Sustainability of Continuously Reinforced Concrete Pavement (CRCP) Containing Recycled Aggregate and Epoxy-Coated Reinforcing

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Abstract
A 32-mile (52 km) segment of concrete interstate highway from Madison to Portage, Wisconsin, was rebuilt in 1984 using recycled aggregate and epoxy-coated bars. In 2008-2009, 3½ miles (5.6 km) of the continuously reinforced concrete pavement (CRCP) was demolished due to the construction of a new interchange at State Road 60 and I-90/I-94. This report documents the condition of the CRCP pavement, the demolition, and the materials after 25 years of service. It is believed that this CRCP pavement was the first to use epoxy-coated reinforcement and possibly the first to use recycled concrete aggregate as well. This project demonstrates the reuse of both steel and concrete and the ability for a highly durable system to incorporate sustainable features.

Continuously Reinforced Concrete Pavement

Concrete pavements have been in use for over 100 years and are designed either with or without steel reinforcement. Continuously reinforced concrete pavement (CRCP) incorporates reinforcing steel in sufficient quantities to ensure that any cracking that does occur in the pavement is held tight, reducing crack widths. Typically, the concrete slab in CRCP is 250 or 400 mm (10 – 15 in.) in thickness, placed upon a stable, non-erodible base. Steel is added at approximately 0.6 – 0.85 percent by volume using 16 or 20 mm ($^5/_8$ or ¾ in.) diameter reinforcing bars. Figure 1 shows a typical CRCP reinforcing layout for a highway pavement using epoxy-coated reinforcing bars and Figure 2 shows typical casting operations.

CRCP has been used for over 90 years and is often used in concrete pavements where high traffic loads are present. It was initially used in 1921 in Virginia and in the 1940's experimental sections of pavement were constructed. By the 1970's, 35 states were using this material for high traffic pavements. Currently, some 45,000 km (28,000 miles) of this type of pavement exists in North America.

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Figure 1: Typical reinforcing layout for CRCP

Figure 2: Typical casting of concrete for CRCP

Pavement History

In 1961, a 52 km (32-mile) long 2-lane concrete pavement was constructed on I-90/94 in Dane and Columbia Counties, between Madison and Portage, Wisconsin. This pavement used a combination of welded wire fabric (WWF) and steel dowels. The 1961 design was based on 2,000 trucks with a maximum weight of 30,000 kg (68,000 lb). In 1984 the average daily traffic (ADT) on this pavement was 30,000 with over 9,000 trucks with a maximum truck weight of 36,000 kg (80,000 lb). The projected demand for 2005 was 45,000 vehicles a day with 13,500 trucks with a weight limit of 36,000 kg (80,000 lb) (Strand 1985).

The 1984 replacement CRCP was designed using "AASHTO Interim Guide for the Design of Pavement Structures (AASHTO 1981)" and "Design of Continuously Reinforced Concrete for Highways (CRSI 1981)." Design parameters were 2,450 80 kN (18-kip) equivalent loads per day, concrete working stress of 3.3 MPa (490 psi), and a modulus of sub-grade reaction of 1 MPa (150 psi). The 1984 CRCP longitudinal steel was 20 mm (¾ in.) diameter bars at 165 mm (6.5 in.) spacing and steel area was 0.67 percent by area as shown in

Figures 3 and 4. This is equivalent to approximately 14.8 kg/m^3 (25 lb/yd^2) of longitudinal bars in the concrete.

