CONSIDERATION OF DIFFERENTIAL ICING CONDITIONS IN THE DESIGN OF PAVEMENT SYSTEMS OVERLYING GEOFOAM LIGHTWEIGHT FILLS

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ABSTRACT

An explicit pavement design procedure to minimize differential icing conditions of pavements underlain by non-earth materials, such as geofoam lightweight fills, is currently not available. Therefore, to initiate the design development process, a differential icing study was performed to evaluate the effect of pavement material type and thickness, geofoam type and thickness, and concrete separation layer thickness on pavement surface temperatures and to provide pavement system design recommendations for minimizing the potential for differential icing conditions. This study demonstrates the use of the Enhanced Integrated Climatic Model (EICM) as an analysis tool to design pavement systems against the potential for differential icing conditions. The pavement surface temperatures between the proposed pavement system over geofoam lightweight fill and the adjacent pavement system over natural soil obtained from the EICM can be compared and the proposed pavement system over geofoam can be modified during design until similar temperatures are obtained at the surface of both pavement systems. Differential icing must be considered in the design of pavement systems placed over geofoam regardless of the thickness of geofoam placed in the embankment. A thicker pavement surface and/or granular base will minimize the potential for differential icing but the effect diminishes with increasing thickness. The use of a concrete separation layer decreases the potential for differential icing, but the effect also decreases with increasing concrete thickness.
INTRODUCTION

Figure 1 shows a comparison of heat flow between a pavement system overlying a geofoam lightweight fill and an adjacent pavement system overlying only a natural soil subgrade during the winter in the evening and morning when air temperatures are lower than the temperature of the pavement system materials. Heat flow occurs from the natural soil subgrade up into the atmosphere in the section of roadway with no geofoam. However, heat flow predominantly occurs only from the pavement system base and surface, which may consist of either an asphalt concrete (AC) or Portland cement concrete (PCC), in the section of roadway with geofoam. Minimal heat flow occurs from the natural soil subgrade through the geofoam because geofoam exhibits good insulative properties. Therefore, heat dissipates faster from the pavement system over the geofoam and this faster heat loss results in a lower pavement surface temperature over the geofoam than in the non-geofoam area. This variance in pavement surface temperatures may initiate differential icing conditions during cold temperatures. This research addresses differential icing conditions of pavements overlying expanded-polystyrene (EPS) block geofoam utilized for the function of lightweight fill.

![Figure 1 Effect of geofoam layer on pavement surface temperatures.](image)

Differential icing is caused by the formation of ice on the pavement surface that is underlain by non-earth lightweight fill material adjacent to a pavement surface underlain by soil that is ice free ($f$). Problems related to differential icing conditions were first observed with the use of insulated pavement systems in the late 1960s to early 1970s (2-5). Differential icing conditions tend to be sudden and unrecognizable until the vehicle is upon the area with icing. Thus, it presents a safety hazard and must be considered in the design of a geofoam pavement system.

The NCHRP 24-11 study (6, 7) revealed that an explicit pavement design procedure to minimize differential icing conditions and solar heating effects of pavements underlain by non-earth materials to include geofoam lightweight fills is currently not available. Therefore, to initiate the design development process, the overall research objective of the differential icing study reported herein was to evaluate the effect of pavement material type and thickness, geofoam type and thickness, and PCC separation layer thickness on pavement surface temperatures and to provide pavement system design recommendations for minimizing the potential for differential icing conditions.
RESEARCH APPROACH

The study of temperature distribution through a pavement system is complex because it involves many variables such as climatic conditions, i.e., daily minimum and maximum air temperatures, cloud cover, wind speed, and precipitation amounts; and pavement material and soil subgrade properties, i.e., thickness, unit weight, thermal conductivity, and heat capacity. Additionally, the assessment of temperature distribution is further complicated by the fact that the thermal properties of soils are dependent on the water content and ice content which vary with time. Therefore, a heat-transfer model that considers these climatic, pavement, and soil subgrade material properties as well as the influence of water content and ice content on soil thermal properties is needed to study the temperature distribution through a pavement system.

The Enhanced Integrated Climatic Model (EICM) is a one-dimensional coupled heat and moisture flow model that provides estimates of temperature distribution in the pavement system and soil subgrade based on climatic inputs and pavement material and soil subgrade properties (8). The EICM analytical model will be incorporated in the AASHTO Mechanistic-Empirical (M-E) Design Guide Software (9). The theoretical basis for the EICM is described in (10-12). Version 3.0 of the EICM was utilized for this research. Detailed input definitions as well as suggested values for the EICM are provided in (13).

