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IDEA *Innovations Deserving Exploratory Analysis Project*

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Report of Investigation

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USE OF PHASE CHANGE MATERIALS TO PREVENT OVERNIGHT FREEZING OF BRIDGE DECKS

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USE OF PHASE CHANGE MATERIALS TO PREVENT OVERNIGHT FREEZING OF BRIDGE DECKS

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EXECUTIVE SUMMARY

When exposed to cooling conditions, many bridge surfaces freeze before nearby road surfaces built on ground. This phenomenon poses a hazard to motorists who are not expecting the icy bridge surface they encounter. The purpose of this project was to investigate the use of Phase Change Material (PCM) and other passive treatment concepts in concrete bridge decks to delay the onset of bridge surface freezing until contiguous land-based road surfaces have frozen. The PCM releases or absorbs heat at an approximately constant temperature as the material freezes or melts, respectively. During cooling of the bridge deck, the PCM freezes at a temperature several degrees above 0°C (32°F), releasing energy and delaying cooling of the deck surface. The addition of insulation to the bottom surface of the deck and the use of a darkened deck surface also were investigated for reducing the problem of early deck surface freezing. The goal of the program was to develop passive thermal bridge deck designs which would eliminate the need for road signs warning, "CAUTION - BRIDGE FREEZES BEFORE ROAD."

CONCEPT AND INNOVATION

The concept investigated during this program enhanced the thermal mass of a bridge deck by increasing the deck's ability to absorb and store thermal energy. The innovation was the use of PCM systems specifically engineered for the bridge deck application to enhance bridge deck energy storage, the use of insulation to reduce energy loss, and the use of coatings to modify the emissivity of the concrete deck to enhance solar energy absorption.

BACKGROUND

Typically, materials undergo a change in their physical form, from solid to liquid, and from liquid to gas, as the temperature is progressively increased from absolute zero. During this phase change from solid to liquid, and liquid to gas, heat is absorbed from the surrounding environment. Conversely, in cooling from gas to liquid, and liquid to solid, heat is given off. The energy that can be stored and released during the changes of state is called latent heat, and can occur over a very narrow range of temperature. Although the latent heat of vaporization is much higher than the latent heat of melting, the latter occurs with a relatively small change in material density and is, therefore, more attractive for structural applications.

Research performed at the University of Dayton Research Institute (UDRI), some of which is documented in Refs. 1-11, has demonstrated that the linear crystalline alkyl hydrocarbons from petroleum refining operations can provide a series of PCMs with very desirable cost/performance properties. UDRI has developed a process to engineer the melting and freezing to an exact temperature by mixing adjacent carbon chain length PCMs. This "engineering" of the melting and freezing to an exact temperature has significant importance for this program. Obtaining an optimized PCM bridge-deck system required the availability of a PCM with an optimized phase change temperature, T_{pc}, at a value above 0°C (32 °F).

Problems exist with the direct use of "neat" (100%) PCM. These problems include volume changes of 10% in melting and freezing, and low viscosity in the liquid state with the attendant problems of leakage. In previous research projects, UDRI developed a number of PCM-containing compounds that alleviate these problems. The three compounds employed in this investigation were a PCM/Silica gel, a PCM/Silica dry powder, and a PCM/High Density Polyethylene/Ethylene-Vinyl Acetate Copolymer/Silica plastic.

IDEA PROJECT INVESTIGATION

The emphasis in this Phase 1 project was twofold. In Stage 1, finite element thermal analysis was used to establish the ability to eliminate the early bridge freezing hazard using PCMs. A laboratory-scale test program was used to validate critical assumptions used in the analytical method. The analytical study established quantities and placement of PCMs required in a bridge deck. In Stage 2, a larger scale experiment was completed to evaluate various design parameters and the accuracy of the analysis method, and for initial investigation of practical implementation issues.

Analytical Design Study

Evaluation of design concepts incorporating PCM was performed using finite element (FE) analysis. FE models were constructed for a generic bridge and road. The bridge was modeled as a 20-cm-thick (8") slab of concrete. The road was modeled to a depth of 3.7 m (12') below the surface where the soil temperature was assumed to be a constant 10.6°C (51°F). Actual weather data for Dayton, Ohio for the period November 1993 through March 1994 was used as input to the analysis. The heat flow at the surface of bridges and roads is influenced by climatic conditions, the surface temperature, and the surface emissivity and absorptivity. The climatic conditions accounted for in this study included air temperature, wind speed, solar inclination, cloud cover, and air vapor pressure. The latent heat storage capacity of the PCM was modeled by considering the specific heat to be a function of temperature which was constant except for the short temperature range over which phase change occurs. In this temperature range, a step increase was added such that the area under the specific-heat-versus-temperature curve equaled the latent heat of fusion.

The analysis showed that for the baseline road and bridge configurations, the total time that the bridge was frozen before the road froze was 90 hours. Sample results for surface temperature versus time for the road, control bridge, and one PCM bridge concept are shown in Figure 1 for a one-day period. The elimination of the bridge freezing hazard in the early evening hours through the use of PCM can be observed in the figure.

Various PCM designs were assessed by comparing the cumulative time of early bridge freezing to the baseline of 90 hours. The parameters studied included the volume fraction of PCM, the phase change temperature, and the influence of insulation on the bridge deck. Results for an 20 cm (8") concrete bridge deck with various amounts of PCM pellets mixed in the top 10 cm (4"), various phase change temperatures, and insulation are shown in Figure 2. It can be seen that the early bridge freezing problem was virtually eliminated. The practical implementation issues for these configurations were not evaluated; however, the results indicate the improvement attainable from PCM technology.

Large-Scale Test Results

Three instrumented reinforced concrete slabs were fabricated. One slab was a control. The second slab had a granulated PCM melt-mix blended into the concrete at 18% volume fraction. The third slab had PCM-gel-filled polyethylene tubes embedded into the concrete. Each slab was 1.2 m x 2.4 m (4' x 8') in planform and 20 cm (8") thick. The specimens were suspended 1.5 m (5') above the ground to allow the exposure of both surfaces to wind (Figure 3). The specimens were subjected to winter weather in Dayton, Ohio during the months of February to April, 1996. The influences of bottom-surface insulation and darkening of the top surface also were investigated. A comparison of temperature time histories for the various treatment concepts was used to assess the performance of the various concepts.

