8-1998

Bridge Deck Deicing

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1998 TRANSPORTATION CONFERENCE PROCEEDINGS

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Concrete bridge decks are prone to ice accumulation. The use of road salts and chemicals for deicing is cost effective but causes damage to concrete and corrosion of reinforcing steel in concrete bridge decks. This problem is a major concern to transportation officials and public works due to rapid degradation of existing concrete pavements and bridge decks. The use of insulation materials for ice control and electric or thermal heating for deicing have been attempted and met limited success. Conductive concrete may be defined as a cementitious composite, which contains a certain amount of electronically conductive components to attain stable and relatively high electrical conductivity. When connected to a power source, heat is generated due to the electrical resistance in the cement admixture with metallic particles and steel fibers. Based on the results of a transient heat transfer analysis, a thin conductive concrete overlay on a bridge deck has the potential to become a cost effective deicing method. Small-scale slab heating experiments have shown that an average power of about 48 W/m2 was generated by the conductive concrete to raise the slab temperature from -1.1°C (30°F) to 15.6°C (60°F) in 30 minutes. This power level is consistent with the successful deicing applications using electrical heating cited in the literature. The work described in this paper is part of an on-going research project being conducted for Nebraska Department of Roads. Two large slabs are under construction for bridge deck deicing experiment in natural environment to monitor power consumption and deicing performance. The construction costs and experimental data will be used to evaluate the cost effectiveness of using a conductive concrete overlay for bridge deck deicing or anti-icing. Key words: conductive concrete, deicing methods, steel fibers, concrete bridge deck, heat transfer.

INTRODUCTION

Traditionally, removing ice from pavement can be accomplished by a combination of several methods, such as plowing, natural melting, traffic movement, and chemical treatment. Most highway winter maintenance depends on using chemicals and fine aggregates as a primary means for deicing and anti-icing (*1*). Various deicing chemicals are available commercially. The most cost-effective product is sodium chloride. However, using chloride has caused damage to concrete and corrosion of reinforcing bars in concrete bridge decks.

The search for improved deicing methods has been a research focus for quite some time. The use of insulation materials and electric or thermal heating has been attempted; however, those techniques were either not cost-effective or could not meet the bridge deck strength requirements. Existing deicing and anti-icing methods have been surveyed and compared in this study.

Xie et al.[2,3,4] at the Canadian National Research Council have developed an innovative concept of using an "electrically conductive" concrete mix. When connected to a power source, heat is generated due to the electrical resistance in the cement admixture with metallic particles and steel fibers and can be used for deicing and anti-icing. Coke breeze (i.e., steel shaving from steel fabricators) and steel fibers are mixed in the cement to increase the electrical conductivity, while maintaining adequate mechanical strength of the concrete. The feasibility of using a conductive concrete overlay for bridge deck deicing has been investigated. Different power supply schemes, such as using solar energy with a backup battery, microwave power, and DC power, are being evaluated for cost-effectiveness. Results from small-scale experiments using conductive concrete mixes for heating concrete decks are presented herein.

LITERATURE SURVEY

Using Deicing Chemicals

The most common deicing chemicals used by highway agencies is sodium chloride (NaCl). The recent statistics indicate that about 10 million tons of sodium chloride is used in a winter in the United States (*1*). Sodium chloride, often referred to as road salt, is usually used alone or mixed with fine aggregates. A recent interview with Nebraska Department of Roads officials has revealed that the deicing operation in Omaha uses road salt mixed with sand. The application rate ranges between 200 to 300 lbs/12 ft lane-mile and about 2000 tons of salt and 5000 tons of sand are usually used in a winter season.

Using chloride deicing salt causes many problems, which include damage to concrete pavement and bridge decks (e.g. surface scaling and corrosion of reinforcement), corrosive damage to automobile bodies, and pollution due to concentrations of sodium and chloride in roadside soils and water runoff (*5,6,7,8,9,10,11*). Furthermore, salt produces osmotic pressure causing water to move toward the top layer of the slab where freezing takes place (*6,7,9*). This action is more severe than the ordinary freezing and thawing. Commonly used deicing chemicals are compared in Table 1.