Although the results of the EICM have been verified on multilayered pavement systems over a natural soil subgrade, the EICM has not been used to evaluate temperature distribution of pavement systems over lightweight fills. Therefore, the applicability of the EICM to lightweight fill materials was initially investigated. The EICM was also used to perform a sensitivity analysis to facilitate the pavement design process by evaluating the effect of pavement material type and thickness and geofoam type and thickness on pavement surface temperatures. The effect of utilizing a PCC load distribution slab between the pavement system and geofoam was also evaluated.

A summary of the application and sensitivity study is described subsequently. Pavement system design recommendations based on the application and sensitivity study are also provided.

APPLICATION STUDY

The purpose of the application study was to determine the applicability of the EICM to evaluate temperature distribution of pavement systems over geofoam lightweight fills. The New York State Department of Transportation (NYSDOT) installed thermistors within the granular subbase of a pavement system placed over EPS-block geofoam, which was used to stabilize a roadway along an unstable slope. A summary of this case history is provided in (7, 14, 15). Figure 2 (a) provides the cross section of the pavement system over EPS-block geofoam and the thermistor location and a summary of the material properties incorporated in the analysis. Table 1, Column A, provides a summary of the required input parameters for the EICM. Table 1, Column B, shows the input values used for the applicability study. The basis for the EICM input values and the material properties is included in (16).
Asphalt Concrete (AC)
Thermal Conductivity=9.97 cal \( \text{cm} \cdot \text{hr} \cdot \circ\text{C} \) (0.67 Btu \( \text{hr} \cdot \circ\text{F} \))
Heat Capacity=0.22 cal \( \text{g} \cdot \circ\text{C} \) (0.22 Btu \( \text{Btu} \cdot \circ\text{F} \))
Total Unit Weight=2,371 kg \( \text{m}^3 \) (148 lbs \( \text{ft}^3 \))

Thermistor Location
Subbase, NYSDOT Type 2
Thermal Conductivity=20.83 cal \( \text{cm} \cdot \text{hr} \cdot \circ\text{C} \) (1.4 Btu \( \text{hr} \cdot \circ\text{F} \))
Heat Capacity=0.25 cal \( \text{g} \cdot \circ\text{C} \) (0.25 Btu \( \text{Btu} \cdot \circ\text{F} \))
Total Unit Weight=2,162 kg \( \text{m}^3 \) (135 lbs \( \text{ft}^3 \))

Portland Cement Concrete (PCC)
Thermal Conductivity=14.88 cal \( \text{cm} \cdot \text{hr} \cdot \circ\text{C} \) (1 Btu \( \text{hr} \cdot \circ\text{F} \))
Heat Capacity=0.22 cal \( \text{g} \cdot \circ\text{C} \) (0.22 Btu \( \text{Btu} \cdot \circ\text{F} \))
Total Unit Weight=2,403 kg \( \text{m}^3 \) (150 lbs \( \text{ft}^3 \))

EPS-Block Geofoam
Thermal Conductivity=0.3 cal \( \text{cm} \cdot \text{hr} \cdot \circ\text{C} \) (0.02 Btu \( \text{hr} \cdot \circ\text{F} \))
Heat Capacity=0.29 cal \( \text{g} \cdot \circ\text{C} \) (0.29 Btu \( \text{Btu} \cdot \circ\text{F} \))
Total Unit Weight=20 kg \( \text{m}^3 \) (1.25 lbs \( \text{ft}^3 \))

Underdrain Filter, NYSDOT Type 1
Porosity=0.4 SG=2.65
Saturated Permeability=8.47 cm \( \text{cm} \cdot \text{sec} \) (0.29 ft \( \text{sec} \))
Dry Unit Weight=2,002 kg \( \text{m}^3 \) (125 lbs \( \text{ft}^3 \))
% Passing #4 Sieve=13 PI=0%
% Passing #200 Sieve=0 D\_(60)=12 mm

Clayey Silt, AASHTO A-4
Porosity=0.38 SG=2.71
Saturated Permeability=6.47 x10\(^{-7}\) cm \( \text{cm} \cdot \text{sec} \) (2.78 x 10\(^{-8}\) ft \( \text{sec} \))
Dry Unit Weight=1,762 kg \( \text{m}^3 \) (110 lbs \( \text{ft}^3 \))
% Passing #4 Sieve=90 PI=3%
% Passing #200 Sieve=60 D\_(60)=0.05 mm

