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BRIDGE WINTER SUPPORT SYSTEMS

Implementation of Conductive Concrete Overlay for Bridge Deck Deicing at Roca, Nebraska

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Conductive concrete is a relatively new material technology developed to achieve high electrical conductivity and high mechanical strength. In research sponsored by Nebraska Department of Roads, a conductive concrete mix specifically for bridge deck deicing was developed. In this application, a conductive concrete overlay is cast on top of a bridge deck for deicing and anti-icing.

This technology has been successfully implemented in a demonstration project at Roca, about 15 mi south of Lincoln, Nebraska. The Roca Spur Bridge has a 36-m (117-ft) long and 8.5-m (28-ft) wide conductive concrete inlay. Temperature sensors and a microprocessor-based controller system were installed to monitor and control the deicing operation of the inlay. The construction was completed and the bridge was opened to traffic in the spring of 2003. Data from the first deicing event showed that an average of 500 W/m^2 (46 W/ft^2) was generated by the conductive concrete to raise the slab temperature about 9°C (16°F) above the ambient temperature.

The details of the construction and deicing operation of the conductive concrete inlay are presented.

INTRODUCTION

Conductive concrete is a cementitious admixture containing electrically conductive components to attain stable and high electrical conductivity. Due to its electrical resistance and impedance, a thin conductive concrete overlay can generate enough heat to prevent ice formation on a bridge deck when connected to a power source.

In research sponsored by Nebraska Department of Roads, Yehia and Tuan developed a conductive concrete mix specifically for bridge deck deicing (*1–6*). In this application, a conductive concrete overlay is cast on top of a bridge deck for deicing and anti-icing. The mechanical and physical properties of the conductive concrete mix were evaluated in accordance with the ASTM and AASHTO specifications (*7*, *8*). Two concrete slabs were constructed with a 9-cm (3.5-in.) conductive concrete overlay for conducting deicing experiments in the natural environment. Deicing experiments were conducted during the winters of 1998–2001 under two scenarios: deicing and anti-icing. The average power density of about 591 W/m^2 (55 W/ft^2) was generated by the conductive concrete to prevent snow accumulation and ice formation.

The Phase 1 findings of this research have shown that conductive concrete overlay has the potential to become the most cost-effective concrete pavement deicing method. The Phase 2 project was completed in the spring of 2003; the conductive concrete has been successfully implemented in a demonstration project at Roca, about 15 mi south of Lincoln, Nebraska. The Roca Spur Bridge has a 36-m (117-ft) long and 8.5-m (28-ft) wide conductive concrete inlay. In this paper, details of the construction of the conductive concrete inlay are presented.

RESEARCH OBJECTIVES

This research focuses on using the newly developed conductive concrete for bridge deck deicing and anti-icing. The implementation of this technology could eliminate the use of road salt and deicing chemicals, which cause concrete deck damage and rebar corrosion. It would also improve winter travel safety on Interstate highway bridges.

BACKGROUND

Conventional concrete is not electrically conductive. Conduction of electricity through concrete may take place in two ways: electronic and electrolytic (*9, 10*). Electronic conduction occurs through the motion of free electrons in the conductive medium, while electrolytic conduction takes place by the motion of ions in the pore solution. In fresh concrete and during hydration, conduction of electricity takes place by the motion of ions. However, in the hardened state, in which no moisture is available, conduction takes place by the motion of free electrons. In order for hardened concrete to be adequately conductive, metallic or other conductive particles must be added to the concrete matrix, and they must be in good electrical contact with each other. In this project, several conductive concrete mixtures were prepared with steel fibers, carbon and graphite products, and steel shaving.

Mix Design, Optimization, and Properties

Part 1: Conductive Concrete Mixes with Steel Shaving and Steel Fibers

In 1998, a conductive concrete mix specifically for bridge deck deicing was developed (*1–5*). In this mix, steel shavings with particle sizes ranging between 0.15 and 4.75 mm (0.007 to 0.19 in.) and steel fibers with four different aspect ratios between 18 and 53 were added to the concrete as conductive materials.

