

USE OF GEOTHERMAL BRIDGE DECK DEICING SYSTEMS TO MITIGATE CONCRETE
DETERIORATION IN MONTANA

by

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DEDICATION

This thesis is dedicated to my late mother, Stacey Turner. While she is no longer with us, her loving support and belief in me has fueled me to be the best I can be—to love and serve unconditionally. I love you to the moon and back.

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ABSTRACT

Reinforced concrete bridge decks face deterioration from thermal stresses, frost action, and early-age cracking. This thesis presents experimental testing and numerical simulations on a bridge deck deicing system's ability to mitigate concrete deterioration. Two experimental bridge deck models were constructed with embedded heat exchanger tubing and instrumented with thermocouples and strain gauges. The models were tested in a cold chamber laboratory under conditions representative of Montana winter weather. The experimental results suggested that a bridge deck deicing system with an inlet temperature of 8 °C shows promise in deicing, reducing thermal movements, and mitigating early-age cracking through thermal shrinkage. The temperature and strain results of the experiment were used to validate a numerical model constructed in COMSOL Multiphysics. Inlet fluid temperatures of 10 °C and 50 °C, chosen from common ground temperatures in Montana, were tested to evaluate the system's effect on frost action and thermal stresses. With a 10 °C inlet fluid temperature, the system showed promise in deicing and mitigating concrete deterioration. While the system did not always raise the surface temperature above 0 °C, the consistent increase in temperature suggested that under certain weather conditions, the system could keep the top surface temperature above 0 °C for a longer period than with no system. The system was also successful in reducing the range of strain due to thermal movements. The system was not able to mitigate the effects of frost action or temperature gradients. The temperature gradients induced by the system were at times worse than without the system, but the difference was insignificant. With a 50 °C fluid temperature, the system was more effective in deicing and mitigating frost action. The range of strain from thermal movements was also reduced more than with a 10 °C inlet fluid temperature. The thermal gradients, however, were at times slightly greater than design gradients provided by design specifications. The excessive gradients, however, only occurred during extreme weather conditions that are less common in Montana. While not perfect, geothermal bridge deck deicing systems show promise for mitigating some mechanisms of concrete deterioration, while keeping other mechanisms within allowable limits.

CHAPTER ONE

EXPERIMENTAL MODEL DEVELOPMENT

Introduction

This chapter was published as a task report for the Montana Department of Transportation (MDT). Weather conditions during Montana winters pose two challenges for concrete bridges: 1) the removal of accumulated snow and ice and 2) deterioration due to temperature fluctuations. While there are current methods for snow and ice removal, there is potential for improvement with regards to cost, effectiveness, and environmental impacts. Deterioration is an issue because as the concrete in bridge decks cracks and spalls, the steel reinforcement is exposed which leads to corrosion and further deterioration of the bridge deck. A ground-source bridge deck deicing system can mitigate temperature fluctuations within concrete bridge decks, and thus reduce the effects of concrete deterioration. It can also be a means of effective removal of accumulated snow and ice. Ground-source bridge deck deicing systems extract heat from the earth and transfer it into the concrete through a closed loop system of heat exchanger pipes embedded in the ground and the concrete bridge deck. Heat transferred from the earth to the concrete reduces temperature fluctuations in the bridge deck.

A survey was conducted among MDT staff to understand their perceptions and preferences concerning snow and ice removal and prevention methods in Montana. Results from the survey show that the three most used methods by MDT are: 1) anti-icing to prevent snow or ice accumulation on the surface before a winter storm, 2) deicing to remove snow and ice during and after a storm, and 3) mechanical removal. The effectiveness of each method in clearing roads

and enhancing traction depends on various factors including weather conditions, pavement temperature, snow thickness, and ice accumulation. Anti-icing methods are typically employed before a winter weather event or in the initial stages of a storm, while deicing methods are used during and after winter weather events when the road surface is covered with a significant amount of snow. Mechanical removal methods are used alone or in combination with other methods during or after a winter weather event. While not used to remove or prevent snow and ice, applying abrasives to road surfaces can play an important role during low-temperature events by increasing traction.

The survey results indicate that the selection of deicing and anti-icing methods and materials depends on various factors, including their effectiveness, cost, environmental impact, ease of application, availability, public feedback, and impact on corrosion. In Montana, the most used materials for deicing or anti-icing bridge decks are salts and other debonding chemicals such as Sodium Chloride (NaCl), Magnesium Chloride (MgCl₂), and Potassium Acetate (KAc). However, studies have shown that deicing chemicals have negative environmental impacts (e.g., Kelting & Laxon, 2010; Shi et al., 2018) and can accelerate the corrosion of steel reinforcement, leading to the collapse of reinforced concrete bridge decks (e.g., Baboian, 1992; Granata & Hartt, 2009; Virmani et al., 1983; Virmani et al., 1984; White et al., 2005; Yunovich et al., 2003). Abrasives, such as crushed stone from local gravel sources, are also frequently used for bridge decks in Montana. However, studies indicate that they can contribute to environmental problems, such as water and air quality, and increase maintenance costs, including road and shoulder clean-up after the winter season (Fischel, 2001).

This chapter contains the construction procedure of a physical bridge deck model used to investigate the feasibility of using geothermal energy for bridge deck deicing in Montana. The bridge deck model was tested in the Cold Hydrodynamics Chamber (CHC) in Montana State University's Subzero Research Laboratory (SRL) to further calibrate and refine an existing numerical model. This chapter starts with a presentation of the final concrete mix design for the bridge deck model. The next section describes the creation and validation of a numerical simulation of a geothermal bridge deck. It also describes the simulations used to evaluate the significance of various parameters in the design of a physical bridge deck model. The final design of the physical bridge deck model is then presented. Next, the details of the construction of the physical bridge deck model and instrumentation are provided. The chapter ends with a discussion of Montana weather with data from Road Weather Information System (RWIS) stations, as well as the results of a survey distributed to the MDT are then presented.

Concrete Mix Design Tests

The concrete mix design introduced by Pourakbar et al. (2021) was developed from a series of tests to determine the cement, aggregate, and water requirements and proportions. No admixtures were chosen for the final mix design.

Cement

Type I/II Portland Cement from Grupo Cementos de Chihuahua's (GCC's) Trident Plant was chosen for this mix design. Type I/II Portland Cement is a general-purpose cement widely used in bridges, foundations, walls, driveways, sidewalks, etc.

Concrete Aggregate Combined Gradation

The coarse and fine aggregates were obtained from Bozeman Brick Block and Tile. Three optimization charts were used to validate the aggregates: 1) the Coarseness Factor chart, 2) the 0.45 Power chart, and 3) the Percent Retained chart. Each chart represents one aspect of an optimized aggregate gradation. The coarseness factor chart, also known as the Shilstone Chart, is a method for determining if the combined aggregate gradation is considered optimized. The chart helps describe the relationship between coarseness factor and workability factor of a concrete mix. The coarseness factor (x-axis) and workability factor (y-axis), both represented in percentages, can be calculated using Equations (1) and (2), respectively:

$$CF (\%) = \frac{Q}{R} \times 100 \quad (1)$$

$$WF (\%) = W + \frac{2.5 \times (C - 564)}{94} \quad (2)$$

where Q is the cumulative % retained on a 3/8" sieve, R is the cumulative % retained on the No. 8 sieve, W is the percent passing the No. 8 sieve, and C is the cementitious material content in lb/yd³. Figure 1 shows the grain size distribution curves for the aggregates obtained from Bozeman Brick Block and Tile.

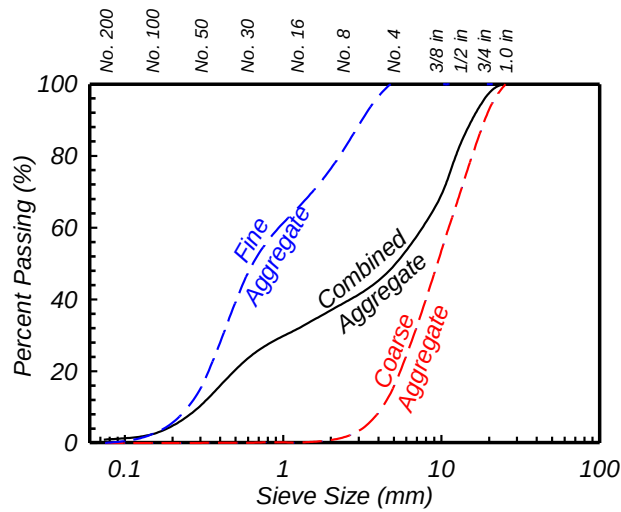


Figure 1: Individual grain size distribution curves

Figure 2 illustrates the coarseness factor chart for the proposed concrete mix design. The chart is divided into four zones, with Zone II generally considered as the most suitable for creating a concrete mix with reasonable workability and durability. Aggregates that plot near the boundaries of or outside Zone II are more likely to cause problems during concrete placement or lead to reduced overall durability of the hardened concrete. As shown in Figure 2, the combined aggregates used in the proposed mix design fall squarely within Zone II, as desired.

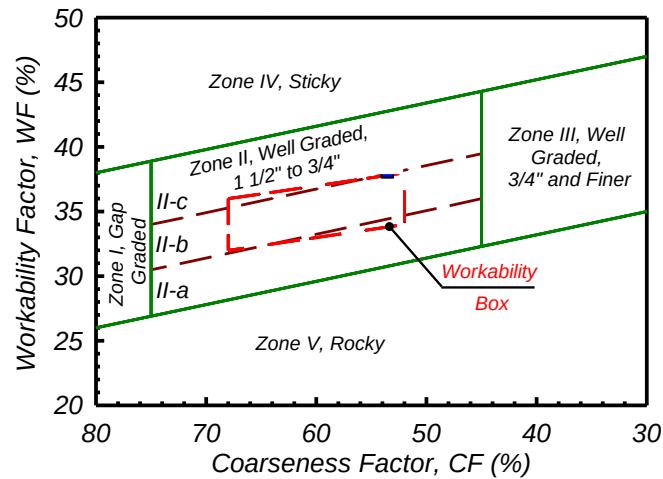


Figure 2: Coarseness Factor chart of concrete mix designs

The 0.45 power line is a method used to predict voids in the concrete's combined aggregates. Figure 3a shows the 0.45 power line which is developed based on the nominal maximum size of the combined aggregates. A gradation line that passes above the power line represents fine aggregates, while the one below the line represents coarse aggregates. Figure 3a shows the grain size distribution of the combined aggregates and the power line. The grading curves for the portion of the combined aggregate passing the No. 30 sieve mostly falls below the power chart line leaving room for the cementitious materials in the final mix. Figure 3a demonstrates that the combined grading is within ± 7 percentage points of the Power Chart line.

The individual percent retained chart (i.e., Haystack Plot) is a method to describe the excess or lacking combined aggregate sizes in the mixture. The chart can also be used to identify workable mixes with a reasonably low water demand. Plots are restricted with high and low lines, generally between 18-22% and 5-12%, respectively. To prevent segregation, it is generally recommended to have at least a total of 13% of the combined aggregate retained on any two adjacent sieves. Figure 3b demonstrates the percent retained on each sieve (y-axis) of the

concrete mix design for each sieve size. In this case, the upper limit is 20% and the lower limit is 8%. As shown here, the concrete mix falls between the “High” and “Low” line, suggesting that the mix is workable and has a reasonably low water demand.

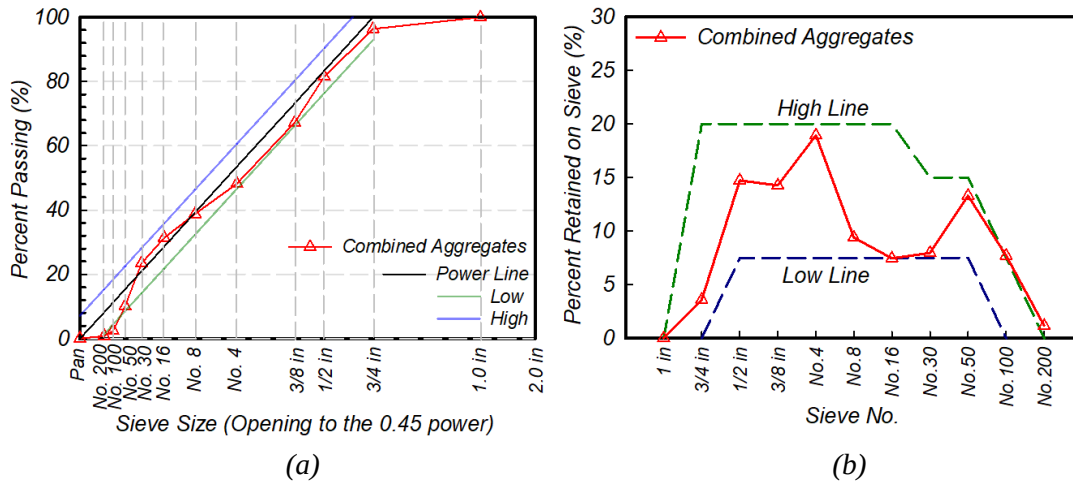


Figure 3: a) 0.45 Power Chart, and b) Percent Retained Chart of the collected mix designs

Final Mix Design

A series of tests were conducted to verify the final mix design reported by Pourakbar et al. (2021). These tests revealed that the mix design needed more water for adequate workability. Compressive strength tests were conducted in accordance with ASTM C39 to assure 7-day strength requirements were met despite the added water. Table 1 shows the final mix design for a 0.042 m³ mix.

Table 1: Mix proportions for 0.042 m³ mix

<i>Item</i>	<i>Item Type</i>	<i>Amount (kg)</i>
<i>Water</i>	-	9.02
<i>Portland Cement</i>	Type I/II from Trident GCC	14.40
<i>Fine Aggregate</i>	O.D. BBB&T Concrete Sand	30.26
<i>Coarse Aggregate</i>		37.88

Bridge Deck Model Design

Data from experiments conducted by Bowers (2016) at Virginia Tech Geotechnical Research Facility was used to create and validate a numerical simulation in COMSOL Multiphysics. Once validated, parametric studies were conducted within the simulation to determine the most significant parameters in the design of a geothermal bridge deck model.

Overview of Past Field Test

The thermal performance of a small-scale bridge deck deicing system was investigated by Bowers (2016). Two bridge deck models were constructed at 1.3 m wide, 3.05 m long, and 0.254 m deep. Cross-linked polyethylene (PEX) tubing with an inner diameter of 16 mm and a thickness of 3 mm (OD 22 mm) was used for heat exchanger pipes. The spacings of the pipes for the two models were 20.3 cm and 30.5 cm. A 20% glycol solution with a flow rate of 15.1 L/m was used as the circulating fluid. The temperature at various locations throughout both models was measured using several imbedded thermistors. Figure 4b shows the cross-sectional locations of the thermistors at one location in the model. Virginia Department of Transportation class A4 concrete mixture, which has a minimum 28-day compressive strength of 27.6 MPa, was used in the bridge deck models. Among the various weather conditions tested by Bowers (2016), a

severe winter weather event that occurred on February 20-22, 2015, in Blacksburg, VA, was explored. Figure 4a shows the conditions during the winter weather event.

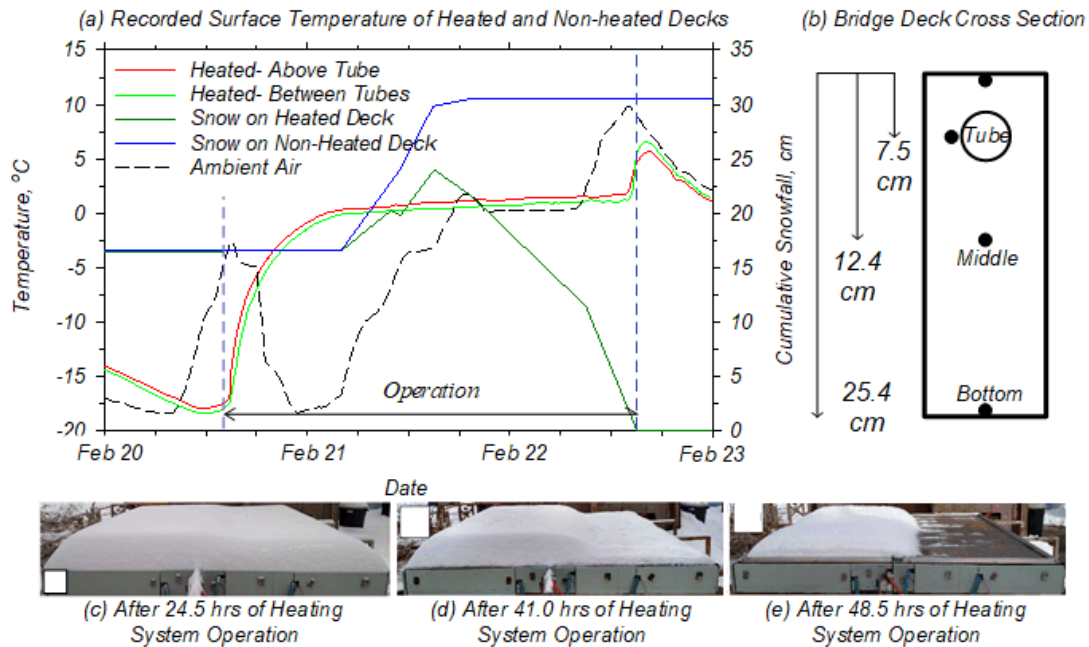


Figure 4: a) Recorded surface temperature of the heated and non-heated decks, ambient temperature, cumulative snowfall; b) cross-sectional location of studied thermistors; and photo of the deck model surface during the storm after: c) 24.5 hours, d) 41 hours, and e) 48.5 hours (Bowers 2016)

A snowstorm occurred before the winter weather event that deposited 20 cm of snow. The bridge deck with the heat exchanger pipe spacing of 20.5 cm began heating after the snowstorm at 14:30 on February 20, 2015. The other bridge deck was not heated and served as a control for the experiment. When the heating was initiated, the temperature and snow depth for both deck surfaces was -18 °C and 16.5 cm, respectively. At 23:30 on February 20, 2015 (9 hours of heating), the average temperature of the surface of the heated bridge deck was above the freezing point despite a 15 °C drop in ambient temperature. The temperature of the surface of the heated bridge deck remained above freezing throughout the rest of the winter weather event. Figure 4c

shows the bridge decks at 15:00 on February 21, 2015 (24.5 hours of heating). The snow depth on the non-heated and heated bridge decks was 29.8 cm and 24.1 cm, respectively. Figure 4d shows the bridge decks at 7:30 on February 22, 2015 (41 hours of heating). The snow depth of the heated bridge deck dropped to 11.4 cm. Figure 4e shows the bridge decks at 15:00 on February 22, 2015 (48.5 hours of heating). By this time, the heated bridge deck was free from snow while the non-heated bridge deck still had a snow depth of 30.5 cm.

Overview of Numerical Simulation

Modeling the bridge deck deicing process is complicated due to the involvement of different heat transfer mechanisms and unsteady weather conditions. The model of a ground-source bridge deck deicing system involves multiple heat transfer mechanisms including conduction, convection, radiation (solar and thermal), and snow melting heat flux. This section presents the results of a 3D numerical model developed to assess the performance of a bridge deck deicing system. The results from the bridge deck heating experiments conducted by Bowers (2016) were first used to validate the numerical model. The validated numerical model was then used to evaluate the performance and feasibility of bridge deck deicing using geothermal energy for Montana weather conditions.

Model Validation Using Data from Bowers (2016)

A 3D numerical model was constructed using the finite element software COMSOL Multiphysics. The heat transfer mechanisms were expressed within the software as follows: Conduction occurs between the circulating fluid and pipe walls and between the pipe and surrounding concrete. For completely insulated boundary conditions (e.g., insulation effect of snow accumulation on the surface), the heat flux, $q = -k\nabla T$, at a surface is equal to zero due to

a Neumann boundary condition. Equation (3) presents the heat conduction in the slab in a Neumann boundary condition.

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = 0 \quad (3)$$

where ρ is the density (kg/m^3), C_p is the heat capacity at constant pressure ($\text{J}/(\text{kg}\cdot\text{K})$), T is the absolute temperature (K), $\partial T/\partial t$ is a time derivatives operator, k is the thermal conductivity coefficient ($\text{W/m}\cdot\text{K}$), and ∇T is the temperature gradient.

The bottom and top surfaces (when not insulated by snow) are exposed to the environment, and thus will experience both convection and radiation. Convection is expressed in Equation (4):

$$-n \cdot q = h \cdot (T_{ext} - T_s) \quad (4)$$

where n is the normal vector on the boundary, h is the convective heat transfer coefficient ($\text{W/m}^2 \cdot \text{K}$), T_{ext} is the external temperature, and T_s is the surface temperature (K). Radiation is expressed in Equation (5):

$$-n \cdot q = \varepsilon \sigma (T_{ext}^4 - T_s^4) \quad (5)$$

where ε is the surface emissivity and σ is the Stefan-Boltzmann constant (a predefined physical constant, $5.67 \times 10^{-8} \text{ (W}\cdot\text{m}^2/\text{K}^4)$). The snow melting process was not considered in these analyses.

The dimensions and material properties were chosen to replicate the field tests by Bowers (2016) for validation purposes. Figures 5a and 5b show an isometric view of the model and the meshed model. The model includes the circulating fluid, the heat exchanger pipes, and the concrete deck. 1D linear elements were used for the fluid flow and heat transfer in the heat exchanger pipes. The flow rate, pressure, and temperature were modeled as the average cross-

section quantities, so they only vary along the length of the pipes. Friction factors were used to account for head loss in the pipes. External wall resistance was added to account for the thickness and thermal conductivity of the pipe wall. The steel reinforcement was not included in the model, but rather, to account for the effects of the rebar, the model was split into three zones through the depth. The material properties for each zone were based on a volumetric average of the concrete and steel reinforcement in each zone. The top and bottom zones have steel reinforcement, while the middle zone does not have steel reinforcement.

To validate the model, the severe winter weather event (February 20-22, 2015) described previously was replicated. Figure 5c shows the COMSOL predicted vs. Bowers (2016) measured temperature at various locations at a cross-section with a heat exchanger pipe. Figure 5d shows the cross-sectional and top surface temperature of the bridge deck after 12 hours of heating. The numerical model accurately predicted the temperature within the Bowers (2016) bridge deck model.

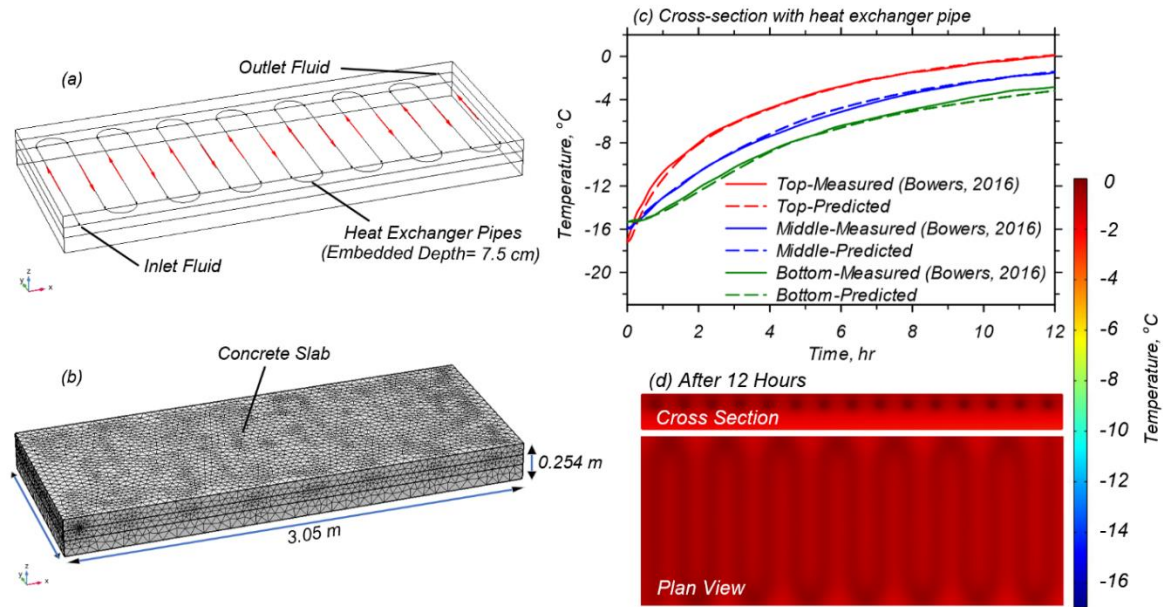


Figure 5: a) Bridge deck model configuration, b) meshed 3D model, c) comparison between experimental results and numerically predicted values of temperature at the top, middle, and bottom of the bridge deck at cross-section with heat exchanger pipes, and d) cross-sectional and top surface temperature of the bridge deck after 12 hours of heating

Parametric Study

A parametric study was developed to evaluate the influence of the ambient temperature, deck dimensions, top reinforcement cover, inlet flow rate, heat exchanger tube spacing, and inlet fluid temperature on the ability of a geothermal bridge deck deicing system to raise the top surface temperature above 0 °C. The results from these studies were used in the design of the bridge deck model.

Ambient Temperature. The effect of ambient temperature on top surface temperature of a geothermally heated bridge deck was tested to evaluate the importance of the parameter in the operation and design of the bridge deck model. Besides ambient temperature, all other testing variables were constant between tests. The inlet fluid temperature was 6 °C. Nine different ambient temperatures were tested, with the highest being -0.5 °C and the lowest being -17 °C.

