using platinized niobium anode wire without installing a conductive layer on the surface of the structure. The experiment with the model deck will be continued to optimize design criteria for the anode spacing and current densities required to protect reinforcing steel in chloride-contaminated concrete.

A cathodic protection system operating in the presence of chloride ions performs two beneficial functions:

1. It prevents the corrosion of the reinforcing steel by maintaining a surplus of electrons on the steel surface, thus preventing the migration of the iron ions into solution.
2. The chloride ion is attracted to the anode, and this reduces the chloride concentration in the vicinity of the reinforcing steel (cathode) (see Figure 7), thus increasing the pH of the cathode.

The cost of protecting a reinforced-concrete structure by using a conductive paving layer is about $\$30/m^2$, whereas platinized niobium wire anodes installed in saw slots would cost about $\$12/m^2$. It is anticipated that this cost will decrease further as design parameters are refined and installation methods perfected.

This new concept of cathodic protection was applied to a new 803-m^2 deck in the fall of 1979. In that application, 600 m of 0.8-mm platinized nobium anode wire was installed in 10x13-mm saw slots cut in the deck at 1-m intervals. The wire anode was grouted in the slot and cathodic protection applied. After approximately 350 h at a current density of 18.5 mA/m^2, a potential of -770 mV to $Cu/CuSO_4$ was achieved midway between the anodes, and the potential-controlled rectifier output was automatically reduced to approximately 9.0 mA/m^2, the current required to maintain -770 mV after polarization was achieved. During January 1980, the circuit resistance varied between 0.9 and 1.2 Ω between the unfrozen and the frozen condition.

The deck has been given numerous applications of deicing salt and has undergone many freeze-thaw cycles without loss of protection or damage to the anode grout material.

The system is a viable method of cathodically protecting reinforcing steel in concrete in both the vertical and horizontal position without conductive overlays. It lends itself to the protection of lightweight decks, parking garages, and support structures for bridges and docks.

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Cathodic Protection for Continuously Reinforced Concrete Pavement in Minnesota

R. G. TRACY

The corrosion of steel in concrete can be suppressed by the use of cathodic protection, which involves applying a low-voltage direct current to the steel from a remote anode so that corrosion is transferred to the remote anode and the steel becomes a protected cathode. The results of the application of cathodic protection to continuously reinforced concrete pavement (CRCP) in Minnesota are presented and discussed. Several segments of CRCP are undergoing rapid, premature deterioration that is directly related to corrosion of the embedded mesh reinforcement. Pavement testing revealed that salt concentration at the reinforcement is high, and copper/copper sulfate half-cell potentials indicated widespread corrosion activity. Essential elements from pipeline and bridge-deck applications of cathodic protection were integrated, and a prototype system was installed along a 1000-ft section of CRCP. Two methods of power (current) application were examined: (a) burying anodes in a trench filled with a conductive aggregate and (b) burying anodes in individual postholes along the pavement shoulder. Both installations were connected to a central rectifier controller, which was interfaced with an automatic device for monitoring and recording the data. An initial data evaluation, expected by late summer of 1980, will provide information on the performance and effectiveness of the system.

During the past three years, an increasing number of continuously reinforced concrete pavements in Minnesota have been exhibiting a spalling type of deterioration. The frequency and extent of this deterioration have progressed from isolated and random in 1975 to widespread and concentrated on certain pavement designs in 1978. The pavements that show severe and moderate delamination and spalling are of the two-course construction type designed with a steel-to-concrete ratio of 0.6 percent. The reinforcement used was deformed wire mesh with specified clear cover of 2-4 in. In most cases, steel was at the minimum cover of 2 in.

BACKGROUND

Construction of continuously reinforced concrete pavement (CRCP) in Minnesota began in 1963 with the placement of a rather extensive test section on I-35W near Faribault. It was hoped that this trial would provide some specifics on construction techniques, design adequacy, and short-term performance. Variable ratios of steel to concrete--0.5, 0.6, and 0.7 percent--were used, and different combinations of base-course thicknesses and end-anchor types were tried. The study was completed in 1968, and a project report (1) was prepared.