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TABLE 1 Comparison of Deicing Chemicals

Deicing Chemical	Temperature Range	Application Rate	Approximate Cost
Sodium chloride(1,11,12) (NaCl)	-10°C to 1°C (14°F to 34°F)	13 to 68 g/m² (170 to 890 lb/12ft lane-mile)	$29/m³ ($26/ton)
Calcium chloride(1) ($CaCl_2$)	-25°C(-13°F)	Not used alone in the U.S.A.	$294/m³ ($267/ton)
Salt mixed with Calcium chloride(1,12) ($CaCl_2$)	-17°C to 0°C (0°F to 32°F)	21-50 l/m³ salt (5 to 12 gal/ton)	$108/m³ ($98/ton)
Calcium Magnesium Acetate(1,11,12) (CMA)	-5°C to 0°C (23°F to 32°F)	15 to 39 g/m² (200 to 500 lb/12ft lane-mile)	$738/m³ ($670/ton)
Urea(1,11)	-9°C (16°F)	26 to 136 g/m² (340 to 1780 lb/12ft lane-mile)	$145-$290/m³ ($130-$260/ton)
Magnesium chloride(11)	-15°C (5°F)	8 to 11 g/m² (100 to 150 lb/12ft lane-mile)	Not Available
Formamide(11)	-18°C (0°F)	Not Available	$290-$435/m³ ($290-$390/ton)
Tetrapotassium(1,11) pyrophosphate (TKPP)	-4°C (25°F)	49 g/m² (640 lb/12ft lane-mile)	$435/m³ ($390/ton)

TABLE 2 Comparison of Different Heating Systems

Heating	Approximate Cost[a]	Annual Operating Cost[a]	Power Consumption
Infrared heat lamp(11)	$8.9/ft² ($96/m²)	Not available	7 W/ft² (75 W/m²)
Electric heating cable(11,22)	$5/ft² ($54/m²)	$0.45/ft² ($4.8/m²)	30 to 40 W/ft² (323 to 430 W/m²)
Hot water(23,24)	$15/ft² ($161/m²)	$250/storm (3 in. snow)	44 W/ft² (473 W/m²)
Heated gas(25)	$35/ft² ($378/m²)	$0.20/ft² ($2.1/m²)	Not available
Conductive concrete overlay[b]	$4.5/ft² ($48/m²)	$0.5/ft² ($5.4/m²)	48 W/ft² (516 W/m²)

[a]Cost figures were quoted directly from the literature, and conversion to present worth was not attempted.
[b]Costs and energy consumption are estimates based on the limited data obtained in this study.

Insulation Against Freezing

One method to reduce salt usage is to provide insulation against frost and ice formation (*13,14*). This concept was used to insulate the underside of a bridge deck and the subgrade of highway pavements and airfield runways. The main objectives were to reduce heat loss from the surface and prevent ice and frost formation, and to decrease the number of freeze-thaw cycles and salt usage. Since 1962, the polystyrene foam (Styrofoam) has been used in Michigan (*14*), Iowa (*14*), Minnesota (*14*), Missouri (*15*), Nebraska (*16*) and Alaska (*17*), to insulate beneath the roads and airfields to prevent subgrade freezing. Canada (*18*), Sweden (*19*) and Britain (*20*) also experimented using polystyrene foam for insulation under highway pavements which effectively prevented frost action in the subgrade.

Heating Systems

Heating systems (*11,21,22,23,24,25*) for use in pavements have typically been embedded resistive electrical heaters or pipes containing a heated fluid. The circulating fluid systems generally use fossil fuel energy sources. Different heating systems are compared in Table 2.

