University of North Dakota

Proposal Title: Snow-Melting for Concrete Pavements Using Shallow Geothermal Energy and Artificial Intelligence Technique

Final Report

Keywords: Geothermal, Hydronic Heating Pavement, Artificial Intelligence, Transportation Infrastructure

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Executive Summary

This project aims to establish the concrete snow-melting panel to collect the data in winters to better understanding the effectiveness of the alternative snow-melting system. Two concrete hydronic snow-melting panels were established since December 2020 on UND campus. The feasible geothermal aquifers and available temperatures have been identified that produce abundant and quality deep geothermal hot water. The thermal performance of the hydronically heated pavement (HHP) using the direct geothermal hot water in western North Dakota was studied. Two concrete slabs containing heat pipes were prepared to simulate the road and bridge pavement. A semi-automatic temperature data acquisition system was incorporated to (1) control the inlet temperature and flow rate of hot water, and (2) record the top, middle and bottom surface temperatures of the slabs, outlet and air temperatures. Results show that the temperatures of two concrete slabs variations during the 36-hour heating period can be classified into the rapid heating stage, slow heating stage, and fluctuation stage. The top surface temperature of the road and bridge slabs reaches 32 °F after heating 12.5 h and 14 h respectively with 59 °F and 7.5 gpm hot water. In addition, the temperature differences between inlet and outlet temperature when the inlet temperature is 77 °F and 95 °F during the operation stage were much steadier than that is 59 ℃ and the top surface temperature of both concrete slabs is greater than 40 °F. This study recommends an optimal inlet temperature of 77 °F for the two concrete slabs under most unfavorable climate condition in western North Dakota. In addition, the numerical analysis using finite element method was conducted to compare with the collected data. Finally, the feasibility and economic analysis were conducted.

To achieve the goal of this research, the following steps are needed to implement and highlighted in this study:

- Established two concrete pavement panels containing embedded pipes. Both panels are 36 in x 76 in x 8 in.
- Strength tests for concrete samples: 7, 14 and 28 days cured for quality control.
- Collect and record data for two concrete panels: air temperature, top, middle and bottom surface temperatures, and inlet and outlet temperatures of hot water.
- Data analysis and numerical analysis using COMSOL
- Feasibility and Economic analysis for this alternative snow-melting system

Merit

Evaluate the feasibility of the hydronically heated pavement to be impleted to the roardways and bridge decks. The propose method has the benefit including: reduce energy comsumption; lower CO_2 emission, ; utilize a renewable heat source and; increase roadway safety in winter.

Conclusion and Suggestion

Results show that the proposed system is feasible based on the effectiveness of snow-removal during winter. Several new findings have been identified including the heated pavement under extreme weather conditions, feasible temperatures of water, optimal volumetric flow rates and the potential applicable area. Considering the available water temperatures, heat consumption, and weather conditions, the snow can be melted in most unfavorable conditions. However, there are still further research should be conducted and design parameters can be optimized to improve the effectiveness of this alternative snow-melting system. To further improve the effectiveness, several relevant influential factors for the HHP system such as the embedded pipe patterns, embedment depth, thermal conductivity of concrete etc. need to be further investigated in the lab. Other material properties such as mechanical properties of concrete and insulation of concrete panels should be tested using the existing model experiments. Most importantly, visual monitoring system for snow-melting or de-icing process is required to validate the time-dependent variations under dynamic weather conditions. Moreover, more parametric studies using numerical analysis to validate these influential factors and their significances provide cost-effective solutions in optimal designs.

In addition, the future research should also focus on other alternative snow-melting or de-icing methods for the locations lack of geothermal hot water. Alternative heat sources such as shallow geothermal foundations and loops can be explored. Microwave or electric-magnetic methods can also provide efficient and more environmentally friendly methods.