The top surface temperature of the test with ambient temperature of $-0.5\text{ }^{\circ}\text{C}$ took around 0.6 hours to reach $0\text{ }^{\circ}\text{C}$. The top surface temperature of the test with ambient temperature of $-17\text{ }^{\circ}\text{C}$ took around 9.2 hours to reach $0\text{ }^{\circ}\text{C}$. Figure 6 shows the top surface temperatures from these tests along with top surface temperatures for tests with the intermediate ambient temperatures. As expected, the results suggest that as the ambient temperature increases, the time it takes for the geothermal system to raise the top surface temperature above $0\text{ }^{\circ}\text{C}$ decreases.

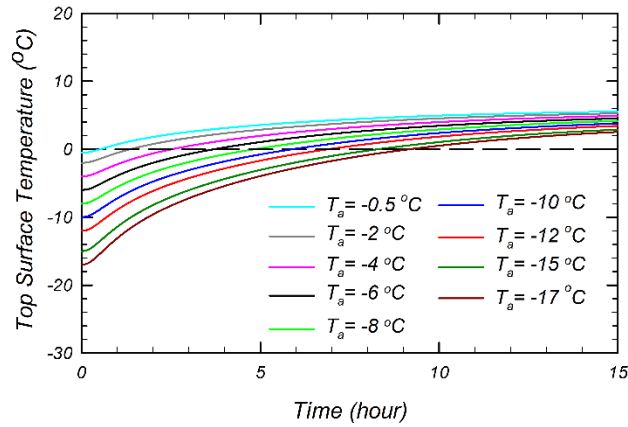


Figure 6: Parametric study results for ambient temperature

Bridge Deck Dimensions. A parametric study for bridge deck dimensions was conducted because the base model, which measures 3.05 m long, 1.30 m wide, and 0.25 m deep, is too large to be tested in the CHC. A smaller model was developed to determine whether it could produce similar results to the base model in the ambient temperature study. The smaller model had dimensions of 1.50 m long, 1.20 m wide, and 0.20 m deep. Figure 7b shows a schematic of both models. The smaller model was tested with ambient temperatures of $-4\text{ }^{\circ}\text{C}$ and $-12\text{ }^{\circ}\text{C}$. At an ambient temperature of $-4\text{ }^{\circ}\text{C}$ the top surface temperature of the smaller model took 2.8 hours to reach $0\text{ }^{\circ}\text{C}$, while the base model took 2.6 hours. At an ambient temperature of $-12\text{ }^{\circ}\text{C}$ the top surface temperature of the smaller model took 7.5 hours to reach $0\text{ }^{\circ}\text{C}$, while the base model took

6.9 hours. Figure 7a shows the top surface temperature of both the base model and smaller model at ambient temperatures of $-4\text{ }^{\circ}\text{C}$ and $-12\text{ }^{\circ}\text{C}$. The results suggest that there is a negligible difference in the ability of the base model and a smaller model to bring the top surface temperature to $0\text{ }^{\circ}\text{C}$.

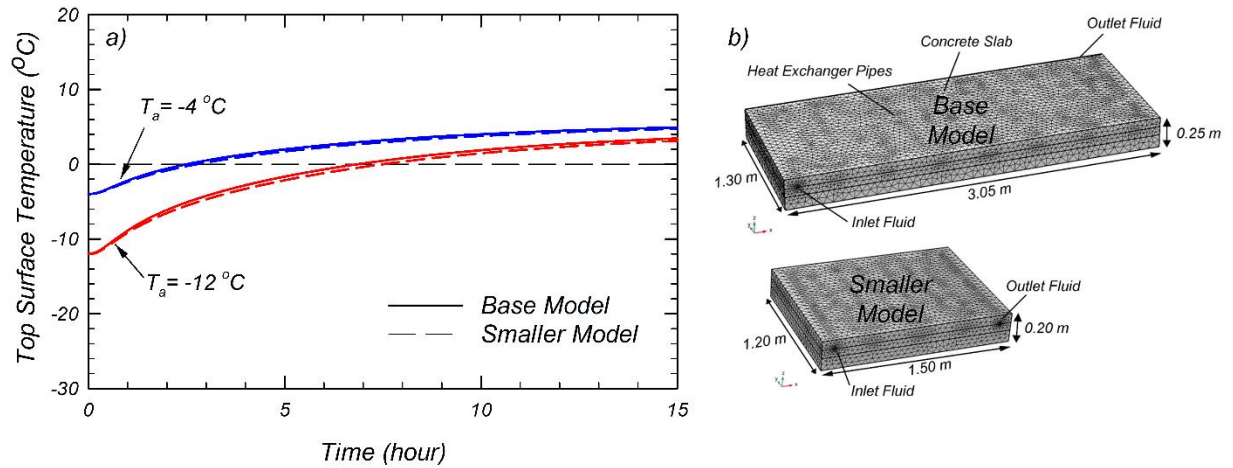


Figure 7: a) Parametric study results for Base Model and Smaller Model and b) schematic of Base Model and Smaller Model

Top Reinforcement Cover. In a physical bridge deck model, the heat exchanger tubes are typically attached to the bottom of the top reinforcement. The effect of top reinforcement cover was tested to evaluate the importance of the depth of the heat exchanger tubes in the design of a geothermal bridge deck. The top surface temperature was found for models with top reinforcement covers of 4.5 cm, 5.5 cm, and 6.0 cm. All other parameters were constant for the three tests. The ambient temperature and inlet fluid temperature were $-17\text{ }^{\circ}\text{C}$ and $6\text{ }^{\circ}\text{C}$, respectively. The top surface temperature of the 4.5 cm, 5.5 cm, and 6.0 cm cover tests took 8.2 hours, 8.5 hours, and 8.8 hours to reach $0\text{ }^{\circ}\text{C}$, respectively. Figure 8a shows the top surface temperature for each top reinforcement cover condition. As expected, the results suggest that as top reinforcement cover decreases, the time it takes for the geothermal system to raise the top

surface temperature above 0 °C also decreases. The difference, however, between top reinforcement cover conditions between 4.5 cm and 6.0 cm is negligible.

Inlet Fluid Flow Rate. The effect of inlet fluid flow rate was tested because the calibrated numerical model uses a flow rate greater than the maximum flow rate in the CHC. The top surface temperature was evaluated for the 15 L/min flow rate used by Bowers (2016), as well as flow rates of 10 L/min, 15 L/min, 20 L/min, and 25 L/min. All other parameters were constant for the four tests. The ambient temperature and inlet fluid temperature were -17 °C and 6 °C, respectively. The top surface temperature of the 10 L/min, 15 L/min, 20 L/min, and 25 L/min flow rate tests took 8.9 hours, 8.2 hours, 8 hours, and 7.9 hours to reach 0 °C, respectively. Figure 8b shows the top surface temperature for each inlet fluid flow rate condition. The results suggest that as the flow rate increases, the time it takes for the geothermal system to raise the top surface temperature above 0 °C decreases. The difference, however, between inlet fluid flow rate conditions between 10 L/min and 25 L/min is negligible.

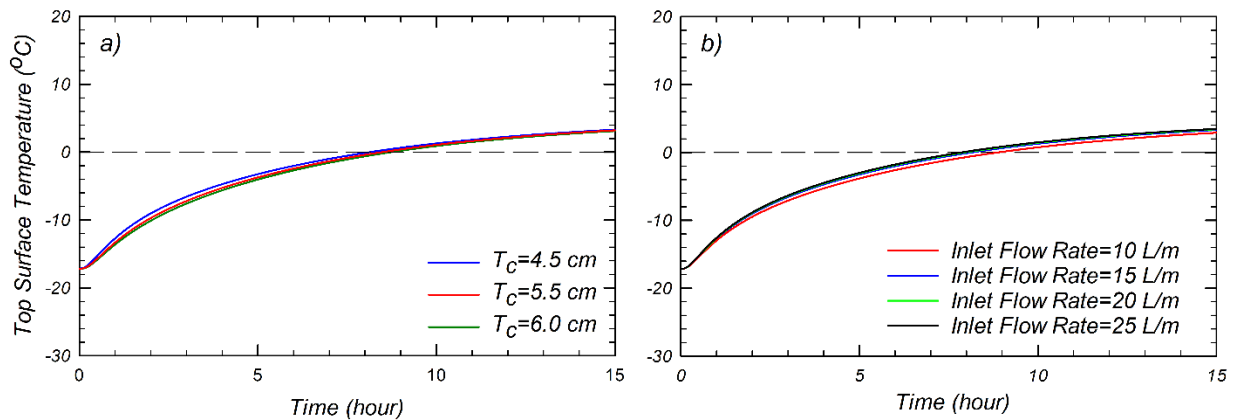


Figure 8: Parametric study results for a) top reinforcement cover and b) inlet fluid flow rate

Heat Exchanger Tube Spacing. The effect of heat exchanger tube spacing was tested to evaluate the importance of the parameter in the operation of a geothermal bridge deck. The top surface temperature was modeled for heat exchanger tube spacings of 15 cm, 20 cm, and 30 cm. All other parameters were constant for the three tests. The ambient temperature and inlet fluid temperature were set at $-17\text{ }^{\circ}\text{C}$ and $6\text{ }^{\circ}\text{C}$, respectively. The top surface temperature of the 15 cm, 20 cm, and 30 cm spacing tests took 5.5 hours, 8.2 hours, and 14.2 hours to reach $0\text{ }^{\circ}\text{C}$, respectively. Figure 9a shows the top surface temperature for each tube spacing condition. The results suggest that as heat exchanger tube spacing decreases, the time it takes for the geothermal system to raise the top surface temperature above $0\text{ }^{\circ}\text{C}$ decreases.

Inlet Fluid Temperature. The effect of inlet fluid temperature was tested to evaluate the importance of the parameter in the operation of a geothermal bridge deck. Nine different inlet fluid temperatures were modeled, representing the range of mean earth temperatures in Montana, with the highest being $10.0\text{ }^{\circ}\text{C}$ and the lowest being $6.0\text{ }^{\circ}\text{C}$. All other parameters were constant for the tests, with the ambient temperature set at $-17\text{ }^{\circ}\text{C}$. The top surface temperature of the $10.0\text{ }^{\circ}\text{C}$ and $6.0\text{ }^{\circ}\text{C}$ inlet fluid temperature tests took 6.2 hours and 9.1 hours to reach $0\text{ }^{\circ}\text{C}$, respectively. Figure 9b shows the top surface temperature for each inlet fluid temperature condition. The results suggest that as inlet fluid temperature increases, the time it takes for the geothermal system to raise the top surface temperature above $0\text{ }^{\circ}\text{C}$ decreases.

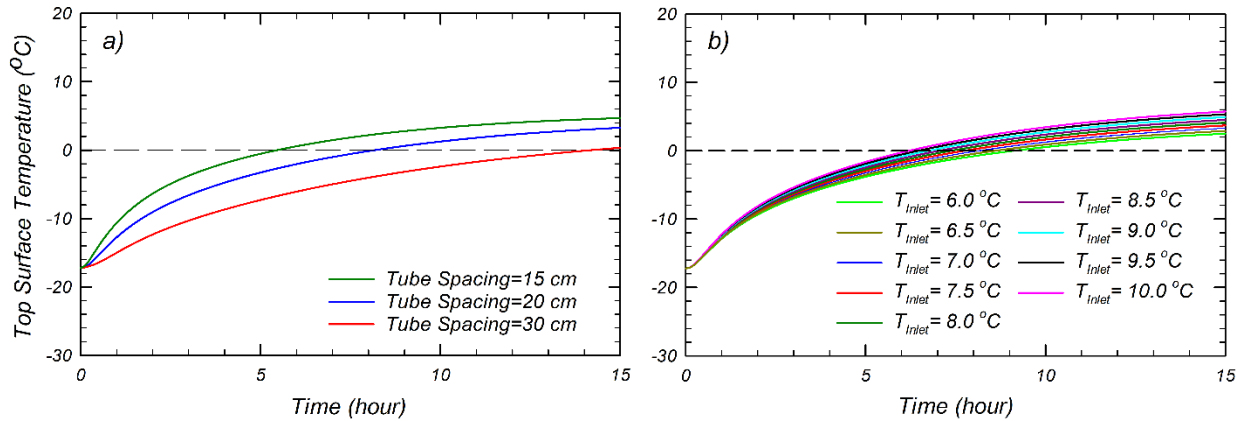


Figure 9: Parametric study of a) heat exchanger pipe spacing and b) inlet fluid temperature

Summary of Parametric Study. The effects of bridge deck dimensions, top reinforcement cover, and inlet fluid flow rate are negligible in the design of a geothermal bridge deck model. Any discrepancy in Montana code for reinforcement cover or the CHC's limitations for bridge deck dimensions and inlet fluid flow rate will not significantly affect the simulation's validation based on the past field tests. The effects of ambient temperature, heat exchanger tube spacing, and inlet fluid temperature are significant in the design of a geothermal bridge deck model. The heat exchanger tube spacing will match the design of the past field tests to assure validation of the simulation. The ambient and inlet fluid temperatures will be consistent with Montana's weather and geothermal conditions to accurately assess the feasibility of using geothermal energy to deice bridges in Montana.

Physical Model Design

While most of the experimental bridge deck design replicated Bowers' bridge deck (2016), two model parameters were modified due to the limitations of the CHC. The bridge deck model was designed to be 1.0 m wide, 1.6 m long, and 0.2 m deep. The 1.0 m width allows the bridge deck model to fit through the CHC door. Figure 10 shows a schematic of the proposed

bridge deck model. A flow rate of 5.5 L/min will be used because it is the maximum flow rate provided by the CHC. Other design parameters include 12.7 mm cross-linked polyethylene (PEX) tubing for the heat exchanger tubes with 20 cm spacing and a 30% propylene glycol solution for the circulating fluid. Refer to Appendix 1 for more detailed drawings of the model.

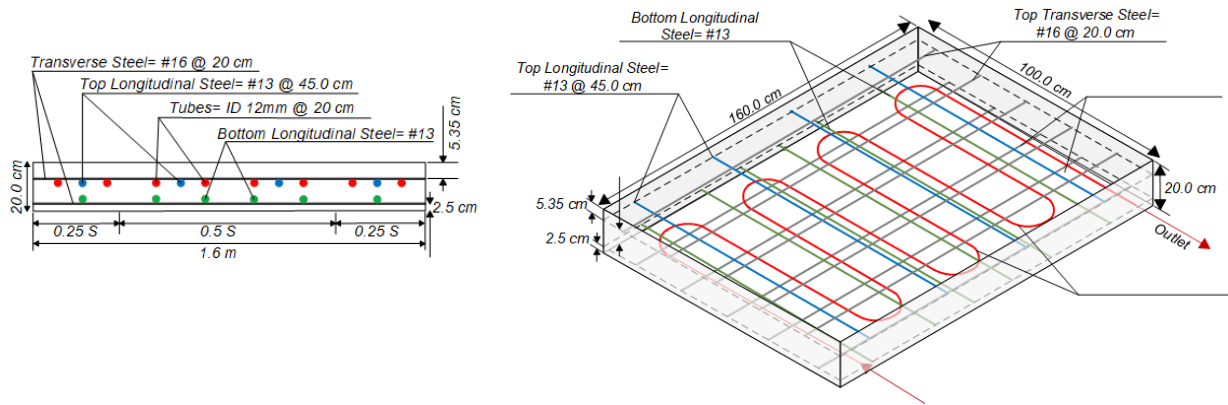


Figure 10: Proposed bridge deck model schematic

Model Construction and Instrumentation

In the spring and summer of 2022, the bridge deck model was constructed and prepared for testing. The required instrumentation was prepared and installed for data acquisition.

Form Construction

The bridge deck model was constructed in Montana State University's Bulk Materials Lab. To construct the formwork, Douglas-fir 2×10s and corrugated steel were utilized. The boundary conditions for this experiment require the top and bottom of the concrete to be uninsulated. Rather than removing the specimen from the form to expose the bottom, corrugated steel is the permanent bottom of the specimen. Because concrete's thermal conductivity is 1-3 W/mK, and steel's is much greater at approximately 50 W/mK, the steel bottom does not insulate

the bottom of the concrete (Nagy & Szagri 2018). Figure 11a shows the bridge deck model form. Once the formwork was constructed, steel reinforcement grids were configured according to the specifications with rebar ties. Figure 11b shows the finished steel reinforcement grids. PEX tubing was then attached to the top reinforcement grid using rebar ties.

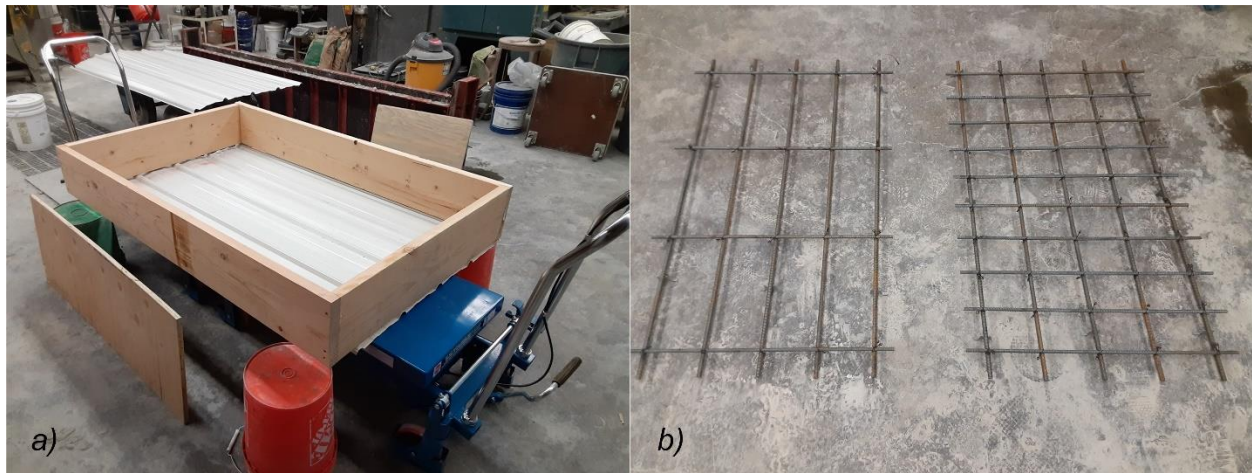


Figure 11: a) Bridge deck model form and b) finished reinforcement grids

The bottom reinforcement grid was then placed on plastic rebar chairs, facilitating the appropriate clear cover, while the top reinforcement grid was hung from additional steel set on the top of the forms with wire. To finish the form, two 12.7 mm holes were drilled in the form work to allow the PEX tubing to run through, and duct tape was used to mark the “fill line.” Figure 12 shows the completed form without thermocouples. Thermocouple preparation and placement is discussed later in this chapter.

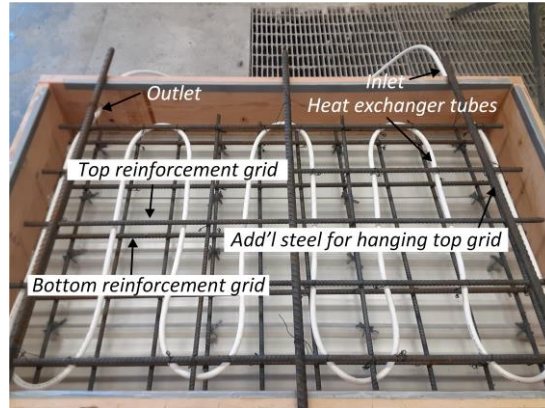


Figure 12: Completed form without thermocouples

Concrete Mixing, Pouring, and Curing

To facilitate later transport of the specimen, the formwork was placed on scissor lift carts and cinder blocks. Four batches of concrete were needed to reach the “fill line” and 32 compression cylinders were cast. Once the top surface was finished, the form was covered in plastic wrap for 24 hours. After 24 hours, the plastic wrap was replaced with wetted towels on the concrete surface and a plastic tarp to trap moisture. Figures 13a and 13b show this process. The towels were re-wetted every two days during the 28-day curing period. Curing took place in the laboratory, kept at room temperature.

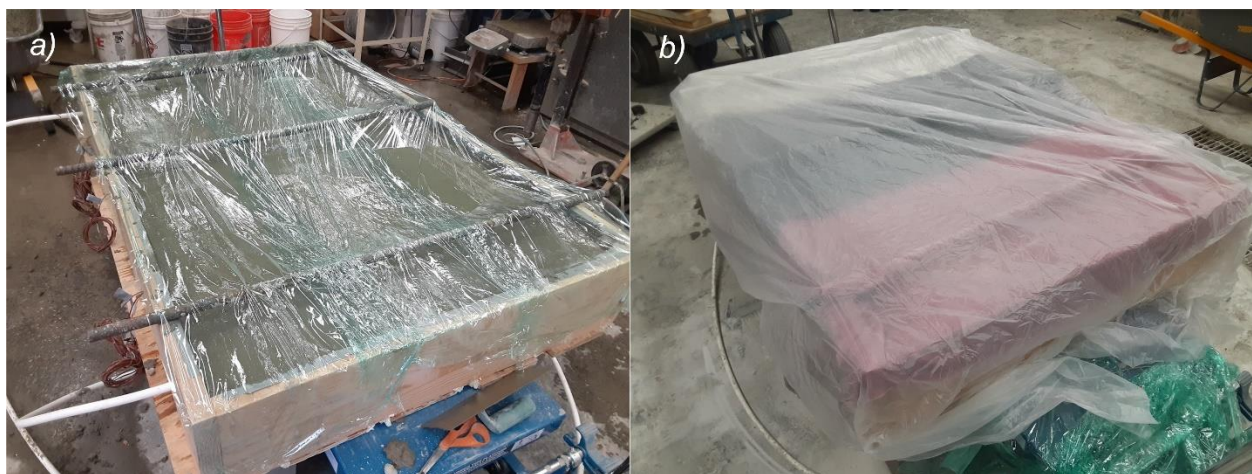


Figure 13: a) Initial 24-hour set and b) 28-day damp towel cure

Bridge Deck Test Preparation

After 28 days, the bridge deck model test preparation began. The steel on top of the forms was removed by stripping the wires at the surface of the concrete. The wood formwork was then removed, taking care not to damage the thermocouples. The wires holding up the top steel reinforcement grid caused some finishing issues in the six locations where wire was used. The rough areas were grinded smooth with a grinder. Figure 14 shows the bridge deck model after the steel and wood formwork were removed.



Figure 14: Cured bridge deck model

After the initial test preparation was completed, the model was moved from the Bulk Materials Lab (Cobleigh 109) to the CHC (Cobleigh 112C) (Figure 15a). Hydraulic scissor lift tables were used to transport the bridge deck once inside Cobleigh Hall (Figure 15b). After passing through the SRL into the CHC (Figure 15c), the bridge deck model was placed on cinder blocks in its final location (Figure 15d).

Once the model was moved to the CHC, the PEX tubing was attached to an inlet valve on one end and allowed to drain into an outlet reservoir on the other. To complete the preparation process, insulation was added to the sides of the model and the exposed PEX tubing. Figure 16 shows the bridge deck model in the CHC prepared for testing.

The objective of the physical bridge deck experiments is to further validate the numerical simulation's ability to assess the feasibility of using geothermal energy in Montana to 1) deice concrete bridge decks and 2) mitigate bridge deck cracking. To achieve this, data is needed for

the internal and external concrete temperature and the concrete strain. Figures 17a and 17b shows the general schematic of the instrumentation and the proposed locations of the thermocouples and strain gauges, respectively. Imbedded Type-T thermocouples (x30) were installed to monitor the internal temperature of the specimen. A thermal camera was used to supplement the thermocouple data by monitoring the surface temperature of the specimen. GEOKON vibrating wire strain gauges (x5) were used to monitor strain in the bridge deck model.



Figure 16: Bridge deck model prepared for testing

Other instrumentation was used to measure the conditions in the CHC. An anemometer was used to measure the wind speed from the CHC fans and a pyranometer was used to measure the solar intensity of the solar simulator. Additional thermocouples were added to measure the ambient temperature and the inlet and outlet fluid temperatures. A McMaster-Carr flow meter was attached near the inlet to measure the flow rate.