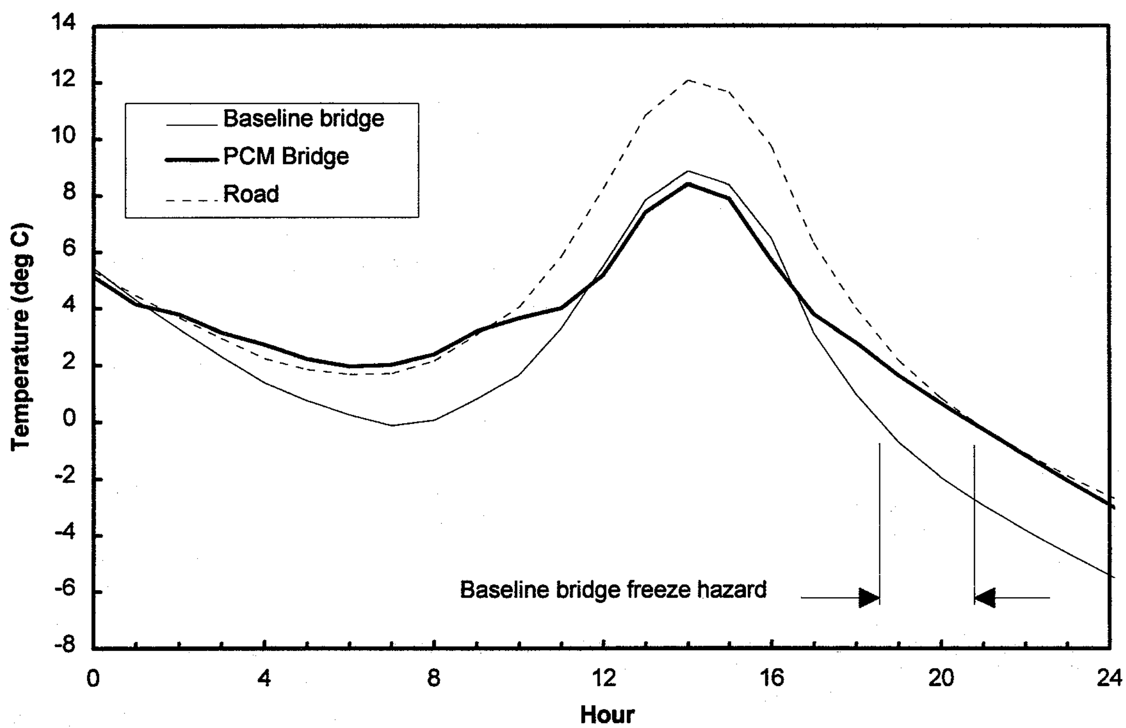

FIGURE 1 Surface temperature analysis results for Dayton, Ohio, November 27, 1993. (PCM bridge: 30% PCM pellets in upper half of 20-cm deck,4°C (39°F) phase change temperature.)

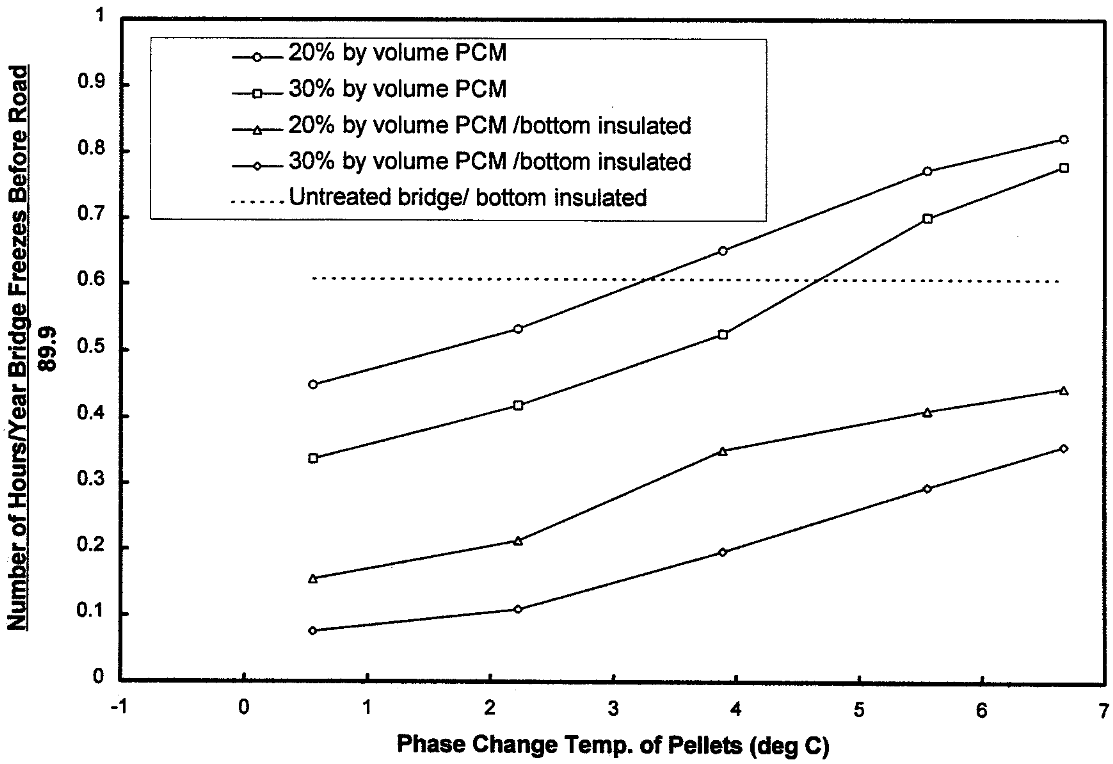

FIGURE 2 Hazard reduction as affected by phase change temperature for a 20-cm-thick deck with PCM pellets in the top half.

FIGURE 3 Outdoor exposure test sight.

The PCM performance was less than predicted by analysis. The primary reason for the reduced performance was the reduction in the thermal conductivity of the concrete/PCM mixture. This reduction resulted in reduced solar energy transmission into the concrete for charging the PCM and reduced transmission of the PCM energy to the surface of the concrete. Proper selection of additives for the formulation of the concrete/PCM mixture can eliminate the thermal conductivity problem. Darkening of the surface reduced concrete emissivity, demonstrating a reduction in the early freezing of the test slab.

The impact of insulation in the experiment indicated that the complete environment in which the bridge was placed needed to be considered. In some cases, insulation would be helpful; here, it would not be helpful.

PLANS FOR IMPLEMENTATION OF IDEA PROJECT

The goal of this Phase 1 effort was to obtain a recommendation for a PCM-based bridge configuration which can be expected, based on analysis and experiment, to virtually eliminate the early freezing of bridge deck surfaces. Such a bridge design was defined as a deck with 20% to 30% PCM; however, primary design issues including material strength, durability, producibility, inspectibility, and cost have not been completely addressed. Material issues need to be addressed using laboratory tests. A full-scale bridge demonstration project cannot be pursued until the primary design issues are completely addressed and any problems solved.

IDEA PRODUCT

The purpose of this project was to investigate the use of Phase Change Material (PCM) and other passive treatment concepts in concrete bridge decks to delay the onset of bridge surface freezing until contiguous land-based road surfaces have frozen. During cooling of the bridge deck, the PCM freezes at a temperature several degrees above 0°C (32°F), releasing energy and delaying cooling of the deck surface. Two additional design concepts were investigated for reducing the problem of early deck surface freezing. One was the addition of insulation to the bottom surface of the deck. The second was the use of a darkened deck surface in comparison with a light colored deck surface characteristic of concrete. The IDEA Product is the design of a bridge deck which incorporates 20% to 30% PCM and a surface darkening additive. This design will eliminate early bridge deck freezing.

CONCEPT AND INNOVATION

The concept was to develop ways to enhance the thermal mass of a bridge deck and the deck's ability to store thermal energy. If this concept could be developed, then the bridge deck would not freeze before the roadway. The innovation was the use of PCM systems specifically engineered for the bridge deck application.

All materials undergo a change in their physical form, from solid to liquid, and from liquid to gas, as the temperature is progressively increased from absolute zero. During this phase change from solid to liquid, and liquid to gas, heat is absorbed from the surrounding environment. Conversely, in cooling downward from gas to liquid, and liquid to solid, heat is given off to the environment. The energy that can be stored and released during the changes of state is called latent heat, and can occur over a very narrow range of temperature. Although the latent heat of vaporization is much higher than the latent heat of melting, the latter occurs with a relatively small change in material density and is therefore more attractive for structural applications.

Through research performed at the University of Dayton Research Institute (UDRI), some of which is documented in Refs. 1-11, we have determined that the linear crystalline alkyl hydrocarbons from petroleum refining operations can provide a series of PCMs with very desirable cost/performance properties including:

- high thermal energy storage (45-60 calories/gram),
- low-cost and available in large quantities,
- self-nucleating (no supercooling),
- stable to repeated thermocycling,
- non-toxic, not chemically reactive,
- non-hydrolyzable in an alkaline environment (e.g., concrete), and
- selectable melting temperatures from well below 0°C (32°F) to above 100°C (212°F).