Study results indicated that a minimum steel-to-concrete ratio of 0.6 percent was needed for proper pavement performance. It was also apparent that smooth wire mesh is not acceptable as reinforcement for CRCP. Pavement design was modified to reflect the study findings, and construction of CRCP as standard practice began in 1967.

Three CRCP sections were completed in the Minneapolis-St. Paul (Twin Cities) area during 1967. Other sections were designed and built at various locations in Minnesota between 1967 and 1970. By 1970, however, CRCP was dropped as a pavement design, partly because of the continued evaluation of the original test section at Faribault and evidence of rupture (tension failure) on some of the first sections in the Twin Cities metropolitan area. A 1970 report that documents the field performance of CRCP reveals evidence of corrosion at transverse cracks (2).

Isolated cases of shallow potholing began to show up on the oldest sections of CRCP early in 1974. I-94 from Cedar Avenue to Riverside Avenue, and again from the east end of the Dartmouth Bridge to MN-280, exhibited what appeared to be random and minor spalling. A second area of this type of deterioration also appeared on several miles of I-35W near Arden Hills. Initial spalling on I-94 appeared to be somewhat concentrated immediately beneath overpasses. Spalling of the I-35W section, however, was random. A distinguishing feature common to both sections was that spalling generally occurred in the wheel-path zone. The spalling condition continued to grow more severe, and during 1975 open holes frequently had to be patched.

Maintenance patching of the two sections mentioned above had reached a significant level by 1976. On the 4000-ft section of I-94 between Cedar and Riverside Avenues, a five-member maintenance crew spent nearly one month chipping and patching holes. Similar operations were occurring at the I-35W location. Spalls were now also exposing deformed wire mesh on ramps near the deteriorating pavement sections. Other sections of pavement not previously reported as showing surface potholing also required patching in 1976.

In August 1976, research personnel from the central office of the Minnesota Department of Transportation (DOT), while investigating bridge-deck repair and protection systems, conducted a brief survey of the deteriorating I-94 CRCP section. Tests performed during this survey included cover measurement, delamination detection, and half-cell potentials for corrosion detection. A visual survey was also performed. Strong evidence was found to support the theory that (chloride) corrosion-induced spalling was now occurring on CRCP. A discussion with the maintenance foreman and crew revealed that all patched spalls extended to the welded-wire-fabric reinforcement. Massive pack rust was evident on both the bars and the underside of concrete removed from delaminated areas.

Results from the survey of half-cell potentials indicated that all readings were at or well into the corrosion range of greater than 0.35 V to a copper/copper sulfate (Cu/$CuSO_4$) half-cell (CSE). The delamination survey revealed that 13 percent of the pavement tested was delaminated. Further discussion with the foreman provided additional information. His estimate was that, for each open spall patched, three or four hollow (delaminated) areas were being left untreated. At the time of the survey (August 1976), almost all of the noticeable spalling type of deteriorations had been confined to the oldest sections of CRCP in the metropolitan area.

It is interesting to note that two-course construction was used on the distressed pavement sections. The continuous-reinforcement steel used was a welded wire mesh fabric that consisted of deformed 0.45-in-diameter wires on 3-in centers. The ratio of steel to concrete was 0.6 percent for both the I-94 and I-35W sections that showed distress. Specified cover for the bar mats was 2-4 in; however, most of the steel was closer to the minimum cover.

Joint survey efforts by district and central office personnel were initiated to collect information, first for the two rapidly deteriorating sections of pavement (I-94 and I-35W) and then, on a much broader scope, for all sections of CRCP in Minnesota. The results of the survey of the Twin Cities metropolitan area showed the following:

1. Three sections (3.75 miles) of Interstate are in a rapidly deteriorating, or critical, condition. Delaminated areas and open spalls constitute 20-30 percent of the roadway area.
2. Classified as being in fair condition is 13.75 miles of Interstate that is showing some evidence of the beginnings of the spall type of deterioration.
3. On 39.10 miles of Interstate classified as good, there is currently no evidence of spalling.