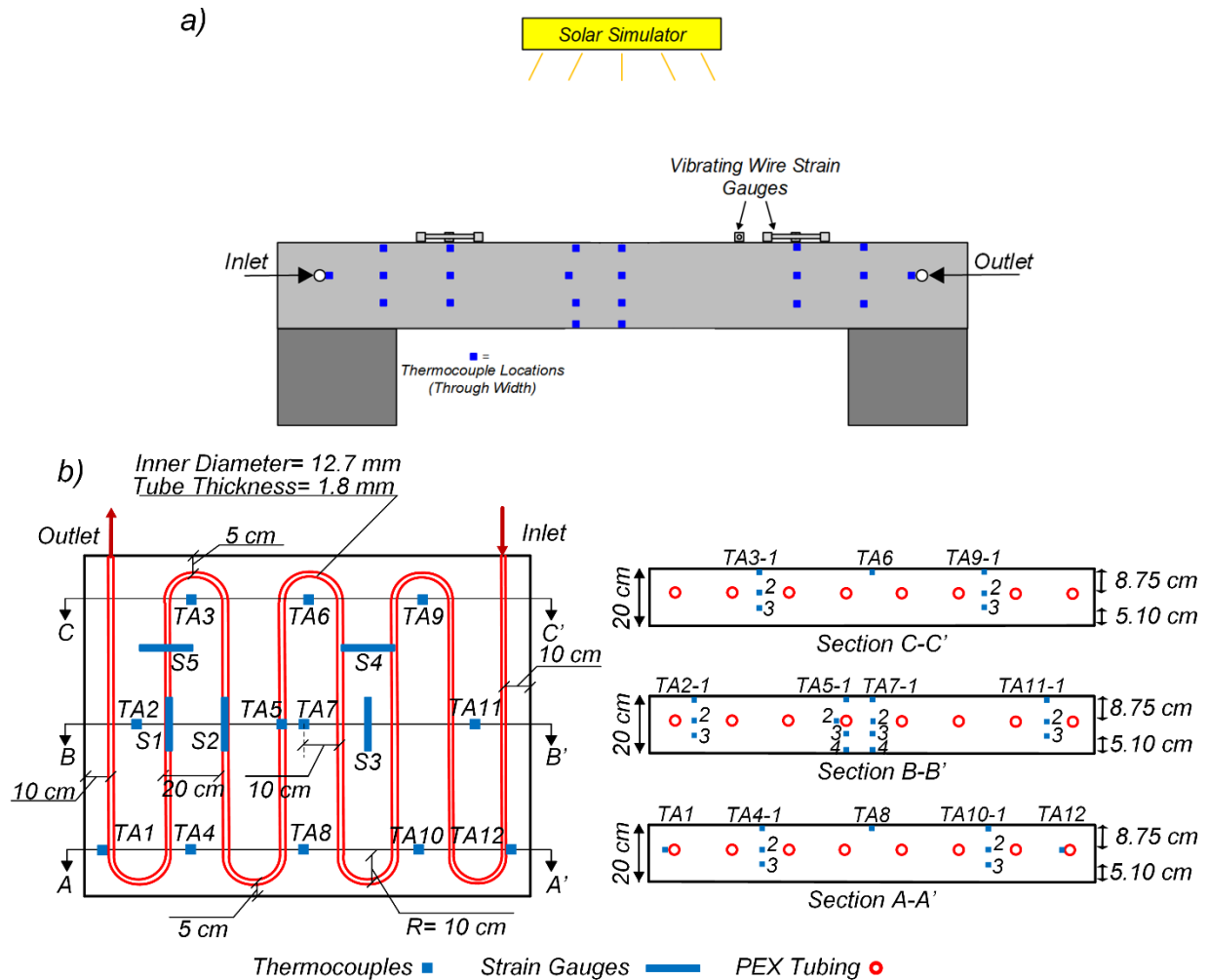


Figure 17: a) Instrumentation schematic and b) proposed locations of thermocouples and strain gauges

Thermocouple Preparation. The thermocouples were prepared using a thermocouple welder. The process includes unwelded thermocouples (Figure 18a) being placed in a copper holder, then inserted in the thermocouple welder (Figure 18b). The welded thermocouples (Figure 18c) were then validated using a mixture of ice and water at approximately 0 °C.

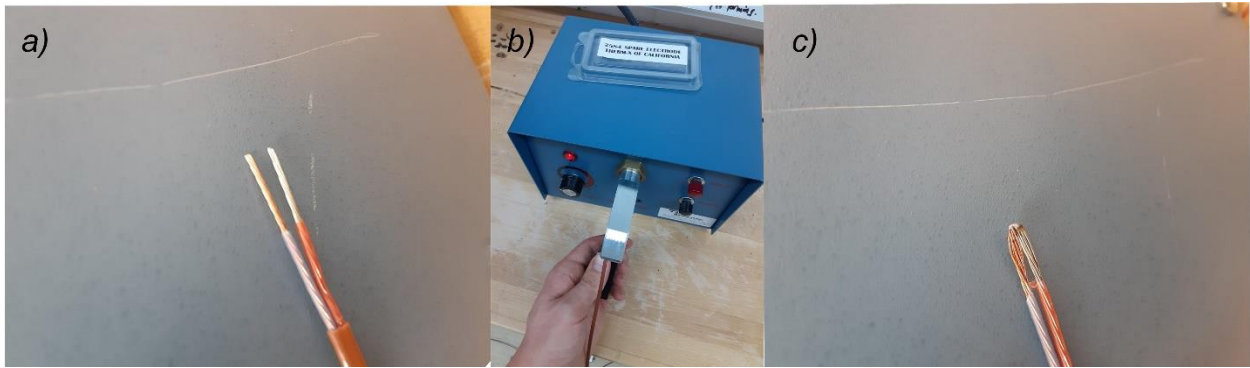


Figure 18: a) Thermocouples before welding, b) thermocouple welder, c) and welded thermocouple

Once validated, the thermocouples were placed using zip ties. Figures 19a and 19b show the placed thermocouples. Holes were drilled in the wood formwork for the thermocouples to be fed through.

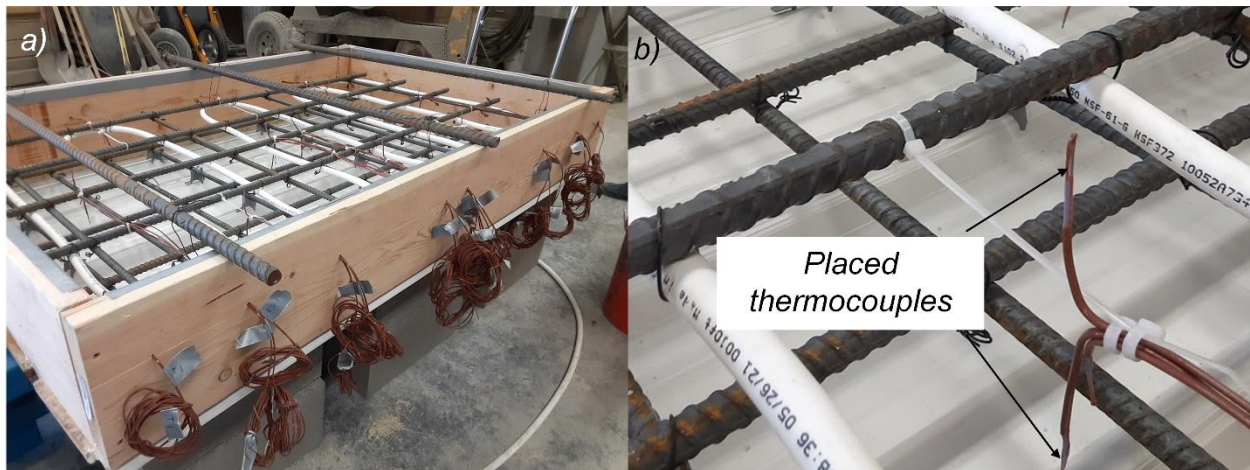


Figure 19: a) Completed form with thermocouples and b) closeup of placed thermocouple

Vibrating Wire Strain Gauge Installation. The GEOKON wire strain gauges were installed by epoxying the mounting blocks into drilled holes in the top surface. Figures 20a and 20b shows the strain gauges and mounting blocks before and after placement.

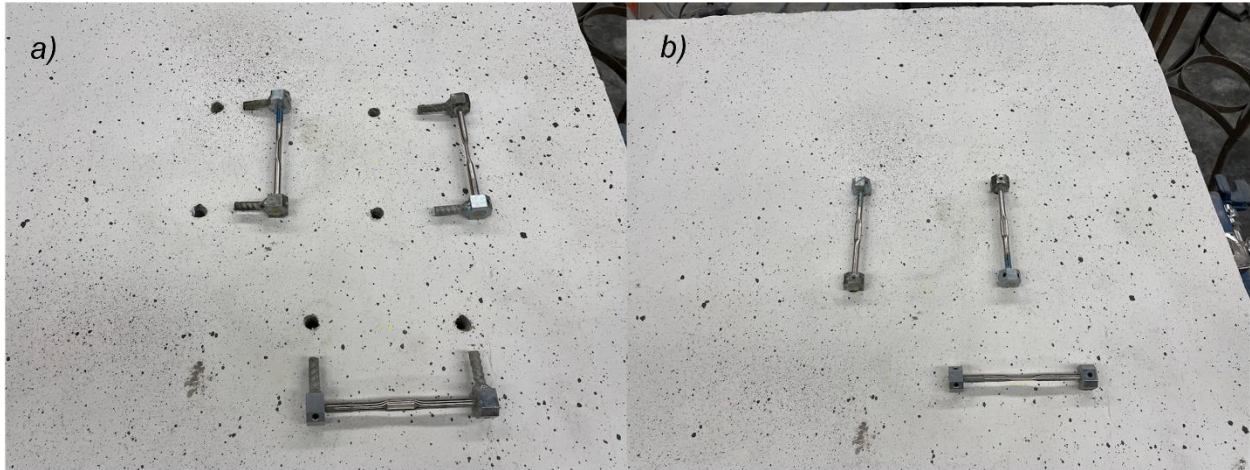


Figure 20: a) Strain gauges with mounting blocks ready for epoxy and b) installed strain gauges

Weather Scenarios

RWIS stations provide detailed weather information which can be used for winter road and bridge maintenance (Al-Kaisy & Ewan 2017). The 73 stations in Montana include an air temperature and humidity sensor, wind speed and direction sensor, in-pavement temperature sensor, subsurface temperature sensor, precipitation sensor, and a camera. Figure 21a shows the locations of the 73 RWIS stations in Montana. Time histories of the weather data from the 73 RWIS stations were collected from 2015 to 2020. The data indicates that November through February were the coldest months of the year from 2015 to 2020 (Figure 21c). To test the feasibility of a ground-source bridge deck deicing system, extreme conditions from these months must be considered. Figure 21b shows an example of a winter weather event in Montana. The event was recorded in Great Falls, MT, in January 2019, and will be replicated in future testing. With temperatures below freezing and high snow accumulation, the Great Falls event represents extreme weather in Montana.

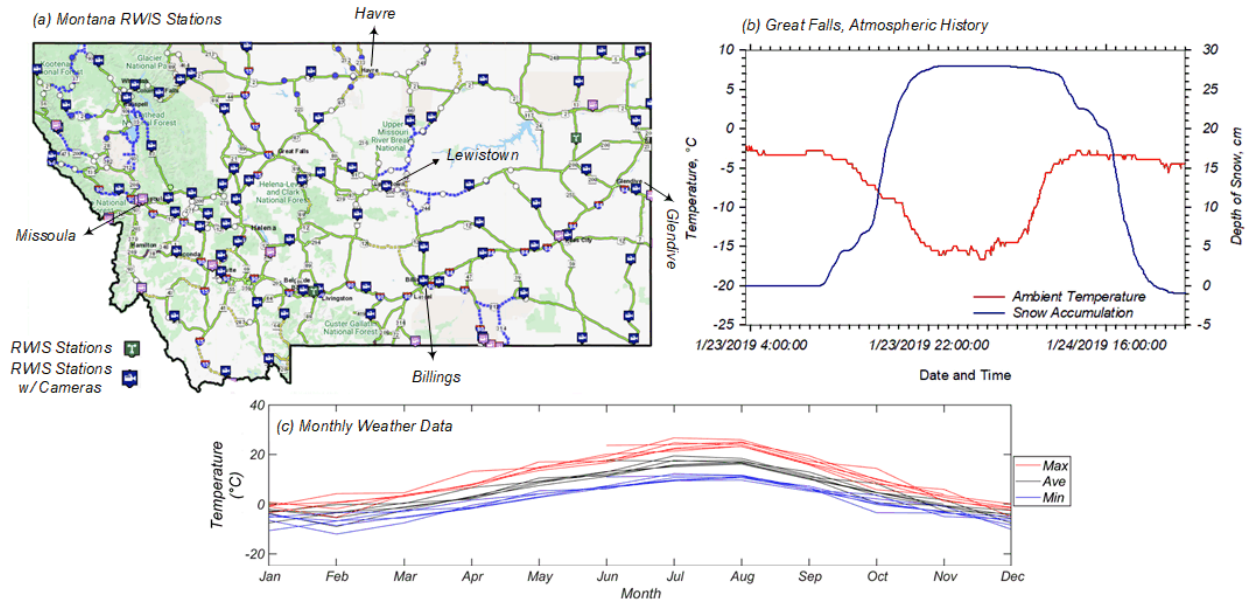


Figure 21: a) Locations of MDT RWIS sites (map source: <https://roadreport.mdt.gov/>), b) atmospheric history of Great Falls, MT, on January 23-24, 2019, c) and monthly average ambient temperature for 2015-2020

Experimental Weather Scenarios

Data from the RWIS stations was used to develop testing scenarios for a geothermal bridge deck deicing system in Montana. The two stages of testing are the synthetic and daily fluctuation scenarios.

Synthetic. The purpose of the synthetic scenario is to test a series of variables with and without the geothermal heat system running. Figure 22 shows the synthetic testing procedure. The specimen is first tested without the geothermal heat system running. Each phase of the test lasts 12 hours or however long the internal temperatures take to stabilize. First, the model is left to reach equilibrium with the non-cooled room temperature. Then, the ambient temperature is dropped to -10°C . After 12 hours at -10°C , the solar simulator is activated at its maximum capacity of W/m^2 . In the last phase, the ambient temperature is dropped to -20°C . The entire process is then repeated while the geothermal heat system is running.

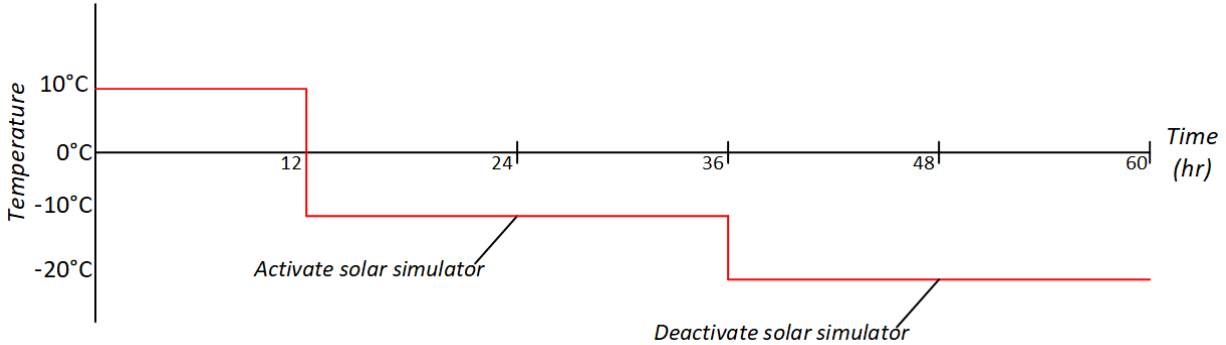


Figure 22: Synthetic testing procedure

Daily Fluctuation. In Montana, large daily temperature fluctuations are experienced during the late winter months. The second stage of testing simulates these fluctuations. Figure 23 illustrates the daily fluctuation testing procedure. The ambient temperature starts at the average daily maximum temperature for February and March. After 3 hours at the maximum, the temperature is gradually dropped over a period of 6 hours to the average daily minimum temperature for February and March. Once the temperature reaches the minimum, it remains constant for a period of 6 hours. After that, it is gradually returned to the maximum temperature over a period of 6 hours. This temperature remains constant at the maximum for 3 hours. The 24-hour cycle is then repeated to simulate consecutive days.

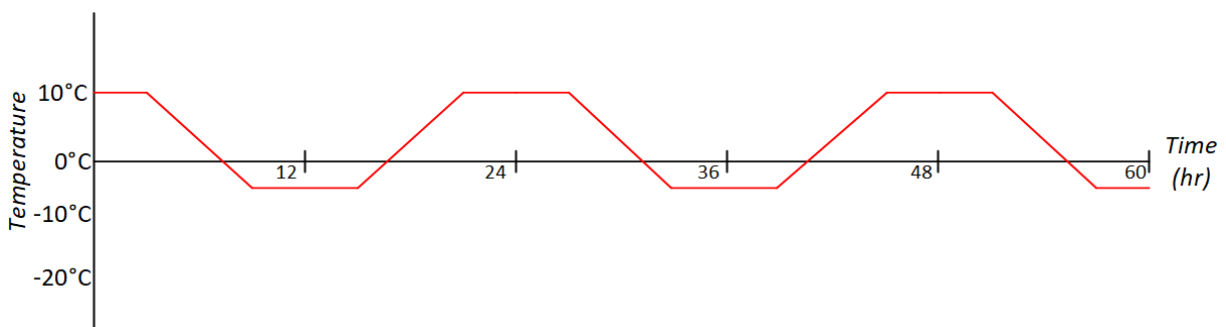


Figure 23: Daily fluctuation testing procedure

CHAPTER TWO

MODEL SCALE EXPERIMENTS

Introduction

This chapter will be submitted as a journal paper in 2024. Reinforced concrete bridges face numerous challenges caused by environmental factors. Weather conditions such as freezing temperatures, precipitation, and solar radiation can cause concrete deterioration through various mechanisms. Three mechanisms that cause deterioration are thermal stresses, frost action, and early-age cracking (Imbsen et al. 1985, Johnson 2005, Saffiuddin et al. 2018). As these deterioration mechanisms induce cracking in concrete bridge decks, steel reinforcement embedded in the concrete becomes exposed to water, deicing chemicals, and other environmental factors. This exposure leads to deterioration of the reinforcing steel and overall integrity of the bridge (Granata & Hartt 2009; Yunovich et al. 2003).

Research has shown that thermal stresses can exceed stresses produced by live loads (Johnson 2005; Reynolds & Emanuel 1974). Thermal stresses are caused by thermal movements and thermal gradients. Thermal movements occur due to changes in the average temperature of the concrete bridge deck over time, resulting in uniform expansion and contraction across its length and width. The expansion or contraction introduces stresses if the movement is restrained by the bridge supports (Roeder & Moorty 1991). He et al. (2019) reported that the stresses from thermal movement restriction in a bridge deck increased from 0.8 MPa to 12 MPa (15x) when the support conditions changed from simply supported to fixed end supported. Thermal gradients occur when a nonuniform temperature profile develops through the depth of the bridge deck.

This commonly occurs when the top surface is exposed to more heat from the sun compared to the bottom surface. The temperature gradient makes the top surface expand more than the bottom, causing negative moment bending behavior in the deck. Thermal bending introduces additional stresses, especially at the top surface. Additionally, if the temperature profile is nonlinear, “self-equilibrating” stresses develop internally due to the compatibility of the cross-section (Radolli & Green 1975). Barr et al. (2014) observed tensile stresses from thermal gradients up to 3.45 MPa, which was 39% greater than the design limit proposed by the AASHTO LRFD Bridge Design Specifications for the bridge location in California. Cracking occurs when the induced stresses exceed the concrete's tensile capacity.

Frost action occurs when water inside concrete voids freezes and expands. As the water turns to ice, it exerts pressure on the surrounding voids to enlarge. If the voids cannot accommodate the expansion, they grow and connect with other voids, forming an interconnected network of cracks in the concrete (Johnson 2005). Wardeh et al. (2011) found that after 240 freeze-thaw cycles, the compressive strength of plain concrete was reduced to 40% of the initial 28-day strength. Early-age cracking is also a concern for concrete bridge decks. One cause of early-age cracking is thermal shrinkage, which occurs when the concrete temperature decreases from its peak at curing to the ambient air temperature. This shrinkage induces tensile stresses in the concrete since the bridge deck is restrained by the supporting girders. If the tensile stress exceeds the low concrete tensile capacity at early ages, full-depth transverse cracks can form in the deck shortly after construction (Babaei & Fouladgar 1997). Cooler ambient temperatures intensify this phenomenon because the difference between the cured concrete temperature and the ambient temperature is greater. Purvis et al. (1995) recorded thermal strains 14% greater than

the maximum strain before expected cracking of the early-age concrete with an ambient temperature of around 4 °C.

There are several accepted practices in place to mitigate thermally-induced concrete deterioration. To avoid thermal stresses, expansion joints are employed to allow for some expansion and contraction of the bridge deck. While effective in reducing thermal stresses, expansion joints often have a shorter lifespan than the rest of the bridge and therefore require additional maintenance (Li et al. 2023). Causes for the short lifespan of expansion joints include drainage issues, impairment of their range of motion by debris, and ineffective transitions from the joint to the bridge deck surface (Lima & Brito 2006). Crumley and Haddick (2023) reported that in recent years in Montana, numerous premature expansion joint failures have been observed, often due to construction issues. Air entraining admixtures (AEAs) have been used since the 1930s (Jackson 1944) to increase concrete's resistance to frost action. AEAs are added to concrete mix designs to provide air void systems that give more space for expansion as water changes phases. Despite the many benefits of AEAs, their performance can be inhibited by other admixtures such as superplasticizers and shrinkage reducing admixtures (Tunstall et al. 2021). Many practices related to concrete mixing, placing, and curing are recommended by researchers to reduce early-age cracking in concrete bridges. Recommendations include limiting the amount of cement in the mix design, increasing the speed of placement, and maintaining a differential concrete temperature for at least 24 hours after it is placed (Wan et al. 2010; Deng et al. 2016; Babaei & Fouladgar 1997). These practices have been proven to mitigate early-age cracking, but are dependent on material availability, weather conditions, and contractor skill.

Using geothermal energy to deice concrete bridge decks, with systems that circulate fluid through pipes embedded in the deck, has been studied extensively in recent years (Bowers 2016; Ghasemi-Fare et al. 2015; Han & Yu 2017). These ground-source deicing systems have proven effective for snow and ice melting by transferring heat from the earth into the concrete. In addition to deicing, geothermal systems may provide benefits related to concrete health and durability. By regulating bridge deck temperatures, geothermal energy could potentially mitigate multiple mechanisms of thermally-induced cracking and deterioration. Mohammadzadeh et al. (2023) found that using shallow geothermal energy, transferred through heat exchanger tubes, could reduce internal and top surface concrete temperature fluctuations during summer weather. During the month of September 2021, they recorded concrete surface temperatures up to 20 °C lower in a bridge deck with a geothermal system than a bridge deck with no geothermal system. The reduced temperature fluctuation suggests reduced straining and/or stressing of the bridge deck. Further research is needed, but initial findings show promise for geothermal energy to mitigate cracking and deterioration while providing a sustainable deicing option. Controlled field implementation combined with modeling will determine the full potential of geothermal systems for both deicing and enhancing concrete bridge deck durability.

This paper summarizes results from physical experiments evaluating the use of geothermal energy to deice concrete bridge decks and mitigate concrete deterioration. Two scaled bridge deck models were constructed with embedded heat exchanger tubing and outfitted with thermocouples and strain gauges. The models were subjected to weather scenarios representative of winter events in Montana, both with and without the deicing system activated. The effectiveness of the system was examined for (1) deicing capability based on surface

temperature data, (2) frost damage risk minimization using temperature profiles throughout the depth, (3) thermal movement and gradient reduction based on strain and internal temperature measurements, and (4) thermal shrinkage mitigation by reducing concrete curing and ambient temperature differentials. The experimental results provide insights into the potential benefits of geothermal energy for enhancing durability and extending the service life of concrete bridge decks in cold climates. Additionally, the data obtained offers a useful dataset for validating numerical modeling to further optimize the design and operation of geothermal systems in concrete bridge applications.

Experimental Models

A series of experiments were completed in the Cold Hydrodynamics Chamber (CHC) of the Subzero Research Laboratory at Montana State University to test the feasibility of using geothermal energy to deice bridge decks in Montana and mitigate thermally-induced concrete deterioration. The CHC can control the ambient temperature from $-25\text{ }^{\circ}\text{C}$ to $10\text{ }^{\circ}\text{C}$ and has a temperature-controlled water reservoir, which can pump a steady flow of water to and from the chamber. The chamber also has a solar simulator with a maximum intensity of 490 W/m^2 as measured from the surface of the bridge decks.

The experiments were performed on two physical models. Model 1 was designed to evaluate the feasibility of using geothermal energy to deice concrete bridge decks and mitigate thermal stresses and frost action. Model 2 was designed to evaluate the effects of geothermal energy on early-age cracking. The design and dimensions of Model 1, shown schematically in Figure 24, were determined based on results from numerical simulations (Turner et al. 2023) and constrained by the size of the Cold Hydrodynamics Chamber (CHC). The dimensions of the

bridge deck were 160 cm long, 100 cm wide, and 20 cm thick, based on a standard deck slab thickness provided in the MDT Structures Manual (2002). Model 2 was designed as a quarter-scale representation of Model 1, as shown in Figure 25, with all design parameters consistent with Model 1. A control bridge deck (Model 2c) was designed to replicate Model 2, but with no heat exchanger tubes. The rebar size and configuration for the 20 cm thick bridge decks were based on specifications from the MDT Structures Manual (2002). Rigid insulation was used to insulate the sides of the bridge decks, while corrugated steel was used as a permanent bottom form. Since steel has a much higher thermal conductivity than concrete, the steel did not insulate the bottom. The concrete mix design was developed through a series of experiments testing MDT-approved mix designs, as discussed by Pourakbar et al. (2021).