Electrically Conductive Concrete

Conductive concrete may be defined as a cement-based composite that contains a certain amount of electronically conductive components to attain stable and relatively high electrical conductivity. Some of the applications are: 1) electromagnetic shielding often required in the design and construction of facilities and equipment to protect electrical systems or electronic components; 2) radiation shielding in nuclear industry; 3) anti-static flooring in the electronic instrumentation industry and hospitals; and 4) cathodic protection of steel reinforcement in concrete structures.

Xie et al. (*2,3,4*) summarized several researchers' efforts in investigating some conductive concrete composition. The conductive concrete cited in the literature can be classified into two types: 1) conductive fiber-reinforced concrete, and 2) concrete containing conductive aggregates. The first type has higher mechanical strength but lower conductivity with a resistivity value of about 100 Ω.cm. The reason for the lower conductivity is due to the small fiber-to-fiber contact areas. The second type has a higher conductivity with a resistivity value of 10 to 30 Ω.cm, but relatively low compressive strength (less than 25 MPa). Lower mechanical strength is due to the high water content required during mixing to offset the water absorption by conductive aggregates, such as carbon black and coke. Xie et al. (*2,3,4*) patented a new conductive concrete mix developed at the Institute for Research in Construction, National Research Council of Canada. With the newly developed mix, both high conductivity and mechanical strength can be achieved simultaneously. However, this mix has not been utilized in actual field applications. The material costs of conductive concrete are compared against those of conventional concrete in Table 3.

TABLE 3 Material Costs of Conductive Concrete Versus Conventional Concrete

Material	Cost/lb	Conductive Concrete	Conventional Concrete
		Cost/yard^3	
Steel fiber	$0.40	$80.0	0
Conductive material (coke breeze, steel shaving, etc.)	$0.10	$70.0	0
Sand	$0.0024	$2.6[a]	$2.4
1/2 in. limestone	$0.0024	$3.9[a]	$4.7
Cement	$4/(sac 94 lb)	$35[a]	$32
Total		$191.5	$39.1

[a]Due to the use of conductive materials, more sand and cement and less limestone were used than in conventional concrete.

TABLE 4 Physical and Thermal Properties of Conductive Concrete

Composition	Mass Density (kg/m^3)	Heat Capacity (kJ/kg-°K)	Thermal Conductivity (W/m-°K)
Steel	7850	0.42	47
Conventional Concrete	2300	0.88	0.87
Conductive Concrete	3133	0.71	4.4

SIMPLIFIED HEAT TRANSFER ANALYSIS

Conductive concrete may be considered as a "composite," whose constituents are steel fibers, steel shaving, and regular concrete. Based on the volume fraction of the steel fibers and shaving contained in the composite, expressions of "apparent" physical and thermal properties of conductive concrete may be derived from those of the constituent materials (*26*).

The "apparent" physical and thermal properties for a conductive concrete mix with 15 percent of steel fibers and shaving by volume can be derived from those of steel and concrete. These physical and thermal properties of conductive concrete are compared with those of steel and conventional concrete in Table 4.

Heat Transfer Analysis for Bridge Deck Deicing

With the apparent physical and thermal properties of the conductive concrete (with 15% of steel fibers and shaving by volume) determined, a simplified heat transfer analysis has been conducted to determine the power consumption in using conductive concrete overlay for bridge deck deicing.

A hypothetical case is proposed here with realistic parameters given as follows: ambient temperature T_a= -10°C (14°F), initial overlay temperature T_{ov} = -10°C (14°F), wind blowing across bridge deck at 24 km/hr (15 mph), a 3.2 mm (1/8 in.) thick layer of ice on deck surface, and a 51 mm (2 in.) thick conductive concrete overlay on top of a 152 mm (6 in.) thick regular concrete deck. The power consumption and the associated cost of deicing a concrete deck of 1 m (3.3 ft) by 1 m (3.3 ft) surface area, as illustrated in Figure 1, are determined based on energy balance. The bottom face of the conductive concrete overlay must be thermally insulated to prevent heat loss by conduction into the concrete deck. The four sides of the overlay element can be considered to be adiabatic boundaries. The effect of radiant heat transfer is ignored in the analysis. A stepwise transient heat transfer analysis was conducted with 1 kW of power input to the conductive concrete overlay. The time step, Δt, of the analysis was 10 sec.