More than 150 trial mixes were prepared to optimize the volumetric ratios of the steel shavings and fibers in the mix proportioning. The evaluation criteria were mechanical properties (compressive and flexural strength), slab heating performance, power source (DC versus AC), size effect, electric resistivity, and electrode configuration. The optimized mix was evaluated in accordance with the ASTM and AASHTO specifications. The compressive strength, flexural strength, modulus of elasticity, and rapid freeze-and-thaw resistance of the conductive concrete mix after 28 days have met the AASHTO requirements for bridge deck overlay. Two concrete slabs, 2 m by 2 m and 1.2 m by 3.6 m (7 ft by 7 ft and 4 ft by 12 ft) and 15-cm (6-in.) thick were constructed with a 9-cm (3.5-in.) conductive concrete overlay for conducting the deicing experiment in the natural environment.

Slab Heating Tests

Slab heating tests were conducted under two different initial slab temperatures at 23°C (74°F) and –1.1°C (30°F). The slabs were 305 mm by 305 mm by 51 mm (1 ft by 1 ft by 2 in.). Average power of 516 W/m^2 (48W/ft^2) was generated by the conductive concrete to raise the slab temperature from –1.1^{o}C (30^{o}F) to 15.6^{o}C (60^{o}F) in 30 min. This power level was consistent with the successful deicing applications using electrical heating cited in Henderson and Zenewitz (*11, 12*).

Part 2: Conductive Concrete Mixes with Carbon Products and Steel Fibers

During the research and development of the conductive concrete, several disadvantages to using steel shavings in the mix were noticed. First, there was no wide availability of supplies of steel shavings. Second, steel shavings acquired from metal fabricators are usually contaminated with oil and requires cleaning. And third, steel shavings pose a safety hazard for handling and requires a specialized mixing procedure to ensure uniform distribution.

In the spring of 2001, a conductive concrete mix utilizing graphite and carbon products to replace steel shavings was developed (*6*). Ten trial mixes with seven carbon and graphite products were included in the preliminary experimental evaluation. The evaluation criteria used for each trial batch were workability and finishability, compressive strength, heating rate, and electric resistivity. All mixes contained 1.5% of steel fibers per volume of conductive concrete, in addition to the carbon and graphite products used for conductive materials. The added carbon and graphite products amounted to 25% per volume of the trial mixes. The conductive concrete mix using 25% combined carbon and graphite products and 1.5% steel fibers per volume was tested extensively to evaluate its mechanical and physical properties. Material testing was conducted in accordance with the ASTM and AASHTO specifications. The compressive strength, flexural strength, and freeze and thaw resistance of the mix were determined. The test results are summarized in Table 1.

Field Applications and Durability Test

A conductive concrete patch was constructed on December 3, 1999, in one I-480 westbound lane over the Missouri River (near the Nebraska–Iowa border) for durability evaluation. The patch was 6.4 m by 3.65 m by 9 cm (21 ft by 12 ft by 3.5 in.), and the optimized mix design with steel shavings was used. The workability and finishability for the conductive concrete was similar to that of conventional concrete. The overlay was visually inspected every 6 months for 2 years. There was no fiber exposure, but reflective cracking developed in the overlay due to cracking of the substructure.

TABLE 1 Mechanical Properties of Conductive Concrete with Carbon Products

Tests	Results
Compressive strength	41–55 MPa (6,000–8,000 psi)
Flexural strength	5.3–5.9 MPa (770–850 psi)
Rapid freeze-and-thaw resistance	None of the specimen failed after 300 cycles
Modulus of elasticity	27,565 MPa (3.8 by 10^6 psi)

Deicing and Anti-Icing Experiments

Several deicing and anti-icing experiments were conducted during the winters of 1998–2001. In the anti-icing experiments, the overlays were preheated 2 h to 10 h (depending on the initial temperature of the overlay) before and heated during the storms. In addition, deicing experiments, in which the overlays were heated only during the storms, were conducted to evaluate the heating rate of the conductive concrete.

In each experiment, the applied voltage current going through each overlay and the temperature distribution within each overlay were measured as well as the air temperature, humidity, and wind speed and direction. Figure 1 shows the 1.2 m by 3.6m (4 ft by 12 ft) slab during a deicing experiment. In the winter of 2000 most of the experiments were conducted with an initial overlay temperature –9°C (–15°F). At this temperature most deicing chemicals became ineffective. The heating rate was consistent with the winter 1998 experiments. The average heating rate was 0.56°C/min (1°F/min) during the snowstorms. The average energy cost was about $\$0.8/m^2$ ($\$0.074/ft^2$) per storm at a cost of 8 cents per kW-h.