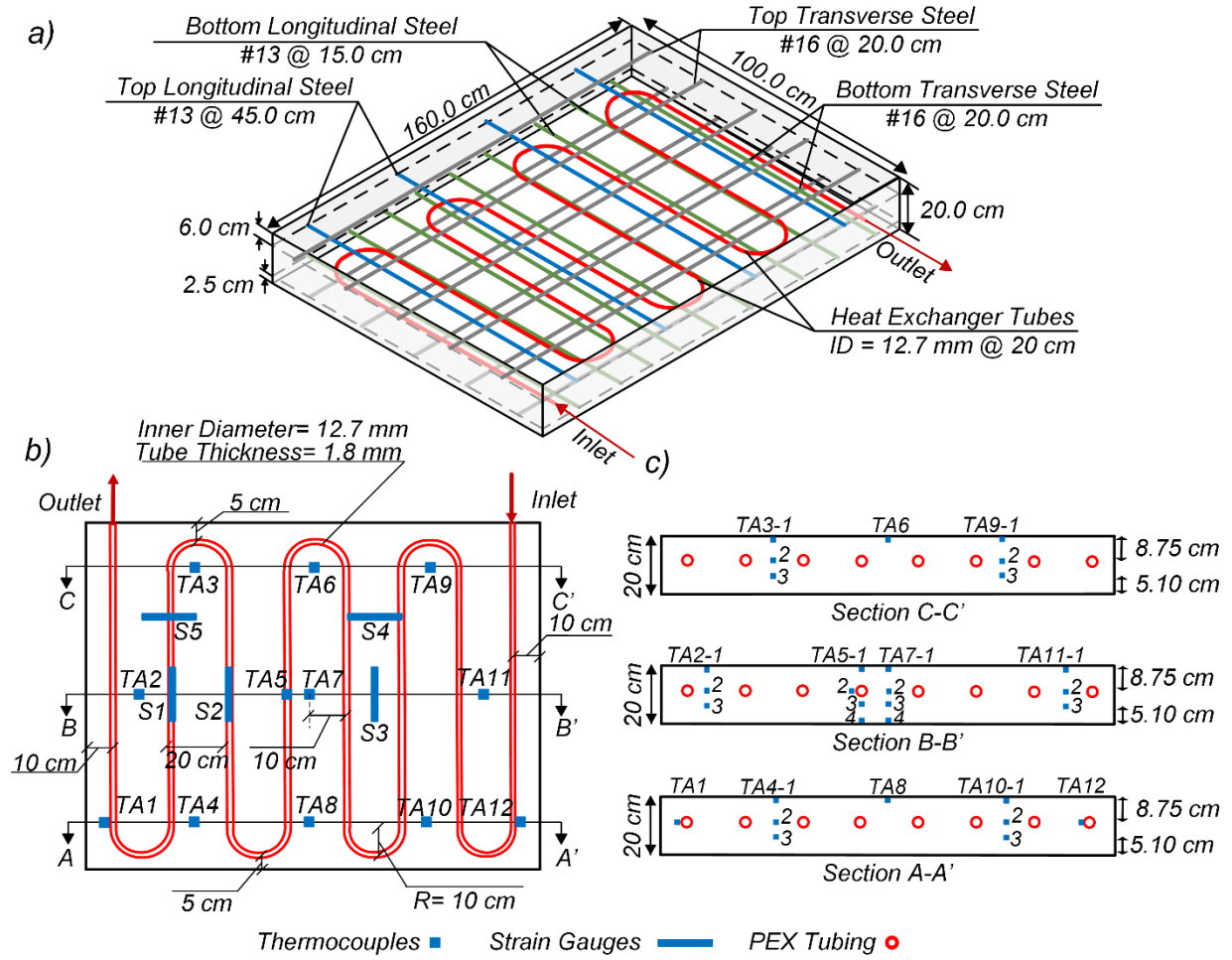


Figure 24: Model 1 design: a) 3D view, b) plan view with surface locations of sensors, and c) section views with depth location of sensors.

For the heat exchanger tubes, 12.7 mm cross-linked polyethylene (PEX) tubing was used with 20 cm center-to-center spacing. The maximum fluid flow rate possible in the CHC of 5.5 L/min was used for all experiments to circulate a 30% glycol mixture through the heat exchanger tubes. A computational parametric study showed that for the dimensions of the experimental bridge deck, fluid flow rate has a negligible effect on the efficiency of the deicing system (Turner et al. 2023). An inlet fluid temperature of 8 °C was used for all experiments because the ground temperature seasonal variation is minimal (Kusuda & Achenbach 1965). Model 1 and Model

2/2c were instrumented with Type-T thermocouples to measure the concrete temperature at various locations. The thermocouple layouts for Model 1 and Model 2/2c are shown in Figures 24 and 25, respectively. Five vibrating wire strain gauges were installed on the top surface of Model 1 to measure the concrete strain. The strain gauge configuration for Model 1 is shown in Figure 24b.

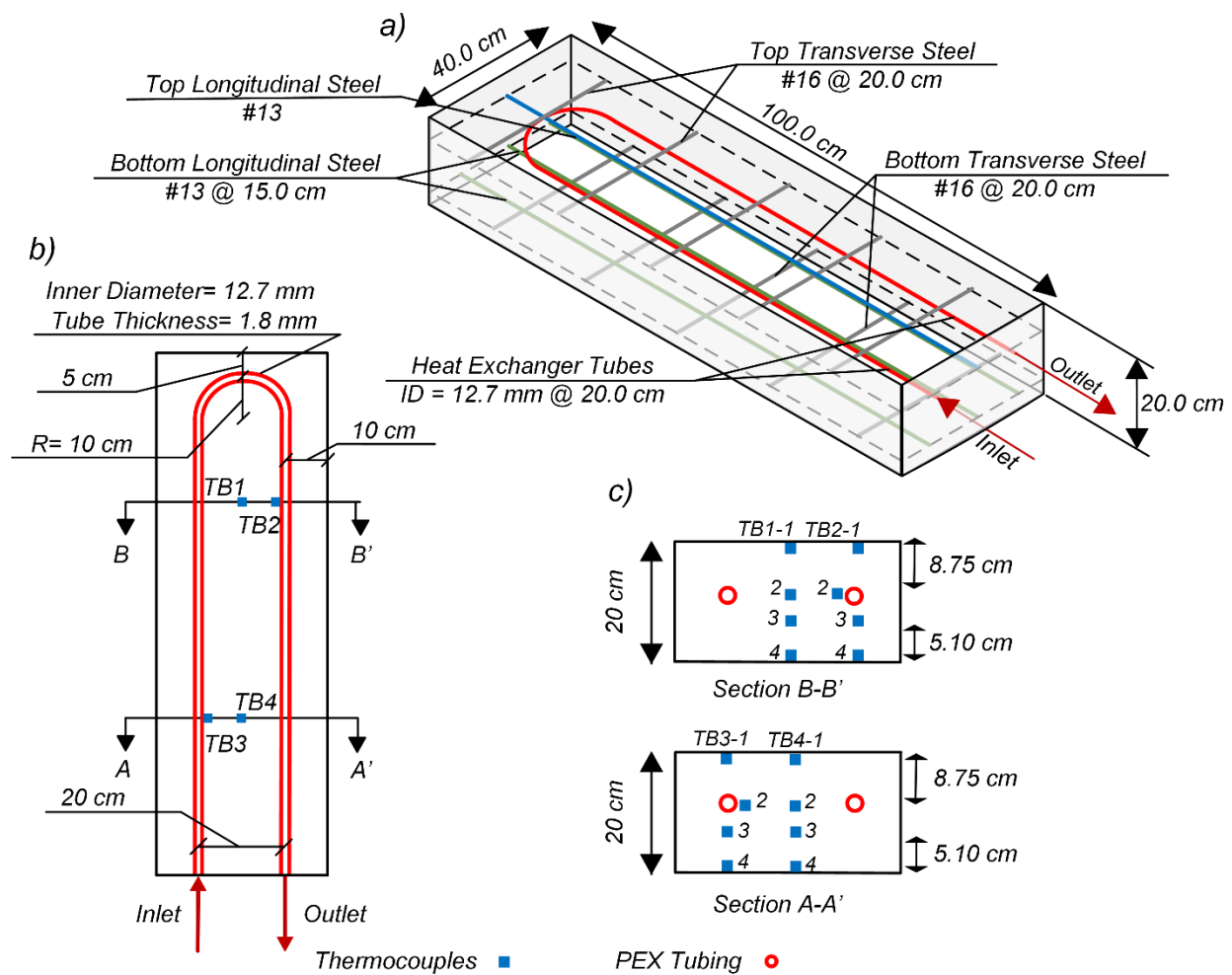


Figure 25: Model 2 Design: a) 3D view, b) plan view with surface locations of sensors, and c) section views with depth location of sensors.

Weather Scenarios and Testing Sequence

Two weather scenarios were designed to test the ability of Model 1 to deice the top surface and mitigate thermally-induced concrete deterioration: 1) Synthetic Weather Scenario and 2) Daily Fluctuation Weather Scenario. The scenarios aimed to replicate a range of winter conditions experienced in Montana, with maximum and minimum temperatures and solar radiation levels selected based on historical weather data collected from Road Weather Information System (RWIS) stations across the state from 2015-2020. The 73 RWIS stations in Montana include an air temperature and humidity sensor, wind speed and direction sensor, in-pavement temperature sensor, subsurface temperature sensor, precipitation sensor, and a camera. Average monthly ambient temperatures in Montana, shown in Figure 26, demonstrate that the coldest months are typically November through February. Each test was run with and without the deicing system in operation.

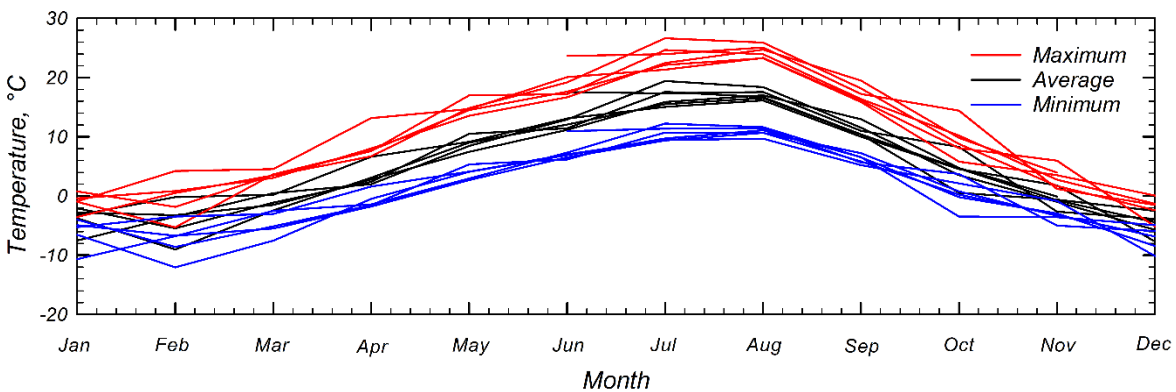


Figure 26: Montana Monthly Average Ambient Temperature for 2015-2020.

The Synthetic Weather Scenario was designed to isolate the effects of low temperatures and solar radiation on the efficiency of the system. The test has four 24-hour stages with varying ambient temperatures and solar intensities, as shown in Figure 27a. Before Stage 1, the concrete

temperature is stabilized with an ambient temperature of 10 °C. In Stage 1, the ambient temperature is set to -10 °C, with no solar radiation. The solar simulator is then activated at 490 W/m² for Stage 2 while the ambient temperature remains at -10 °C. For Stage 3, the ambient temperature is set to -20 °C while the solar simulator stays activated at 490 W/m². For the final stage, the solar simulator is deactivated while the ambient temperature remains at -20 °C.

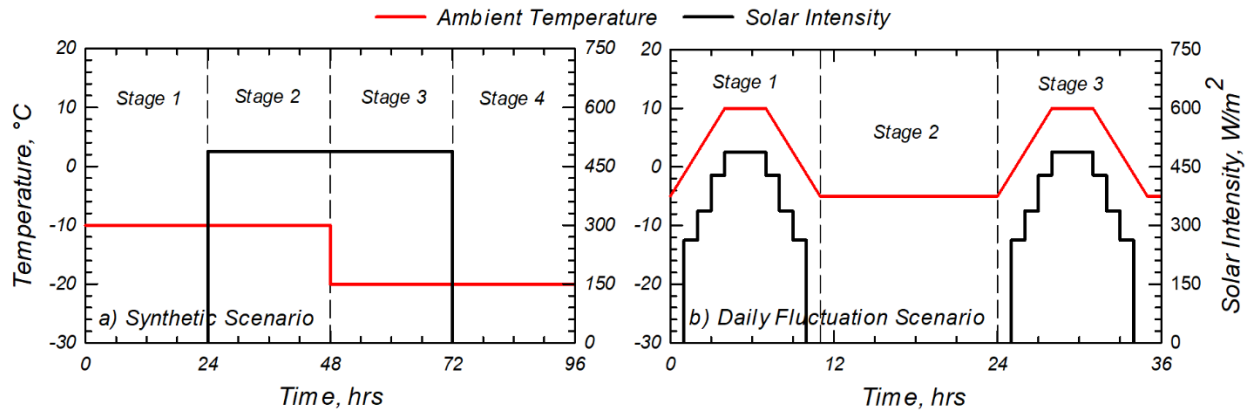


Figure 27: Ambient temperature and solar intensity of Model 1 weather scenarios: a) Synthetic and b) Daily Fluctuation.

The Daily Fluctuation Weather Scenario mimics a typical late winter day in Montana with large diurnal swings (Figure 27b). The test is split into three stages of various lengths. Before Stage 1 the concrete temperature stabilizes with an ambient temperature of -5 °C. During the first four hours of Stage 1, the ambient temperature linearly increases to 10 °C while the solar intensity increases at 1-hour intervals to the maximum capacity. The incremental capacities were chosen from the solar simulator's preset capacities: 0%, 55%, 71%, 90%, and 100%. After 3 hours at 10 °C and 490 W/m², the ambient temperature then linearly decreases to -5 °C and the solar intensity incrementally decreases to 0 W/m² over the span of four hours. During Stage 2,

the ambient temperature and solar intensity remain at $-5\text{ }^{\circ}\text{C}$ and 0 W/m^2 , respectively, for 13 hours. Stage 3 is identical to Stage 1 and starts at hour 24.

One experiment was designed for Model 2/2c to evaluate mitigation of thermal shrinkage by running the deicing system during the curing process and early age of the concrete. The chamber was set at $3\text{ }^{\circ}\text{C}$ for the duration of curing because it is the maximum temperature at which the CHC can keep the fluid temperature constant at $8\text{ }^{\circ}\text{C}$. After 28 days, 2-in cores were extracted from the bridge deck to compare compressive strengths with the control model bridge deck, Model 2c.

Results and Discussion

The results and discussion section presents the data collected and analyzed from laboratory experiments conducted to evaluate the deicing system's effectiveness. For Model 1, concrete temperature and strain data were collected to evaluate the system's ability to deice and mitigate thermal deterioration. Experiments using the Synthetic and Daily Fluctuation Weather Scenarios produced temperature data throughout the concrete depth and strain data for the top surface. This data was used to assess deicing performance, frost action effects, and thermal stress impacts. For Model 2, temperature and 28-day strength data were collected to evaluate early-age cracking mitigation. The concrete temperature during curing and strength results were used to examine the system's influence on the temperature differential between curing and stabilization and resulting strength development. Some thermocouples were displaced during concrete placement, prompting additional tests to identify reliable thermocouples for each depth. The following sections discuss the results for each application of the experimental deicing system.

Due to routine defrost cycles in the CHC to prevent freezing of the condenser coils, frequent temperature spikes are observed in the results.

Application for Bridge Deck Deicing

The deicing system's ability to maintain the concrete surface temperature above 0 °C was evaluated using temperature data from thermocouples near the top surface of Model 1. Thermocouples TA2-1, TA7-1, and TA8 were analyzed as they best represented the top surface temperature.

In the absence of solar radiation, the deicing system increased the surface temperature compared to when it was not in operation. Figures 28a and 29a show the Synthetic Scenario without and with the system running, respectively. Stages 1 and 4 present the top surface temperature results with no solar radiation. During Stage 1 of the Synthetic Scenario, the surface stabilized at the ambient temperature of -10 °C without the system. With the system operating, the stabilized surface temperature increased 7 °C to -3 °C. This demonstrated the system's ability to provide a surface temperature increase during cold weather. Stage 4 of the Synthetic Scenario provided similar results, with the system causing a 9 °C increase in the stabilized surface temperature to -11 °C compared to -20 °C without the system. Despite the colder conditions, the system continued to cause increased surface temperatures. While the system did not raise the surface temperature above 0 °C during these stages, it successfully reduced the effects of cold ambient temperatures.

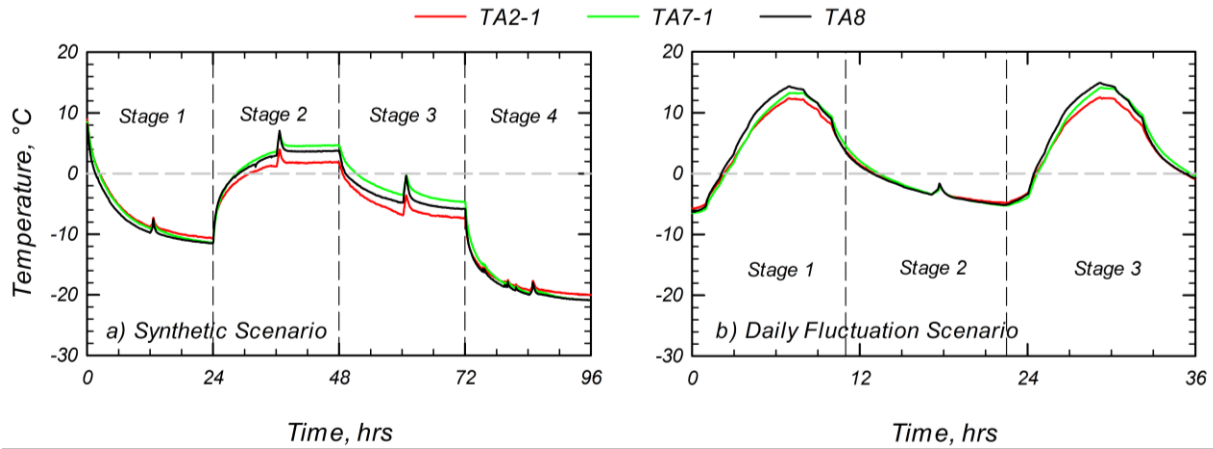


Figure 28: Top surface thermocouple results for a) Synthetic and b) Daily Fluctuation Weather Scenarios without deicing system active.

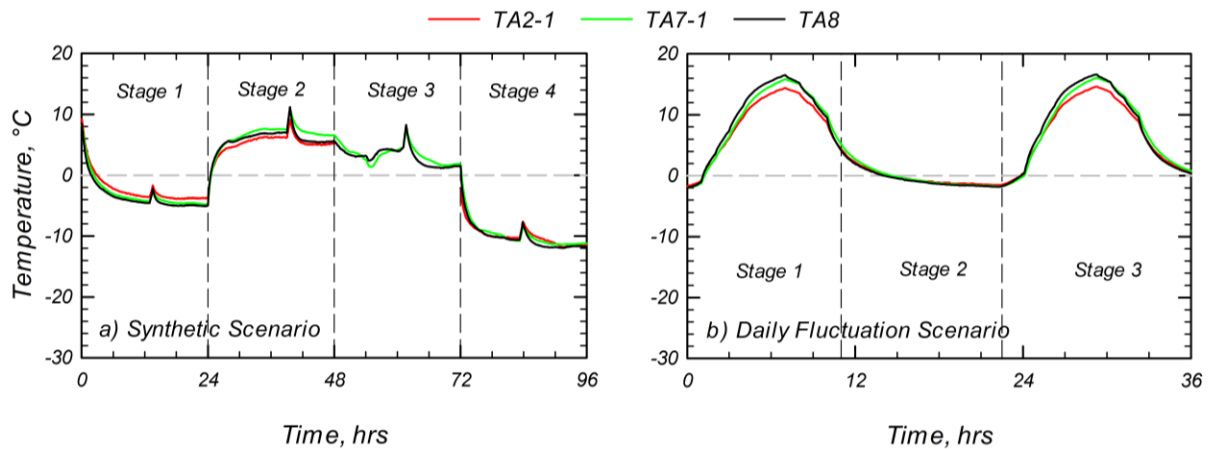


Figure 29: Top surface thermocouple results for a) Synthetic and b) Daily Fluctuation Weather Scenarios with deicing system active.

Stages 2 and 3 of Figures 28a and 29a present the top surface temperature results when solar radiation was present. Early during Stage 3 with the system running, a malfunction caused the solar simulator to deactivate. The malfunction was quickly corrected, and the surface temperatures stabilized within the 24-hour stage. Thermocouple TA2-1 was most affected by the malfunction, so the data was removed for clarity. Thermocouples TA7-1 and TA8 are still presented, despite the malfunction early in Stage 3. Solar radiation further increased the bridge deck surface temperature. In general, the thermal energy from sunlight can improve the

performance of geothermal systems in winter weather by adding to the heat input from the fluid circulation. During Stage 2 of the Synthetic Scenario, with the ambient maintained at $-10\text{ }^{\circ}\text{C}$ and radiation applied at 490 W/m^2 , the surface temperature stabilized at $6\text{ }^{\circ}\text{C}$ with the system running, which was $16\text{ }^{\circ}\text{C}$ higher than the ambient temperature. Without the system, the surface stabilized $13\text{ }^{\circ}\text{C}$ above the ambient temperature. During Stage 3 of the Synthetic Scenario, with the ambient temperature decreased to $-20\text{ }^{\circ}\text{C}$ and the same solar radiation activated, the surface reached $1\text{ }^{\circ}\text{C}$ with the system versus $-6\text{ }^{\circ}\text{C}$ without. This amounts to a surface temperature $21\text{ }^{\circ}\text{C}$ above the ambient temperature with the system, and $15\text{ }^{\circ}\text{C}$ above without. During Stages 2 and 3, the compounded effects of the system and the solar radiation raised the stabilized temperature above $0\text{ }^{\circ}\text{C}$, whereas the solar radiation alone only accomplished this during Stage 2.

The Daily Fluctuation Scenario mimicked ambient temperature and solar intensity fluctuations consistent with late winter diurnal cycles in Montana. Figures 28b and 29b show the Daily Fluctuation results without and with the system running, respectively. During the early morning hours with minimal solar intensity, the surface temperature stayed below $0\text{ }^{\circ}\text{C}$ for the first 2.5 hours without the deicing system. With the system active, the surface exceeded $0\text{ }^{\circ}\text{C}$ after only 1.5 hours, showing the system's ability to raise the temperature above freezing faster. As the solar intensity increased incrementally, the peak surface temperature reached $13\text{ }^{\circ}\text{C}$ without the system and $15\text{ }^{\circ}\text{C}$ with the system. The $2\text{ }^{\circ}\text{C}$ higher peak demonstrates the additional heat from the system coupled with the solar effects. In the late evening as solar intensity declined, the surface fell below $0\text{ }^{\circ}\text{C}$ at hour 13.5 without the system but not until hour 14.5 with the system. This showed the system's capacity to maintain the surface temperature above freezing longer into the nighttime hours. Over the entire Daily Fluctuation Scenario, the deicing

system raised the surface temperature above the 0 °C target for 75% of the time versus only 62% of the time without the supplemental heat from the system.

Overall, while the system was not successful in raising the surface temperature above 0 °C during all stages of the various experiments, the results indicated that with a fluid temperature of 8 °C, the system always increased the surface temperature. This suggests that higher fluid temperatures could further enhance the performance of the system.

Application for Mitigating Frost Action

The deicing system's ability to mitigate damage caused by frost action was evaluated by its ability to keep the concrete temperature at all depths above 0 °C. Thermocouples TA7-1, TA7-2, TA7-3, and TA7-4 are presented for frost action results because they were found to accurately represent the concrete temperature throughout the depth.

Figures 30a and 31a present the TA7 thermocouple temperature results for the Synthetic Scenario without and with the system running, respectively. Again, Stages 1 and 4 show the temperature results without solar radiation. Without solar radiation, as previously discussed, the deicing system raised the surface temperature, but it also elevated the temperature throughout the depth of the bridge deck. During Stage 1 of the Synthetic Scenario, the top and bottom surface stabilized at -5 °C with the system activated, which was 5 °C above the ambient temperature. The internal concrete temperature (measured by Thermocouples T7-2 and T7-3) stabilized even higher, at -2 °C, due to the proximity to the heat exchanger tubes and the lack of exposure to ambient conditions. Similar behavior was observed in Stage 4 of the Synthetic Scenario, with the top and bottom surface temperatures stabilizing at -11 °C and the internal temperature stabilizing at -8 °C compared to the ambient temperature of -20 °C. This suggests that without solar

radiation, the top and bottom surfaces of the bridge deck are the most susceptible to frost action when the system is running. The results also suggest that while the system did not raise the concrete temperature at all depths above 0 °C without solar radiation, it did raise the temperature at all depths compared to when the system was not running.