(a) Actual Pavement Section
(b) Model Pavement Section

Figure 2 Comparison between field and model pavement section layers. Actual pavement section is located at Station 58 m, 1.5 m right (1+90 ft, 5 ft right).
Table 1  Summary of EICM Input values

<table>
<thead>
<tr>
<th><strong>Column A</strong></th>
<th><strong>Column B</strong></th>
<th><strong>Column C</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sta. 1+90 ft</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5 ft Right</td>
<td></td>
</tr>
<tr>
<td><strong>Model Initialization</strong></td>
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<td></td>
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<tr>
<td>Model description:</td>
<td>with geofoam</td>
<td>sensitivity analysis</td>
</tr>
<tr>
<td>Year to be modeled:</td>
<td>1997</td>
<td>1996</td>
</tr>
<tr>
<td>First month in analysis period:</td>
<td>September</td>
<td>September</td>
</tr>
<tr>
<td>First day of month in analysis period:</td>
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<td>1</td>
</tr>
<tr>
<td>Length of analysis period (days):</td>
<td>365</td>
<td>365</td>
</tr>
<tr>
<td>Time increment for output (hours):</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Time increment for calculation (hours):</td>
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<td>0.1</td>
</tr>
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<td>Enter latitude to calculate solar radiation:</td>
<td>42.14</td>
<td>42.14</td>
</tr>
<tr>
<td>Longitude (optional):</td>
<td>-74.18</td>
<td>-74.18</td>
</tr>
<tr>
<td>Elevation (optional) (m, ft):</td>
<td>440, 1445</td>
<td>440, 1445</td>
</tr>
<tr>
<td><strong>Climatic/Boundary Conditions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hourly temperatures (°C, °F):</td>
<td>Created by interpolating two weather stations</td>
<td></td>
</tr>
<tr>
<td>Hourly rainfall (cm, in.):</td>
<td>Created by interpolating two weather stations</td>
<td></td>
</tr>
<tr>
<td>Hourly wind speed (m/sec, ft/sec):</td>
<td>Created by interpolating two weather stations</td>
<td></td>
</tr>
<tr>
<td>Percent sunshine:</td>
<td>Created by interpolating two weather stations</td>
<td></td>
</tr>
<tr>
<td>Hourly water table depth (m, ft):</td>
<td>9, 30</td>
<td>9, 30</td>
</tr>
<tr>
<td><strong>Thermal Properties</strong></td>
<td></td>
<td></td>
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<tr>
<td>Surface short-wave absorptivity:</td>
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<td>0.85 (AC) 0.80 (PCC)</td>
</tr>
<tr>
<td>Upper temperature limit of freezing range (°C, °F):</td>
<td>0, 32</td>
<td>0, 32</td>
</tr>
<tr>
<td>Lower temperature limit of freezing range (°C, °F):</td>
<td>-1.1, 30</td>
<td>-1.1, 30</td>
</tr>
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<td><strong>Infiltration and Drainage Model Inputs</strong></td>
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<td></td>
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<td>Linear length cracks/joints on one side of pavement (m, ft):</td>
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<td>0, 0</td>
</tr>
<tr>
<td>Total length surveyed for cracks and joints (m, ft):</td>
<td>91, 300</td>
<td>91, 300</td>
</tr>
<tr>
<td>One side width of base (m, ft):</td>
<td>9.1, 30</td>
<td>9.1, 30</td>
</tr>
<tr>
<td>Slope ratio/base tangent value (percent):</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Type of fines added to base course (clay, silt, inert filler):</td>
<td>inert filler</td>
<td>inert filler</td>
</tr>
<tr>
<td>Percentage of fines in base course:</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>Percentage of sand in base course:</td>
<td>13</td>
<td>70</td>
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<tr>
<td>Percentage of gravel in base course:</td>
<td>87</td>
<td>10</td>
</tr>
<tr>
<td>Internal boundary condition (flux, suction):</td>
<td>suction</td>
<td>suction</td>
</tr>
<tr>
<td><strong>Material Properties</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>For materials not sensitive to moisture changes, i.e., asphalt and PCC: See Figure 2 and 4 for these values.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness of layer (cm, in.):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of elements in layer:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity (cal/cm-hr-°C °C/hr-ft-°F):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat capacity (cal/g-°C °C/lb-°F):</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 1 (continued)