IMPLEMENTATION PROJECT

Selection of Bridge Site

The findings of the Phase 1 research showed that the conductive concrete overlay had the potential to become the most cost-effective bridge deck deicing method. In 2001, Nebraska

FIGURE 1 Deicing experiment during the winter of 2000.

Department of Roads approved a demonstration project at Roca, about 15 mi (24 km) south of Lincoln, to implement a conductive concrete overlay on a highway bridge.

The Roca Spur Bridge has a 36-m- (117-ft-) long and 8.5-m- (28-ft-) wide conductive concrete inlay. A railroad crossing is located immediately following the end of the bridge, making it a prime candidate for deicing application, as shown in Figure 2.

Bridge Construction

The Roca Spur Bridge is a three-span slab-type bridge has a 45.7-m (150-ft) long and 11-m (36-ft) wide concrete deck. The slab thickness is 0.3 m (12 in.). A 102-mm (4-in.) thick inlay of conductive concrete was taken into account during the design phase. Figures 3 and 4 show a general plan of the bridge, cross-sectional elevation, and cross section of the slab. Polyvinyl chloride (PVC) conduits and junction boxes were embedded into the slab during construction, as shown in Figure 5. The conduits had no effect on the structural integrity of the bridge. Conventional concrete with 30 MPa (4500 psi) compressive strength was used to cast the slab.

Conductive Concrete Inlay

The conductive concrete inlay is 36 m (117 ft) in length and 8.5 m (28 ft) in width. The inlay consists of 52 individual 1.2 m by 4.1 m (4 ft by 14 ft) conductive concrete slabs, as shown in Figure 6. The slabs were divided into two groups separated by a 150-mm (6-in.) -gap along the centerline of the bridge to allow for the electrical connections.

FIGURE 2 A railroad crossing is located immediately following the end of the bridge.