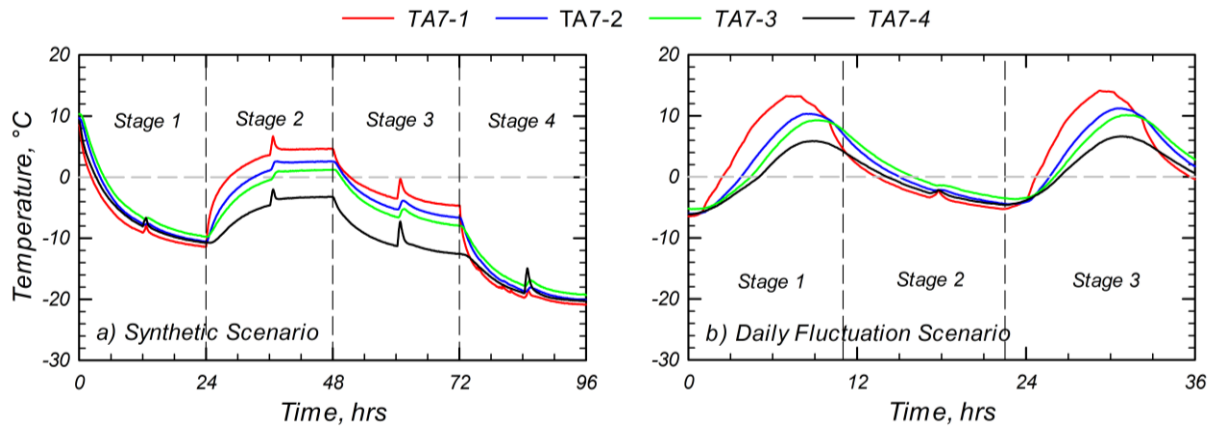


Figure 30: TA7 thermocouple results for a) Synthetic and b) Daily Fluctuation Weather Scenarios without deicing system active.

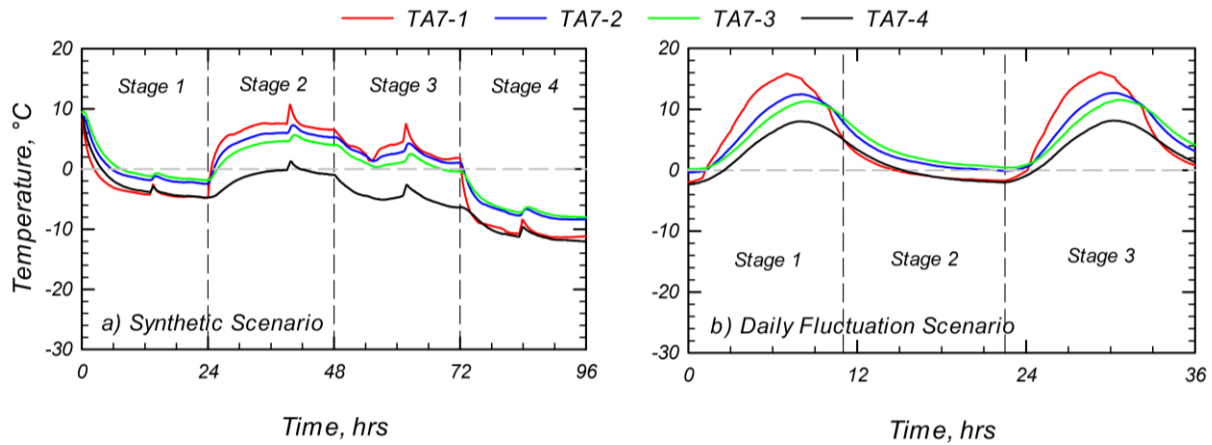


Figure 31: TA7 thermocouple results for a) Synthetic and b) Daily Fluctuation Weather Scenarios with deicing system active.

With the addition of 490 W/m² of solar radiation, the top surface of the bridge deck was not as susceptible to frost action as the bottom surface. Stages 2 and 3 illustrate the results with the addition of solar radiation. During Stage 2 of the Synthetic Scenario, the top surface

temperature stabilized at 7 °C while the bottom stabilized at -1 °C with the system running. Without the system running, the temperature at all locations stabilized at least 2 °C lower, showing that the system can increase the temperature at all depths of the concrete with the addition of solar radiation. This was confirmed during Stage 3 of the Synthetic Scenario, with the top and bottom surface temperatures stabilizing 7 °C higher when the system was running at, 2 °C and -6 °C, respectively.

The Daily Fluctuation Scenario represents a typical freeze-thaw cycle observed in Montana during the later stages of winter with ambient temperatures above and below 0 °C and varying solar intensity. Figures 30b and 31b show the results for the Daily Fluctuation Scenario without and with the system running, respectively. Without the system running, all depths of the concrete started below 0 °C, rose above 0 °C due to the increasing ambient temperature and solar intensity, then returned to below 0 °C. When the system was running, the same freeze-thaw pattern was observed. The system, however, caused the concrete temperature to rise above 0 °C faster, and stay above longer. With the system running, the bottom surface rose above 0 °C after 2.5 hours compared to the 5 hours required without the system. The system also kept the bottom surface above 0 °C for 1.5 hours longer than when the system was not running. While the system did not prevent the freeze-thaw cycle from happening, it caused the concrete at all depths to stay above 0 °C for 84% of the test, rather than 49% without the system.

While the system did not prevent all frost action in the bridge deck, the results show that for the experimental inlet fluid temperature of 8 °C, the concrete temperature is always higher with the system running. Higher inlet fluid temperatures could prove to mitigate frost action that would otherwise take place due to subzero ambient temperatures.

Application for Mitigating Thermal Stresses

Thermal stresses are a major threat to the structural integrity and durability of concrete bridge decks. They are caused by the interaction of thermal movements, thermal gradients, and the bridge deck support conditions, as illustrated in Figure 32. Thermal movements cause axial expansion or contraction of the bridge deck as its average temperature through the depth fluctuates. Thermal gradients are nonuniform temperature profiles through the depth of the deck that cause the top and bottom surfaces to expand or contract at different rates. In a simply supported deck, these effects produce strains but no stresses since the deck can deform freely. In a fully fixed deck, the displacements are restrained at the supports, translating the strain into stress. Condition 1 of Figure 32 shows a uniform temperature profile which causes only thermal movement of the bridge deck. When restrained, the bridge deck undergoes uniform compression or tension. Condition 2 represents a non-uniform, linear temperature profile. In this condition, thermal movement still occurs in the bridge deck, along with bending behavior due to the thermal gradient. When restrained, additional stress from bending is added to the axial stress. Condition 3 shows a non-uniform, nonlinear temperature profile in a concrete bridge deck. The same stress behavior from Condition 2 is observed in Condition 3, except that with a non-linear temperature profile, the bridge deck undergoes self-equilibrating stress with or without restraint. The self-equilibrating stresses are induced due to the strain compatibility requirement through the cross-section. When thermal stresses exceed the concrete's tensile strength, cracking occurs that enables deterioration mechanisms to commence. Cracks provide pathways for water and deicing chemical infiltration, resulting in reinforcement corrosion that can threaten the structural integrity of the bridge. Minimizing thermal stresses is thus critical to prevent cracking, extend service life, and reduce maintenance costs.

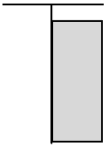
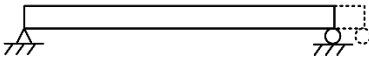
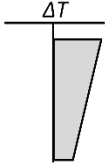
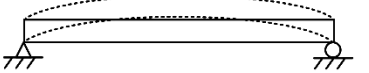
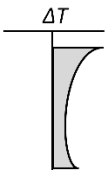
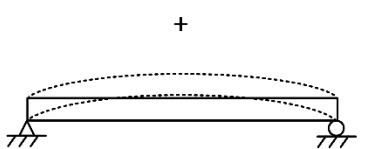
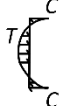
<i>Temperature Profile</i>	<i>Simply-Supported Deflected Shapes</i>	<i>Simply-Supported Stress Behavior</i>	<i>Fully Fixed Stress Behavior</i>
1) 		<i>None</i>	<i>Axial Stress</i> 
2) 		<i>None</i>	<i>Axial Stress</i>  + <i>Bending Stress</i> 
3) 		<i>Self-Equilibrating Stress</i> 	<i>Axial Stress</i>  + <i>Bending Stress</i>  + <i>Self-Equilibrating Stress</i> 

Figure 32: Thermal stress mechanisms due to temperature profiles and support conditions. (Radolli & Green 1975)

The deicing system's ability to mitigate cracking caused by thermal stresses is evaluated in Model 1 by analyzing its effectiveness in reducing thermal movements and gradients. The model was assumed to be mostly unrestrained due to the low coefficient of friction between the corrugated steel base of the model and the supporting cinder blocks, allowing the concrete to expand, contract, and bend freely. Strains due to thermal movements of the bridge deck were calculated using thermocouple results without and with the deicing system active. Although not calculated for the discussion presented herein, strain due to thermal movements could be used to

quantify a deicing system's influence on stresses that would develop under fixed support conditions. In an unrestrained condition, the strain at any location of a member can be calculated as follows:

$$\varepsilon_c = \alpha_c(T - T_0) \quad (6)$$

where ε_c is the strain in the concrete, α_c is the coefficient of thermal expansion of concrete ($\mu\text{ε}/^\circ\text{C}$), and T_0 is the reference temperature of the concrete. The relationship between the thermocouple data and strain was validated using the strain gauge results. Figure 33 shows a comparison between the measured top surface strain and strain calculated using equation (1) with a concrete thermal expansion coefficient of $8.5 \mu\text{ε}/^\circ\text{C}$ which is within the accepted range for concrete (Alungbe et al. 1992, Mehta & Monteiro 2014). The presented strains are relative to the starting temperature for each experiment. The T7 thermocouple data was used for these calculations. The results show good agreement in the magnitude and pattern of the measured and estimated top surface strains. This suggests that the thermocouples can be used to evaluate concrete strain through the depth using equation (1). The slight differences between the measured and calculated strains can be attributed to the precision of the strain gauges and minor restraint from the reinforcing steel and the friction between the corrugated steel form and the cinder block supports. Overall, there was little variation and the temperature data was considered validated.

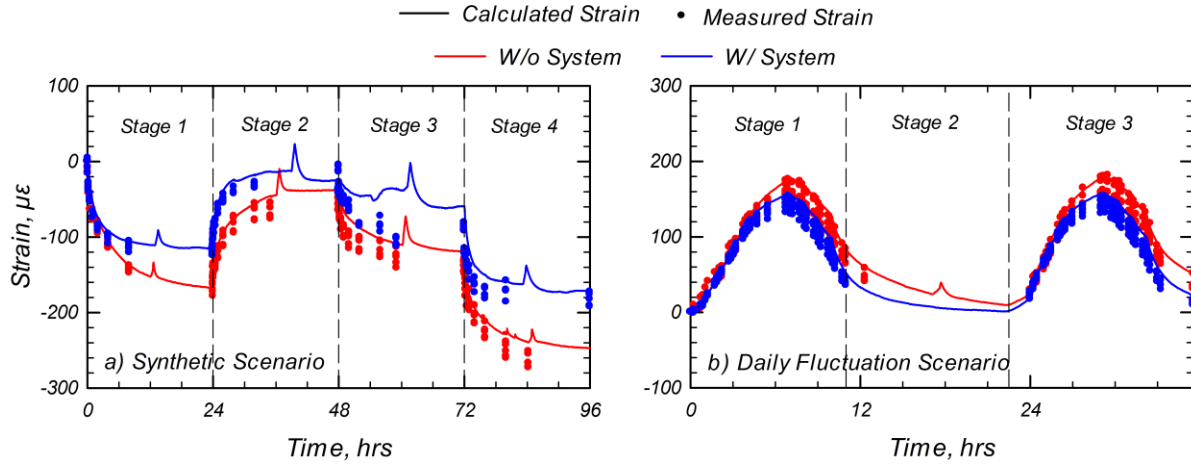


Figure 33: Top surface strains calculated from TA8 and measured from strain gauges for Model 1: a) Synthetic and b) Daily Fluctuation Scenarios.

Figure 34 presents average strains through the bridge deck depth of Model 1 calculated by averaging the T7 thermocouple measurements. The results include the average strain for the Synthetic (Figure 34a) and Daily Fluctuation (Figure 34b) Scenarios. These profiles quantify the thermal movement effects at different stages—how the concrete expands and contracts axially as its temperature changes. In a restrained deck, these movements would translate directly into compressive or tensile stresses in the concrete. For the Synthetic Scenario without the deicing system, the stabilized relative strain magnitudes reflected the temperature fluctuations and solar radiation. As expected, contractions (negative strains) increased in magnitude with larger changes in temperature and decreased in magnitude (reapproaching zero) when solar radiation was present. In Stages 1, 2, and 3 the strains were reduced 41%, 36%, and 46%, respectively, when the system was running compared to no system. The most extreme contractions occurred during Stage 4 and were equal to $-252 \mu\epsilon$ and $-155 \mu\epsilon$ without and with the system running, respectively, a 39% decrease. By regulating the temperature changes, the system successfully reduced the axial movements that would create thermal stresses in a fixed deck.

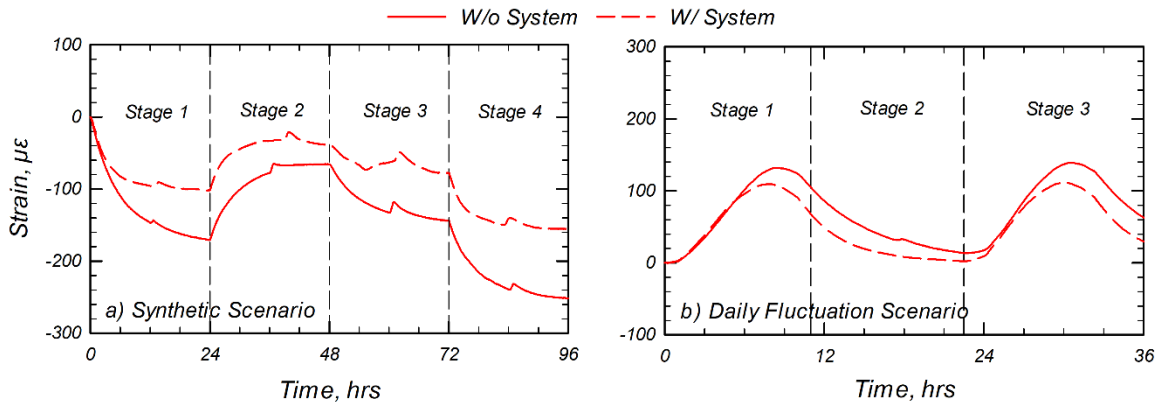


Figure 34: Average strains through depth of Model 1 calculated from TA7 thermocouples for the a) Synthetic and b) Daily Fluctuation Weather Scenarios.

Unlike the Synthetic Scenario, the Daily Fluctuation Scenario represents realistic ambient temperature swings that prevent the concrete from reaching stable temperatures. Figure 34b shows the relative thermal movement strains over this daily cycle without and with the deicing system. During the first six hours of the experiment, increasing ambient temperature and solar intensity produced comparable strains with and without the system. As peak ambient temperature and solar intensity were reached, the strains diverged. The system limited the peak strain to 110 $\mu\epsilon$, occurring 0.5 hours sooner than the 133 $\mu\epsilon$ peak without (a 17% reduction). The strains remained 20-35 $\mu\epsilon$ lower with the system until hour 19. As conditions cooled into the overnight Stage 2, the difference in strains narrowed until both stabilized around 0 $\mu\epsilon$. In the second daily heating and cooling cycle of Stage 3, the pattern observed in Stage 1 was repeated. Overall, the system running resulted in reduced strain throughout most of the experiment and never increased strain. By limiting peak expansion and contraction, the system can mitigate associated stresses even in fluctuating real-world conditions.

The thermal gradients through the depth of the bridge deck using the T5 thermocouples are displayed in Figure 35, quantifying bending effects and nonlinearities with and without the

system at various stages of testing. Figure 35a shows the stabilized thermal gradients observed during the Synthetic Scenario without and with the system active. The results suggest that although the deicing system increased concrete temperatures through the depth, the system was not successful in mitigating an overall thermal gradient, resulting in bending behavior. Without the system running, the concrete stabilized near the ambient temperatures of -10°C and -20°C during Stages 1 and 4, respectively, producing no gradient through the depth (shown by the almost vertical lines in Figure 35a). Activating the deicing system during these stages increased concrete temperature, but also induced gradients up to 5°C . The gradients caused by the system were also nonlinear, which induces self-equilibrating stress. Introducing solar radiation in Stages 2 and 3 produced gradients, with $7\text{--}8^{\circ}\text{C}$ differences between the top and bottom surfaces. The system increased the gradients by 1°C in both stages, showing minimal impact on bending effects. Again, nonlinear profiles existed with internal temperatures exceeding a linear gradient.

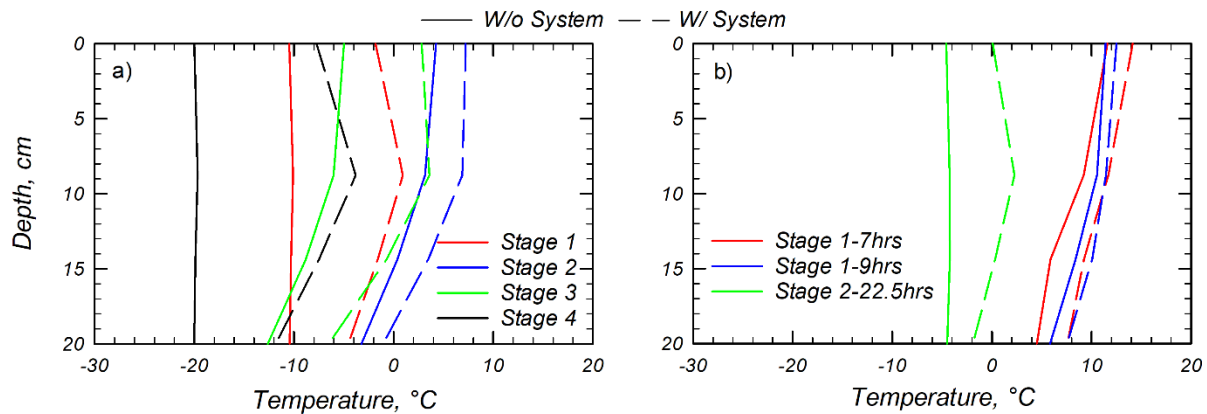


Figure 35: Temperature gradients from TA5 thermocouples for a) Synthetic and b) Daily Fluctuation Weather Scenarios.

The Daily Fluctuation Scenario provided more dynamic thermal gradients over the daily cycle compared to the Synthetic results. When the top surface temperature peaked during Stage 1 at hour seven, similar 7°C gradients existed with and without the system running. By hour nine

when the temperature at lower depths peaked, comparable 5 °C gradients were observed without and with the system. This shows the system had minimal influence on bending during peak heating conditions. By the end of the overnight Stage 2, the ambient temperature drop stabilized the concrete without the system, erasing gradients, while the system maintained a nonlinear 2 °C gradient. The daily fluctuations produced cyclical gradient patterns, unlike the consistent offsets of the Synthetic Scenario. During the cycles, the system consistently had little effect on bending.

The system proved to be primarily beneficial with regards to thermal stresses. The relative strain magnitudes due to thermal movements were mostly reduced by the system, and never increased. During stabilized conditions, the stabilized strains were reduced by 40%, whereas the peak strains in realistic conditions (during the Daily Fluctuation Scenario) were reduced by 18%. The results reveal the system can regulate concrete temperatures without introducing large gradients or detrimental stresses, across static and dynamic scenarios. The results suggest the system did not significantly influence bending stresses but maintained warmer internal temperatures. The lack of large gradient increases demonstrate an acceptable tradeoff for the temperature control benefits. Optimizing the fluid flow could further improve the gradient response, but overall, the system achieved more uniform average temperatures without critically increasing bending or self-equilibrating stresses.

Application for Mitigating Early-Age Cracking

Early-age cracking is a major concern in concrete bridges because of the resulting accelerated deterioration. Thermal shrinkage is one mechanism of early-age cracking that is especially prevalent in cold weather. When concrete cures in cold conditions, the concrete temperature will decrease from the curing temperature to the ambient temperature. As the

concrete temperature drops, the concrete will contract which can cause cracking when the deck is restrained. The deicing system's ability to mitigate early-age cracking through minimizing thermal shrinkage is evaluated by its ability to reduce the difference between the maximum concrete temperature after it's hardened, and the minimum stabilized concrete temperature. The compressive strength of Model 2 will be compared to Model 2c to evaluate whether the deicing system has a negative effect on the concrete strength.

Figure 36 shows the concrete temperature from a representative thermocouple at each depth for Model 2 (with system) and Model 2c (without system). The Model 2 thermocouples in between and in line with the heat exchanger tubes showed similar results, so one thermocouple at each depth was sufficient to report. The system was successful in decreasing the difference between the curing temperature and the stabilized concrete temperature. With the system (inlet temperature of 8 °C), the concrete stabilized at 4 °C on the top and bottom surfaces, and 5 °C at the internal depths. Without the system, all concrete depths stabilized around the ambient temperature of 2 °C. While the reduction in thermal shrinkage in this experiment is small, it suggests that with higher inlet fluid temperatures, the effectiveness of the system in reducing thermal shrinkage could increase.

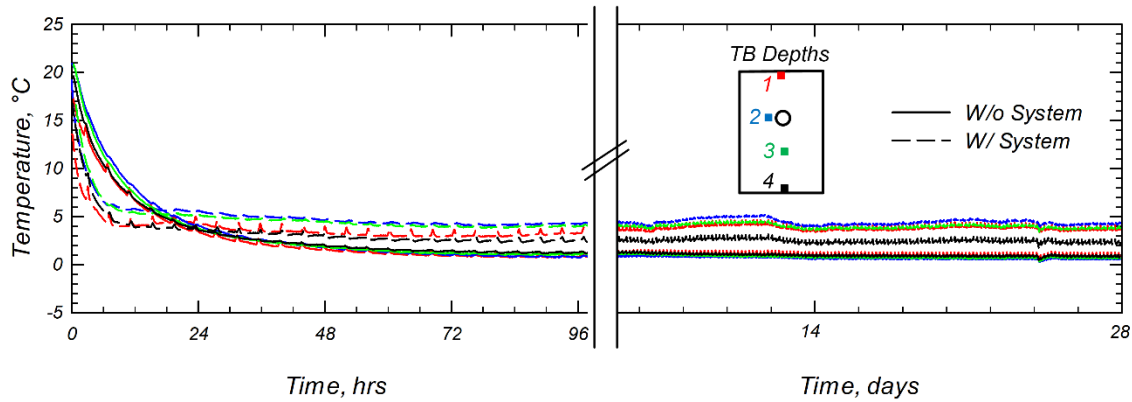


Figure 36: Model 2 (with system) and Model 2c (without system) thermocouple results at each depth.

Cores were extracted and tested from Model 2 and Model 2c, adhering to ASTM C42/C42M – 20 (2023). In accordance with section 7.1.2, it is reported that 50.8 mm cores were obtained due to limited clear distance between reinforcement. The cores were obtained on day 28 and tested on day 35, allowing the required time to eliminate moisture gradients. The average compressive strength from the Model 2 (with system) cores was 49% of the 28-day ideally cured compressive strength, while the Model 2c (without system) cores had 44% of the ideal 28-day strength. The reduction in strength gain between the cores and the ideally cured cylinders is due to the inhibition of the hydration process due to the cold temperatures and lack of moisture in the CHC. The increase in strength gain relative to the ideal 28-day strength of the Model 2 (with system) cores compared to the Model 2c (without system) cores could be attributed to the higher temperatures in Model 2 due to the system. While these initial findings are promising, additional research is warranted to confirm that the added heat from a geothermal deicing system increases the strength gain of concrete when curing in cold conditions.

Conclusion

Two models were constructed and tested in Montana State University's Subzero Research Laboratory to evaluate the feasibility of using geothermal energy in concrete bridge decks in Montana. Model 1 was designed and tested to evaluate the efficiency of a deicing system in deicing and mitigating concrete deterioration from thermal stresses and frost action in concrete bridge decks. Model 2 was designed and tested to observe a deicing system's effect on early-age cracking in bridge decks. Representative weather scenarios were developed from Montana weather data from 73 RWIS stations in Montana.

The results show that the deicing system was successful in deicing the bridge deck under certain Montana weather conditions by bringing the top surface temperature of the bridge deck above 0 °C. The results also showed that the top surface temperature was higher when the system was running during both weather scenarios. This suggests that with a higher inlet fluid temperature, the system would deice even more effectively.

The system was not successful in mitigating the effects of frost action during the weather scenarios. While the concrete temperature at all depths was not consistently kept above 0 °C, it was always higher when the system was running. This suggests that with higher inlet fluid temperatures, the system could mitigate the effects of frost action.

The results showed that the deicing system was successful in reducing strains due to thermal movements of the bridge deck. The system consistently reduced the average relative strain of the bridge deck by 40% during the Synthetic Scenario and the peak relative strain by 18% during the Daily Fluctuation Scenario. In a fully restrained condition, these strain reductions would equate to stress reductions. The system was not successful in mitigating the

effects of bending caused by thermal gradients. During stages without solar radiation, the system induced gradients between the top and bottom surface temperatures; however, the 5 °C maximum difference between the top and bottom surface temperatures is considered insignificant. During stages with solar radiation, the thermal gradients were similar without and with the system running. The thermal gradients observed while the system was running were non-linear. Further analysis is needed to evaluate the effect of the self-equilibrating stresses due to the non-linearity of the gradients. While the other applications for deicing systems would likely benefit from higher inlet fluid temperatures, thermal gradients could worsen.