<table>
<thead>
<tr>
<th>Column A</th>
<th>Column B</th>
<th>Column C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total unit weight ( ( \frac{g}{cm^3}, \frac{lbs}{ft^3} )):</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*For materials sessitive to moisture changes, i.e., soil materials: See Figure 2 and 4 for these values.*

| Thickness of layer (cm, in.): | | |
| Number of elements in layer: | | |
| Porosity of layer: | | |
| Specific gravity, SG: | | |
| Saturated permeability ( \( \frac{cm}{hr}, \frac{ft}{hr} \)): | | |
| Dry unit weight ( \( \frac{g}{cm^3}, \frac{lbs}{ft^3} \)): | | |
| Percent passing No. 4 sieve: | | |
| Plasticity Index, PI (%): | | |
| Percent Passing No. 200 sieve: | | |
| Diameter D\(_{60}\) (mm): | | |

**Initial Temperature Profile**

<table>
<thead>
<tr>
<th>Surface (°C, °F):</th>
<th>11.7, 53.1</th>
<th>19.1, 66.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom (°C, °F):</td>
<td>7.2, 45</td>
<td>7.2, 45</td>
</tr>
</tbody>
</table>

The NYSDOT provided thermistor and air temperature data for February 17 through 20, 1998 for this research. However, pavement surface temperatures and other climatic data such as cloud cover, wind speed, and precipitation amounts were not measured. Therefore, the application study consisted of adjusting the interpolated climatic data from the Albany International Airport in Albany, NY, and the Dutchess County Airport in Poughkeepsie, NY, weather stations, which are the two nearest weather stations to the case history site, until a suitable combination that yielded model thermistor location temperatures similar to the field thermistor temperatures for February 17 through 20, 1998. Figure 3 shows a comparison between the model and field temperatures obtained at the thermistor location with the adjusted climatic data for February 20. As shown, good agreement was obtained between the model and field thermistor location temperatures. Further details of the climatic adjustments made and the basis for these adjustments is included in (16).

The adjustment of the interpolated climatic data is reasonable because for evaluating differential icing potential during pavement system design, it is sufficient to utilize estimated values for the climatic variables provided both the pavement system model over geofoam and the adjacent pavement system model over natural soil subgrade are subjected to the same climatic values.
The EICM was developed to analyze traditional pavement systems overlying natural soil subgrade. Consequently, several limitations were encountered when the EICM was initially used to model the actual field pavement system over the geofoam shown in Figure 2 (a). A summary of these problems is presented below:

- Material layers can only be created in the EICM by identifying the layer as either AC, PCC, stabilized material, or as a soil layer. Default material properties are initially provided for these layers but these properties can be revised. For example, if an AC layer is initially selected, the default material properties, i.e., thermal conductivity, heat capacity, and total unit weight, can be changed to other values say material X property values. Thus, although the default material type is indicated in the EICM as AC, the analysis is based on the material X properties that are input. Therefore, the material properties that are input are more critical in the analysis than the material type initially selected.
- At least two soil layers are required in the model. Granular bases and subbases are treated as soil layers. Additionally, soil layers cannot be placed above AC and/or PCC layers.
- The number of PCC layers below an AC layer is limited to one. However, more than one AC layer can be included in the model provided that each ACC layer is limited to about 140 cm (55 in.) in thickness.

Based on the above limitations, the default material layers shown in Figure 2 (b) were used in the EICM to model the actual pavement cross section shown in Figure 2 (a). However, the material properties that were used in the analysis depict the actual pavement material layer...
shown in Figure 2 (a). Italic lettering is used to represent EICM default material types. As indicated by Figure 2, the asphalt, subbase, PCC and geofoam layers of the field pavement section were modeled as materials not sensitive to moisture change, i.e., PCC and asphalt default layer types, while the underdrain filter and clayey silt subgrade materials were modeled as materials sensitive to moisture, i.e., default soil types.

The application study revealed several limitations with using the EICM to model a pavement system over geofoam. However, methods that can be used to overcome these limitations were presented herein. Therefore, the EICM can be used as an analysis tool during design to compare the pavement surface temperatures of the two models, i.e., with and without geofoam, and to modify the proposed pavement system over geofoam until similar temperatures are obtained at the surface of both pavement systems. It is sufficient to utilize estimated climatic data values and pavement and soil subgrade material property values provided that both models are subjected to the same values.