The temperature at the bottom surface of the conductive concrete overlay, at the interface between ice and conductive concrete,

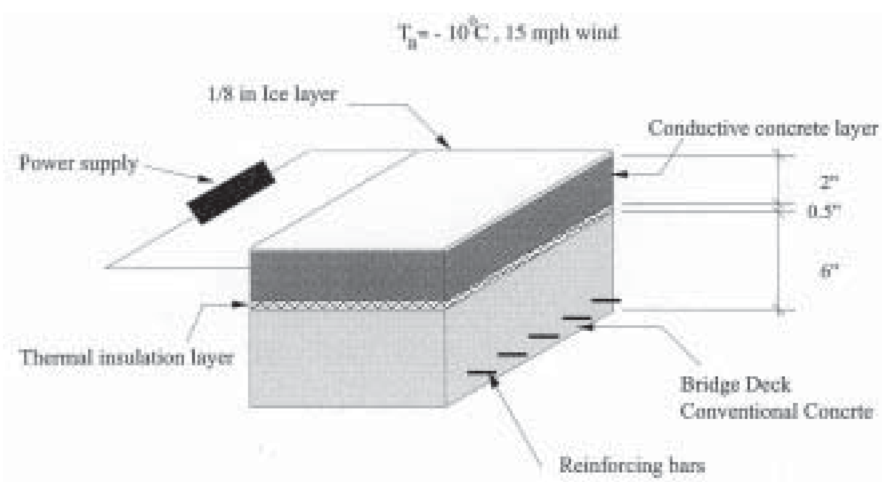

FIGURE 1 Concept of using conductive concrete overlay for bridge desk deicing.

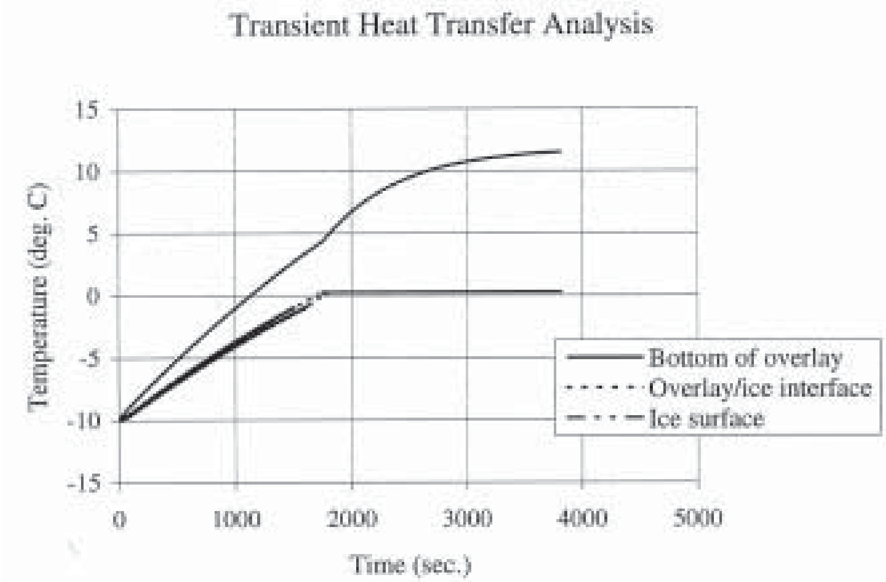

FIGURE 2 Temperature time-histories from a transient heat transfer analysis.