The first assessment of this situation, based on miles assigned to each category, may lead one to believe that problem pavement sections are only a small fraction of the total pavement in place and so as such are not indicative of CRCP performance. Although this may be true, there are other factors that deserve consideration.

Two of the three sections currently classified as critical are among the highest-volume Interstate sections in Minnesota, carrying more than 100 000 vehicles/day. The third section carries 25 000 vehicles/day. The six sections (13.75 miles) classified as fair are also broken down according to daily traffic volumes: One carries more than 110 000 vehicles, four carry from 55 000 to 80 000 vehicles, and one carries 13 000 vehicles. The remaining six sections, those classified as good, carry from 11 000 to 32 000 vehicles/day.

There is reason to believe that deterioration of the type encountered will continue on the critical sections of pavement. It is highly probable that, in time, it will advance into those sections currently classified as fair. A case in point is a section of I-94 between Snelling Avenue and MN-280 in St. Paul. During 1975 and 1976, there were perhaps 10-15 spalls on the entire 2-mile, six-lane section of CRCP. By the summer of 1977, the number of spalls had exceeded 100. In 1978, spalls were occurring with a frequency that made counting and patching futile.

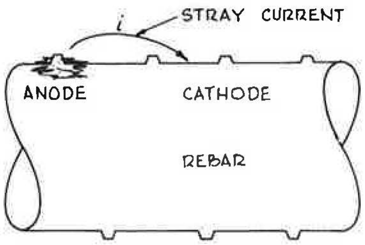
EXPERIMENTAL SYSTEM

In late 1978 and early 1979, an experimental cathodic protection system was installed along a 1000-ft section of two-lane CRCP near Arden Hills, Minnesota. Two methods of anode installation were tried to determine which would be the easiest and most effective.

Design Concept

One of the few systems available today for stopping stray-current corrosion of steel is cathodic protection. It has been successfully implemented to

Figure 1. Electrical aspect of the corrosion process.



protect buried pipelines for more than 30 years (3). During the past 4 years, it has proved an effective means of arresting the corrosion of rebars in concrete bridge decks (4,5).

Corrosion of steel is an electrical as well as a chemical process. In its basic form, it is caused by stray current discharging from one area of the steel (the anode) and returning to another (the cathode) (see Figure 1). Corrosion, or oxidation, occurs at the anode. As corrosion continues, its byproduct, pack rust, accumulates at the anode while no harmful side effect is experienced at the current-receiving cathode. When all steel is placed in a current-receiving mode, discharge is stopped and corrosion ceases.

The concept of integrating the essential components of bridge-deck and pipeline cathodic systems to protect rapidly spalling pavements in Minnesota is being examined in a laboratory and field test program. There would be several advantages in using such a system on pavements if it proves to be effective at controlling corrosion:

1. All essential component parts would be located off the traveled roadway.
2. The cost of installing and operating such a system would be small in relation to the combined costs of maintenance or pavement replacement, to say nothing of the social impact caused by extensive traffic delay and disruption.
3. The effectiveness of the cathodic system can be determined over a short period of time.

Buried pipelines are protected by placing anodes in a conductive backfill material, usually near the in-place pipeline (3). A ground connection is attached to the pipeline and, when the system is energized, an electrical potential field is set up between the pipe and the anode. Current flows through the field to the pipe, which is the cathode of the system. When the pipe is in a current-receiving mode, stray current discharge cannot occur and corrosion is stopped (see Figure 2).

Reinforcing bars in concrete bridge decks have also been protected by using impressed current. This type of protection requires a somewhat more specialized system. To conduct the current, a coke-modified asphalt overlay and special anodes are placed on the deck surface. The special asphalt creates the electrical field needed to distribute current to protect the rebars (see Figure 3).