In past research, UDRI prepared blends of adjacent polydisperse carbon chains in varying proportions, and precisely located a single intermediate melting and freezing temperature, without a significant reduction in heat of fusion and crystallization. This engineering of the melting and freezing to an exact temperature had significant importance for this program. Obtaining an optimized PCM bridge-deck system required the availability of a PCM with an optimized value of the phase change temperature, T_{pc}. The optimum T_{pc} was determined from the analytical study. This optimized PCM was obtainable by blending the commercially available materials NP-15 and A-12, which differ in mean carbon chain length by one. NP-15 has a phase change temperature of 6.8° C (44.3 °F), compared to -10.7°C (12.7 °F) for A-12.

There are problems associated with the direct use of "neat" (100%) PCM. These problems include volume changes of 10% in melting and freezing, and low viscosity in the liquid state with the attendant problems of leakage. To alleviate these problems, UDRI developed a number of PCM-containing compounds. The three compounds employed in the investigation include the following:

- *PCM/Silica (77/23) wt.% Gel.* Special grades of hydrophobic and hydrophylic silica have been developed that at about 23% wt. composition, convert the normally fluid liquid PCM to a stiff gel with reduced leaking tendency and improved heat transfer. This containment can advantageously be combined with the macro containment in tubes for use in the bridge deck applications.
- *PCM/Silica (65/35) wt. % Dry Powder.* This PCM compound retains the full latent heat of the 65% PCM but exhibits no volume change during the phase change. It remains in a powder form, both above and below the phase change temperature.
- *PCM/High Density Polyethylene/Ethylene-Vinyl Acetate Copolymer/Silica (60/16/8/16) wt. % (Melt-Mix Pellets).* This low-cost mixture provides a material that can be used to make PCM-containing pellets. The compound maintains a constant volume and solid material form as it passes through the phase change of the PCM.

The heating and cooling response of the bridge deck is a function not only of the internal properties of the deck materials and design, but also of factors influencing the radiative, convective, and conductive heat transfer with the environment. Therefore, the influence of adding insulation to the bridge deck, and of darkening the bridge deck surface (thereby increasing the radiation absorptivity) were considered during this program.

INVESTIGATION

This Phase 1 investigation was conducted in two stages. The goal of Stage 1 was to study, analytically, a range of PCM bridge deck design concepts, and to conduct small-scale tests to verify the analysis method. The goal of the Stage 2 effort was to demonstrate the performance of promising PCM bridge deck designs through a large-scale outdoor exposure test. The outdoor test employed three instrumented test slabs suspended above the ground to simulate a bridge deck environment. The following sections contain a discussion of the Stage 1 and Stage 2 efforts. Details of the Stage 1 effort are given in Ref. 13. Details of the Stage 2 effort are given in Ref. 14.

STAGE 1 PROGRAM

Discussions with regional and state department of transportation officials led to the conclusion that early bridge freezing was often associated with steel beam/reinforced concrete deck bridge designs. The concrete decks are thin—a typical range is 19.6 cm to 24 cm (7.75" to 9.5")—and are, therefore, prone to rapid thermal response to changing conditions. On this basis a 20-cm-thick concrete slab was adopted as the baseline bridge deck design. Analytical simulations were performed using both simple slabs, and slabs connected to steel support beams.

Design Concepts

Several concepts were considered for modifying a basic 20 cm (8") thick concrete slab. The concepts were assessed both independently and in various combinations during the analytical program. The specific design concepts were:

1. PCM melt-mix pellets blended directly with the concrete. A range of pellet volume percentages were explored.
2. PCM gel contained in a series of metal or polymer tubes located 2.5 cm (1") below the slab's top surface.
3. PCM melt-mix strips, or PCM dry powder, fixed to the undersurface of the slab.
4. Insulation applied to the bottom of the slab to reduce heat loss.
5. Asphalt coating applied to the top of the slab to increase absorption of solar radiation energy.

The specific configuration dimensions and properties are discussed in a later section.

Thermal Analysis Theory

The temperature distribution within a body as a function of time is governed by the classic continuum heat equation for a solid:

$$\frac{\partial T}{\partial t} = \frac{K}{\sigma\rho}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \qquad (1)$$

where K is the thermal conductivity, σ is the specific heat, ρ is the mass density, T is the temperature, and t is time. The latent heat of fusion of the PCM was easily modeled within the context of the heat equation by treating σ as a temperature dependent property. For a narrow temperature range dT in the vicinity of the phase change temperature, σ was assigned a value which was raised by an amount $d\sigma$ above the nominal specific heat. The product $dTd\sigma$ was selected to equal the latent heat.

Climatic Influence and Representation

At the boundaries of a solid, the heat flow, Q_s, into the surface is related to the thermal gradient at the surface by the equation:

$$Q_s = K\frac{\partial T}{\partial x_n} \qquad (2)$$

where x_n is the local outward coordinate direction normal to the surface. For the problem of temperatures in bridge decks and roads, Q_s is dependent on the surface temperature, the surface material properties, and on climatic influences that produce radiative, convective, and conductive heat transfer between the bridge and the environment. Previous researchers have developed analytical models for computing Q_s in terms of surface temperature, ambient air temperature, wind speed, degree of cloud cover, time of year, time of day, latitude, and air vapor pressure. The model used in the analytical study to account for all of these factors was the one presented in Ref. 12, and details of the use of the method are discussed in Ref. 13. The influence of falling precipitation and standing water or ice were not taken into account in the simulations.

Detailed weather data for Dayton, Ohio for the period November 1993 through March 1994 were obtained from the National Oceanic and Atmospheric Administration (NOAA) records and used as input to the climatic influence relations for the simulations in this study. The data include readings for temperature, relative humidity, sky cover, and wind speed, taken at three-hour intervals for the entire five-month period.

The environmental influence relations used in the analysis were different for the top and bottom surfaces of the bridge deck models. The full set of influences were applied to the top surface, assuming that the surface was level and completely exposed to sunlight. On the bottom surface, heat transfer with the air through convection and conduction were modeled, but it was assumed that there was no net radiative heating or cooling. For the steel beam/concrete deck configuration, it was assumed that in the cavities between the steel beams the wind velocity was reduced to 30% of the free-air value.

Thermal Analysis Implementation

The primary tool for thermal analysis was the ABAQUS finite element program licensed from Hibbitt, Karlsson & Sorensen, Inc., Pawtucket, RI. ABAQUS was used to perform two-dimensional finite element heat transfer simulations, fully accounting for the latent heat of fusion of the PCM. Incorporation of the climatic influence relations for boundary heat transfer was performed by writing custom procedures in the FORTRAN computer language which were compiled and linked with ABAQUS at run time. Two-dimensional finite element models simulating infinite length in one direction were produced for a road bed, a 20-cm-thick slab, a 20-cm-thick slab on steel beams, 20-cm-thick slabs with PCM-filled tubes of various diameters embedded below the top surface, and 20-cm-thick slabs with 2.5 cm - 5.1 cm (1" to 2") thick additions of PCM affixed to the bottom surface. Bottom-side insulation, when simulated, was modeled using a zero-heat-flux boundary condition.

The FE models were designed to simulate one-dimensional (through-the-thickness) response as much as possible, so the simple homogeneous slab configurations and the road bed were modeled using a single stack of rectangular two-dimensional elements, with symmetry conditions applied at the side edges. The PCM-in-tube configurations and the steel beam/concrete deck configurations required the creation of two-dimensional FE models which included detailed unit cell representations of the tubes or steel beams, as appropriate.

Thermal Simulations and Hazard Assessment

The FE models were subjected to a simulated five-month period of weather exposure using weather data for Dayton, Ohio for the period November, 1993 through March, 1994. The first two-week period was used as an initialization period for the roadbed and bridge temperatures, and was therefore not used to assess the treatment concepts. The surface temperature histories thus computed were used to assess the thermal performance of various designs. The roadbed model was used to compute baseline road surface temperatures. Baseline bridge deck models without PCM, insulation, or surface modification were used to establish a baseline hazard measure by computing the total number of hours over the simulation period that the bridge deck was frozen—surface temperature below 0°C (32°F)—while the road was thawed—surface temperature above 0°C (32°F). The hazard values (number of hours) for the different treatment concepts were computed in a similar manner and compared to the baseline values to determine the improvement due to the modifications.