SENSITIVITY STUDY

To facilitate the pavement design process, a sensitivity analysis was performed to study the effect of pavement surface type and thickness, base type and thickness, and geofoam type and thickness on pavement surface temperatures. The effect of utilizing a PCC load distribution slab between the pavement system and geofoam was also evaluated.

Figure 4 shows the pavement system models used to perform the sensitivity analysis. The EICM default material types utilized are indicated in parentheses. A sand layer was placed between the geofoam and subgrade because a thin layer of sand is typically placed on top of the natural soil subgrade to provide a level working platform for placement of the geofoam blocks and to meet the EICM minimum requirement of two soil layers.

Table 1, Column C, provides a summary of input values used for the sensitivity analysis. The basis for these input values is included in (16). Climatic data was interpolated from the same weather stations used in the application study. February 16, 1997, was selected as the primary analysis date to compare the sensitivity analysis results because the interpolated hourly air temperatures were all below freezing.

Figure 5 illustrates the effect of geofoam thickness on pavement surface temperatures. The sensitivity study was performed by using a 2.5 cm (1 in.) asphalt concrete and no base material to model a worst case scenario as shown by Model A in Figure 4. Also shown in Figure 5 are the pavement surface temperatures obtained on a model with no geofoam, Model B in Figure 4. As illustrated in Figure 5, the presence of geofoam contributes to lower pavement surface temperatures in the morning and evening but yield higher temperatures during the afternoon.
### Figure 4 Pavement system models and material properties used in the sensitivity analysis.

**Asphalt (PCC)**
- Thermal Conductivity: \(9.97 \text{ cal cm}^{-1} \text{ hr}^{-1} \text{ °C}^{-1} (0.67 \text{ Btu ft}^{-1} \text{ hr}^{-1} \text{ °F}^{-1})\)
- Heat Capacity: \(0.22 \text{ cal g}^{-1} \text{ °C}^{-1} (0.22 \text{ Btu lb}^{-1} \text{ °F}^{-1})\)
- Total Unit Weight: \(2,371 \text{ kg m}^{-3} (148 \text{ lbs ft}^{-3})\)

**Geofoam (Asphalt)**
- Thermal Conductivity: \(0.3 \text{ cal cm}^{-1} \text{ hr}^{-1} \text{ °C}^{-1} (0.02 \text{ Btu ft}^{-1} \text{ hr}^{-1} \text{ °F}^{-1})\)
- Heat Capacity: \(0.29 \text{ cal g}^{-1} \text{ °C}^{-1} (0.29 \text{ Btu lb}^{-1} \text{ °F}^{-1})\)
- Total Unit Weight: \(20 \text{ kg m}^{-3} (1.25 \text{ lbs ft}^{-3})\)

**Sand (Soil A-2-4)**
- Porosity: 0.28
- SG: 2.68
- Saturated Permeability: \(8.47 \times 10^{-3} \text{ cm sec}^{-1} (2.78 \times 10^{-4} \text{ ft sec}^{-1})\)
- Dry Unit Weight: \(1,954 \text{ kg m}^{-3} (122 \text{ lbs ft}^{-3})\)

**Subgrade (Soil: A-7-6)**
- Porosity: 0.42
- SG: 2.77
- Saturated Permeability: \(8.47 \times 10^{-9} \text{ cm sec}^{-1} (2.78 \times 10^{-10} \text{ ft sec}^{-1})\)
- Dry Unit Weight: \(1,458 \text{ kg m}^{-3} (91 \text{ lbs ft}^{-3})\)

**Note:** Actual material layer type (ICM default material type)
Figure 4  (continued).

Figure 5  Effect of geofoam thickness on pavement surface temperature for a model with no base and 2.5 cm asphalt concrete.

Note: Actual material layer type (ICM default material type)
During the morning and evening when the air temperatures are low, heat flow occurs upwards from the soil subgrade to the pavement surface and into the atmosphere as shown by Figure 1. However, because of the insulative properties of the geofoam, heat cannot flow freely from the soil subgrade to the base and pavement surface. Consequently, the temperature of the pavement surface overlying geofoam is lower than the non-geofoam pavement surface especially in the early morning when most of the heat has dissipated from the base and pavement overlying the geofoam. This observation is in agreement with field pavement surface temperature data reported in (15). Hence, both field results and the sensitivity analysis results of Figure 5 show differential pavement surface temperatures between geofoam and non-geofoam areas.