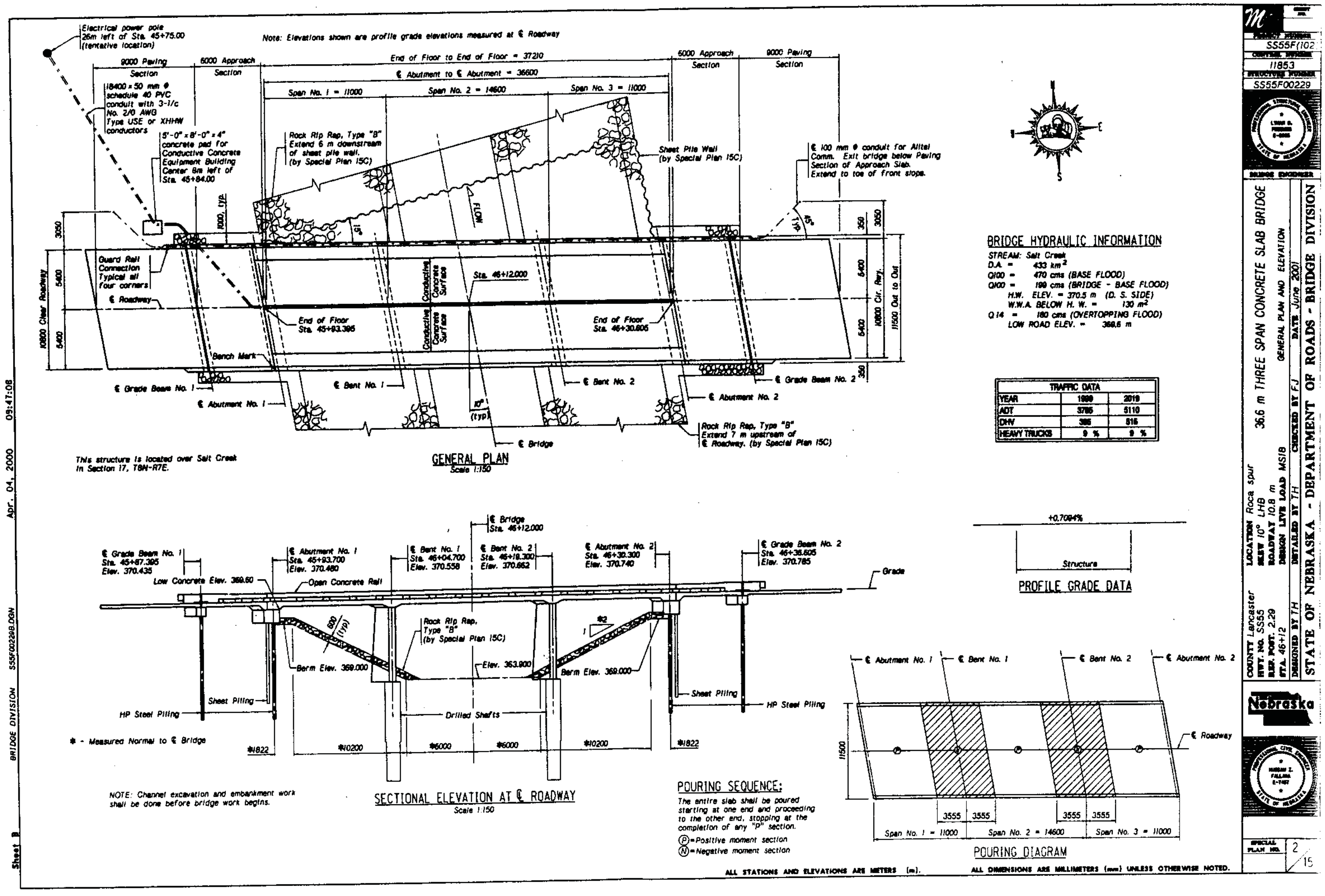


FIGURE 3 Roca Super Bridge: cross section and top view.

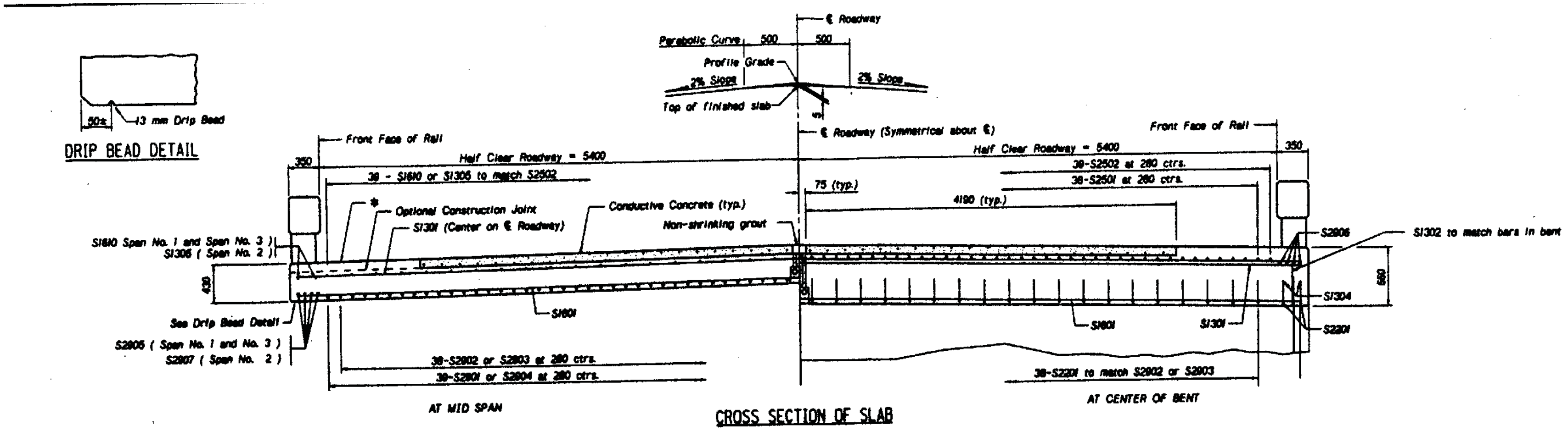


FIGURE 4 Cross section of slab.

FIGURE 5 First conductive concrete overlay during construction at Roca, Nebraska.