Material Properties

The properties of the various materials used in the FE analyses are listed in Table 1. Some of the values were measured, some were found in references, and other values were computed using rules of mixture. The basis for all values is documented in detail in Ref. 13. Both concrete and asphalt appear in the table because the influence of the different surface absorptivities also was studied.

TABLE 1 Properties of Materials Used in Analysis

Material	Density ρ (g/cm^3)	Thermal Conductivity K (Kcal/h-m-°C)	Specific Heat σ (cal/g-°C)	Heat of Fusion (cal/g)	Absorption Coefficient α	Emissivity Coefficient ε
Concrete	2.32	1.19	0.2	0.0	0.7	0.9
Asphalt	2.32	0.60	0.2	0.0	0.9	0.9
Gravel	1.76	1.12	0.2	0.0	N.A.	N.A.
Soil	2.00	1.33	0.2	0.0	N.A.	N.A.
PCM Melt Mix	0.98	0.24	0.481	21.6 (N) 33.06 (T)	N.A.	N.A.
PCM Dry Powder	0.55	0.01	.433	23.39 (N) 35.78 (T)	N.A.	N.A.
PCM Gel	0.92	0.17	0.451	27 (N) 41.33 (T)	N.A.	N.A.
PCM Neat	0.87(s) 0.77(l)	0.14	0.496	36 (N) 55 (T)	N.A.	N.A.

(l) liquid
(s) solid
(N) Latent heat of NP-15 used
(T) Latent heat of tetradecane used
N.A. Not applicable

Two different values of latent heat appear, one of which corresponds to NP-15, 35 cal/g (64.8 BTU/lbm) and the other of which corresponds to tetradecane, 50 cal/g (99.0 BTU/lbm). Tetradecane is a highly refined material composed primarily of molecules with a single carbon chain length. NP-15 has the same mean carbon chain length as tetradecane, but there is a small range of variation in the chain lengths, resulting in a lower value of latent heat. NP-15 offers the advantage of low cost, while tetradecane offers the advantage of maximum latent heat per unit mass.

The phase change temperature of the PCM was taken as a variable to identify the optimal value corresponding to a given design concept. Adjustment of the phase change temperature was available in practice through material blending, as discussed in a preceding section.

Analysis Model Configurations

Nineteen different bridge deck configurations were used in the analytical study. Configuration 1 was a baseline 20 cm (8") thick concrete deck. Configurations 2 - 19 are illustrated in Figure 4. Some of the configurations were modeled both as simple slabs, and as slabs attached to steel support beams. The steel beam/concrete deck configurations featured steel beams spaced evenly at 2.6-m (8.5') intervals. A standard roadbed configuration was modeled with the following composition: a concrete surface layer 23 cm (9") thick, a gravel base layer 15 cm (6") thick, and a compacted earth subgrade layer.

Baseline Results

The baseline bridge deck and road models were subjected to the five-month simulated weather exposure period. For each model, two simulations were performed, one corresponding to concrete surface properties, and the other corresponding to asphalt surface properties. The hazard index for early bridge freezing was computed for each of the four possible combinations of bridge deck and road. The results were:

- 89.9 hours for concrete road/concrete bridge,
- 50.9 hours for concrete road/asphalt bridge,
- 175.4 hours for asphalt road/concrete bridge,
- 108.2 hours for asphalt road/ asphalt bridge.

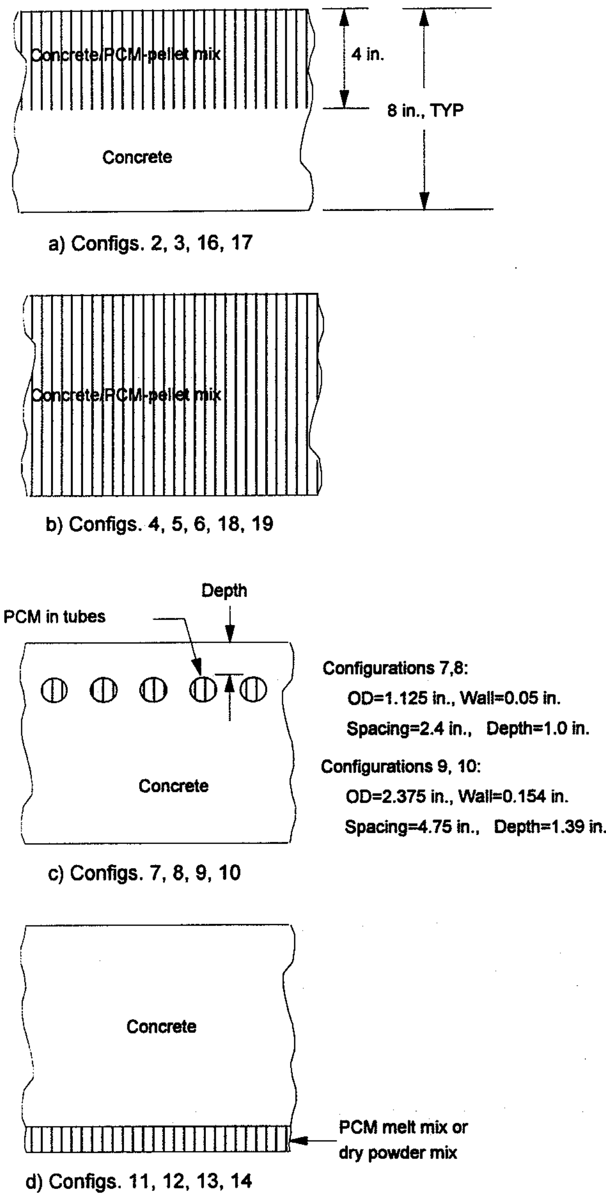

FIGURE 4 Configuration concept definitions for analytical design study.

It can be seen that for the two cases where the road and bridge surfaces were identical, the hazard index values were similar (89.9 hours and 108.2 hours for concrete/concrete and asphalt/asphalt, respectively). However, the situation was much worse when the deck surface was concrete and the road surface was asphalt. The smallest hazard index for early bridge freezing occurs when the deck surface was asphalt and the road surface was concrete. The results indicated the great benefit of having a bridge deck with lower emissivity than the plain concrete deck.

Design Study Results

All configurations evaluated were subjected to the simulated five-month weather exposure period. Some configurations were modeled both with and without bottom-side insulation. Several different phase change temperature values were investigated. Concrete surface properties were used for all deck configurations. The hazard index value for each configuration was computed with reference to the concrete-surface road, and a relative hazard index was obtained by dividing the hazard index value (in hours) by the value 89.9 hours computed for the baseline bridge deck. The relative hazard results are summarized in Table 2. Two values of relative hazard are listed for configurations 15-19 that include steel support beams. The first value applies to the temperature over the beam centerline, and the second applies to the bridge surface location centered between beams. For each configuration, the table lists the latent heat storage capacity per square meter of deck planform area. PCM pellet percentages refer to volume percentages. PCML refers to a PCM compound based on the latent heat properties of NP-15, and PCMH refers to a PCM compound based on the latent heat properties of tetradecane.

Conclusions from the analytical design study include the following:

1. All of the PCM concepts studied provided some reduction in the relative hazard.
2. 20% pellets by volume in the top four inches combined with bottom-side insulation reduced the relative hazard by 84% for a concrete-surfaced bridge deck and road combination.
3. The danger of early bridge freezing was worst after several days of warm weather, because the roadbed and ground become heated to a depth of several feet, providing a reserve of heat energy for delaying cooling of the road surface.
4. The baseline hazard due to early bridge freezing was least for an asphalt-surfaced bridge deck adjoined by a concrete-surfaced roadway.
5. The hazard was worst for a concrete-surfaced bridge deck adjoined by an asphalt-surfaced roadway.
6. The closer the PCM was to the deck surface, the closer the optimum phase change temperature was to 0°C (32°F). For pellet configurations, the optimum phase change temperature was in the range 0.6-2.2°C (33-36°F). For the PCM slab-on-bottom configuration, the optimum phase change temperature was near 5.6°C (42 °F).
7. Bottom-side insulation significantly reduced the relative hazard for both the baseline configuration and configurations containing PCM.
8. The presence of steel beams did not significantly affect the hazard index.