During the afternoon the pavement surface temperatures increase due to solar heating of the pavement surface and heat flow occurs from the pavement surface down into the soil subgrade, i.e., the heat flow is in the opposite direction from the flow direction shown in Figure 1. Day time pavement surface temperature differences between geofoam and non-geofoam areas are likely to be the greatest during the summer.

As shown in Figure 5, pavement surface temperatures are not sensitive to the thickness of geofoam. This observation is in agreement with the conclusion reached from insulated pavement studies that only a thin layer of geofoam, on the order of 10 cm (4 in.) is required to protect the soil subgrade against freezing. Thus, differential icing must be considered in the design of pavement systems placed over geofoam regardless of the thickness of geofoam placed in the embankment.

The effect of geofoam thermal properties on pavement surface temperatures was evaluated by using Model A in Figure 4. The thermal conductivity of EPS-block geofoam is dependent on the density of the geofoam. The thermal conductivity values for the EPS-block geofoam material types typically used as lightweight fill directly below the pavement system fall within the range of 0.15 and 0.30 cal/cm-hr-°C (0.01 and 0.02 Btu/hr-ft-°F) at temperatures of 0°C (32°F) (7). The heat capacity does not vary for the typical geofoam types used as lightweight fill in roadways and is approximately 0.29 cal/g-°C (0.29 Btu/lb-°F) (17). The results of the sensitivity study revealed that pavement surface temperatures are not sensitive to the range of thermal conductivity and heat capacity values found in typical geofoam types used as lightweight fill directly below pavement systems. Therefore, the selection of the type of geofoam to utilize directly below the pavement system should be based on load bearing, Step 14, and structural pavement design, Step 15, of the recommended design guideline for geofoam applications in highway embankments (6, 7) and not on the effects of differential icing.

Figure 6 illustrates the effect of AC thickness on pavement surface temperatures. The sensitivity study was performed with no base as shown by Model C in Figure 4. As indicated in Figure 6, as the AC thickness increases, pavement surface temperatures increase during the morning and evening hours but decrease during the afternoon. Similar observations were obtained for a PCC surface. Therefore, a thicker pavement surface will minimize the potential for differential icing and may also minimize the effects of solar heating. Figure 7 shows a comparison between an AC surface and a PCC surface. An AC pavement surface is more effective in minimizing differential icing effects than a PCC surface for pavement surface thicknesses up to approximately 18 cm (7 in.). A PCC surface is more effective at minimizing differential icing conditions for pavement surface thicknesses greater than 18 cm (7 in.) but the impact of PCC thickness diminishes at 25 cm (10 in.).
Figure 6  Effect of asphalt concrete thickness on pavement surface temperature for a model with no base and 30.5 cm of geofoam.

Figure 7  Effect of pavement surface type on pavement surface temperature for a model with no base and 30.5 cm of geofoam at 11:00 p.m.
A sensitivity study was also performed to determine the effect of granular base thickness and thermal properties on pavement surface temperatures. The EICM estimates the thermal properties for moisture sensitive materials such as a granular base, granular subbase, and soil subgrade based on Kersten’s relationships (18) except for the heat capacity during freezing, which is determined using the procedure described in (19). The variance in water content with time is based on the soil-water characteristic curves developed in (20-22). However, since the base in this sensitivity study was modeled as a moisture insensitive material due to the modeling limitations with the EICM, representative base thermal properties were needed for the sensitivity study. The range of base thermal conductivity investigated was 4.5 to 22.3 cal/cm-hr-˚C (0.3 to 1.5 Btu/hr-ft-˚F) and the range of base heat capacity investigated was 0.17 to 0.25 cal/g-˚C (0.17 to 0.25 Btu/lb-˚F). The basis for these thermal properties is included in (16).

Figure 8 shows the influence of base thickness on pavement surface temperatures for Model D in Figure 4 and for a granular base with a thermal conductivity of 22.3 cal/cm-hr-˚C (1.5 Btu/hr-ft-˚F) and a heat capacity of 0.17 cal/g-˚C (0.17 Btu/lb-˚F). As indicated in Figure 8, as the base thickness increases, pavement surface temperatures increase during the morning and evening hours but decrease during the afternoon. Similar observations were obtained for a granular base with a thermal conductivity of 4.5 cal/cm-hr-˚C (0.3 Btu/hr-ft-˚F). Therefore, a thicker base will minimize the potential for differential icing and may also minimize solar heating. However, the impact of base thickness on pavement surface temperatures decreases with increasing base thickness and is dependent on the thermal properties of the base material. The higher the thermal conductivity, the greater the thickness at which the base no longer influences pavement surface temperatures. Initially, a base with a thermal conductivity of 4.5 cal/cm-hr-˚C (0.3 Btu/hr-ft-˚F) provides a higher pavement surface temperature but at a thickness of 15 cm (6 in.), the base with a thermal conductivity of 22.3 cal/cm-hr-˚C (1.5 Btu/hr-ft-˚F) yields higher pavement temperatures. Granular base thickness of pavement systems over geofoam will typically exceed 15 cm (6 in.). Therefore, a base with a higher thermal conductivity will result in slightly higher pavement surface temperatures. However, the difference in pavement surface temperatures obtained for the range of base thermal conductivities investigated in this study was only about 1 ˚C (1.8 ˚F)