and at the ice surface are updated at the end of each time step based on conservation of energy and the solution process was continued until the average temperature in the ice reached 0°C. The ice would start melting at this point and continue to absorb heat for phase change into water. During the phase change, the temperature of the ice remains at 0°C. The stepwise solution algorithm was modified slightly to accommodate phase change and the solution was continued until the ice layer was completely melted. The time histories of the temperature variations for the case studied are presented in Figure 2. If the thermal energy generation in the conductive concrete overlay was 1 kW/m2, it would take about 30 minutes for the ice to start melting. It would take about an hour from the ice layer to melt completely. The highest temperature reached at the bottom of the conductive concrete overlay was 11.5°C (52.7°F). The cost of energy consumption was calculated to be about $0.05/m^2, if the average energy cost is $0.05/kW-hr for the United States. Based on the analysis results, it is very feasible to use a conductive concrete overlay for bridge deck deicing.

LABORATORY EXPERIMENTS

Test Specimens

Over fifty trial mixes of conductive concrete have been prepared using steel fibers with aspect ratios between 18 to 53 and steel shaving. Electric resistivity (*27*) and compressive strength were determined for each batch. The volume fractions of the steel fibers and shaving in the concrete mix have been optimized to provide the required conductivity and adequate compressive strength. The workability and surface finsihability are similar to those of conventional concrete.

Small Slabs Heating

A number of small slabs (1 ft x 1 ft x 1 in) were used to determine the required power to heat the slab. Steel plates were cast in the slabs for electrodes in the small slab heating tests. All tests were conducted in a room temperature of 74°F. Two thermocouples were installed in each slab to measure the mid-depth and surface temperature, both located at the center of the slab. The experimental results from six slabs showed that the temperature at the mid-depth in the slab increased at a rate of approximately 1°F per minute with 35 volts of DC power. The current going through the conductive concrete specimen varied from about 0.2 A to 5 A. Figure 3 shows the changes in the core and surface temperature of the 1 ft by 1 ft slabs with time. Some of the slabs were placed in a refrigerator before testing, and the results showed consistent heating of the slabs with different initial temperature. The power input was variable because there was no constant power control on the power supply. Figure 4 shows the thermal energy consumption versus average slab temperature curves for the test slabs. An average power of about 48 W/m2 was generated by the conductive concrete to raise the slab temperature from -1.1°C (30°F) to 15.6°C (60°F)in about 30 minutes. This power level is consistent with the successful deicing applications using electrical heating cited in the literature. It was noted that the specimen had a higher electrical resistance at lower temperature, while the voltage was kept constant. This phenomenon was also reported by Whittington (*28*).

SURVEY OF POWER SOURCES FOR CONDUCTIVE CONCRETE HEATING

Various power sources for heating the conductive concrete overlay have been surveyed and are being tested for feasibility studies.