TABLE 2 Summary of Relative Hazard Results from Analytical Design Study.

DESIGNATION	LATENT HEAT
PCML	64.8 Btu/lbm (representative of NP-15)
PCMH	99.0 Btu/lbm (representative of tetradecane)

Relative Hazard = Hazard Index (Hours) / 89.9 (Hours)

20.32 cm Deck Configuration	Config. No.	PCM	Insulate Bottom	Phase Change Temperature (deg C)						Heat Storage Capacity BTU/sq. ft.
				N/A	0.56	2.22	3.89	5.56	6.67	
No Beams	1	No PCM		1.00						0
			X	0.61						
	2	20% PCML Pellets; Top 10.16cm			.45	.53	.65	.77	.82	43.19
			X		.16	.21	.35	.41	.45	
	3	30% PCML Pellets; Top 10.16cm			.34	.42	.53	.70	.78	64.41
			X		.08	.11	.20	.30	.36	
	4	20% PCMH Pellets; 20.32cm			.20	.28	.43		.67	131.93
	5	40% PCMH Pellets; 20.32cm			.08	.05	.19		.45	263.86
	6	60% PCMH Pellets; 20.32cm			.05				.30	396
	7	Neat PCML in 2.54cm CU Tubes							.95	27.21
	8-a	Neat PCML in 2.54cm PVC Tubes			.84	.67	.71	.81	.86	27.21
	8-b	Neat PCMH in 2.54cm PVC Tubes				.58	.64			41.56
	9	PCML Gel in 5.08cm Steel Pipes			.86	.71	.77		.93	44.41
	10	PCML Gel in 5.08cm Steel Pipes With 20% NP-15 Pellets on top At Phase Change = .55C			.47	.44	.48		.56	67.2
	11	2.54cm PCML Melt-Mix on Bottom							.78	53.99
	12	5.08cm PCML Melt-Mix on Bottom					.54		.60	107.98
			X			.29	.24	.23	.24	
	13	2.54cm PCML Dry Powder on Bottom	X		.51		.48		.49	32.75
	14	5.08cm PCML Dry Powder on Bottom	X				.46		.47	65.46
Beams	15	No PCM		.97/.92						0
			X	.62/.60						
	16	20% PCML Pellets; Top 10.16cm			.45/.41	.53/.49	.64/.60		.81/.77	43.19
	17	30% PCML Pellets; Top 10.16cm			.31/.28	.39/.35	.51/.47		.75/.7	64.41
	18	20% PCMH Pellets; 20.32cm				.27/.21				131.93
	19	40% PCMH Pellets; 20.32cm				.05/.03				263.86

Small-Scale Test Program

A small-scale test program was conducted to verify the analytical method. Two different types of tests were performed. The first was designed to provide experimental data for validating the thermal analysis of structures containing PCM, specifically with regard to the latent heat properties of the PCM. The second type of test was designed to provide experimental data for verifying the analytical treatment of the effect of climatic parameters on the temperatures of road surfaces.

Four concrete specimens were fabricated. Each specimen was 30.5 cm (12") square in platform and 20.3 cm (8") thick, with eight or more embedded thermocouples distributed through the thickness at the center of specimen. All tests were performed with 2.5 cm (1") of polystyrene foam insulation covering all surfaces except the top. The insulation on the sides was intended to promote one-dimensional thermal response. The bottom insulation was used so that thermal influences would be limited to the top surface. One specimen was plain concrete, one included NP-15 melt mix pellets, one included pure NP-15 in copper tubes mounted below the surface, and one included Paravan-147 melt mix pellets.

In the first set of tests, a room-temperature specimen was lowered upside down until the top surface was immersed in a bath of agitated ice water. The purpose of the tests was to generate a thermal response corresponding to an imposed-temperature 0°C (32°F) boundary value problem, thus enabling a verification of analytical modeling of material properties, including the latent heat properties of the PCMs. Temperature readings from the thermocouples were recorded periodically for several hours. Generally good agreement was obtained between analytical results and experimental data. Detailed results are presented in Ref. 13.

In the second test, a specimen was mounted outdoors on the roof of the Caldwell Street Center building at the University of Dayton, Dayton, Ohio. The purpose of the test was to provide experimental data for assessing the mathematical modeling of the influence of climatic parameters on roadway surfaces. Key climatic parameters (mean wind velocity, dry bulb air temperature, wet bulb air temperature, and cloud-cover percentage) were monitored and the thermal response of the specimen to the climatic influences was measured. Data were recorded every 30 minutes. Three test runs, ranging in duration from 7 to 17 hours, were conducted. Analytical simulations were then performed using the measured climatic data, and experimental and analytical results were compared.

When the measured climatic data were used with the baseline analysis method to compute the thermal response, there were significant discrepancies compared to the measurements. Studying the discrepancies lead to the hypothesis that convective cooling was under-represented, and solar heating was over-represented. Possible reasons include length-scale effects in the convective heat transfer which were not accounted for, uncertainty in quantifying the cloud cover, non-linear effects of wind speed which were not accounted for due to the use of time-averaged wind-speed values, and possible inaccuracies of the anemometer for very low wind speeds. Modifications to the influence equations were successful in improving the predicted temperature response (see Ref. 13). It was impractical to repeat all design study analyses using modified thermal influence coefficients. However, the purpose of the analytical simulations was to compare the temperature response of different configurations, not to predict actual temperatures, and the analytical predictions were sufficiently accurate for this purpose.

STAGE 2 PROGRAM

The focus of the Stage 2 program was a large-scale outdoor exposure test to measure the thermal performance of PCM-treated bridge deck concepts which showed promise during the Stage 1 design study. Three large 1.2 m x 2.4 m (4' x 8') in planform and 20-cm-thick instrumented reinforced concrete slabs were fabricated. One slab was plain concrete and served as a control specimen. The second slab had a granulated PCM melt-mix blended into the concrete. The third slab had PCM-gel-filled polyethylene tubes embedded in the concrete. The concrete mix in each of the three specimens was consistent with ODOT specifications. The specimens were suspended approximately 1.5 m (5') above the ground to allow the exposure of both the upper and lower surfaces to wind. The specimens were subjected to winter weather in Dayton, Ohio from February to April, 1996. Temperature data were recorded at five-minute intervals during this period using an automated data collection system. The influences of bottom-surface insulation and darkening of the top surface also were investigated. A comparison of temperature time histories for the various treatment concepts was used to assess the performance of the various concepts. Key details of the program are presented in this section.

Selection of the PCM Configurations

The first PCM design selected was a 20%/80% volume mix of PCM melt-mix pellets and concrete. The Stage 1 analysis showed this design to be an effective configuration, especially when used in conjunction with bottom-side insulation. The addition of the pellets raises concerns about the strength of the concrete; however, the emphasis in this program was to assess the potential gain in performance from the standpoint of thermal management. The issue of PCM impact on concrete strength was not evaluated. The second design selected featured tubes which were filled with PCM gel and embedded below the surface of the deck. Results obtained in the Stage 1 program suggested that metal tubes had the detrimental effect of forming a heat-conducting bridge through part of the deck thickness, hastening the drain of the thermal energy inside. For this reason, high-density polyethylene tubes were used to contain the PCM gel. A gel was selected because it reduced the chance and severity of leakage of the liquid-state PCM, should holes be present in the capped tubes. Based on the Stage 1 results and additional analyses, the optimal phase change temperature (T_{pc}) was found to be 1.7°C (35°F) for the pellet/concrete mix, and 2.8°C (37 °F) for the PCM-in-tubes concept for low-conductivity tube materials. To simplify material preparation, the compromise T_{pc} value of 2.2°C (36°F) was selected for both PCM design concepts.