Results from the early age cracking experiments suggest that the system was successful in reducing the difference between the peak curing temperature and the stabilized temperature of the concrete, thus reducing thermal shrinkage. More research is needed to understand the effect of a geothermal deicing system on the compressive strength gain of concrete curing in cold weather, but initial results suggest that a deicing system may have positive impacts.

Moving forward, the experimental results in this study will be used to validate a numerical model for further investigation of the benefits and efficiency of a geothermal deicing system in Montana. The numerical model will be used to perform a parametric study on variables such as inlet fluid temperature and tubing spacing across various weather conditions in order to make informed recommendations for future system installments.

CHAPTER THREE

NUMERICAL SIMULATIONS

Introduction

This chapter will be submitted as a journal paper in 2024. Cracking of reinforced concrete bridge decks poses major concerns because it leads to service life reduction and increased maintenance costs (Nelson et al. 2021). Thermally-induced stresses and frost action are two mechanisms that contribute to concrete cracking over time (Imbsen et al. 1985, Johnson, 2005). As cracks propagate, they enable infiltration of water and deicing chemicals. This exposure corrodes the steel reinforcement embedded within the concrete, accelerating deterioration and damage (Granata & Hartt 2009; Yunovich et al. 2003). Preventing cracks is thus critical to ensure long-term bridge deck integrity.

Frost action occurs when water freezes and expands in concrete voids. If the voids in concrete are too small to accommodate the expansion of freezing water, they grow and connect with other voids to form a network of cracks in the concrete (Johnson 2005). Air entraining admixtures (AEAs) were developed to increase the concrete's resistance to frost action by providing air void systems that give more space for freezing water to expand (Jackson 1944). Despite the many advantages of AEAs and their widespread use, AEAs can cause significant decreases in compressive strength, dependent on dosage. Tolegenova et al. (2022) found that an increase in air content from 1.09% to 15.03% led to a 42.0% decrease in concrete's compressive strength. Tunstall et al. (2021) also reported that other additives such as superplasticizers and shrinkage-reducing admixtures can inhibit the functionality of AEAs.

Thermal stresses are caused by the combination of restraint of the bridge deck, the overall expansion or contraction of the bridge deck (called thermal movements), and temperature gradients which induce bending and self-equilibrating stresses when the gradient is nonlinear (Radolli & Green 1975; Brenner; Hagedorn 2016). The effects of thermal stresses are commonly mitigated by employing expansion joints. Expansion joints prevent excessive stresses by allowing for some expansion and contraction of the bridge deck. While effective and widely implemented, expansion joints often have a much shorter life span than the rest of the bridge (Li et al. 2023). The effects of thermal movements and gradients are also accounted for in the AASHTO LRFD Bridge Design Specifications (2021). AASHTO provides contour maps and equations to calculate the design thermal movements and gradients for bridges based on climate conditions. If the thermal movements and gradients measured in a bridge deck are within the design specifications, they were sufficiently accounted for in the structural design of the bridge.

Ground-source heat pump (GSHP) systems could also be employed to mitigate concrete deterioration (Mohammadzadeh et al. 2023). GSHP systems supply heat to concrete bridge decks by circulating fluid through pipes embedded in the concrete and ground. Previous studies on GSHP systems have focused primarily on bridge deck deicing. Researchers found key parameters influencing deicing performance include pipe spacing, pipe depth, inlet fluid temperature, and inlet fluid flow rate (Bowers 2016; Balbay & Esen 2010; Liu 2005; Ghasemi-Fare 2015; Yu et al. 2017). Feng and Yin (2019) performed simulations on a model created in ANSYS and found that narrower pipe spacing and shallower pipe embedment led to increased surface temperatures. Additionally, narrower pipe spacing led to more consistent temperatures across the surface of the bridge deck. Balbay & Esen (2010) used a model constructed in

FLUENT to study the effect of inlet fluid temperature on the surface temperature distribution. They found that a higher inlet fluid temperature resulted in an increased average surface temperature. Yu et al. (2017) performed a series of investigations on a model created in COMSOL Multiphysics to evaluate the effects of flow rate and inlet fluid temperature on deicing performance. They concluded that while a decreased flow rate does negatively affect the deicing performance of the bridge deck, it is negligible compared to the effects of the inlet fluid temperature. Along with studying the effects of various parameters on a bridge deck deicing system, Bowers (2016) and Ghasemi-Fare et al. (2015) also investigated the thermal gradients induced by GSHP systems. Their results demonstrated measurable gradients, though generally within allowable limits per AASHTO (2021). Bowers (2016) concluded that caution should be taken when activating the system when the bridge deck temperature is low. The initial temperature gradients induced by the system before the bridge deck temperature stabilizes can be harmful. Ghasemi-Fare et al. (2015) concluded that activating the system when the bridge deck has a uniform temperature gradient can also be harmful. Mohammadzadeh et al. (2023) observed reduced internal and top surface concrete temperatures of up to 12 °C and 20 °C, respectively, during summer weather when using shallow geothermal energy in a model bridge deck. Further research is needed on optimizing GSHP deicing efficiency with considerations for mitigating concrete deterioration.

This research evaluates the effect of various parameters of a bridge deck deicing system on the ability to deice and mitigate concrete deterioration of bridge decks in Montana. A numerical model was constructed in COMSOL Multiphysics to evaluate the effect of various parameters of a bridge deck deicing system. Concrete temperature and top surface strain results

from experiments conducted in Chapter 2 were used to validate the numerical model. Once constructed and validated, the model was used to evaluate the system's performance with inlet fluid temperatures consistent with Montana well data. A sensitivity analysis was then conducted to evaluate the effect of ambient temperature, solar radiation, inlet fluid temperature, and heat exchanger tube spacing on the system's ability to deice and mitigate concrete deterioration of bridge decks in Montana.

Overview of Experiments

A model-scale bridge deck model with embedded heat exchanger tubing was constructed and tested in the Cold Hydrodynamics Chamber (CHC) of Montana State University's Subzero Research Laboratory. The goal of the experiments was to evaluate the feasibility of using geothermal energy to deice bridge decks and mitigate various mechanisms of concrete deterioration in Montana. Figure 37 shows the schematics of the model. Cross-linked polyethylene (PEX) was used for the heat exchanger tubes with a 12.7 mm diameter and 20 cm center-to-center spacing. A 30% glycol mixture was circulated through the heat exchanger tubes at 5.5 L/min and with an inlet temperature of 8 °C. The model was instrumented with thirty Type-T thermocouples to measure the concrete temperature and five vibrating wire strain gauges to measure the strain on the top surface.

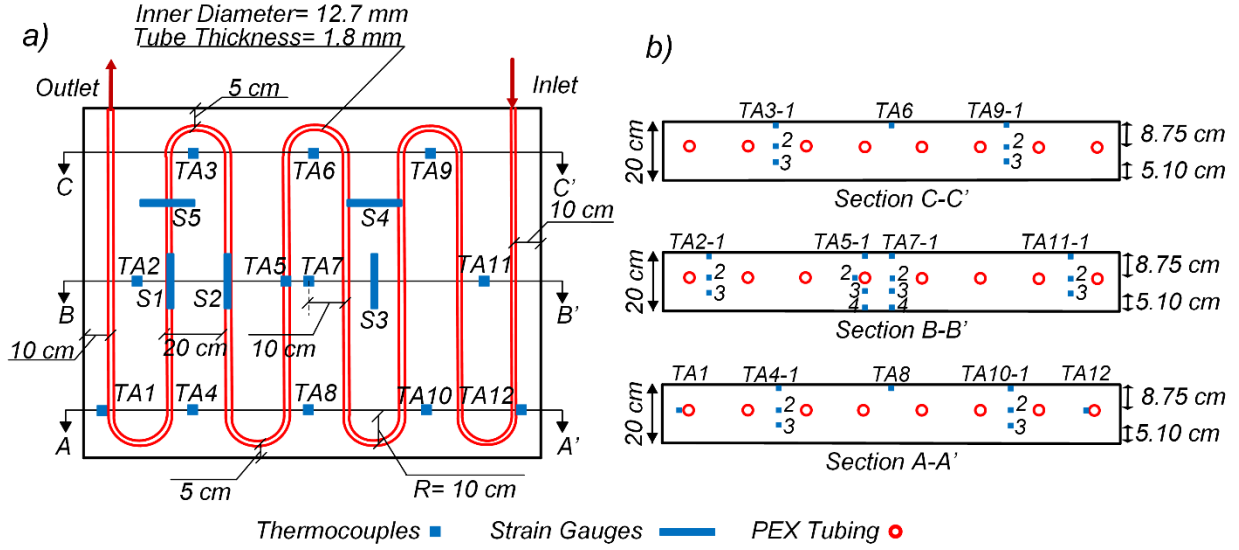


Figure 37: Experimental model configuration with sensor locations

Weather scenarios were developed based on time histories of Montana weather from 2015-2019 collected from Road Weather Information System stations. The concrete temperature and top surface strain were measured as the weather scenarios were replicated in the CHC with and without the deicing system running. Figure 38 shows the measured conditions of the experiments performed in Chapter 2 with the system running. The Synthetic Scenario (Figure 38a) was designed to isolate the effects of low temperatures and solar radiation on the efficiency of the system. In the four 24-hour stages of the test, various ambient temperatures and solar intensities were employed. The ambient temperature was set to -10 °C during Stages 1 and 2, and -20 °C during Stages 3 and 4, while the solar simulator was activated at 490 W/m² (as measured from the bridge deck surface) during Stages 2 and 3. The Daily Fluctuation Scenario (Figure 38b) was developed to mimic a typical late winter day in Montana with large diurnal swings. During Stage 1, the ambient temperature increased linearly from -5 °C to 10 °C, remained at 10 °C for four hours, then returned to -5 °C. Following the same pattern, the solar intensity

increased in one-hour intervals from 0 W/m² to 490 W/m², remained at 490 W/m² for four hours, then returned to 0 W/m². During Stage 2, the ambient temperature and solar intensity remained at -5 °C and 0 W/m² for the duration of the stage. Stage 3 followed the same behavior as Stage 1.

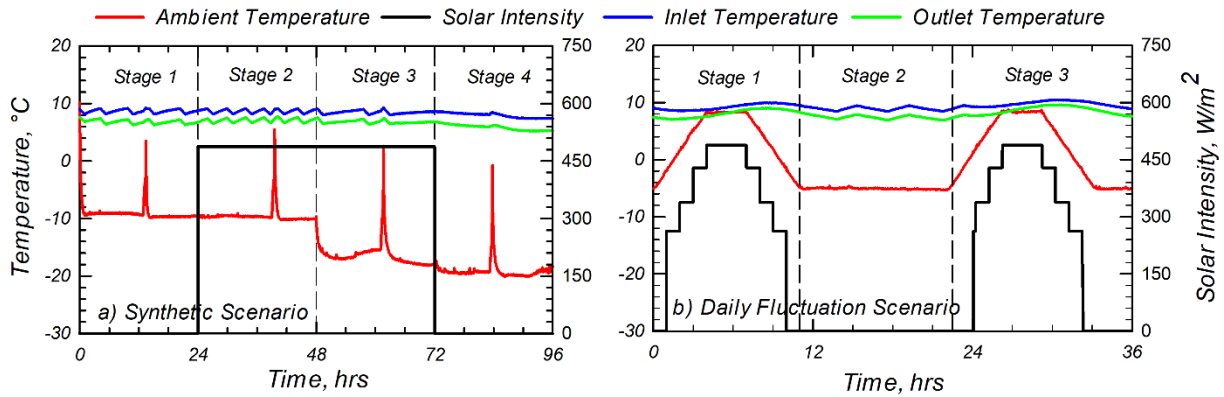


Figure 38: a) Synthetic and b) Daily Fluctuation Scenarios

In Chapter 2, it was concluded that a deicing system with an inlet temperature of 8 °C can bring the top surface temperature above 0 °C with ambient temperatures below 0 °C. The system was not always successful in raising the surface temperature above 0 °C, but the surface temperature was always higher when the system was running. This suggests that higher inlet fluid temperatures could increase the efficacy of the system for deicing.

When investigating the system's effect on frost action, it was found that the system was not successful in keeping the concrete temperature at all depths above 0 °C. Again, however, the concrete temperature was higher when the system was running at all depths, suggesting that higher inlet fluid temperatures could also mitigate frost action.

It was also concluded that the system could successfully reduce strains due to thermal movements by up to 40% in stabilized conditions, and 18% in realistic diurnal cycles. Thermal gradients were induced by the system during stages of testing without solar radiation, but the

gradient magnitude was insignificant at 5 °C. When solar radiation was present, the thermal gradients were similar without and with the system running. The gradients induced by the system were always non-linear, which resulted in self-equilibrating stresses.

Overview of Numerical Model

Modeling a bridge deck deicing system involves accounting for multiple heat transfer mechanisms. Figure 39 shows the effect of conduction, convection, and radiation on a bridge deck deicing system. The accumulation of snow was not considered in these analyses, eliminating the inclusion of snow melting heat flux in the model. The heat transfer mechanisms and their governing equations are extensively described in the literature (Bowers 2016; Ghasemi-Fare et al. 2015; Pourakbar 2021). Consequently, they will be only briefly described in the following section.

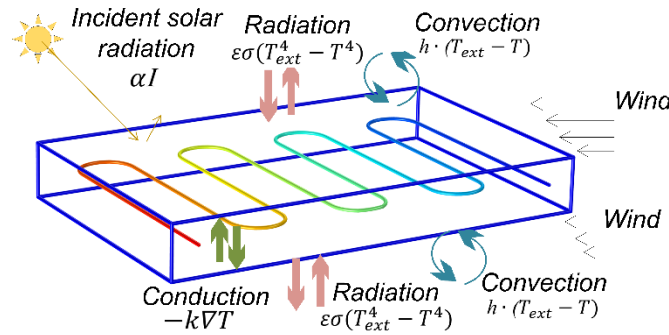


Figure 39: Heat transfer mechanisms

Conduction occurs between the circulating fluid and the heat exchanger tube walls and between the tube walls and the surrounding concrete. The following differential equation presents the heat conduction in the bridge deck:

$$\rho C_p \left(\frac{\partial T}{\partial t} \right) + \nabla \cdot \mathbf{q} = Q \mathbf{q} = -k \nabla T \quad (7)$$

where ρ is the density (kg/m^3), C_p is the heat capacity at constant pressure ($\text{J}/(\text{kg}\cdot\text{K})$), T is the absolute temperature (K), $\frac{\partial}{\partial t}$ is the time derivatives operator, $\mathbf{q}$ is conductive heat flux vector (W/m^2), Q is the heat source (or sink) (W/m^3), k is the thermal conductivity coefficient ($\text{W/m}\cdot\text{K}$), and ∇T is the temperature gradient. For completely insulated surfaces of the bridge deck, the heat flux is equal to zero (a Neumann boundary condition) and is described as follows:

$$\mathbf{q} = -k \nabla T = 0 \quad (8)$$

Both convective and radiative heat transfer is experienced by exposed surfaces (uninsulated). Heat transfer due to convection on an exposed surface is described as:

$$-\mathbf{n} \cdot \mathbf{q} = h \cdot (T_{ext} - T) \quad (9)$$

where $\mathbf{n}$ is the normal vector on the boundary, h is the convective heat transfer coefficient ($\text{W/m}^2\cdot\text{K}$), T is the surface temperature (K), and T_{ext} is the external temperature. Heat transfer due to radiation is governed by two equations describing the effects of thermal radiation (Equation 10) and solar radiation (Equation 11):

$$-\mathbf{n} \cdot \mathbf{q} = \varepsilon \sigma (T_{ext}^4 - T_s^4) \quad (10)$$

$$-\mathbf{n} \cdot \mathbf{q} = \alpha I \quad (11)$$

where ε is the surface emissivity, σ is the Stefan-Boltzmann constant (a predefined physical constant, $5.67 \times 10^{-8} \text{ (W}\cdot\text{m}^2/\text{K}^4)$), α is the absorptivity coefficient, and I is the direct radiation incident to a horizontal surface (W/m^2).

Model Development

The 3D numerical model was constructed in COMSOL Multiphysics to replicate the bridge deck constructed in Chapter 1. Figure 40 shows the numerical model configuration. The model was constructed with the geometric dimensions and material properties shown in Table 2 to replicate the conditions of the experiments. Specific material properties were assigned based on accepted values and confirmed during the validation process. The model was divided into three zones, with the top and bottom zones having reinforcing steel. The reinforcing steel was not directly modeled, but rather, respective volumetric averages of concrete and steel were used to assign material properties to the model. The heat exchanger tubes were modeled using the Nonisothermal Pipe Flow interface which computes the temperature, velocity, and pressure fields in pipes using one-dimensional assumptions (COMSOL 2017). The Wall Heat Transfer node was added to assign the tubing thermal conductivity and thickness. Friction losses were accounted for using the Churchill friction model. Conduction, convection and radiation were modeled using the Heat Transfer in Solids interface (COMSOL 2018a). The sides of the bridge deck were insulated, while the top and bottom surfaces were left exposed to thermal and solar radiation and convection.

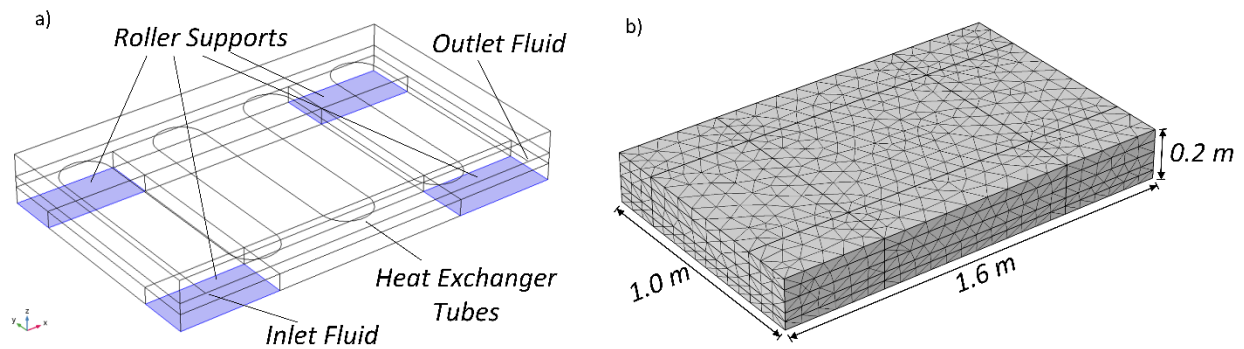


Figure 40: (a) Numerical model configuration and (b) meshed model

To account for the stress and strain of the bridge deck, the Solid Mechanics interface was added which is intended for general structural analysis (COMSOL 2018b). To account for the structural boundary conditions, roller supports were defined at the bottom surface of the bridge deck, equal in area to the cinder block supports of the physical model. Springs with small stiffness constants were added to the exterior sides above the rollers to provide enough restraint for the simulation to converge, but not enough to affect the strain results.

Table 2: Material properties of the experimental and numerical models.

<i>Parameter</i>	<i>Experimental</i>	<i>Numerical</i>
<i>Bridge Deck Dimensions</i>		
Length (m)	1.60	1.60
Width (m)	1.00	1.00
Height (cm)	20.00	20.00
Depth of circulation pipes (cm)	8.75	8.75
<i>Circulation Fluid (30% Glycol)</i>		
Flow rate (L/m)	5.50	5.50
Dynamic Viscosity (mPa·s)	4.80	4.80
Thermal conductivity (W/m·k)	0.40	0.40
Specific heat capacity (J/kg·k)	3538.00	3538.00
Density (kg/m ³)	1070.00	1070.00
<i>Concrete</i>		
Thermal conductivity (W/m·k)	1.00	1.00
Specific heat capacity (J/kg·k)	880.00	880.00
Density (Kg/m ³)	2400.00	2400.00
Coefficient of thermal expansion (μ ϵ /°C)	10.00	10.00
Surface emissivity	0.85	0.85
Absorptivity coefficient	0.58	0.58
<i>Concrete/Rebar Zones</i>		
Top height (cm)	-	9.00
Bottom height (cm)	-	6.67
Top thermal conductivity (W/m.k)	-	1.60
Top specific heat capacity (J/kg.k)	-	874.37
Top density (Kg/m ³)	-	2475.71
Bottom thermal conductivity (W/m.k)	-	2.16
Bottom specific heat capacity (J/kg.k)	-	869.24
Bottom density (Kg/m ³)	-	2544.80

Model Validation

The numerical model was validated using the results from the Synthetic and Daily Fluctuation Scenario experiments performed in Chapter 2. Temperature results from thermocouples TA8, TA11-2, TA10-3, and TA7-4 were used for validation to provide concrete temperatures at various locations. All five strain gauges were used for validation of the strain of the model.

Figure 41a shows the temperature results for the Synthetic Scenario. During Stages 1 and 4, the experimental and predicted results were very similar. When solar radiation was introduced in Stages 2 and 3, the predicted results underestimated the temperature for all locations except the bottom surface (TA7-4) where agreement was still observed. During the first half of Stage 3, a solar simulator malfunction occurred that caused irregular temperature behavior at the top surface. The malfunction was quickly resolved as shown by the agreement by the end of the stage. Besides the large difference between the predicted and experimental results at the top surface due to the malfunction, the maximum difference was around 1.5 °C. The differences during Stages 2 and 3 suggest slight inaccuracies in the modeling of the solar radiation. Figure 41b shows the temperature results for the Daily Fluctuation Scenario. During this scenario, agreement was observed for the entirety of the experiment at the top surface (TA8). Differences of up to 1.5 °C were observed during Stages 1 and 3 for the internal concrete temperatures (TA11-2 and TA10-3) and during Stage 2 for the bottom surface (TA7-4). The inaccuracies during Stage 1 are again likely due to inaccuracies in the modeling of solar radiation. The differences at the bottom surface (TA7-4) during Stage 2 also suggest slight inaccuracies in the implementation of the convective heat transfer coefficient at the bottom surface. Overall, the temperature results show good agreement for both scenarios.

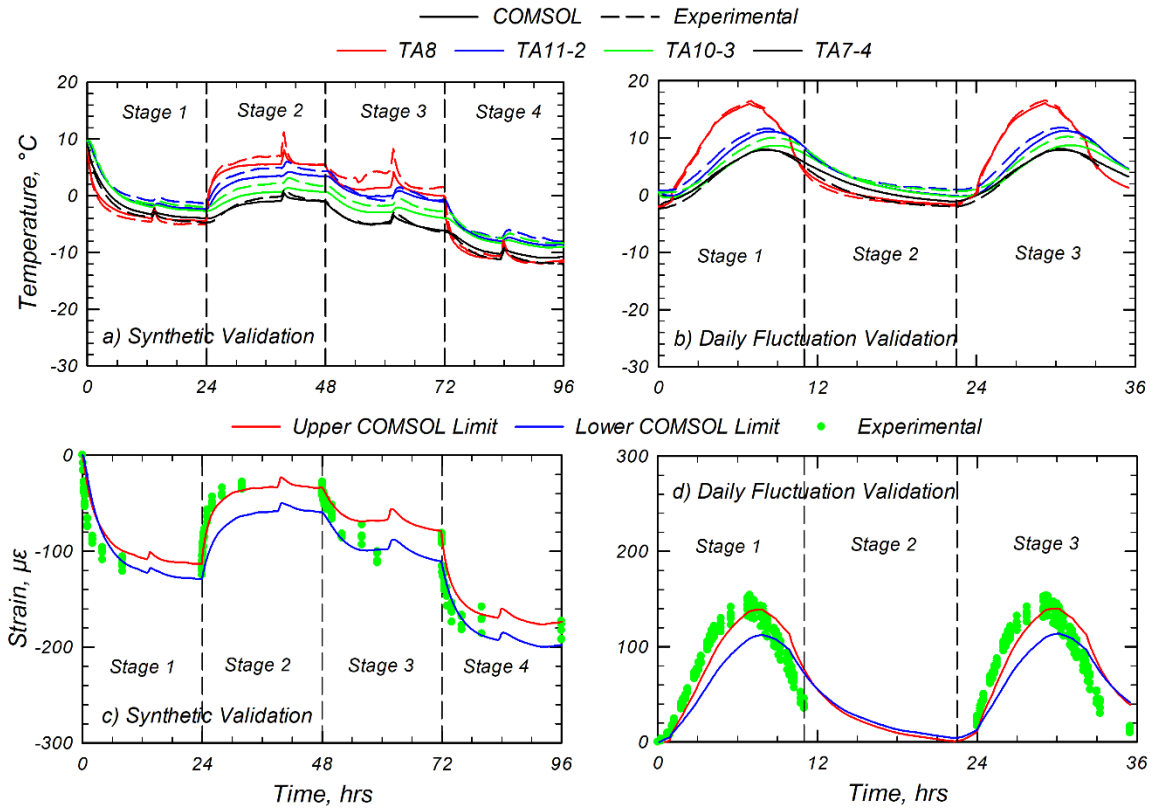


Figure 41: Predicted and experimental temperature results for the (a) Synthetic and (b) Daily Fluctuation Scenarios and strain results for the (c) Synthetic and (d) Daily Fluctuation Scenarios

Figure 41c shows the top surface strain results for the Synthetic Scenario. During all stages, the stabilized predicted and experimental strains show agreement. The predicted strains appear to be slightly delayed, however, in reaching the stabilized value. The differences in the strain results are likely due to the complex interaction between the concrete and reinforcing steel material property interactions, as well as the structural boundary conditions. Similar behavior was observed in the Daily Fluctuation Scenario (Figure 41d). The peak predicted strains were similar in magnitude but were reached about one hour later than the experimental strains.