The effect of base heat capacity on pavement surface temperatures was also investigated. The sensitivity study was performed using similar material layers as Model D in Figure 4 except that a 30.5 cm (12 in.) base was used as shown by Model E in Figure 4. The sensitivity study indicated that for a given thermal conductivity, the higher the heat capacity, the higher the pavement surface temperatures in the morning and evening. The heat capacity effect on pavement temperatures increases with increasing thermal conductivity. For example, at 11:00 p.m. the difference in pavement temperatures between a heat capacity of 0.17 and 0.25 cal/g-˚C (0.17 and 0.25 Btu/lb-˚F) was 3.9˚C (7.1 ˚F) for a base thermal conductivity of 22.3 cal/cm-hr-˚C (1.5 Btu/hr-ft-˚F) compared to a difference of 2.1˚C (3.9 ˚F) for a base thermal conductivity of 4.5 cal/cm-hr-˚C (0.3 Btu/hr-ft-˚F). During the afternoon, for a given thermal conductivity, the higher the heat capacity, the lower the pavement temperature. The heat capacity effect on pavement temperatures during the afternoon also increases with increasing thermal conductivity.

A thicker granular base thickness will minimize the potential for differential icing. This observation is in agreement with the conclusion from observations of insulated pavement systems in Norway (2) and Sweden (3) that differential icing can be minimized by providing a sufficient thickness of soil material on top of the geofoam mass. However, the impact of granular base thickness on differential icing is dependent on the thermal properties of the granular base,
i.e., thermal conductivity and heat capacity. A granular base with a higher heat capacity will minimize the potential for differential icing. The higher the heat capacity of the granular base, the better the base acts as a heat sink during the afternoon and the more heat that is provided to the pavement surface during the evening and morning. The heat capacity effect on minimizing differential icing conditions increases with increasing thermal conductivity. Therefore, granular bases and subbases with higher heat capacities and thermal conductivities are more effective at minimizing differential icing conditions. The thermal conductivity of granular bases increase with an increase in water content, ice content, degree of saturation, and soil density. Therefore, as was noted by Tan et al. (23), granular bases with smaller particle size will have higher thermal conductivities. Thus, differential icing can also be minimized by utilizing base and/or subbase materials with sufficient “fines” to hold water, which has a relatively high heat capacity, to provide sufficient retained heat to keep the pavement surface as close to the temperature of the adjacent pavement sections.

Figure 8 Effect of base thickness on pavement surface temperature for a model with 2.5 cm asphalt concrete and 30.5 cm of geofoam. Base thermal conductivity of 22.3 cal/cm-hr-°C and heat capacity of 0.17 cal/g-°C.

The effect of placing a PCC separation layer between the pavement system and the geofoam was investigated using Model F in Figure 4. No base was included to model a worst case scenario. A PCC separation layer results in higher pavement surface temperatures during the morning and afternoon but lower temperatures during the afternoon. Therefore, the use of a PCC separation layer decreases the potential for differential icing conditions and may also decrease the impact of solar heating on the pavement system. The effect on pavement temperatures diminishes with increasing PCC separation thickness and was negligible at PCC thicknesses greater than 10 cm (4 in.).
CONCLUSIONS

The objective of designing a pavement system overlying a non-earth lightweight fill to minimize the potential for differential icing conditions is to design a pavement system over the non-earth lightweight fill that will yield similar pavement surface temperatures as the adjacent pavement system underlain by a natural soil subgrade especially during the winter. Therefore, although an explicit pavement design procedure to minimize differential icing conditions and solar heating effects is currently not available, an analysis can be made using a heat-transfer model that estimates temperature distribution in the pavement system and that considers climatic, pavement, and soil subgrade material properties as well as the influence of water content and ice content on soil thermal properties. This study demonstrated the use of the EICM as an analysis tool to design pavement systems to minimize the potential for differential icing conditions. The pavement surface temperatures between the proposed pavement system over non-earth lightweight fill, such as EPS-block geofoam, and the adjacent pavement system over natural soil obtained from the EICM can be compared and the proposed pavement system over lightweight fill can be modified during design until similar temperatures are obtained at the surface of both pavement systems.