PCM Blend Study

Two linear alkyl hydrocarbon materials, NP-15 and A-12, were blended to adjust the value of T_{pc}. Differential scanning calorimeter (DSC) characterizations were performed at heating/cooling rates of 2°C/min (3.6°F/min). Melting and crystallization temperatures were measured, and latent heat was determined. T_{pc} was taken to be the mean of the melting and crystallization temperatures. T_{pc} was measured at 6.8°C (44.3°F) for NP-15 and -10.7°C (12.7°F) for A-15. An 80%/20% blend of NP-15/A-12 was found to have a T_{pc} value of 1.9°C (35.4°F), approximately equal to the target value of 2.22°C (36°F), so this blend was selected as the PCM for the slab test program. Latent heat values for NP-15, A-12, and the 80%/20% blend were measured to be approximately 38, 44, 38 cal/g (68, 79, and 68 BTU/lbm), respectively.

PCM Compounds and Properties

The PCM-containing compounds were produced by Phase Change Laboratories (PCL), Inc., of San Diego, California. The desired composition for the PCM melt mix was NP-15/A-12/High Density Polyethylene/ Ethylene-VinylAcetate/ABS Silica/Santowhite Powder in approximate mass percentages 48/12/16/8/16/0.6. Santowhite Powder is an antioxidant. This formula can be used to create a melt-mix compound which has a room-temperature consistency similar to polyethylene. The melt mix can be extruded into pellets. For reasons of availability and timing, PCL chose to use Ethylene/Methyl Acrylate (EMA) copolymer in place of Ethylene-Vinyl Acetate. It was believed that this substitution would not affect the latent heat properties of the compound, however, it was known from past experience that the resulting melt-mix was low strength and chalky compared to the requested compound. The EMA compound was granulated for use in a concrete/melt-mix blend. The latent heat of the EMA compound was computed to be 22.7 cal/g (40.8 BTU/lbm) based on the mass fraction of PCM. However, the latent heat was measured at 16.1 cal/g (28.9 BTU/lbm). This measured value is 29% less than expected. The cause of the reduced latent heat was not determined.

The composition for the PCM gel was NP-15/A-12/ABS Silica/Santowhite Powder in approximate mass percentages 61.6/15.4/23/0.8 . The latent heat of the gel was not measured, but was computed to be 28.3 cal/g (51 BTU/lbm) based on the mass fraction of PCM.

Test Specimens

The three test slab configurations are described as follows:

Specimen 1: This specimen was a control specimen constructed of Class S Type III concrete in accordance with Ohio Department of Transportation specifications.

Specimen 2: This specimen featured granulated PCM melt-mix combined with Class S Type III concrete, with additional water to aid in mixing. The specimen was made with 76.5% by volume baseline concrete, 17.9% by volume granulated PCM melt-mix , and 5.6% by volume added water. The melt-mix fraction of 17.9% was slightly lower than the 20% target value.

Specimen 3: This specimen included PCM gel contained in ten 6 cm OD, 5.3 cm ID (2.4" OD, 2.1" ID) high density polyethylene (HDPE) tubes. The tubes were embedded in Class S Type III concrete, with the tops of the tubes 2.5 cm (1") below the slab surface. The tubes were 2.2 m (7'3") long and spaced 11.1 cm (4.4") on center.

Steel reinforcement was designed for each of the three slabs, based on the American Concrete Institute Building Code Requirements for Reinforced Concrete. The concrete strength in Specimen 2 was assumed to be reduced to half the nominal strength of the baseline concrete to account for the effect of the added PCM melt-mix granules. Each specimen was instrumented at two planform locations, specifically at the center of each 1.2 m x 1.2 m (4' x 4') half of the slab planform. The duplication in instrumentation provided the ability to investigate the effect of applying different external slab treatments to the two halves of a slab. At each planform location four Type T thermocouples were located through the thickness, for a total of eight thermocouples per specimen. Thermocouples were positioned at depths of 0 cm, 5.1 cm, 10.2 cm, and 20.3 cm (0", 2", 4", and 8"). Details of the slab fabrication process are discussed in Ref. 14.

Estimates for the Thermophysical Properties of the Slabs

The specific heat and latent heat of mixtures were assumed to be governed by a mass-fraction rule of mixtures. The baseline concrete properties used were 2.3 g/cm^3 (141.3 lbm/ft^3) density and 0.2 cal/g BTU/(lbm °F) specific heat. Water has a density of 0.9 g/cm^3 (62.4 lbm/ft^3) and a specific heat of 1.0 cal/g-°C. The PCM melt-mix had a computed density of 0.9 g/cm^3 (56.4 lbm/ft^3) and a specific heat of 0.48 cal/g-°C. Using these values along with the measured latent heat of the PCM melt mix and the theoretical latent heat of the PCM gel, the specific heat and latent heat values of the three specimens were determined on the basis of planform area. These values are presented in Table 3.

TABLE 3 Specific Heat and Latent Heat Area-Loadings of Test Specimens

Specimen No.	Specific Heat, Area Basis (cal/cm^2 °C)	Latent Heat, Basis (cal/cm^2)
1	2.99	0
2	3.18	52.9 (measured)
3	3.06	40.9 (theoretical)

Outdoor Test Installation

Following fabrication and one week of cure in a heated facility, the slabs were transported to the outdoor test site on February 20, 1996. The site was in the parking lot of the Shroyer Park Facility of the University of Dayton Research Institute (UDRI), located in Dayton, Ohio. Each slab was supported at the ends by wooden stands, allowing free air movement under the slabs. A photograph of the test site is provided in Figure 3. The thermocouple leads were connected to the data acquisition system which was housed inside a small heated equipment enclosure. An isolated thermocouple was affixed to the parking lot pavement using a thin layer of roofing tar, to measure a simulated road surface temperature. A second isolated thermocouple was suspended in air on the shaded side of the shed housing the data acquisition system to measure the air temperature.

Automated Data Acquisition

Analog-to-digital conversion of the thermocouple output signals was performed using a DaqBook/100 (IOtech, Inc. of Cleveland, Ohio) external analog-to-digital conversion unit. Two DBK19 Thermocouple Cards were used, providing the ability to monitor up to 28 thermocouples. The accuracy of temperature measurements for the DaqBook/DBK19 combination is approximately 0.8°C (1.5°F) according to the manufacturer. The DaqBook was connected to a Compaq 25 MHz 486 SCL Notebook Computer through the computer's printer port. The DaqView software by IOTech was used with the computer to perform data conversion and logging functions. Data were recorded automatically at five minute intervals. The test slabs were cleared of significant frozen precipitation on a daily basis.

Test Conditions

Data were recorded for the period from February 26, 1996 to April 10, 1996. The slabs were tested initially in the as-fabricated configuration, with all surfaces exposed. As the test program progressed, modifications were made to the slabs to investigate the influence of various treatments. In some cases, the modifications were made only to one half of a slab. Although this undoubtedly caused some thermal interaction between adjoining slab halves with different treatments, it was nonetheless desirable to assess a greater variety of thermal influences than would have been possible with only three distinct configurations. Modifications included insulation of the side edges (to eliminate the edge effects), insulation of the bottom surface, and darkening of the top surface. The complete record of the modifications and implementation dates is included in Ref. 14.

Results

Numerous plots of the data from the outdoor tests are presented in Ref. 14. Conclusions from the test results presented in Ref. 14 are discussed here.