Electrode Configuration

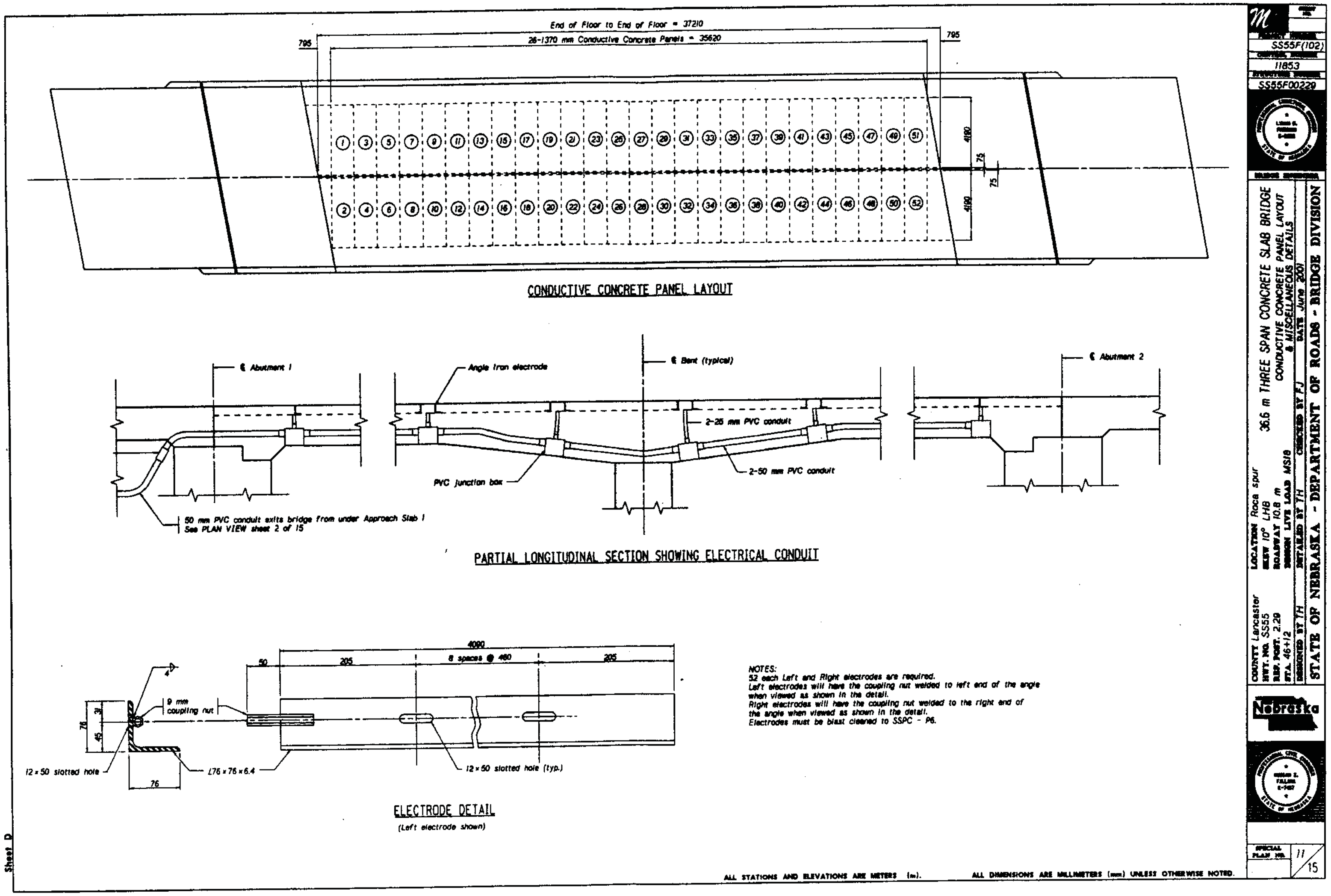
In each slab, two 76 mm by 76 mm by 6 mm (3 in. by 3 in. by ¼ in.) angle irons spaced 1,067 mm (3.5 ft) apart were embedded for electrodes, as shown in Figure 7. Figure 8 shows the electrodes layout during construction. The angles had perforations greater or equal to the 13-mm (0.5-in.) maximum aggregate size to allow concrete to flow through to provide good conductivity. In addition, the angles were sandblasted to remove mill scale for better conductivity. Coupling nuts were welded to one end of the angle irons for making an electrical connection.

Instrumentation

Temperature sensors, thermocouple wires, type TX, were installed at the center of each slab at about 13 mm (0.5 in.) below the surface to measure the slab temperature. The sensors were installed before casting the inlay. Separate PVC conduits were used to house the thermocouple wires.