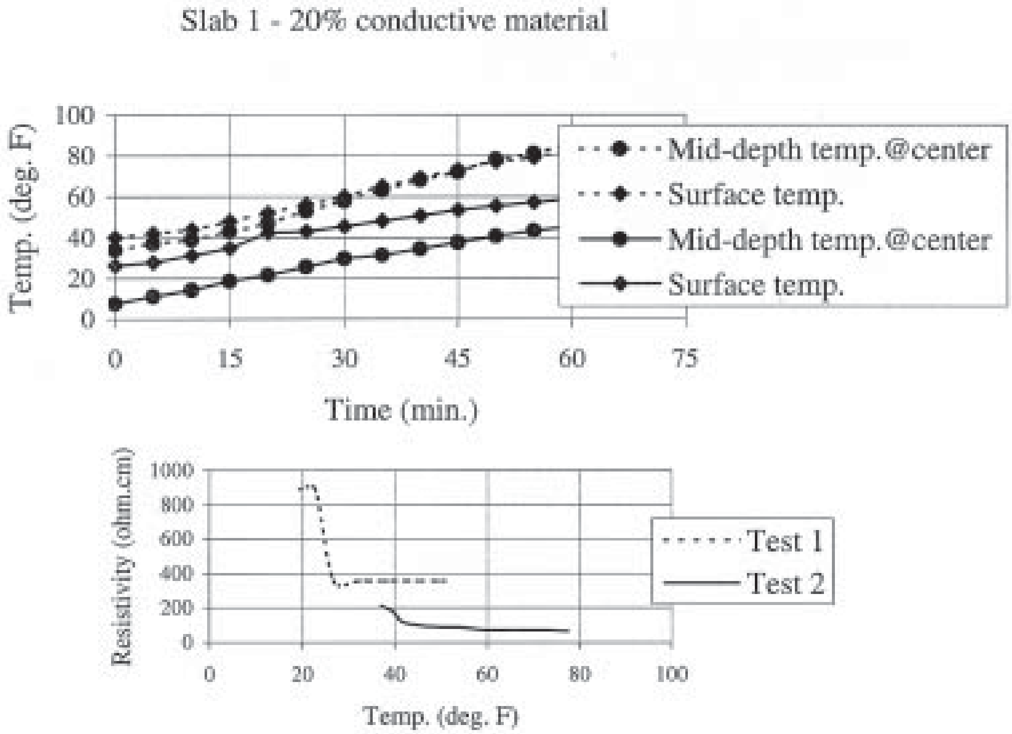

FIGURE 3a Temperature time-histories from heating tests (Slab 1).

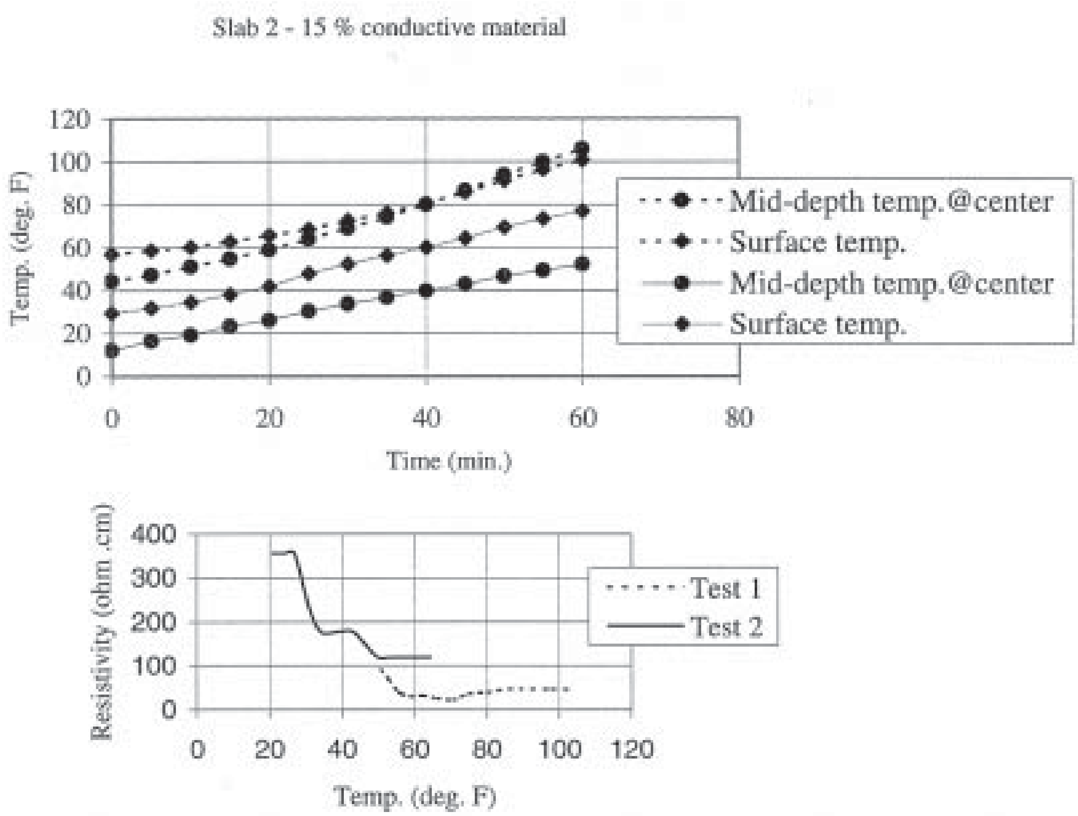

FIGURE 3b Temperature time-histories from heating tests (Slab 2).