The concrete/PCM melt-mix blend appears to have significantly reduced conductivity compared to plain concrete. The evidence supporting this theory follows. In the absence of a phase change, the surface of Specimen 2 responded more quickly to heating and cooling conditions than did the surface of Specimen 1. An inspection of temperature distributions through the thickness showed steeper thermal gradients in Specimen 2 than in Specimen 1. Since the specific heat of the two specimens was similar (Table 3), the difference in surface temperatures suggests a difference in thermal conductivity. The decreased thermal conductivity is detrimental to the goal of delaying bridge surface freezing during cooling conditions, because the deck surface cooling is accelerated. Specimen 3 exhibited the same qualitative behavior in this regard as Specimen 2, though to a lesser degree. However, the mechanism of reduced conductivity was different. The tubes containing the PCM were made of polyethylene, which is a poor conductor compared to concrete. Thus the tubes formed a thermal barrier between the top layer of concrete and the rest of the specimen.

The influence of latent heat in Specimen 2 was evident in the data when the phase change temperature was traversed. However the detrimental influence of the reduced conductivity worked counter to release of the latent heat, so that the sought-for delay of cooling to 0°C (32 °F) was not achieved. A typical response can be seen in the test data shown in Figure 5. The air temperature and surface temperatures are plotted for a 24-hour period in the figure. The parking lot temperature typifies the response of an asphalt-surface road. Specimens 1 and 2 both have bottom surface insulation and darkened top surfaces. After a cool night (-6°C (22°F) air temperature), solar heating during the day caused the pavement and slab surface temperatures to climb dramatically, reaching peak values between 22°C (72°F)

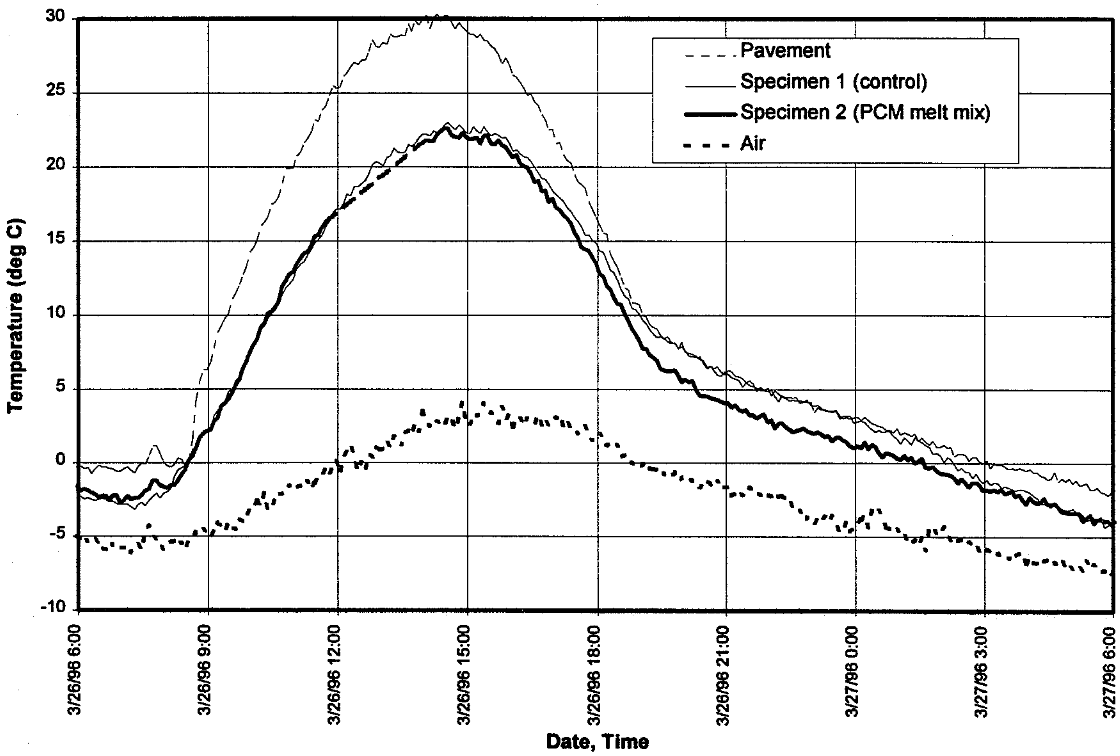

FIGURE 5 Air, pavement, and surface temperature measurements for the period 6:00 3/26/96 to 6:00 3/27/96.

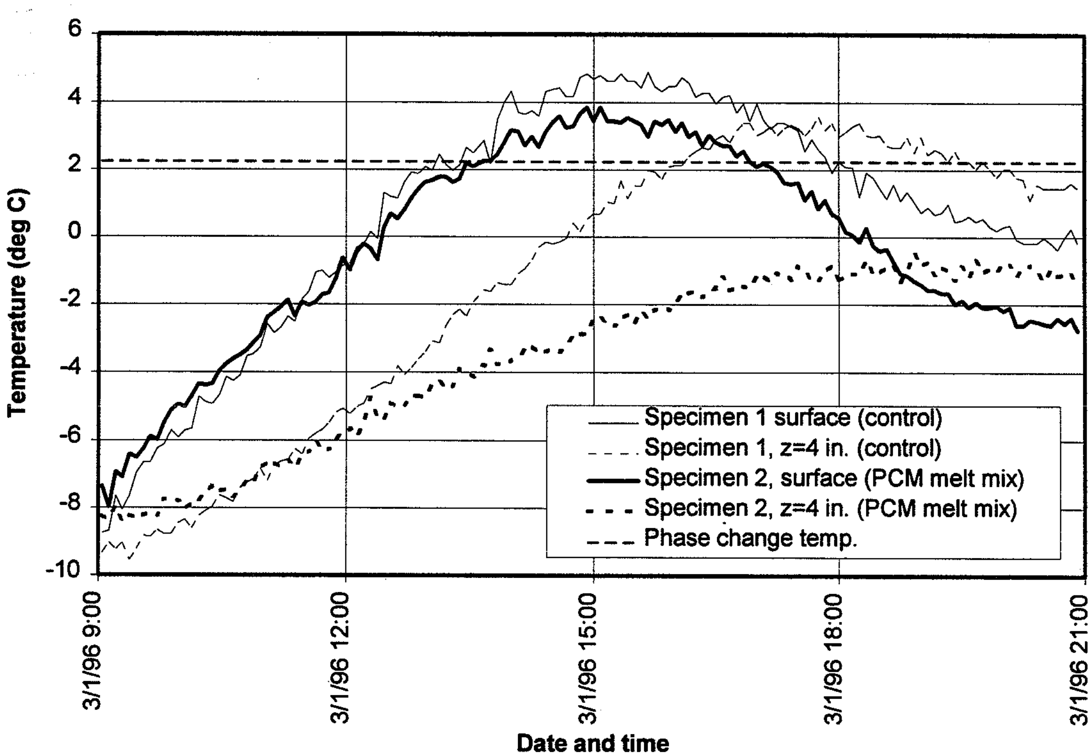

FIGURE 6 Top surface and internal slab temperature measurements for the period 9:00 3/1/96 to 21:00 3/1/96.

and 30°C (86°F), far in excess of the peak air temperature of 3°C (38°F).

Cooling conditions began at 16:00 on 3/26/96 and continued until after 6:00 the next morning. The PCM slab surface initially cooled more rapidly than the control slab, reaching 3°C (38°F) approximately two hours before the control. As the surfaces cooled beyond this temperature, the control slab cools more quickly, so that both slab surfaces reach -3°C (27°F) at the same time. This data clearly illustrates the ability of the phase change energy to slow surface cooling. However, due to reduced conductivity in Specimen 2, there was such a large temperature disadvantage before the phase change began that the desired freezing delay was not achieved.