Casting Concrete

The conductive concrete mix with steel fibers and carbon and graphite products was used to cast the inlay. Several, 2 yd^3 trial batches were prepared to examine the mixing procedure and travel time from the mixing plant to the job site. In addition, the contractor and the pouring and finishing crews practiced at a test site. On the casting date, the westbound lane was poured first and the eastbound lane next, as shown in Figure 9. Figure 10 shows that the workability and finish of the mix are similar to those of conventional concrete. After hardening, the



NOTES:
52 each Left and Right electrodes are required.
Left electrodes will have the coupling nut welded to left end of the angle when viewed as shown in the detail.
Right electrodes will have the coupling nut welded to the right end of the angle when viewed as shown in the detail.
Electrodes must be blast cleaned to SSPC - P6.

FIGURE 6 Conductive concrete panel layout.

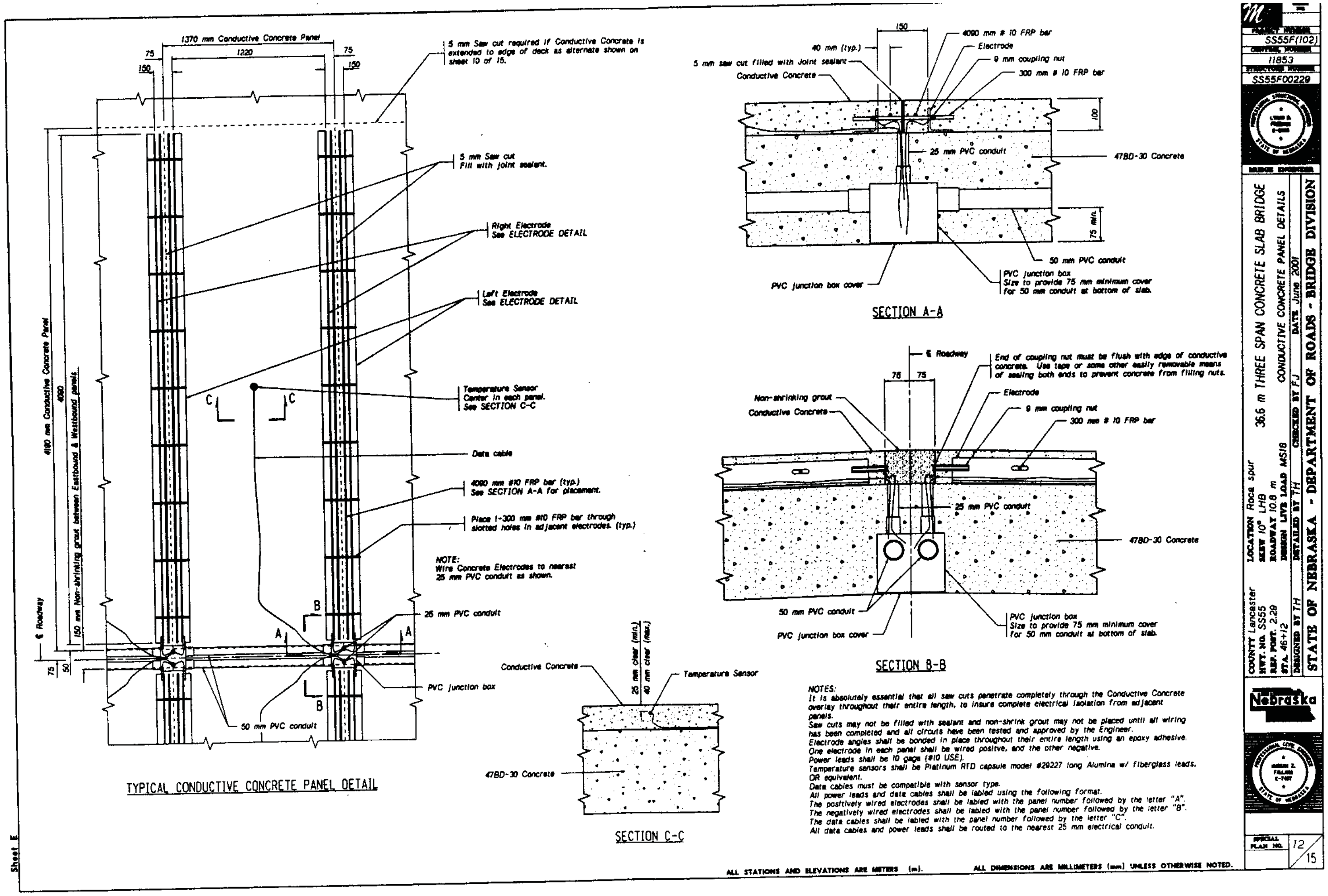


FIGURE 7 Electrode layout and sensors locations.