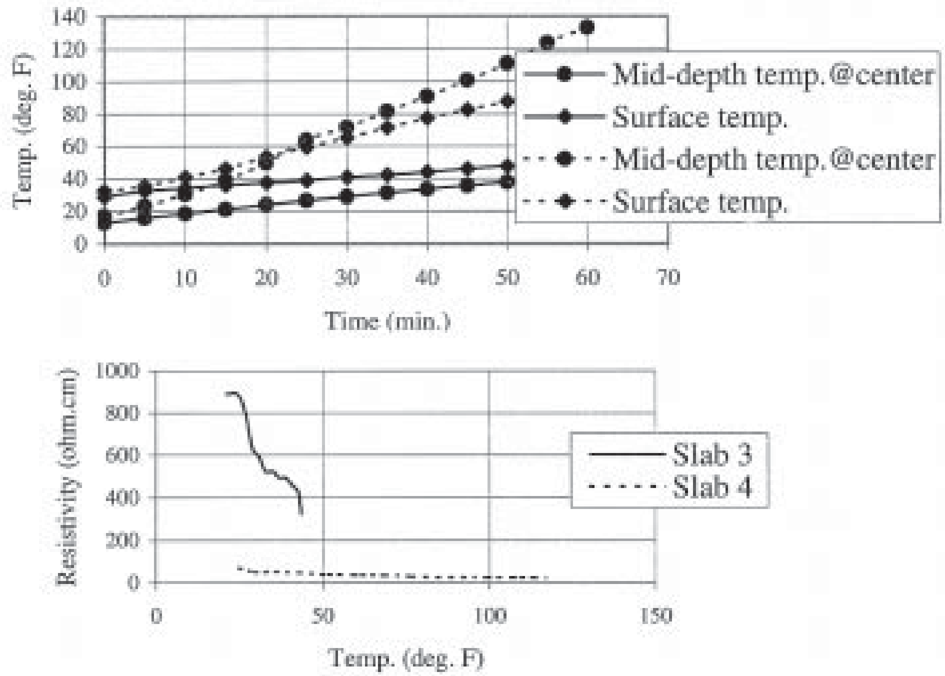

FIGURE 3c Temperature time-histories from heating tests (Slabs 3 and 4).

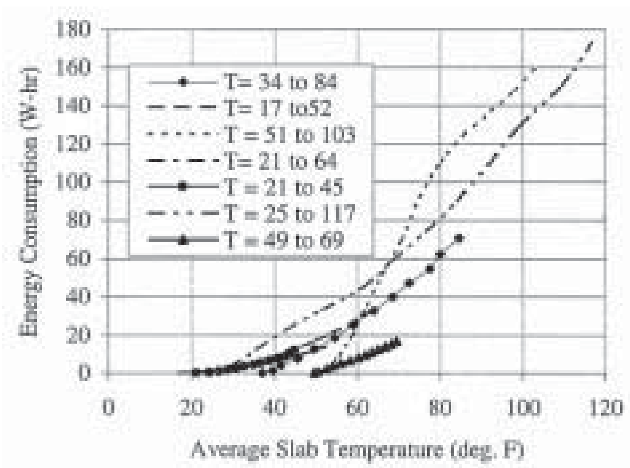

FIGURE 4 Energy consumption in small slab heating tests.