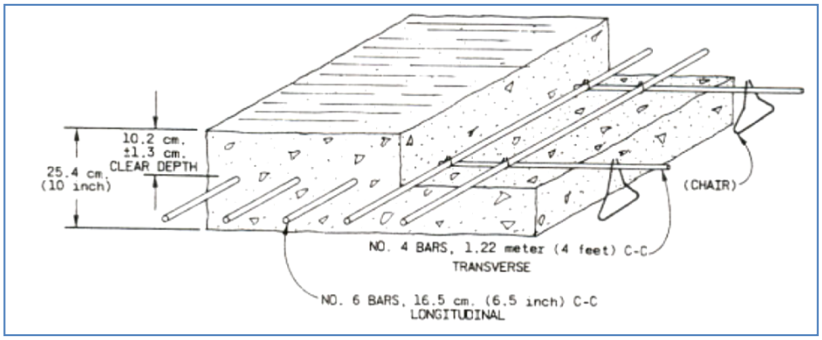

Figure 3: CRCP design

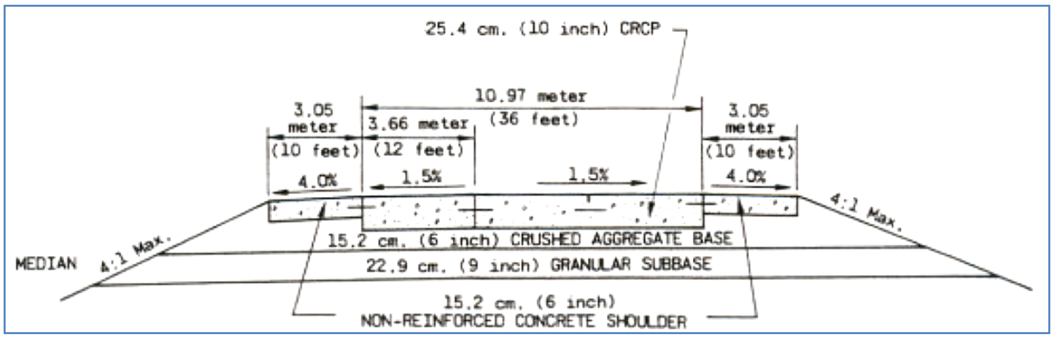

Figure 4: Pavement Cross-section

Removal of the original 1961 CRCP resulted in 310,000 m^3 (405,000 yd^3) of waste concrete and a decision was made to recycle this material into new pavement to reduce the amount of material sent to landfill. All reinforcing material used for the initial pavement was also recycled.

Concern was expressed within the Wisconsin Department of Transportation regarding the high chloride content of the recycled concrete and its effect on corrosion of steel. Tests and calculations made using the typical batch proportions for the 1984 concrete indicated that the chloride in the recycled concrete would be approximately 0.8 to 1.2 kg/m^3 (1½ to 2 lb/yd^3). This amount of chloride was significantly greater than the amount generally assumed for corrosion to occur for uncoated bars or corrosion threshold of 0.71 kg/m^3 (1.2 lb/yd^3).

Epoxy-coated reinforcing steel was initially used in many bridge structures starting in 1973 to reduce damage from chloride induced corrosion. In order to protect the CRCP from chloride induced corrosion damage, epoxy-coated bars were chosen to be used for this project. The 52 km (32-mile) segment was the first CRCP that used epoxy-coated reinforcement and possibly the first to use recycled concrete aggregate as well.

Current Work

In 2008 and 2009, a 5.6 km (3½ mile) portion of this 1984 CRCP was demolished due to the construction of a new interchange at State Road 60 and I-90/I-94**,** and vertical realignment was required. The removal process of this section of 1984 pavement was evaluated along with the condition of the epoxy-coated reinforcement.

Pavement Condition

Data was obtained for the condition of the project prior to demolition. It was reported that no joint crack filling had been conducted on this pavement. Further, no distressed joints or cracks along with no longitudinal joint distress of transverse faulting were noted. This study shows that after 25 years, the CRCP pavement was generally performing well.

Concrete Pavement Replacement

The 1984 concrete pavement was removed by the Zignego Company of Waukesha, Wisconsin**,** using the following sequence:

- Removal of asphaltic overlay (placed as a temporary measure in 2009);
- Breaking of concrete pavement;
- Raking of reinforcing bar;
- Piling of reinforcing bar;
- Loading rebar for recycling;
- Minor clean-up of bars; and
- Grading and compacting of broken concrete for subgrade.

These steps are discussed below.

Milling of Asphaltic Overlay: While the northbound lanes were being rebuilt, the northbound and southbound traffic was reconfigured onto the existing southbound lanes. An overlay was placed on the southbound lanes to mitigate risk of a pavement failure due to the additional load and traffic volume. Removal of the 75 mm (3 in.) asphaltic layer was conducted over a period of three days, using a standard pavement milling machine.

CRCP Breaking: The 1984 CRCP had to be broken to such a degree that the reinforcing steel was free of the concrete. This was achieved utilizing four self-propelled guillotine-type concrete breakers with each machine breaking an 2.4 m (8 foot) width. The hammer weighs 5,400 kg (12,000 lb), has a drop height of up to 2.75 m (108 inches), and drops the weights at a rate of up to 35 cycles per minute. Each drop of the weight broke a section of pavement approximately 150 x 300-mm x 2.4 m (6 to 12 inches by 8 feet) in width. During a six-hour period, the machines moved approximately 800 m (2,600 ft) or at a rate of 130 m/hr (400 ft/hr).