There is a possibility that cathodic protection of the steel in CRCP can be provided by integrating essential elements from the pipeline and bridge-deck systems (see Figure 4). The concept involves burying anodes in a trench or in postholes backfilled with conductive coke aggregate. The trench or postholes could be located along either the median or the right shoulder on a four-lane system and would run parallel to the pavement. A ground connection would be attached to the continuous reinforcing at several locations to complete the circuit. When energized, the anodes would create a potential field between themselves and the steel within the CRCP. This field would conduct current to the rebars in a way similar to that in which the soil conducts current to the pipeline. It is believed that corrosion can be stopped when the pavement-reinforcing steel is in a current-receiving mode and that the forces necessary to generate the pressure that causes cracks and, eventually, potholes in the pavement would then be eliminated.

Design Criteria

Two electrical parameters are commonly used in designing a cathodic system: half-cell potentials and current density.

Potential

Perhaps the oldest and most frequently referenced criterion is the 0.85 V CSE polarized potential criterion used by the pipeline industry (3) (voltages in the negative according to the standard method). This criterion is based on the recognition that the most anodic potential of steel in soil is on the order of 0.80 V CSE. Protecting the structure requires establishing a slightly higher cathodic potential and having some allowance for a safety factor--thus, the 0.85 V CSE value. For protecting reinforced-concrete pipe and reinforced-concrete bridge decks, the additional consideration of preventing hydrogen over voltage and possible debonding of the steel from the concrete leads to imposing an upper limit of 1.10 V CSE on the acceptable polarized potential (6).

More recent research has shown that, although 0.85 V CSE may be realistic as a criterion for steel in soil, it is not necessarily accurate for steel in a concrete environment (7). Bridge-deck testing with the $Cu/CuSO_4$ half-cell shows that measured potentials in excess of 600 mV are rather uncommon (8). Work by Hausmann also supports the position that lower polarized potentials may protect steel in concrete (7).

Other potential criteria suggested for cathodic protection relate to the shift in potentials during the polarization process rather than a fixed range of 0.85-1.10 V. The National Association of Corrosion Engineers (NACE) suggests that for pipelines a potential shift of 300 mV is indicative of achieving cathodic protection. For steel embedded in concrete, however, it is loosely held that a lesser shift in potential is required. Kubit (9) has sug- gested that polarization and depolarization curves provide a very reliable basis for determining cathodic protection needs and that depolarization shifts of 100 mV or less may signify achievement of cathodic protection.

Current

Current-density requirements are essential to the proper design of any cathodic system. Current density is associated with protection in two ways: (a) It is a function of the polarized potential, and (b) it may be viewed as a fixed range, perhaps similar to the 0.85-1.10 V CSE criterion. When Stratfull (4) protected the first bridge deck, he found that the current-density requirements were 0.7 mA/ft^2 of steel surface. At that time, it was assumed that he was protecting the top mat of rebars only (he may have protected the bottom mat as well). Fromm (5) has reported that current densities to achieve cathodic protection range from 0.15 to 0.50 mA/ft^2 of bridge-deck surface in

Figure 2. Pipeline cathodic protection system.

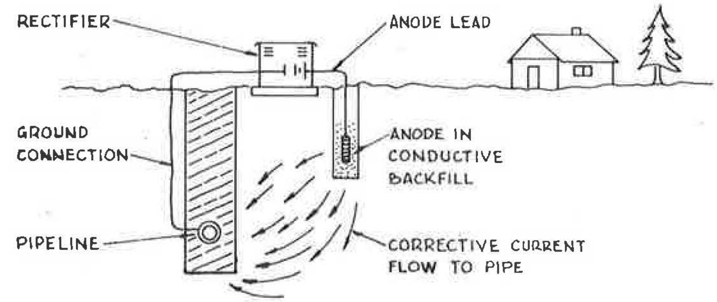


Figure 3. Bridge-deck cathodic protection system.