TABLE 5 Summary of Test Results

Composition	Compressive Strength[a] (psi)	Electric Resistivity[a] (Ω-m)
Conventional concrete	9425 (65 MPa)	5.4×10^5
Concrete with 2% steel fibers by volume	7918 (54 MPa)	5.4×10^5
Concrete with 15 to 20% steel fibers and shaving by volume	5000-6000 (35-40 MPa)	5 to 10

[a]Values were evaluated at the 28th day.

DC Power Supply

The simplest power source for heating the conductive concrete overlay is DC power. Through a regulated power supply, an AC power can be transformed to the required voltage and current depending on the resistance of the specimens. The voltage should not exceed 48 volts, which is the safe threshold of a human being.

Photovoltaic Power Generation

One alternative to power conductive concrete overlay is to use photovoltaic (PV) power generation. PV cells are made of silicon and first developed in the mid-1950s (*29*). PV systems are either grid-connected or stand-alone. Grid connected systems are connected to local utility lines and require inverters to convert the electricity from DC to AC. Stand-alone systems are not connected to the electric power grid, and generally use 12, 24, or 48 volt DC power. A stand-alone system with a backup battery has the potential to become a viable power source for the conductive concrete overlay.

Radio Frequency (RF) and Microwave

Another power source under investigation is the use of radio frequency (RF) and microwave heating to prevent ice formation on bridges. In direct electrical heating, a DC or AC power is applied to a conductive concrete overlay on the bridge surface to generate heat to melt the ice. RF power may be used to focus the heat to the ice formation directly.

The conductive concrete surface layer, together with the bridge sides, constitutes a lossy RF resonator with snow/ice or water forming on the surface. With sufficient concrete conductivity and proper arrangements of the conductive layers, RF excitation may generate enough heat for direct absorption by the ice formation. This scheme is similar to the heating process of a microwave oven. The feasibility of this approach depends on the RF properties of the conductive concrete mix. The RF characteristics of the conductive concrete mix is being studied at the two ISM (Industrial, Scientific and Medical) frequencies of 915 MHz and 2450 MHz in the L-band and S-band, respectively, which have been allocated by the FCC for commercial and industrial microwave applications.

CONCLUSIONS

The existing deicing methods for bridge deck and roadways have been surveyed and compared. Although using road salt is the most cost effective deicing method, it has detrimental effects on concrete structures and causes environmental concerns. The use of insulation materials for ice control and embedded electric or thermal heating for deicing have been attempted, however, they could not provide consistent deicing function or they were expensive to operate and difficult to maintain. A transient heat transfer analysis conducted has illustrated that the concept of using a conductive concrete overlay for bridge deck deicing is highly feasible and could become a cost effective deicing and anti-icing method. The experimental data from the small-scale slab heating tests have showed that the conductive concrete can achieve the desired electric conductivity and adequate mechanical strength. The heating was stable and uniform with 15 to 20 percent of conductive materials by volume. Small-scale slab heating experiments have shown that an average power of about 48 W/m2 was generated by the conductive concrete to raise the slab temperature from -1.1°C (30°F) to 15.6°C (60°F) in 30 minutes. This power level is consistent with the electrical heating applications cited in the literature for successful deicing.

The work described in this paper is part of an on-going research project being conducted for Nebraska Department of Roads. Two large slabs are under construction for bridge deck deicing experiment in natural environment to monitor power consumption and deicing performance. The construction costs and experimental data will be used to evaluate the cost effectiveness of using a conductive concrete overlay for bridge deck deicing.

ACKNOWLEDGMENTS

The authors would like to thank Dr. Maher K. Tadros, Dr. Bing Chen, and Dr. Lim Nguyen of the College of Engineering and Technology of the University of Nebraska–Lincoln, for their valuable suggestions during the planning of this research project. The financial supports provided by Nebraska Department of Roads and the Center for Infrastructure Research of the University of Nebraska–Lincoln are gratefully acknowledged.

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