Figure 5: Concrete Breaking

Bar Extraction: Bars were extracted using an excavator mounted with a three tine rake attachment. These machines raked through the broken concrete, extracting bars. Over a period of six hours, the two machines progressed over 1,200 and 400 m (4,000 and 1,300 ft), respectively. This corresponded with a rate of 660 and 34 m/hr (650 and 200 ft/hour), respectively. After the reinforcement was extracted it was collected into piles.

Due to the epoxy coating, the bars were readily separated from the concrete. When uncoated reinforcing bars are used without the coating, the concrete tends to adhere to the bar surface, making both extraction and recycling more difficult.

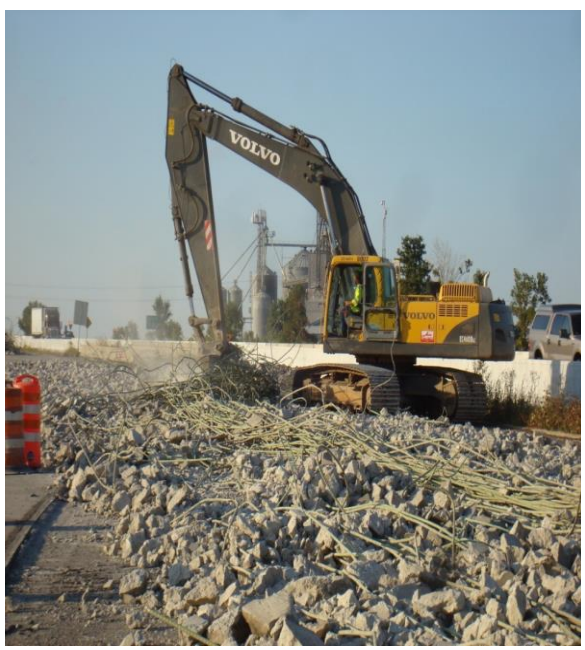

Figure 6: Bar Extraction

Bar Recycling: After extraction, bars were loaded into 36,000 kg (80,000 lb) semi-trucks with an excavator fitted with a grapple attachment. The bars were then taken approximately 160 km

(100 miles) north to a mini-mill for recycling. After the initial loading operations with the grappler, an electro-magnet was attached for final clean-up operations. The final clean-up consisted of the excavator collecting the majority of the remaining bars with only a minor amount picked up by hand.

Subgrade Preparation: Clean-up and Leveling: The subgrade of the new pavement consisted of the broken concrete that was leveled and compacted. Following the bar extraction and clean-up as described above, the concrete rubble was leveled and compacted using a roller.

Figure 7: Compaction of sub-base using roller

Material Evaluation

Fourteen cores were removed from three areas of the southbound pavement. Cores were removed from both cracked and uncracked concrete.

One core without steel was retained by WisDOT for compression strength testing. Two core samples were submitted for petrographic evaluation and an additional six cores were submitted for chloride analyses. Steel samples were also analyzed for chemistry and tensile properties.

Bar Condition: The condition of the epoxy-coated reinforcing bars was evaluated in the six submitted cores. Other than a bar specimen from a core at the construction joint, all the epoxy-coated bar specimens were rated as having minor areas of rust and local coating cracks or better. This corrosion did not cause any concrete deterioration. Corrosion on the specimen from the longitudinal joint was rated as ~~a~~ severe.

Reinforcing Bar Properties: Based on the bar markings**,** it was determined that the reinforcing bar had a yield strength of 420 MPa (60,000 psi). Two reinforcing bar specimens were tested in tension and their chemistry assessed. The yield strengths of specimens were 440 and 503 MPa (63,700 psi and 73,000 psi). The tensile strength of the specimens was 744 and 802 MPa (108,000 psi and 116,400 psi). Elongation of the specimens was 24% and 22%. The bars met applicable ASTM A615 specifications, based on the tension tests and chemical analysis.

Coating Adhesion: In many instances epoxy adhesion to the steel surface was poor as shown in Figure 8. Samples of bar were evaluated to determine the cause of this poor coating adhesion. From analysis of two submitted samples, it was reported that improper surface preparation had occurred prior to the coating being applied. There was little or no anchor pattern on the steel and was likely the main contributing factor to coating delamination. Based on a visual inspection of the extracted bars, no correlation between bars with poorly bonded coating to those with oxides could be determined. In 1991, CRSI introduced an Epoxy Coating Plant Certification Program that requires plants to monitor steel surface properties prior to coating and coating performance after coating. This program has significantly reduced the incidence of poor coating adhesion.