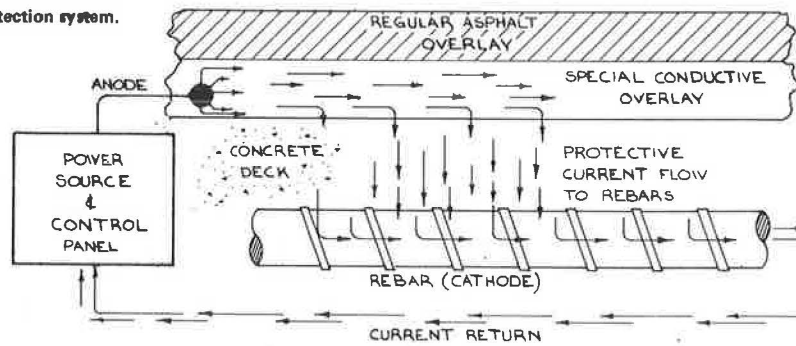
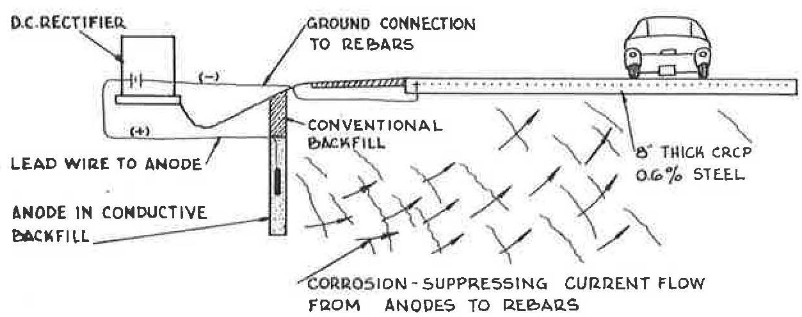


Figure 4. Cathodic protection installation for CRCP.



Canada. Vrable (10) notes that others have related current-density requirements to the condition of the concrete. Neither Fromm nor Vrable specify whether the current densities are associated with square feet of deck surface or the steel surface within a square foot of deck. It is also important whether protection is assumed to be applied to both mats of steel or only one, since there tends to be a difference. It was Vrable's assessment that current-density requirements normally do not exceed 1.0 mA/ft^2 of surface (10). I have assumed here that the surface-area designation in question is associated with the steel surface and not with the pavement surface.

System Design and Control

The first and major consideration in this effort, as with any experimental system, was designing it so that the probability of its successful operation would be high. A prerequisite to achieving effective cathodic protection is uniform current distribution. If distribution is nonuniform, hot spots (overprotection) will occur at some locations and cool spots (underprotection) will occur at others.

Several factors have an effect on the characteristics of current distribution; some can be controlled, others cannot. These factors are

1. Resistivities in the medium separating the anode and cathode,
2. The continuity of the steel in the structure being protected,
3. The uniformity of the applied potential, and
4. The proximity of the source (anode) to the protected structure (pavement).

The two most commonly used methods for applying impressed-current cathodic protection to pipelines is the distributed anode ground bed and the remote anode ground bed (3). Experience with these two methods seems to indicate that the distributed ground bed offers the most uniform applied potential and is the most responsive to control efforts.

In general, the design concept of the distributed anode ground bed involves placing an array of anodes along the structure requiring protection. The anodes are usually placed in a continuous trench backfilled with a conductive aggregate or in postholes as prepackaged assemblies, each of which contains the anode and an appropriate amount of conductive fill material. In both cases, the anode leads are connected to a main line from the controller. It is common practice to provide separate circuits or staggered anode wiring arrangements so that, if part of the system goes out, the domino effect is avoided and protection can be maintained. When the review of all available

Figure 5. Trench method of cathodic protection for CRCP.