FIGURE 8 Electrode layout during construction.

FIGURE 9 Casting the westbound lane with conductive concrete.

FIGURE 10 Finishing the conductive concrete inlay.

conductive concrete inlay was cut by saw to a 102-mm (4-in.) depth along the perimeters of the individual slabs, as shown in Figure 11, and the gaps were filled with polyurethane sealant. The gap along the centerline of the bridge was then filled with a nonshrink, high-strength grout after finishing all the power connections to the individual slabs.

Power Supply, Sensors, and Control Circuit

A three-phase, 600 A and 220 V AC power is available from a power line nearby. A microprocessor-based controller system was installed in a control room to monitor and control the deicing operation of the 52 slabs. Figure 12 shows the control circuit after installation. The system includes four main elements: a temperature-sensing unit, a power-switching unit, a current-monitoring unit, and an operator-interface unit. The temperature-sensing unit takes and records the thermocouple readings of the slabs every 15 min. A slab’s power is turned on by the controller if the temperature of the slab is below 4.5°C (40°F) and turned off if the temperature is above 12.8°C (55°F). The power-switching unit controls power relays to perform the desired on/off function. To ensure safety, a current-monitoring unit limits the current going through a slab to a user-specified amount. The operator-interface unit allows a user to connect to the controller with a PC or laptop via a phone modem. The operator interface displays all the temperature and electrical current readings of every slab in real time. A user also has the option of using a PC or laptop to download the controller-stored data into a spreadsheet.

FIGURE 11 Total of 52 slabs after saw cut the inlay.

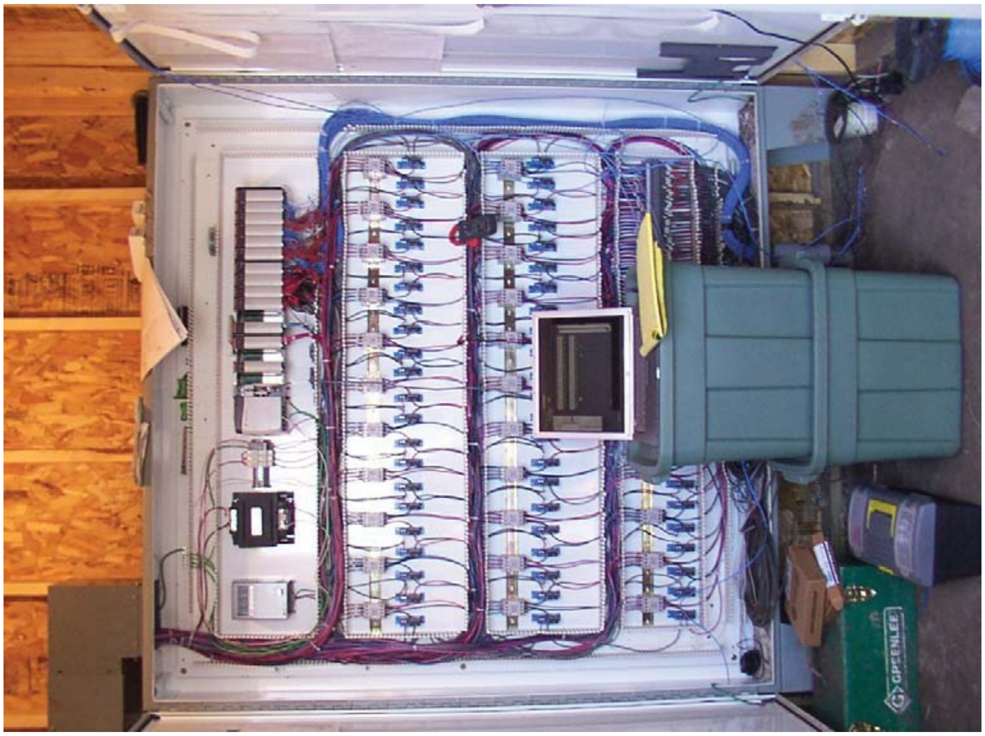


FIGURE 12 Microprocessor-based controller system.