Figure 8: Poor coating adhesion due to inadequate surface preparation of the steel

Petrographic Analyses: An in-depth petrographic examination was conducted on two cores in accordance with ASTM C 856. The visual condition of the epoxy-coated bars and determination of the percentage of recycled concrete aggregate in one of the cores were also conducted.

The depth of carbonation was limited to the top of the cores and was negligible. Ettringite deposits were present in the voids of the concrete of both cores. Air entrainment was estimated on the order of 6 to 9% and the w/c ratio was estimated to be 0.40 to 0.50. One of the cores was examined using image analysis and determined to contain 34% recycled concrete. No chemical damage or salt scaling was observed on the concrete specimens.

Chloride Analysis: Six cores were evaluated for acid-soluble chloride according to ASTM C1152. Three of the cores were from cracked locations (Cores 1, 8 and 11) and three were from non-cracked locations (Cores 2, 6 and 10). The resulting chloride contents are shown in Figure 9.

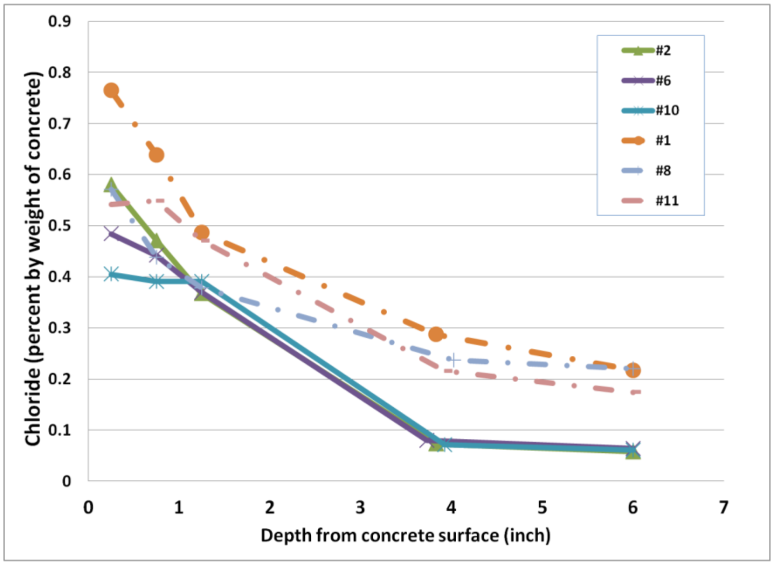

Figure 9: Chloride data from cracked and uncracked cores

The background chloride level for the uncracked cores was approximately 0.06 percent by weight of sample, which was almost twice that of the commonly assumed corrosion threshold of 0.035 percent. Thus, at the time of construction the bars were exposed to sufficient chlorides to initiate corrosion of uncoated black bars. The source of the chlorides was the recycled concrete as aggregates in the mixture.

Fick's law of diffusion is commonly used to evaluate chloride values and to determine surface chloride concentrations and diffusion coefficients. Using Fick's law of diffusion, the measured chloride values and the concrete age (25 years), an estimate of surface chloride (C_o) and diffusion coefficient (D_{eff}) were obtained.

The surface chloride values showed very little deviation for the three uncracked cores, with chloride ranging from 0.46 to 0.58 percent by weight of concrete. The uncracked cores had an apparent diffusion coefficient from 1.56 x 10^{-12} m^2/yr (2.41 x 10^{-9} in^2/yd). As expected, the cracked cores exhibited considerably higher chloride contents, both at the bar level and at a depth of six inches from the top of the concrete cores. Considerable chloride was found throughout the uncracked cores, ranging from 0.058 to 0.071 percent by weight of concrete at the 150 mm (six-inch) level.

Transverse "Tie" Bars: Transverse "tie" bars are used to minimize movement in the longitudinal construction joints between the lanes of concrete pavement or between the lanes and the shoulder. These bars are frequently placed after the slip former passes and while the concrete is still "green" and are bent in order to be clear of the slip former trailing crawler tracks. As a project engineer from WisDOT indicated, these bars are then straightened prior to the placement of the adjoining concrete lane / shoulder without any further epoxy patch coating.