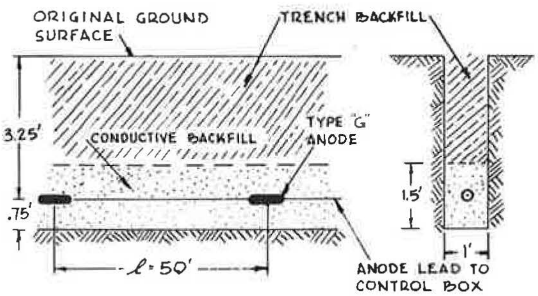
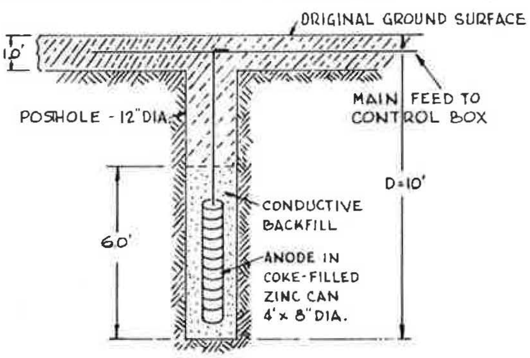


Figure 6. Posthole method of cathodic protection for CRCP.



information was complete and all options had been considered, a decision was reached to use the distributed anode ground bed for our trial system. It was felt that this approach would minimize interference problems, maximize system control capabilities, and provide the most uniform applied potential and current density, thus improving the chances for successful operation. It was also decided that a rectifier with constant current output would be used in the initial trial.

Anode Installation Schemes

The two schemes for anode installation, the continuous trench and the posthole approach, were both used in this trial. The test area was divided into two major sections, each 500 ft long. The first 500-ft section would be protected by using a continuous trench and the second 500-ft section by using the posthole method. Each test area was further subdivided into five zones, and each zone can be independently controlled at the rectifier.

Continuous Trench

One method of achieving uniform current distribution is to provide an array of anodes at some predetermined uniform interval that run parallel to the structure being protected. An anode's ability to discharge current to the surrounding soil is limited by (a) the resistivity of the soil, (b) the applied potential, and (c) the surface area of the anode.

Although the soil resistivity cannot be altered, the "effective" surface area of the anode can. Current discharge from an anode to the surrounding soil can be enhanced by placing a conductive (low-resistance) material around the anode. This can increase the effective anode surface area many times. The conductive material, in effect, becomes a secondary anode. By using a continuous trench, as shown in Figure 5, and spacing the anodes at uniform intervals, a very efficient current-distribution network can be created. Current will radiate out from the conductive backfill along the entire length of the trench.

Posthole (Vertical Anode) System

The posthole approach also uses the concept of increased effective anode surface area. It does so, however, in a different way. Holes 10-12 in in diameter are drilled along the structure that is being protected. Conductive backfill is placed and tamped in the hole around an anode. This column of conductive material (usually 6-8 ft high) then becomes the effective anode (see Figure 6).

The anodes placed in both systems will be controlled from a rectifier located halfway along the system. The present thinking is to use a current-controlled rectifier with reference cells for monitoring installed in the CRCP slab. Each test section will be divided into five zones, each roughly 100 ft in length. The anodes supplying power to a zone will be regulated at the rectifier according to the potential in that zone.

Several bases for assessing system performance will be considered. The widespread and accepted method is polarization testing. Here, $Cu/CuSO_4$ or some other suitable reference electrode is used to measure potentials. The electrode is placed in close proximity to the steel being protected, and readings are taken. The current state of the art from both laboratory investigations and field experience supports the criterion of 0.85-1.10 V relative to the $Cu/CuSO_4$ electrode as being representative of protective polarization.

Other available, but less frequently used, criteria are the 100-mV shift for instantaneous-off potential measurements or a 300-mV shift between the system-off and total polarization status. The final technical criterion that will be considered is current-density requirements. There is considerable evidence that current densities on the order of 0.3-0.7 mA/ft^2 of steel are realistic values in achieving cathodic protection.