Another time segment showing interesting thermal behavior is presented in Figure 6. A plot of the surface and internal (z = 10 cm). temperatures of Specimens 1 and 2 is presented in Figure 6 for the period 3/1/96 9:00 to 3/1/96 21:00. This period was preceded by a day of very cold weather, so slab temperatures begin around -8°C (17°F), and the PCM was in its low-energy state. Daytime heating on 3/1/96 caused the temperature of the slab surfaces to climb, and the two slab surfaces were within one degree of each other until the temperatures climbed above 2°C (36°F), at which point the control slab warmed faster than the PCM slab. The mid-thickness temperature climbed much more rapidly in the control slab than in the PCM slab. The control slab reached peak temperatures of 5°C and 3°C (41°F and 38°F) at the surface and at z = 10 cm (4"), respectively, whereas the corresponding temperatures for the PCM slab were 3°C and -1°C (38°F and 30°F). The PCM slab surface dropped below 0°C (32°F) more than two hours before the control slab. Because of the combined effects of the low conductivity of the PCM slab and the phase change energy absorbed at 2°C (36°F), the majority of the thickness of the PCM slab never reached the phase change temperature, and thus the PCM remained mostly uncharged and was unable to delay cooling. Specimen 3 exhibits the same qualitative behavior with respect to phase change transitions as Specimen 2, though to a lesser degree. The lower latent heat area loading of Specimen 3 (Table 3) provides an explanation for the lesser influence of the PCM.

Darkening of the top slab surface had a strongly beneficial effect on the surface temperature of a concrete deck. Heating of the top surface by solar radiation was increased due to the increased surface absorptivity. In the test program, the result was that the surface temperature of a darkened slab was always warmer than the surface of a similar slab with an undarkened surface. Darkening of the top surface offers a potentially simple and inexpensive approach for significantly reducing the early freezing hazard of concrete-surfaced bridge decks.

In the Stage 1 analytical design study, insulation was found to have a strongly positive influence. The test data, however, gave mixed results. During several cooling trends, bottom-surface insulation significantly delayed top-surface cooling through 0°C (by as much as two hours). However, there also were cases where the specimens were cold throughout from a cold weather spell, and the insulation delayed daytime warming. When cooling ensued later in the day, the surface of the insulated specimen cooled through 0°C more quickly (by as much as two hours) than on the uninsulated specimen.

Whether or not bottom-surface insulation is a net benefit or detriment to the problem of early freezing may be a strong function of the situation of the bridge with respect to lower surface heating and cooling. In the analytical study, the underside of the deck was given a neutral boundary condition with respect to radiation. In other words, the boundary condition was that no net energy gain or loss occurred through radiation. Convective and conductive heat transfer due to air and wind were modeled. For the test configuration, heating of the ground pavement near the specimens may have resulted in significant slab undersurface heating due to radiation, since the slabs were relatively small and thus did not block much of the ground surface from solar heating. This condition may have made insulation a mixed blessing for the tests. For a large-area bridge deck, however, the ground underneath may tend to stay cold because of constant shade, and may work to cool the bridge deck in terms of the net flux of thermal radiation energy. Under-surface insulation would be beneficial in this situation. A large number of interrelated factors characterize the general situation of a bridge with respect to lower surface heating. Factors include the exposure to wind, the orientation with respect to solar radiation, the type of groundcover underneath (vegetation/water/dirt), and so forth. No information was found in the literature which discussed the correlation of these factors with the early freezing problem, and yet a strong correlation may exist. A study to determine such correlations would be valuable in helping to focus efforts aimed at reducing the early freezing hazard.

PLANS FOR IMPLEMENTATION

The program successfully demonstrated the influence of PCM on bridge surface temperatures. The trends and impacts seen indicate the real potential of reducing the bridge deck early freezing with a PCM/bridge deck design. The specific implementations tested demonstrated adverse effects which worked against the performance improvement offered by the use of the PCM. The adverse effects seen during outdoor tests were directly related to the reduced thermal conductivity in the

PCM/concrete designs. The modification of the PCM/concrete thermal conductivity can easily be accomplished by adding the proper ingredient to the concrete. Implementation of the PCM concepts to a full-scale bridge deck is not appropriate at this time. The system modifications identified need to be validated and implementation issues need to be addressed.

CONCLUSIONS

The results of the efforts completed during this Phase 1 program lead to the following conclusions.

1. The phenomenon of early bridge deck freezing is influenced by a large number of interacting bridge design factors, and environmental influences. No scientific data are available in the literature or from federal, state, or local DOTs which define specific weather, bridge, and environmental conditions leading to early bridge freezing. This lack of data makes the task of designing, analyzing, and assessing the performance of freeze-delaying technology difficult.
2. Passive thermal treatments (PCMs, insulation, emissivity changes) can significantly reduce the hazard of early bridge freezing; however, there are design issues which must be addressed before a final design and demonstration can be completed.
3. Based on the analytical design study, passive thermal treatment concepts incorporated into a bridge deck can reduce by over 90% the amount of time that a bridge surface is frozen when the neighboring roadway is not frozen.
4. The large-scale experiment did not demonstrate the effectiveness of the PCM in reducing the early freeze hazard. One reason for this was the reduced thermal conductivity of the PCM/concrete deck. The reduction in thermal conductivity reduced access to the thermal energy distributed through the slab thickness.
5. The large-scale experiment did demonstrate the effectiveness of the PCM in significantly reducing the rate of surface cooling. However, because of the detrimental effects of the reduced thermal conductivity, the reduced cooling rate did not positively impact the time that the deck surface reached 0 °C (32 °F).
6. Based on the experimental results, increasing the absorptivity (darkening) of the surface of a concrete slab will increase the surface temperature at all times. Therefore, darkening the surface of concrete bridge deck is a simple way to reduce the early freezing hazard.
7. The effectiveness of bottom-surface insulation appears to be extremely dependent on the environmental setting of the bridge deck. Critical factors include the orientation of the bridge underpass with respect to the wind direction and solar radiation, the bridge width and height, and the type of ground cover (vegetation/water/dirt) underneath the bridge. The analytical study showed benefits to the use of b_1 - s_1 insulation, but the experimental results did not support this conclusion. The discrepancy is believed to be due to the strong bottom-surface heating associated with the test configuration.
8. The danger of early bridge freezing was the worst after several days of warm weather, because the roadbed and ground became heated to a depth of several feet, providing a reserve of heat energy for delaying cooling of the road surface.
9. The baseline hazard due to early bridge freezing was least for an asphalt-surfaced bridge deck adjoined by a concrete-surfaced roadway. The hazard was worst for a concrete-surfaced bridge deck adjoined by an asphalt-surfaced roadway.

RECOMMENDATIONS

Based on the results of this Phase 1 program, the following recommendations for further development of a passive thermal system to control early bridge freezing are made.

1. A program to refine the passive thermal control system design, based on the results of this Phase 1 program, and demonstrate the effectiveness of the concept is required. This program must address the critical design issues, material issues and demonstration issue defined as result of this Phase 1 program. The design issues include the optimum thermal conductivity, phase change temperature, phase change material, and deck absorptivity. The material issues involve obtaining the defined optimum design parameters using materials which have the potential to be compatible with bridge deck construction. The demonstration issue is the completion of a large-scale (but not a bridge) test which successfully demonstrates the function of the passive thermal control system.
2. After the successful large-scale demonstration of the passive thermal control system, a program will be needed to address all of the practical implementation issues for the incorporation of the passive thermal control system into a real bridge structure. Issues such as cost, installation method, strength, durability, and reparability must be

evaluated. The passive thermal control system design modifications needed to meet implementation constraints will be developed.
3. The final functional design for the passive thermal control system must be demonstrated on an operational bridge for a period of at least two years to validate the operation of the system.
4. A study to establish the specific circumstances of early bridge freezing is needed. Such a study would better define the operational environment over which a passive thermal system for the control of early bridge freezing must be functional. This definition would provide a better focus for the design and evaluation of concepts to delay bridge freezing.

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