Numerical Simulation Weather Program

Historical Montana weather data was collected from Road Weather Information System (RWIS) stations from 2015-2020 to find representative weather conditions to replicate in the numerical simulations. Figure 42 shows the average monthly ambient temperatures collected from the RWIS stations. The data shows that a bridge deck deicing system should be designed for the months of November through February, as they have the lowest average temperatures. The data was used to develop a weather program that consists of six 24-hour stages, shown in Figure 43, that isolates the effects of low temperatures and solar radiation on the effectiveness of the system. The test begins with the concrete temperature stabilized at 0 °C. The ambient temperature is immediately dropped to -5 °C at the start of Stage 1 with no solar radiation. During Stage 2, the ambient temperature remains at -5 °C and the solar intensity is increased to 488 W/m². The ambient temperature then drops to -10 °C while the solar intensity remains at 488 W/m² for Stage 3. The solar radiation is then removed while the ambient temperature remains at -10 °C for Stage 4. Stage 5 sees a decrease in ambient temperature to -20 °C with no solar radiation. The test ends with Stage 6 where the ambient temperature remains at -20 °C and the solar intensity is raised to 488 W/m².

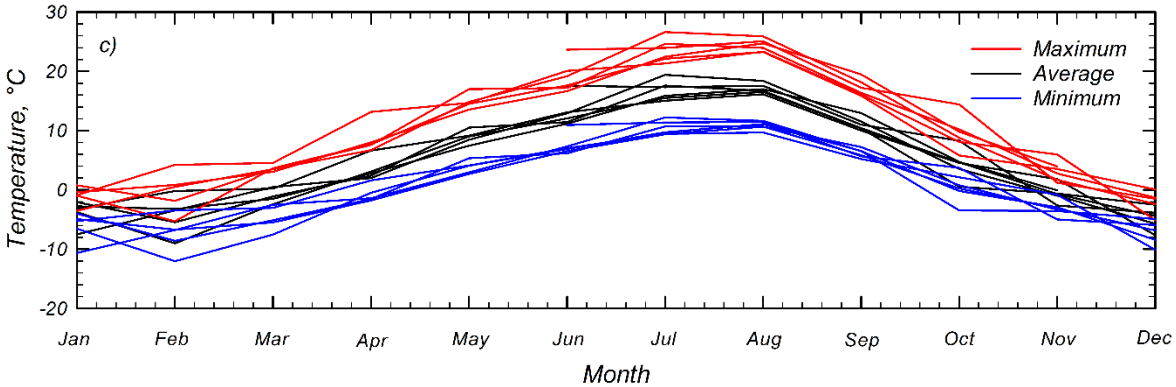


Figure 42: Montana Monthly Average Ambient Temperature for 2015-2020

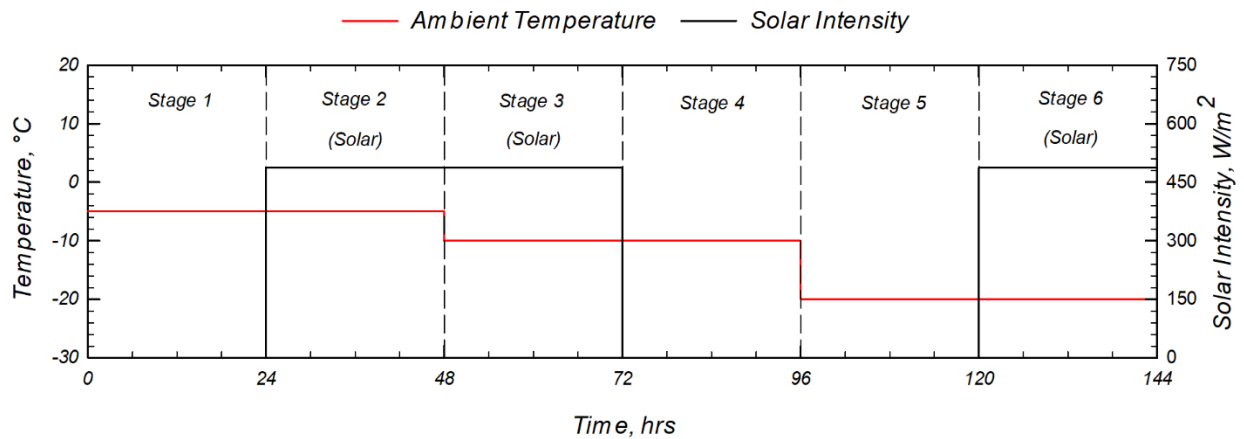


Figure 43: Numerical simulation weather scenario with six stages of varying ambient temperature and solar intensity

The available inlet fluid temperatures for use in a geothermal bridge deck deicing system were found using temperature data from wells in Montana provided by the Montana Bureau of Mines and Geology. Undisturbed ground temperatures were obtained by interpolating the well temperatures. Figure 44a shows undisturbed ground temperatures up to 150 m in Montana with the wells used for interpolation. The distribution of the well data, shown in Figure 44b, shows two trends with medians of 10 °C and 50 °C. Ground temperatures around 10 °C were more common, while the 50 °C ground temperature was rarer, occurring in geothermal hotspots such as near Yellowstone National Park.

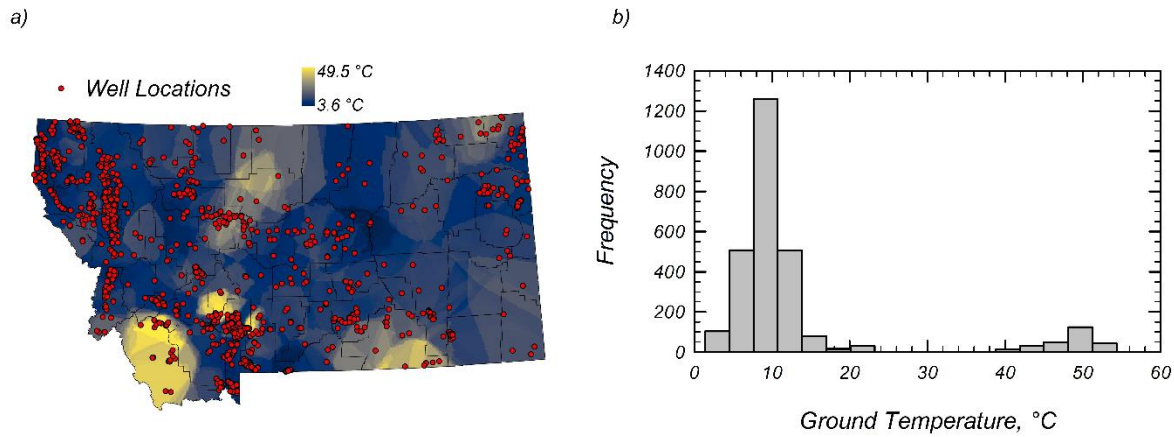


Figure 44: (a) Ground temperature data from Montana wells up to 150 m deep and (b) distribution of Montana ground temperatures

Results and Discussion

The results and discussion section presents the data collected and analyzed from numerical simulations to evaluate a geothermal deicing system's effectiveness. A weather program was developed based on Montana weather data, and two inlet fluid temperatures, 10 °C and 50 °C, were tested based on Montana well data. The tests present stabilized results due to various ambient temperatures and solar intensities with and without the system running. Transitions between the stabilized results were not analyzed. The top surface temperature was first analyzed to ensure that a deicing system with the given inlet fluid temperatures is feasible. Once the feasibility was evaluated, the system's effect on frost action was analyzed by evaluating the system's ability to keep the minimum concrete temperature above 0 °C during the various stages of testing. By keeping the concrete temperature above 0 °C, even when the ambient temperature is well below 0 °C, the system can reduce the effects of frost action by reducing the number of freeze-thaw cycles in the concrete.

After analyzing the frost action results, the system's effect on thermal stresses was evaluated. Thermal stresses are caused by the interaction of thermal movements, thermal gradients, and bridge deck support conditions. Thermal movements cause axial expansion and contraction of the bridge deck as the average concrete temperature fluctuates. Thermal gradients are nonuniform temperature profiles through the depth of the bridge deck that cause expansion and contraction at different rates. Vertical gradients cause bending behavior when the top and bottom surfaces have different temperatures. Transverse gradients are not considered in this study. When the bridge deck is not restrained, thermal movements and linear gradients cause strain, but no stress, as the deck is free to deform. In a fully restrained bridge deck, the deformations are resisted at the supports, translating strain to stress. When temperature gradients are non-linear, self-equilibrating stresses are also observed regardless of support conditions. These stresses occur because of the tendency of plane sections remaining plane due to the strain compatibility requirement through the cross-section. When thermal stresses exceed the concrete's strength, cracking ensues which accelerates the deterioration process. By reducing thermal stresses in concrete bridge decks, cracking is reduced which can extend the bridge's service life. The boundary conditions of the numerical model constitute a mostly unrestrained bridge deck, so the strains will be analyzed here and assumed to translate to stresses in a restrained bridge deck system. The thermal movements were analyzed as the average strain along the length of the bridge deck, while the thermal gradients were analyzed as the average temperatures at various depths of the bridge deck.

In the AASHTO LRFD Bridge Design Specifications (2021), AASHTO provides methods to calculate the design thermal movements and gradients throughout the United States. To calculate the design strain due to thermal movement, the following equation is employed:

$$\varepsilon_T = \alpha(T_{MaxDesign} - T_{MinDesign}) \quad (12)$$

where α is the coefficient of thermal expansion ($\mu\epsilon/^\circ\text{C}$) and $T_{MaxDesign}$ and $T_{MinDesign}$ are the maximum and minimum temperatures provided via contour maps from AASHTO. The maximum temperature provided for Montana is 41°C while the minimum is -40.0°C . Using the coefficient of thermal expansion (shown in Table 2), a design strain due to thermal movements of $810 \mu\epsilon$ was calculated for the given bridge deck in Montana. The ambient temperatures in the simulations range from 0°C to -20°C , so the design strain due to thermal movement was not exceeded.

Figure 45a shows a schematic from AASHTO (2021) to aid in calculating the design temperature gradient. Using the methods they describe, design temperature gradients were calculated for Montana, as shown in Figure 45b. The positive design temperature gradients (when the top surface is warmer than the bottom surface) were 8°C and 30°C , between the bottom and the middle and between the bottom and top, respectively. The negative design temperature gradients (when the bottom surface is warmer than the top surface) were -2°C and -9°C , between the bottom and middle and between the bottom and top, respectively. The temperature gradients with and without the system running were compared to the design temperature gradient to ensure the observed gradients are accounted for in the structural design of the bridge.

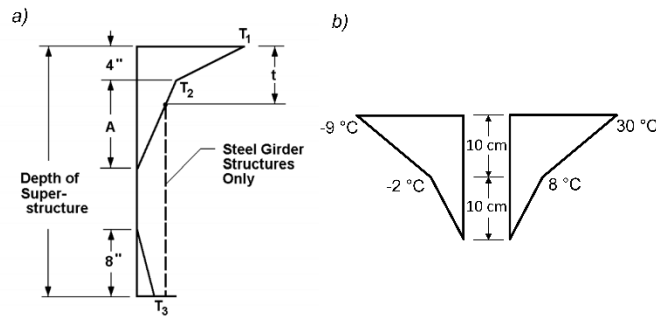


Figure 45: (a) Positive vertical temperature gradient in concrete and steel superstructures (AASHTO 2021) and (b) positive vertical temperature gradient for bridge deck in Montana

Application with 10 °C Inlet Fluid Temperature

The deicing system's ability to maintain the average concrete surface temperature above 0 °C was evaluated for an inlet fluid temperature of 10 °C. Figure 46a shows the average top surface temperature during the various testing stages with and without the system running. The system was unable to bring the stabilized surface temperature above 0 °C without solar radiation present. During Stages 1, 4, and 5, the stabilized surface temperatures with the system running were -2 °C, -6 °C, and -13 °C, respectively, while the surface temperatures without the system running stabilized at the ambient temperatures. While the stabilized surface temperatures with the system running were below 0 °C, they were on average 5 °C greater than the surface temperatures without the system. When solar radiation was present, the surface temperatures stabilized above 0 °C with and without the system during Stages 2 and 3. Stage 2 saw a surface temperature of 10 °C with the system and 9 °C without the system, while Stage 3 saw surface temperatures of 6 °C and 4 °C with and without the system, respectively. During Stage 6, the surface temperature again stabilized below 0 °C with and without the system, at -1 °C and -6 °C, respectively, even with the addition of solar radiation.

Overall, the system did not increase the number of stages where the top surface temperature of the bridge deck stabilized above 0 °C. The surface temperatures, however, were always higher when the system was running. This suggests that during realistic, diurnal weather conditions, where ambient temperatures and solar intensities fluctuate, the system could increase the amount of time the surface temperature stays above 0 °C. This behavior was observed during Chapter 2. During the Synthetic Scenario, the system was not always able to bring the surface temperature above 0 °C, but during the Daily Fluctuation Scenario, the surface temperature stayed above 0 °C 21% more when the system was running.

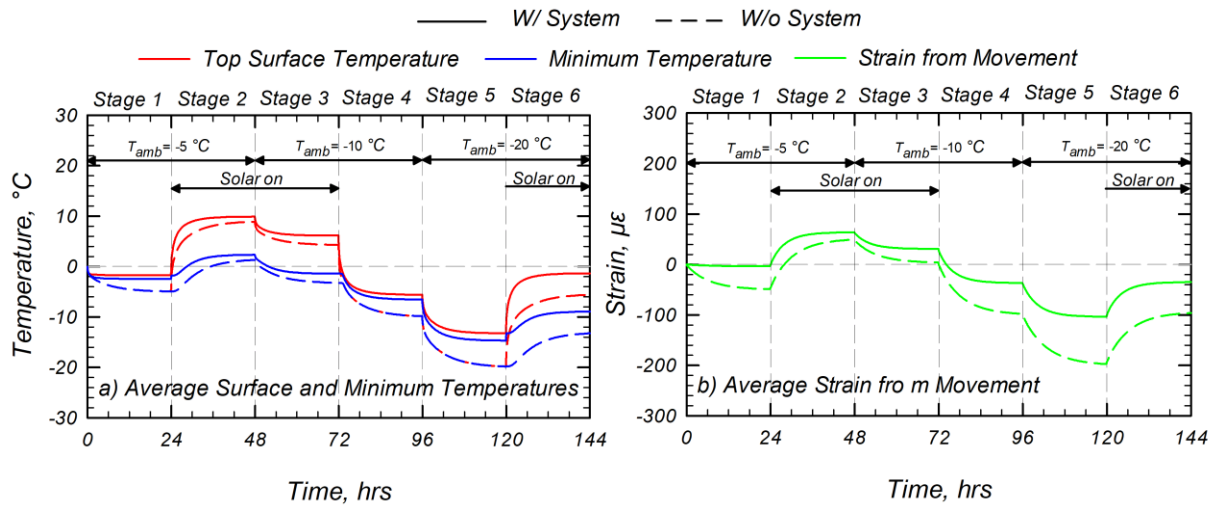


Figure 46: (a) Average surface and minimum temperature and (b) average strain from thermal movement for 10 °C inlet temperature

Figure 46a also shows the minimum temperature of the bridge deck throughout the simulation with an inlet temperature of 10 °C. Even with solar radiation, the minimum temperature only stabilized above 0 °C during Stage 2, with minimum temperatures of 2 °C and 1 °C with and without the system running, respectively. For all other stages, the minimum temperature stabilized below 0 °C regardless of solar radiation or geothermal heat.

While the system always increased the minimum concrete temperature, the concrete experienced the same number of freeze-thaw cycles with and without the system. To mitigate the effects of frost action, the system would need to prevent the minimum concrete temperature from dropping below 0 °C. The results suggest that an inlet fluid temperature of 10 °C is not sufficient to mitigate frost action in Montana weather scenarios.

Figure 46b shows the average strain due to thermal movements with and without the system running. In a fully restrained bridge deck, the thermal movements translate directly into compressive or tensile stresses in the concrete. The stabilized strains with the system running were always higher than the strains without the system running, with a maximum and minimum difference of 94 $\mu\epsilon$ during Stage 5 and 15 $\mu\epsilon$ during Stage 2, respectively. The range of strain due to thermal movement, however, was reduced by 32%, from 247 $\mu\epsilon$ without the system running to 167 $\mu\epsilon$ when the system was running. The strain range with and without the system were well below the design strain range due to thermal movement of 810 $\mu\epsilon$ calculated for Montana by AASHTO (Equation 12).

Overall, the numerical simulations show the system was successful in mitigating the effects of thermal movements. The 32% reduction in strain equates to a 32% reduction in stress in a fully restrained bridge deck. The consistent increase in strain also equates to less contraction in a bridge deck. This is significant because contraction of a bridge deck leads to tensile stresses, while expansion leads to compressive stresses.

Figure 47 shows the stabilized temperature gradients at all stages of testing with an inlet temperature of 10 °C. During stages without solar radiation, no gradients were observed without the system running, as the concrete temperature was allowed to stabilize at the ambient

temperature. When the system was running, the top surface stabilized at a lower temperature than the bottom surface due to higher wind speeds assumed at the top surface. The largest of these gradients was observed during Stage 5 at -1°C . The induced gradients were also non-linear which causes self-equilibrating stresses. When solar radiation was present, gradients were observed with and without the system running. The magnitude of the gradients between the top and bottom surface was almost identical with and without the system, with a maximum variance of 1°C . The gradients during these stages were mostly linear, with only slight deviations. All stabilized gradients with and without the system were below the design temperature gradients established by AASHTO for Montana, shown in Figure 9b.

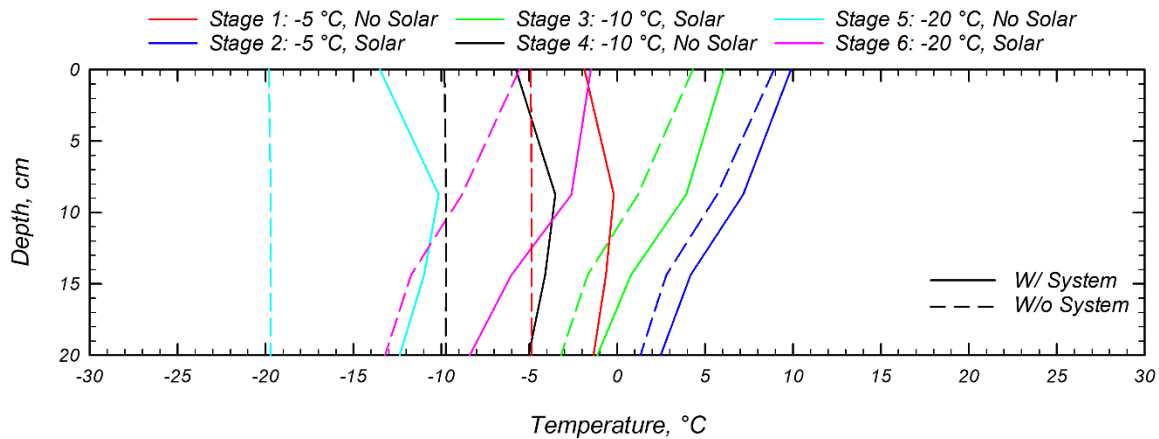


Figure 47: Temperature gradients for 10°C inlet temperature

While the system was not successful in mitigating temperature gradients in the bridge deck, the induced thermal gradients between the top and bottom surfaces were at most 1°C worse than when the system wasn't running, which is insignificant. The self-equilibrating stresses caused by the nonlinearity of the temperature profile were also compressive because the internal concrete temperatures were warmer than if the profile was linear. This suggests that the

system with an inlet temperature of 10 °C doesn't worsen temperature gradients and even induces compressive self-equilibrating stresses which can be beneficial.

Application with 50 °C Inlet Fluid Temperature

Figure 48a shows the average top surface temperature for an inlet fluid temperature of 50 °C during the various stages of the simulation with and without the system running. The system was successful in raising the stabilized surface temperature above 0 °C in every stage except Stage 5. The system could not bring the surface temperature above 0 °C with the low ambient temperature and the lack of solar radiation in Stage 5, but the surface temperature stabilized at 16 °C higher with the system, at -4 °C. During Stages 1 and 4, the system caused surface temperatures of 7 °C and 3 °C, respectively. Without the system, the surface temperatures stabilized 12 °C and 13 °C lower for Stages 1 and 4, respectively. With solar radiation, in Stages 2, 3, and 6, the surface temperature stabilized, on average, 11 °C higher when the system was running.

The system raised the stabilized surface temperature above 0 °C during five of the six stages. During three of those stages, the temperature otherwise remained below 0 °C without the system running. The only stage where the system was unable to bring the concrete temperature above 0 °C was Stage 5. The lack of solar radiation and ambient temperature of -20 °C represent extreme weather that is less common. The results suggest that with an inlet temperature of 50 °C, a geothermal deicing system is mostly successful in bringing the surface temperature above 0 °C in Montana weather conditions.

Figure 48b shows the minimum concrete temperature throughout the simulation with an inlet temperature of 50 °C. Again, the system was successful in every stage except Stage 5.

During this stage, the minimum temperature stabilized at -8°C with the system and -20°C without the system. For the other stages without solar radiation, Stages 1 and 4, the system was successful. Stage 1 saw a stabilized minimum temperature of 4°C , while Stage 4 saw a temperature of around 0°C . These minimum temperatures were 9°C and 10°C increases during Stages 1 and 4, respectively. With solar radiation, the minimum temperature was raised above 0°C during all stages (Stages 2, 3, and 6). The minimum temperature stabilized above 0°C without the system during Stage 2, and below for Stages 3 and 6. On average, the minimum temperature was 11°C higher with the system running.

Overall, the system with an inlet fluid of 50°C was effective in mitigating the effects of frost action. The system brought the minimum stabilized temperature above 0°C in five of the six stages, while the temperature without the system stabilized above 0°C during only one stage. The only stage where the minimum temperature stabilized below 0°C with the system running was Stage 5. As discussed previously, this stage represents extreme weather that is less common in Montana.

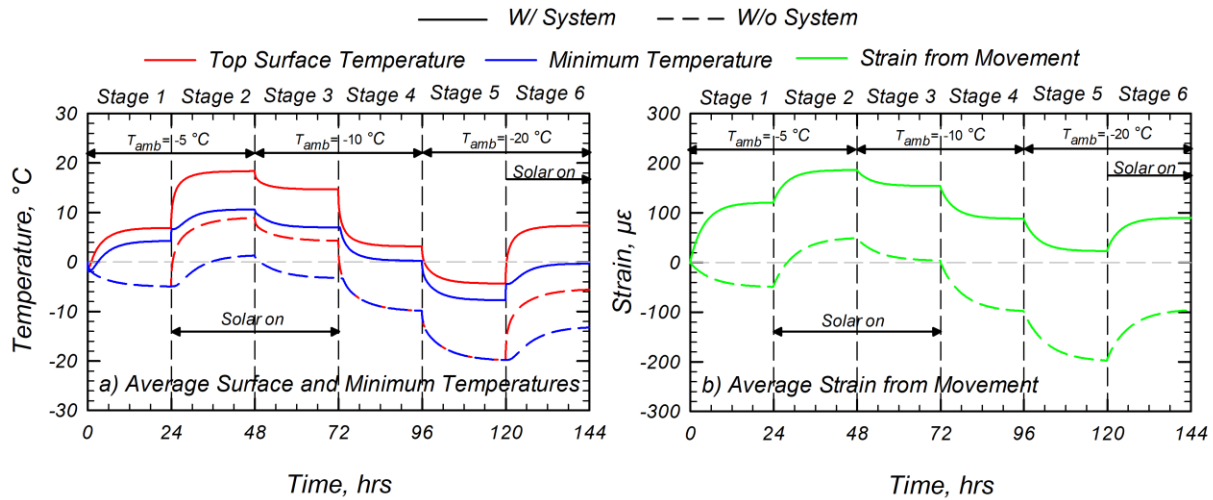


Figure 48 (a) Average surface and minimum temperature and (b) average strain from thermal movement for 50 °C inlet temperature

Figure 48b shows the average strain due to thermal movements with and without the system running. Again, the stabilized strains with the system running were always higher than the strains without the system running, with a maximum and minimum difference of 221 $\mu\epsilon$ during Stage 5 and 137 $\mu\epsilon$ during Stage 2. The overall range of strain was reduced from 247 $\mu\epsilon$ without the system to 163 $\mu\epsilon$ with the system, a 40% reduction. Again, the strain range with and without the system were well below the design strain range from AASHTO.

Similar behavior was observed with an inlet temperature of 50 °C as was observed with an inlet temperature of 10 °C. The range of strain was again reduced, in this case by 40%. The strains were also much larger which means even less contraction was observed. Overall, the 50 °C inlet temperature was, as expected, even more successful than the 10 °C inlet temperature in mitigating the effects of thermal movements.