Laboratory Evaluation

As an aid in determining performance--or, more correctly, working parameters--some preliminary tests are being scheduled. A potentially controlled rectifier to power and regulate the system is also being reviewed but has not been tested. It is not known just how reliable this device will be in the field. Information on the operational characteristics of the rectifier controller is needed. To obtain this information, a laboratory simulation of the system is being conducted. The areas identified for study are (a) the resistivities in the various materials between the anode and the rebar, (b) the time required to achieve polarization, (c) the reliability of the zinc half-cell as a potential sensor, and (d) current densities associated with polarization.

As stated earlier, the field evaluation of this system will involve both internal and external monitoring. Internal monitoring will be restricted to observing and documenting applied potentials and current output to each of the anode circuits. Each circuit will consist of two anodes and two reference cells cast into the pavement slab. The reference cell in the passing lane, which is farthest from the anodes, will be used in setting the power output from the anodes, and the reference cell in the driving lane will be used to monitor applied potentials. In view of the fact that uncertainties still exist about reference-cell reliability, an optional plan to monitor potentials with an internal carbon probe will also be examined.

It is probable that extensive use will be made of the $Cu/CuSO_4$ half-cell as a means of external evaluation. Horizontal potential gradients are anticipated at the structure from the trench system because of the trench's relatively shallow burial. There could well be a tendency for the steel in the pavement near the trench to polarize first and for that farther away to polarize later. This being the case, as polarization occurs, a back electromotive force would develop in the closer steel and redistribution of current would result. A less noticeable horizontal gradient is expected with the posthole method. Because the anodes are buried deeper, they "see" the structure from a better angle, and potentials applied to the structure should be more uniform. $Cu/CuSO_4$ surface testing will again be used to measure applied potentials (absolute) and to check for possible gradients.

It should be obvious by now that there are still many unknowns in relation to the functional aspects of this system. If the situation had permitted, a more comprehensive approach to evaluating cathodic protection for application to CRCP would have been pursued. No doubt this would have consisted of conducting first a laboratory simulation, then a limited field trial, and finally a full-scale experimental test installation. Such an effort would have required 24-36 months to complete. Our present approach is to use the fast-track method, which is not unlike the approach used at the advent of the bridge-deck-spalling repair programs, a technique called "research by crisis".

CONCLUSIONS

In the past three years, more than $100 000/year has gone to patching or other ways of trying to maintain approximately 4 miles of four-lane Interstate highway that is now 10 years old. The distressed pavement is an 8-in slab reinforced with deformed wire mesh that was built by using the two-course construction technique. Since the corrosion phenomenon is for the most part irreversible, cathodic protection is now being examined as one possible solution to serious and rapidly advancing pavement deterioration problems.

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Study of Adhesive-Bonded Composite Concrete-Metal Deck Slabs

DANA J. McKEE AND JOHN P. COOK

The results of a study conducted to determine the effectiveness of an epoxy resin as a shear connector in composite systems are presented. Composite concrete-metal deck slabs were constructed by using an epoxy resin to bond the concrete to the metal deck. Three composite specimens and three noncomposite control specimens were used in the test program. The concrete was plant mixed and trucked to the site by a local concrete supplier. No special additives were used in the concrete. All specimens were loaded to failure on a simply supported span of 3.66 m (12 ft). A four-point loading system was used. The loads were applied slowly, and impact loading was not considered. The noncomposite control specimens showed a fairly high percentage of partial composite action. Two of the three composite specimens failed by excessive deflection without reaching a definitive value of ultimate load. The adhesive-bonded composite specimens, based on serviceability criteria, carried more than twice the load carried by the noncomposite control specimens. The test results indicated that the epoxy bonder performed well as a shear connector and allowed the composite concrete-metal deck slabs to achieve full composite action. Additional studies are required to extend the results to both other composite systems and other types of loading.

There is a considerable attraction to be found in the use of adhesives as shear connectors for composite beams. Mechanical fasteners, while quite effective, furnish a horizontal shear connection only at a set of discrete points. There are also high local stress concentrations in the shear connectors and in the surrounding concrete.

On the other hand, the adhesive furnishes a continuous bonding plane at the point where the two dissimilar materials meet. Several references in the literature (1-5) show the feasibility of the