Powering Scheme and Evaluation of Heating System

The conductive concrete heating system was fully operational in the spring of 2003, but by that time most of the winter storms were missed. However, the system was tested successfully under freezing temperature. The powering scheme is to divide the 52 slabs into 26 groups with each group containing two consecutive slabs. To avoid power surge, the odd-numbered groups were started up in turn at 3-min interval and energized at 208 V for 30 min before the even-numbered groups were started. This powering scheme was used in one event.

It was anticipated that a big snowstorm would occur on April 6, 2003. It was found from the results of Phase 1 that the anti-icing operation was more effective than the deicing (*3*, *4*). Therefore, the system was turned on April 4. However, the snow band just missed Roca and produced less than 6 mm (0.25 in.) of sleet. As shown in Figure 13, there was snow or ice accumulation on the asphalt roadways and the bridge deck was wet during the storm period. The system was shut down early on the morning of April 7. The temperature distribution was very uniform across the bridge. The controller system kept the slab temperature about 9°C (16°F) above the ambient temperature. The maximum current recorded varied between 9 and 18 amps, with an average of 12.5 amps. The peak power density delivered to the slabs varied between 360 to 720 W/m^2 (33 to 67 W/ft^2) with an average of 500 W/m^2 (46 W/ft^2). The energy consumed by the conductive slabs during the 3-day period varied from 12.6 to 34.6 kW-h, with an average of 24 kW-h per slab. The total energy consumption was calculated to be 1,270 kW-h and would cost about $100 based on the rate of $0.08/kW-h.

FIGURE 13 No ice or snow accumulation during the first snowstorm—April 2003.

Construction Costs

Table 2 summarizes the actual construction cost of the conductive concrete inlay. The average cost per unit surface area of the conductive concrete was compared with that of other heating systems in Table 3. The initial construction cost was high compared with cost of the most recent propane-fired boiler heating system installed in the Buffalo River Bridge in Amherst, Virginia, in 1996 (*15*). It is expected that the construction costs of conductive concrete overlay or inlay will drop significantly when the technology becomes widely accepted. In addition, other factors such as life-cycle costs, including system maintenance costs, deck repair costs, and vehicle depreciation caused by deicing chemicals, should be used as the basis for cost-effectiveness comparisons between different deicing systems.

Long-Term Monitoring and Performance Evaluation

Nebraska Department of Roads has approved a 5-year plan for monitoring the conductive concrete overlay. The results will be shared with the engineering community for further evaluation of the new technology.

CONCLUSIONS

The heated bridge deck of Roca Spur Bridge is the first implementation in the world of conductive concrete used for highway bridge deicing. The new mix design containing carbon

TABLE 2 Construction Cost of the Conductive Concrete Inlay

Item	Cost
Placing, finishing, curing, and saw cutting conductive concrete	\$50,020
Conductive concrete materials	\$80,620
Building and installing control cabinet with sensors and power relays	\$43,685
Integrating and programming the deicing operation controller	\$18,850

TABLE 3 Initial Cost Comparison of Different Heating Systems

Heating System	Approximate Cost[a]
Infrared heat lamp, 1970 (*12*)	\$96/m^2 (\$8.9/ft^2)
Electric heating cable, 1961 (*11* ,*12*)	\$54/m^2 (\$5/ft^2)
Hot water, 1993 (*13, 14*)	\$161/m^2 (\$15/ft^2)
Heated gas, 1996 (*15*)	\$378/m^2 (\$35/ft^2)
Conductive concrete, 2002	\$635/m^2 (\$59/ft^2)

[a] Cost figures were quoted directly from the literature, and conversion to present worth was not attempted.

powder and particles is found to be superior to using steel shavings, in that the electrical conductivity and the heating rate are improved without the drawbacks. The construction costs and deicing performance of the heated bridge deck would demonstrate its cost-effectiveness as opposed to other existing deicing technologies. The conductive concrete deicing technology can be readily implemented at accident-prone areas such as bridge overpasses, exit ramps, airport runways, street intersections, sidewalks, and driveways.

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