Figure 49 shows the stabilized temperature gradients at all stages of testing with an inlet temperature of 50 °C. During stages without solar radiation, again, no gradients were observed

without the system running. When the system was running, the bottom surface was up to 3 °C warmer during Stage 5. With solar radiation, the difference between the top and bottom gradients when the system was and wasn't running was never greater than 2 °C. Due to the higher inlet temperature, the gradient was nonlinear regardless of the solar radiation. The nonlinearity of the gradients presented issues in terms of the allowable AASHTO gradients (Figure 45). During Stage 5, the negative gradient of -8 °C between the middle and the top of the deck exceeded the design gradient of -7 °C. During Stage 6, the positive gradient of 9 °C between the bottom and the middle of the deck exceeded the design gradient of 8 °C.

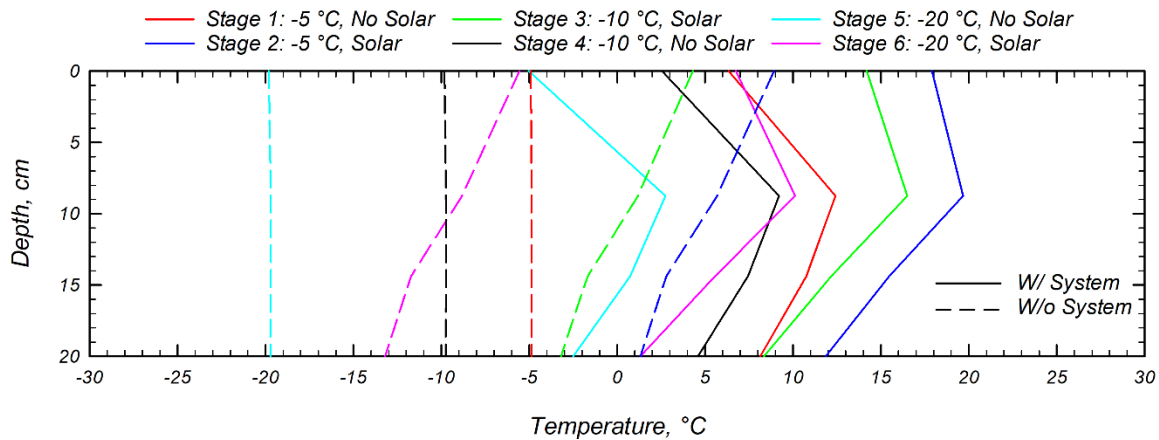


Figure 49: Temperature gradients for 50 °C inlet temperature

The gradients between the top and bottom surface were again insignificant when the system was running. The nonlinearity, however, caused by the 50 °C inlet temperature, exceeded the design gradients established by AASHTO, which means the stresses due to the gradients would not be accounted for in the structural design of the bridge. While this is problematic when considering the feasibility of using a 50 °C inlet temperature, the gradients were only exceeded by 1 °C and only during stages with an ambient temperature of -20 °C. As previously discussed, -20 °C is an extreme ambient temperature that is less common in Montana. While an inlet

temperature of 50 °C was not feasible for an ambient temperature of -20 °C with regard to thermal gradients, it was feasible for higher ambient temperatures.

Sensitivity Analysis

Tornado diagrams with and without solar radiation were created to show the relative influence of various parameters on the effectiveness of the deicing system to deice and mitigate frost action, thermal movements, and thermal gradients. The base model consisted of an inlet temperature of 10 °C, a tube spacing of 20 cm, and an ambient temperature of -10 °C. The base inlet temperature of 10 °C was chosen because it is almost ten times more likely in Montana than an inlet temperature of 50 °C. A separate sensitivity analysis is needed to evaluate the influential parameters of a geothermal deicing system implemented near geothermal hotspots. A range of inlet temperatures from 4 °C to 16 °C were also tested because the range represents the 95% confidence interval of the distribution. A tube spacing of 20 cm was chosen for the base model because it is a common spacing used by other researchers (Ghasemi-Fare et al. 2015; Bowers 2016). Tube spacings of 10 cm and 30 cm were also tested as they are feasible alternatives to the base spacing. The ambient temperatures of -5 °C, -10 °C, and -20 °C, selected from historical Montana weather and tested in previous numerical simulations, were considered in the sensitivity analysis. An ambient temperature of -10 °C was chosen for the base because it is the middle value and shows the effect of increasing the temperature to -5 °C and decreasing the temperature to -20 °C.

Figure 50a shows the effect of various parameters on the top surface temperature without solar radiation. The stabilized top surface temperature of the base model was -5.6 °C. The ambient temperature proved to have the largest effect of the three parameters on the top surface

temperature. A drop in ambient temperature to $-20\text{ }^{\circ}\text{C}$ resulted in a top surface temperature decrease of $7.6\text{ }^{\circ}\text{C}$ to $-13.2\text{ }^{\circ}\text{C}$. An increase in ambient temperature to $-5\text{ }^{\circ}\text{C}$ resulted in a surface temperature of $-1.7\text{ }^{\circ}\text{C}$. The $11.5\text{ }^{\circ}\text{C}$ range in temperatures due to ambient temperature shifts was much larger than the ranges due to shifts in the inlet fluid temperature and tube spacing. The range of inlet fluid temperatures had the next largest effect, with a range of $2.6\text{ }^{\circ}\text{C}$ (from $-6.9\text{ }^{\circ}\text{C}$ to $-4.3\text{ }^{\circ}\text{C}$), while the tube spacing resulted in a slightly smaller effect, with a range of $2.5\text{ }^{\circ}\text{C}$ (from $-6.3\text{ }^{\circ}\text{C}$ to $-3.8\text{ }^{\circ}\text{C}$). When solar radiation was added, the base model produced a top surface temperature of $6.2\text{ }^{\circ}\text{C}$ (Figure 50b). Similar behavior was observed, with ambient temperature having the largest effect on top surface temperature. The ambient temperature ranged from $-1.3\text{ }^{\circ}\text{C}$ to $9.9\text{ }^{\circ}\text{C}$ for ambient temperatures of $-20\text{ }^{\circ}\text{C}$ and $-5\text{ }^{\circ}\text{C}$, respectively. The $11.2\text{ }^{\circ}\text{C}$ range was, again, much larger than that of the inlet fluid temperature and tube spacing. Changes to the inlet fluid temperature caused a range of $2.6\text{ }^{\circ}\text{C}$, from $4.9\text{ }^{\circ}\text{C}$ to $7.5\text{ }^{\circ}\text{C}$. While the ranges due to ambient and inlet fluid temperature were consistent with and without solar radiation, tube spacing had a smaller effect in the presence of solar radiation. A range of $1.1\text{ }^{\circ}\text{C}$ (from $5.8\text{ }^{\circ}\text{C}$ to $6.9\text{ }^{\circ}\text{C}$) was observed when changing the tube spacing. Overall, ambient temperature had the largest effect on the system's deicing ability regardless of solar radiation. This is likely due to the ambient temperature's direct effect on the top surface temperature, whereas the inlet fluid temperature and tube spacing are directly affecting the concrete 8.75 cm below the top surface. The results also confirm, as expected, that higher ambient and inlet fluid temperatures and smaller tube spacings result in higher top surface temperatures.

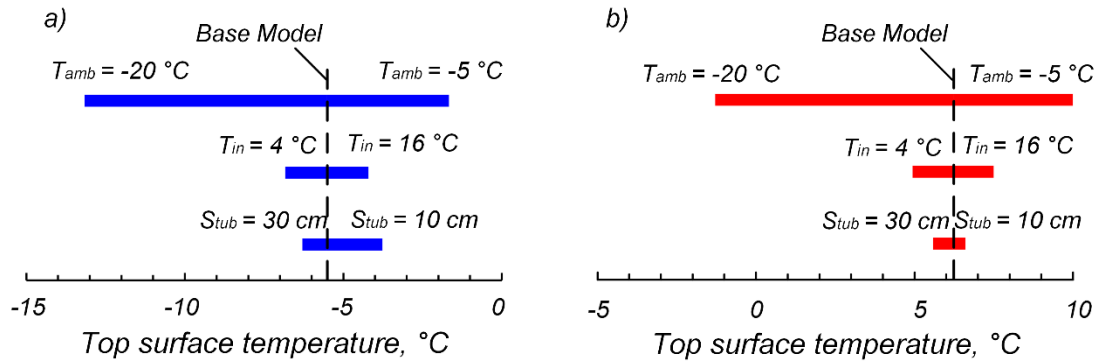


Figure 50: Effect of various parameters on top surface temperature (a) without and (b) with solar radiation

Similar behavior was observed for the minimum concrete temperature as was observed for the top surface temperature. Figure 51a shows the effect of various parameters on the minimum concrete temperature without solar radiation. The minimum temperature of the base model was -6.5 $^{\circ}\text{C}$. As was the case for top surface temperature, the ambient temperature had the largest effect on the minimum temperature, with a range of 12.2 $^{\circ}\text{C}$, from -14.7 $^{\circ}\text{C}$ to -2.9 $^{\circ}\text{C}$. The inlet fluid temperature and tube spacing had the same range of 2.0 $^{\circ}\text{C}$, from -7.6 $^{\circ}\text{C}$ to -5.5 $^{\circ}\text{C}$ and -7.8 $^{\circ}\text{C}$ to -5.8 $^{\circ}\text{C}$, respectively. In the presence of solar radiation, the minimum temperature of the base model was -1.4 $^{\circ}\text{C}$. The ambient temperature continued to be the most influential parameter with a range of 11.3 $^{\circ}\text{C}$, from -8.9 $^{\circ}\text{C}$ to 2.4 $^{\circ}\text{C}$. The inlet fluid temperature was again the next most influential, causing a range of 2.6 $^{\circ}\text{C}$, from -2.7 $^{\circ}\text{C}$ to -0.1 $^{\circ}\text{C}$. The effect of tube spacing was again less influential with solar radiation than without, causing a range of only 1.0 $^{\circ}\text{C}$, from -2.0 $^{\circ}\text{C}$ to -1.0 $^{\circ}\text{C}$. The same conclusions that were drawn about the system's ability to deice can be drawn about frost action mitigation: ambient temperature is the most influential parameter, and higher ambient and inlet fluid temperatures and lower tube spacings improve effectiveness.

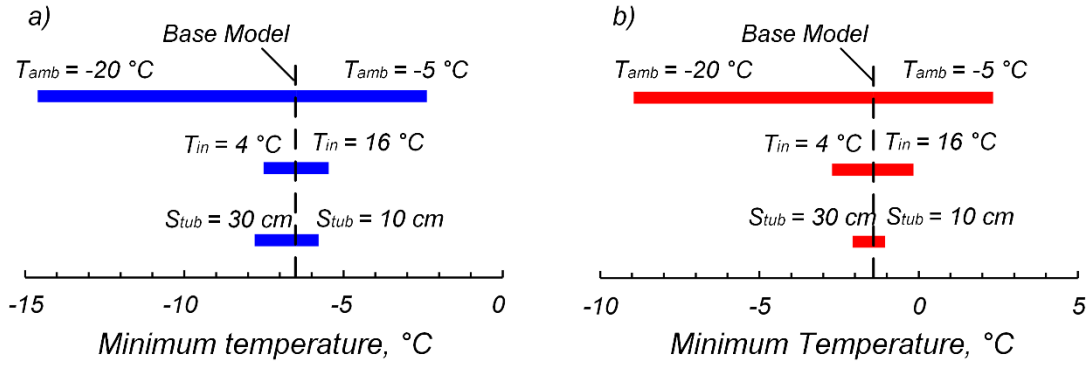


Figure 51: Effect of various parameters on the minimum concrete temperature (a) without and (b) with solar radiation

Figure 52a shows the effect of various parameters on strain from thermal movements without solar radiation. The base model had strains due to thermal movements of $-36.5\text{ }\mu\epsilon$. The effects of the different parameters were more consistent for thermal movements. The ambient temperature was still the most influential parameter, with a range of $100.4\text{ }\mu\epsilon$ (from $-103.4\text{ }\mu\epsilon$ to $-2.9\text{ }\mu\epsilon$), but the inlet fluid temperature influence was only 63% less at $37.5\text{ }\mu\epsilon$ (from $-55.5\text{ }\mu\epsilon$ to $-17.9\text{ }\mu\epsilon$), compared to an average of 79% less for the top surface temperature and minimum temperature. The effect of tube spacing was similar at $35.8\text{ }\mu\epsilon$, from $-47.5\text{ }\mu\epsilon$ to $-11.7\text{ }\mu\epsilon$. When solar radiation was added, the base model exhibited strains due to thermal movements of $31.0\text{ }\mu\epsilon$ (Figure 52b). The range of ambient temperatures and inlet fluid temperatures with solar radiation caused ranges similar to when no solar radiation was present of $98.8\text{ }\mu\epsilon$ (from $-34.9\text{ }\mu\epsilon$ to $63.9\text{ }\mu\epsilon$) and $37.3\text{ }\mu\epsilon$ (from $12.2\text{ }\mu\epsilon$ to $49.5\text{ }\mu\epsilon$), respectively. The effect of tube spacing was again lessened by solar radiation with a range of $15.9\text{ }\mu\epsilon$ (from $26.2\text{ }\mu\epsilon$ to $42.1\text{ }\mu\epsilon$). The only difference between the effect of the parameters on strain compared to temperature was the relative influence of ambient temperature. The average decrease in influence from the ambient temperature and the inlet fluid temperature was 79% for the temperature results and 63% for the strain results. The

results also suggested that higher ambient and inlet fluid temperatures and smaller tube spacings led to higher strains.

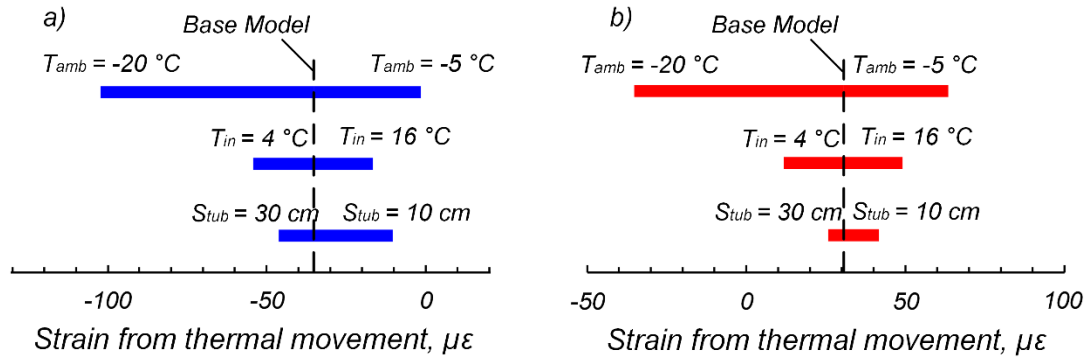


Figure 52: Effect of various parameters on strain due to thermal movement (a) without and (b) with solar radiation

Figure 53 shows the effect of various parameters on the temperature gradient between the top and bottom surfaces without solar radiation. The base model had a gradient of 0.6 °C. The same sequence of influence was observed, but with slight differences in behavior. The ambient temperature was again the most influential factor, but by much less than for the other cases. The gradient range due to the ambient temperature was 0.5 °C (from 0.4 °C to 0.9 °C) and 0.3 °C (from 0.4 °C to 0.7 °C) due to inlet fluid temperature and tube spacing. The other observed difference was that lower ambient temperatures led to higher temperature gradients. For the top surface temperatures, minimum temperatures, and strain due to thermal movements, lower ambient temperatures led to lower temperatures and strains. With the addition of solar radiation, the base model gradient was much higher, at 7.3 °C (Figure 53b), but the ranges due to ambient temperature and inlet fluid temperature were similar, at 0.4 °C from 7.0 °C to 7.4 °C and 7.1 °C to 7.5 °C, respectively. The tube spacing's effect was again reduced by solar radiation, with a range of 0.1 °C (from 7.2 °C to 7.3 °C). While closer tube spacings led to higher temperatures

and strains in the previous cases, it led to lower gradients in the presence of solar radiation. Overall, the effect of various parameters on temperature gradient followed mostly similar behavior as the previous cases, with minor differences. The magnitudes of the temperature gradient ranges, however, were insignificant at less than 1.0 °C, suggesting that the gradients are consistent regardless of the changes to the system studied in this sensitivity analysis.

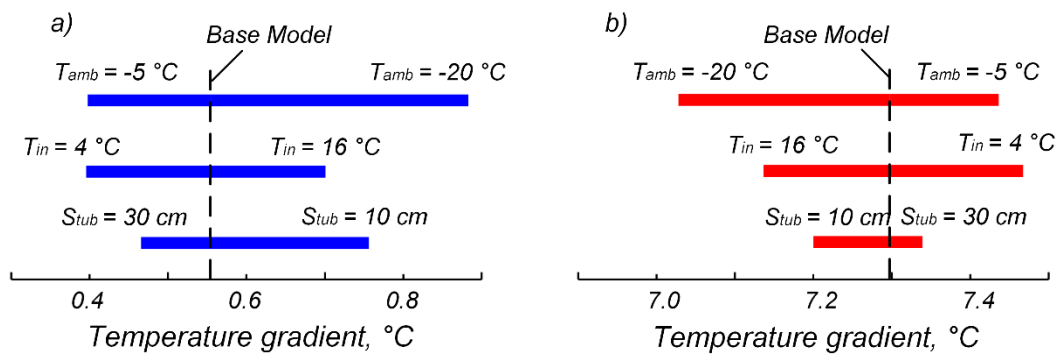


Figure 53: Effect of various parameters on the temperature gradient between the top and bottom surfaces (a) without and (b) with solar radiation

Conclusion

Results from physical experiments performed in Chapter 2 on a model-scale bridge deck deicing system were used to construct and validate a numerical model in COMSOL Multiphysics. The model was used to evaluate the effectiveness of the deicing system in deicing the bridge deck and mitigating various forms of concrete deterioration under representative winter weather in Montana. The weather scenario used to evaluate the system's effectiveness was developed using historical Montana weather data. Inlet temperatures of 10 °C and 50 °C were tested based on ground temperatures from Montana well data.

The results show that a 10 °C inlet fluid temperature has promise for implementation in Montana. The system did not always bring the surface temperature above 0 °C, but the

temperature was always higher when it was activated. This suggests that during diurnal weather cycles, the system could keep the top surface temperature above 0 °C for a longer period. While the system was unsuccessful in mitigating frost action, the range of strain due to thermal movements was reduced by 32% with the system. In a fully restrained bridge deck, the strain reductions translate to stress reductions of the same magnitude. The contraction of the bridge deck was also reduced because the strains were always higher with the system. While the system did not mitigate thermal gradients, all gradients were within the allowable limits from AASHTO.

As expected, the system with a 50 °C inlet fluid temperature performed better with regard to deicing and mitigating frost action. The results show that system can raise the temperature at all depths above 0 °C during most Montana weather conditions. The ability of the system to mitigate thermal movements was also improved, with a reduction in the range of strain of 40%. The design thermal gradients, however, were exceeded during extreme conditions. This suggests that larger design gradients, and therefore, larger superimposed loads would need to be accounted for in the structural design of a bridge using a 50 °C inlet fluid temperature.

The results of the sensitivity analysis showed that the ambient temperature had the largest impact on the efficiency of a bridge deck deicing system to deice and mitigate frost action and strain due to thermal movements. The inlet fluid temperature had the next highest impact which stayed consistent regardless of solar radiation. The tube spacing had a similar effect to the inlet fluid temperature, but its effect was lessened by the presence of solar radiation. The effect of the system changes had insignificant effects on the temperature gradient between the top and bottom surfaces. More research is needed to analyze the effect of various parameters on the internal gradients of a geothermally heated bridge deck.

This research presents results for stabilized conditions. More research is needed to analyze the effectiveness of a GSHP during realistic diurnal cycles in Montana that include snow accumulation and varying wind speeds. Once more weather conditions are analyzed, definitive conclusions can be made about the feasibility of using geothermal energy to deice bridge decks and mitigate concrete deterioration.

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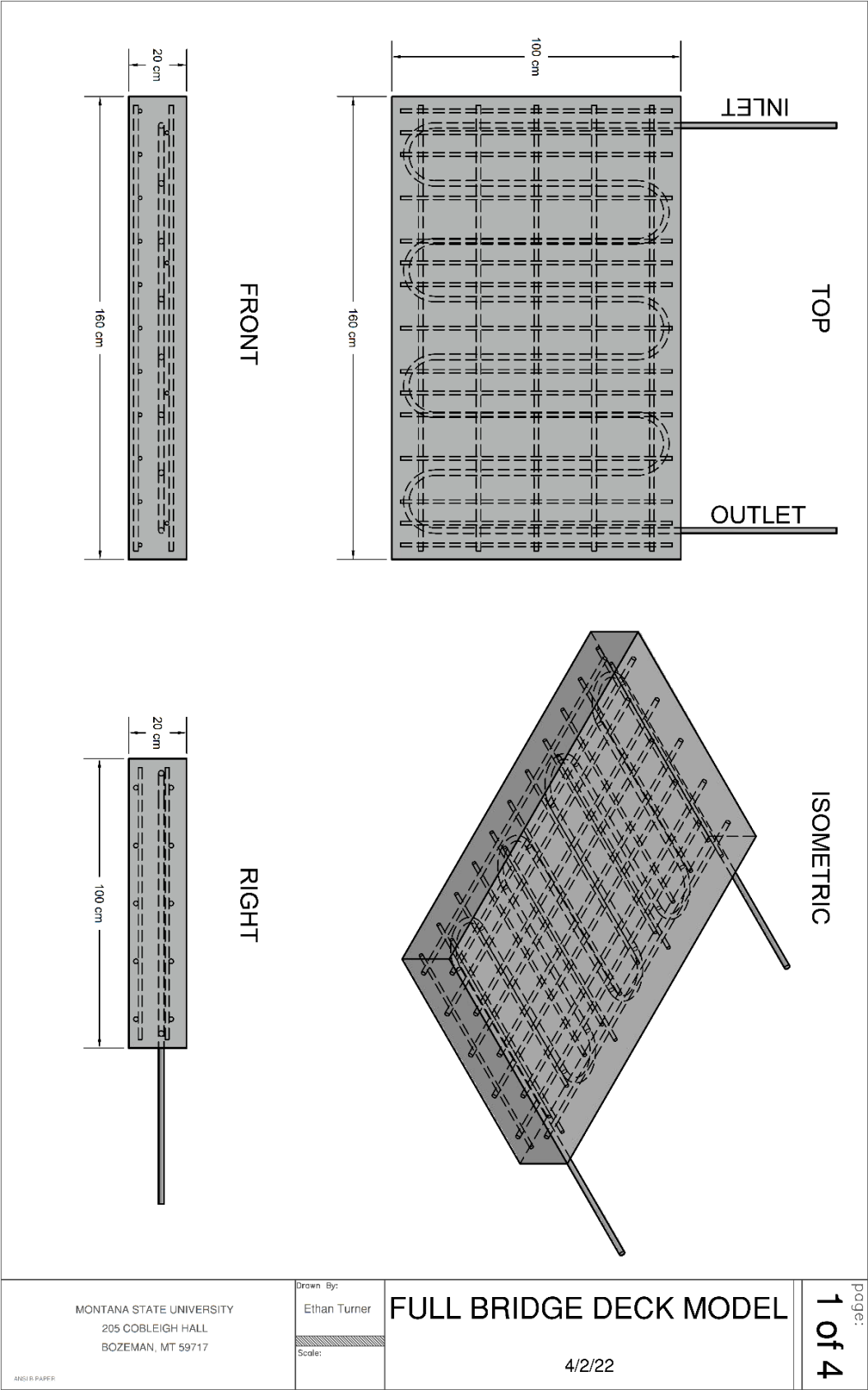
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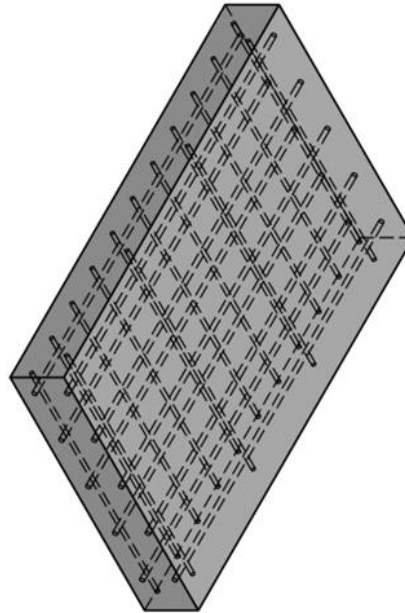
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APPENDIX

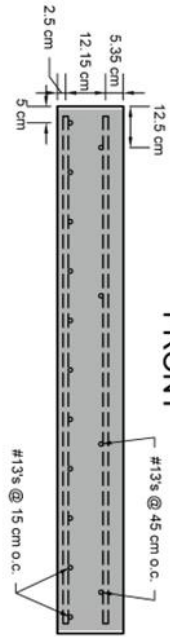
EXPERIMENTAL BRIDGE DECK SCHEMATIC



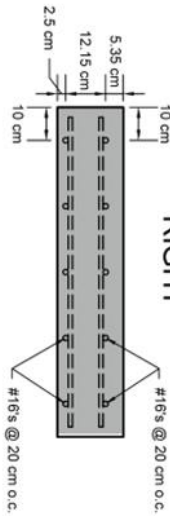
ISOMETRIC



FRONT



RIGHT



REBAR CONFIGURATION

4/2/22

Drawn By:
Ethan Turner

Scale:

MONTANA STATE UNIVERSITY
205 COBLEIGH HALL
BOZEMAN, MT 59717

ANSI 8 PAPER