Some of the tie bars where in poor condition with localized corrosion at the joint location (Figure 10). Upon further inspection**,** no epoxy-coating patching was evident and the coating would have most certainly been damaged during construction. It is generally recommended that epoxy-coated tie bars are not bent in the field.

Figure 10: severely corroded bars at longitudinal joint

Concrete Strength: A core removed from the concrete was evaluated for compressive strength by WisDOT. This single core exhibited a compressive strength of 48.2 MPa (7,000 psi).

Concrete Cover over Reinforcing: Based upon the six cores analyzed for chloride, the concrete cover was 98 mm (3.875 in.) with a range from 94.6 to 102.2 mm (3.725 to 4.025 in.).

Sustainable Features

As discussed above, during the past 25 years, this project has utilized sustainable features. These features include:

- Use of 310,000 m^3 (405,000 yd^3) crushed concrete as aggregate in the 1984 pavement
- Recycling of steel mesh and dowels in the 1984 pavement
- Use of 52,800 m^2 (14,600 yd^3) of crushed concrete as sub-base in the 2009 project
- Recycling of 600 tonne (660 ton) of steel reinforcement in the 2009 project

Without the use of epoxy-coated reinforcing steel in the 1984 CRCP, corrosion of the steel would have occurred, reducing the life expectancy of the pavement. In 2009, further recycling resulted in a substantial quantity of reinforcing steel being recycled and the 25-year-old concrete pavement being used as a sub-base for the new concrete pavement.

Summary and Conclusions

A 52 km (32-mile) segment of interstate highway from Madison to Portage**,** Wisconsin**,** was originally opened in October of 1961 and later rebuilt with an additional lane in each direction in 1984 using recycled aggregate and epoxy-coated bars. It is believed that this pavement is the first CRCP that used epoxy-coated reinforcement and possibly the first to use recycled concrete aggregate as well.

Removal of the original 1961 CRCP resulted in 310,000 m^3 (405,000 yd^3) of waste concrete, which was then used as aggregate within the 1984 pavement. Concern was expressed regarding the chloride content of the recycled aggregate and its effect on corrosion, as a result of the experience the agency had with uncoated steel reinforcement. For this reason, epoxy-coated bars were chosen to be used.

In 2008 and 2009, a 5.6 km (3½ mile) portion of this 1984 CRCP was being demolished due to the construction of a new interchange at State Road 60 and I-90/I-94 and the required realignment.

Prior to demolition the pavement condition was assessed by WisDOT. No joint crack filling had been conducted on this pavement and further, no distressed joints or cracks were noted. No longitudinal joint distress of transverse faulting was documented, or cracking noted.

Pavement recycling and bar extraction proceeded quickly and was aided by the use of epoxy-coated bars which were readily removed from the concrete. During the demolition, cores were removed from both cracked and uncracked concrete and petrographic and chloride analyses conducted. Based upon the work conducted in 2009 on the 25-year-old pavement, it was concluded:

1. The 1984 CRCP condition was regarded as good to excellent.
2. No observable CRCP deterioration (splitting or spalls) was observed due to epoxy-coated steel reinforcement.
3. The 1984 CRCP used approximately 35 percent of crushed and recycled concrete.
4. High chloride values in the 1984 CRCP were present due to the use of chloride contaminated recycled concrete.
5. Corrosion of the reinforcing steel in the CRCP was minimized using epoxy-coated bars.
6. Use of epoxy-coated bars facilitated bar removal from the 1984 CRCP and made extraction of bars easier than if uncoated bars had been used.
7. Epoxy-coated steel reinforcing bars had been exposed to high levels of chlorides for more than 25 years with limited corrosion products visible.
8. A significant portion of the epoxy-coated bars had poor coating adhesion due to poor reinforcing steel surface preparation.
9. Minor corrosion products of epoxy-coated bar tend to occur at concrete cracks.
10. Transverse "tie" bars in the 1984 CRCP exhibit significant localized corrosion at the longitudinal shoulder joint due to bending during construction and the location of the construction joint between pours. Field bending of epoxy-coated tie bars is not recommended.
11. Visible corrosion products on longitudinal bars were generally superficial and tended to occur at the location of transverse cracks.

Acknowledgements
The author wishes to acknowledge assistance from Scott Humphries and Ted Farragut from the Concrete Reinforcing Steel Institute, Kevin McMullen from the Wisconsin Concrete Pavement Association, Jim Perry and Steve Krebs from the Wisconsin Department of Transportation and Jim Riemenschneider from 3M in preparation of this paper.

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