Abstract

The alternative snow-melting methods are considered to be more environmentally friendly than traditional mechanical or chemical de-icing procedures. In addition, more economical than some other alternative snow-melting methods if a hydronic heating system uses a economical heat source. In western North Dakota, six aquifers have been identified in the Williston Basin that can provide geothermal hot water for direct use. Given the availability of these aquifers and co-production wells, the focus of this study is to establish the physical model to collect data collections subjected to various weather conditions from Dec 2020 to Feb 2022. The collected data was analyzed and validated with the numerical analysis using a finite element method. The analysis considers the established pavement scenarios for the direct use of geothermal hot water that consider water temperature, volumetric flow rate, and the heat requirements for weather conditions in western North Dakota. This study investigated the range of inlet temperature between 55 °F and 100 °F. Results show that the optimal inlet water temperature is 65 °F and the inlet flow temperature of water is 3.5 gpm. The system can melt snow effectively under the combined inlet temperature and flowrate of water. The effectiveness and the feasibility of the system were evaluated. Based on the economic analysis, the proposed scenario is recommended and the system used for snow-melting is feasible.

Keywords: Snow-melting, de-icing, heat transfer, geothermal, hydronic heating, numerical analysis

Chapter 1 Introduction

1.1 Background

Previous researchers have studied and documented several alternative snow-melting and de-icing systems. In addition to the snow-melting efficiency of such systems, they are considered to be more environmentally friendly than traditional mechanical or chemical de-icing procedures and more economical than some other alternative snow-melting methods. Besides the heat source, the main governing factors for a hydronic heating system are including concrete panel establishment, pipe scenario, air temperature, snowfall intensity, wind speed and humidity. In western North Dakota, six aquifers have been identified in the Williston Basin that can provide geothermal hot water for direct use that can be considered to be a renewable and economical heat source. The focus of this research is to establish a physical model of concrete snow-melting panels, test the snow-melting functions, mechanical properties of this hydronic snow-melting pavement, conduct the numerical analysis using finite element method and provide the economic analysis to NDDOT.

1.2 Scope of Work

The objectives of this proposed work are to perform a literature review of current snow-melting and alternative snow-melting techniques, heat sources and the applications of deep geothermal energy in western North Dakota. Two physical models will be established to collect the data for snow-melting in winter and calibrated with the numerical analysis using finite element method (FEM). The feasibility and economic analysis will be conducted for the hydronically heated pavement (HHP). Because of its geologic formations, western North Dakota has available geothermal hot water stored in several aquifers to provide a heat resource for direct use. This research focuses on studying the pavement heating technique and evaluate the feasibility of using the geothermal hot water. Considering several factors which affect the efficiency of the HHP, finite element analysis was employed to conduct the parametric study. Influential factors including heating process, pipe arrangement (layout), heat requirement, volumetric flow rate, and air temperature were investigated. The feasibility of the HHP using this direct high-temperature water is recommended.

1.3 Hydronic Snow-Melting System

The hydronic snow-melting method involves embedding pipes in concrete pavement panels several inches beneath the surface and circulating warm fluid through the pipes. Specifically, a hydronic snow-melting system is a closed-loop tube made of flexible polymer (e.g., cross-linked polyethylene, or PEX) in which a fluid or a mixture of hot water and glycol, depending on the type of heat source, circulates. The fluid is warmed to temperatures of 140 °F to 180 °F to provide sufficient heat for snow melting.

1.4 Climatic Conditions in Western North Dakota

Climatic conditions constitute the most important influential factor when designing a snow-melting system for western North Dakota. The magnitudes of these conditions are required for estimating the heat that is needed to melt snow. In western North Dakota, the climatic conditions in winter are extremely severe. According to Ho (2016), North Dakota has higher heat demands in winter for melting snow than other areas in the United States. North Dakota's snowfall period typically starts in October and ends in May, with the highest heat demands falling between November and March. The air temperature also usually stays low during this lengthy snowfall period. These climatic conditions result in extremely high heat demands to melt snow and ice at transportation infrastructure facilities. Unless sufficient heat is available, difficulties associated with snow removal cause travel delays and slow economic activities.

