Supervisor or Foreman, person-hr</th>
<th>Ironworker, person-hr</th>
<th>Crane Operator, person-hr</th>
<th>Lb / Ironworker hr (lb/hr)</th>
<th>Lb / total labor-hr (lb/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECR</td>
<td>572,121 (4,702)(^a)</td>
<td>361</td>
<td>1734</td>
<td>158</td>
<td>329.94</td>
<td>253.9</td>
</tr>
<tr>
<td>CRR</td>
<td>631,089 48,060(^b)</td>
<td>313</td>
<td>1893</td>
<td>188</td>
<td>358.77</td>
<td>283.7</td>
</tr>
</tbody>
</table>

\(^a\) Placed in northbound Span A.
\(^b\) Includes ECR placed in northbound Span A for labor-hour calculations.

TABLE 4 Person-hours to Supervise, Transport, and Place Deck Reinforcing Steel
This project provided an opportunity to compare the full documented construction costs associated with two different concrete reinforcement materials for use in bridge decks. Although the balance of research points to some degree of service longevity advantage for CRR over ECR, advantage in simple unit bid cost has been influential in preserving ECR market share. Yet when all costs of installation were considered in this case study, including early mitigation costs in conformance with VDOT common practices, CRR clearly became cost-competitive long before bridge construction was concluded.

The findings in this project justify an additional cost-effective strategy for corrosion control of reinforcing steel in concrete decks: choose from the beginning, if indicated, a higher bid-cost reinforcing material with a longer expected service life and fewer handling (or other) caveats that might prompt contingency construction costs. To be sure, unit bids for materials could decline in anticipation of contingency cost add-ons, but declines sufficient to offset the costs to the public, and to VDOT’s public relations, of disruptive maintenance operations on routes with significant expected growth in travel, as in this project, are probably not feasible since conservatively estimated RUCs quadrupled unit bid costs for ECR in this study.

Looking back on this project, it is clear that the unit bid-costs that were advantageous to ECR over CRR in the planning phase had little usefulness for cost comparison by the time construction was finished. By limiting cost comparisons to early, simple in-place bids and disregarding the “hidden” differentials in construction-stage costs created by routine early maintenance (i.e. during the construction phase) such as were observed in this project, planning phase costs may be misleading indicators of reinforcement lifecycle costs.

The findings summarized here ought to encourage wider use of CRR reinforcement in new structures replacing functionally obsolete structures when contingency construction costs associated with lower-bid-cost materials are possible, and could solidly argue for this choice if such contingency costs are likely. Over time, data collected from this structure (and other IBRC projects like it) will also establish the physical sustainability qualities of ECR relative to CRR and the environments in which they respectively excel, and, consequently, their relative cost-effectiveness over the service lives of the concrete decks they reinforce.

CONCLUSIONS

- Ironworker productivity per hour was about 9% higher and combined supervisor, crane operator, and ironworker productivity per hour was about 12% higher for CRR than for ECR in the Rt 123 Bridge decks. Ironworker costs per pound of ECR exceeded those of CRR by nearly 7% by the end of bridge construction.

- The initial unit bid-cost differential favoring ECR over CRR in the Route 123 Bridge project was reversed when deck sealing costs were added to the installation costs of
ECR. Final in-place direct cost per unit of ECR, including deck sealing, was about 3% higher than for CRR. Such sealing of cracked concrete above ECR is common practice for VDOT; CRR has not acquired this common practice.

- Future corrosion-mitigation deck maintenance activities will impose higher costs on the public and VDOT commensurate with VDOT projections of the growth in traffic volumes on this structure.

- This case study demonstrates that CRR became cost-competitive by the conclusion of deck construction. Future condition surveys will provide documentation over time of the sustainability of CRR through the monitoring of resources associated with maintenance activities on the Route 123 bridge.

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