The application study revealed several limitations with using the EICM to model a pavement system over geofoam. However, methods that can be used to overcome these limitations were presented herein. Additionally, although precise climatic data and pavement and soil subgrade material properties are difficult to obtain, it is sufficient to utilize estimated values provided that both pavement system models, i.e., model with and without geofoam, are subjected to the same values. For example, it is sufficient to utilize interpolated weather data from several nearby weather stations in the pavement system design provided that the same interpolated climatic data are used in the analysis of both the pavement system over geofoam and the pavement system over natural soil subgrade.

If the use of a suitable heat-transfer model is not feasible during design, it is recommended that a minimum pavement system thickness of 61 cm (24 in.) be used over EPS-block geofoam (6, 7). This recommendation is based on the minimum recommended pavement system thickness from the Norwegian design guidelines (5, 24) of 40 cm (16 in.) to 80 cm (32 in.) and the Swedish guidelines of 40 cm (16 in.) to 50 cm (20 in.) (3, 5).

The sensitivity analysis confirmed that the presence of geofoam contributes to lower pavement surface temperatures during the winter especially in the morning and evening. The pavement surface temperatures are not sensitive to the thickness of geofoam. Thus, differential icing must be considered in the design of pavement systems placed over geofoam regardless of the thickness of geofoam placed in the embankment. Additionally, pavement surface temperatures are not sensitive to the range of thermal properties found in typical EPS-block geofoam types used as lightweight fill directly below pavement systems. Therefore, the selection of the type of geofoam to utilize directly below the pavement system should be based on load bearing and structural pavement design, i.e., Steps 14 and 15, respectively, of the design procedure for an EPS-block geofoam roadway embankment included in (6, 7, 16), and not on differential icing effects.

A thicker pavement surface will minimize the potential for differential icing. An AC pavement surface is more effective in minimizing differential icing effects than a PCC surface for pavement surface thicknesses up to approximately 18 cm (7 in.). A PCC surface is more effective at minimizing differential icing conditions for pavement surface thicknesses greater
than 18 cm (7 in.) but the impact of PCC thickness diminishes at 25 cm (10 in.). A thicker pavement surface may also minimize the effects of solar heating.

A thicker granular base thickness will minimize the potential for differential icing. However, the impact of granular base thickness on differential icing is dependent on the thermal properties of the granular base. Granular bases and subbases with higher heat capacities and thermal conductivities are more effective at minimizing differential icing conditions.

The use of a PCC separation layer decreases the potential for differential icing conditions. The effect on pavement temperatures diminishes with increasing PCC separation thickness and diminishes at a thickness of approximately 10 cm (4 in.). A PCC layer is typically used as a separation layer between the EPS blocks and the pavement system to prevent a load bearing failure of the EPS-block geofoam. The use of a PCC separation layer should be based on load bearing and structural pavement design, i.e., Steps 14 and 15, respectively, of the design procedure for an EPS-block geofoam roadway embankment included in (6, 7, 16), and not on differential icing effects due to the costs involved and the technical viability of not using a PCC separation layer (6, 7, 16).

Pavement system design issues need to be addressed in Steps 2 and 15 of the EPS-block geofoam roadway embankment design procedure (6, 7, 16). A preliminary pavement system is selected during Step 2 and the final pavement system design is performed during Step 15. The objective of pavement system design is to select the most economical arrangement and thickness of pavement materials for the subgrade provided by the EPS blocks. However, a unique aspect of pavement design over lightweight fill is that the design must also consider the external and internal stability of the embankment. Therefore, external stability, i.e., Steps 4 through 10, and internal stability, i.e., Steps 11 through 14, need to be re-evaluated if any changes are made during Step 15 to the initial pavement system assumed during Step 2 to include changes made to minimize potential differential icing conditions.

It is recommended that a study be performed to develop an explicit design procedure of pavements over geofoam lightweight fills that includes differential icing and solar heating effects. Development of such a procedure may require the study of existing pavements over geofoam and the construction of test sections.

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REFERENCES