The air temperature, snowfall rate, snowfall frequency, moisture content of the snow, wind speed, and amount of sunlight all affect the rate at which snow will melt. For a snow-melting system design, the most important factor among these climatic conditions is the snowfall rate. When a snowfall event begins, the snowfall rate usually increases until the peak snowfall rate is reached. In this paper, the weather conditions considered for the heat requirement estimations are based on climatic data averaged over the 15 years from 2002 through 2016. These climatic data were measured by the National Oceanic and Atmospheric Administration and the World Data Center for Meteorology. Table 1.1 presents summaries of the averaged temperature, snowfall, and wind speed data for the four major cities (Bismarck, Minot, Williston, and Dickinson) that are targeted in this study. These climatic data must be considered when estimating the heat requirements for melting snow using the Chapman and Katunich equation (1956). Overall, the snow-melting system must be designed to melt snow under most circumstances.

Table 1.1 Averaged weather data obtained for four major cities in western North Dakota and used for heat estimations

	January	February	March	November	December
Air temperature, °F	14	15.3	30.2	30.6	17.2
Snowfall, inch/hour	0.013	0.013	0.011	0.01	0.014
Wind speed, ft/s	14.76	13.78	14.76	13.78	14.76

Chapter 2 Literature Review

Snow and ice on pavements are responsible for numerous transportation problems and safety concerns, and they can lead to significant inconvenience for travelers in terms of delays. In the past decade, many studies have focused on seeking economically viable de-icing or snow removal methods for airport pavements, bridge decks, and other transportation infrastructure facilities. These studies have concentrated mainly on pavement heating techniques that are considered to be 'alternative' snow-melting techniques (Lund, 2000; Anand et al., 2014; Ho and Dickson, 2016, 2017; Hai and Park, 2017). Conventionally, snow removal strategies have relied on both mechanical and chemical methods. However, the mechanical methods are sometimes inefficient and time-consuming and the chemical methods are detrimental to the environment. A hydronic heated pavement is considered to be more environmentally friendly and sustainable than conventional de-icing methods that use, for example, salts and chemicals. In fact, salts and chemicals are prohibited for use on airport pavements because they are detrimental to both pavement materials and to the metallic materials of aircraft (Hassan et al., 2002). Especially for airport pavements, wet snow and ice can develop a strong bond with the contaminants on pavements. According to the Federal Aviation Administration (FAA), heated pavement systems provide an alternative snow-removal strategy that can mitigate the effects of snowfalls by melting the snow and preventing it from bonding to the pavement surface (Anand et al., 2014). The benefits of pavement heating systems for airports include that they have a positive impact on capacity during winter operations; reduce the negative environmental impacts of chemical de-icers; reduce the time required to clear priority areas; and improve the operational status of the transportation infrastructure. To achieve these benefits of snow removal, the FAA has funded several research projects to study advanced snow-melting techniques for airport infrastructure; these techniques include hydronic and electric pavement heating techniques. In addition, the hydronic pavement heating by harvesting shallow geothermal using energy piles has been successfully demonstrated (Minsk 1999, Yu et al. 2016). Many previous studies have proven that hydronic pavement heating is one of the most efficient alternative snow-melting techniques for roads in winter (Lund 2000; Anand et al. 2014; Hai 2017; Ho and Dickson 2016, 2017; and Park 2017). Hydronic heating pavement (HHP) is considered to be more environmentally friendly than traditional snow-melting methods: mechanical and chemical methods (Anand et al. 2014, Adl-Zarrabi et al. 2016, Ho and Dickson 2017). Melting snow or deicing using HHP is not a new method. In 1948, a HHP system was built in Klamath Falls, Oregon (Pan et al. 2015). From 1994 to 1999, several HHP projects were reported to have been designed, constructed, and operated in the four U.S. states of Nebraska, Oregon, Texas, and Virginia (Minsk 1999, Pan et al. 2015). Anand et al. (2014) compared the costs of different snow-removal techniques using the Des Moines International Airport as their study example. Their results showed that hydronic heated pavements have a low operational cost but a high installation cost compared to traditional (mechanical and chemical) methods. The operational costs of a hydronic heated pavement depend mainly on the price of the energy source, such as fossil fuels, natural gas, shallow geothermal energy, etc. Geothermally heated hydronic systems incorporate a heat pump to harvest geothermal hot water within 200 feet in depth. Through harvesting shallow geothermal heat, which is generally between 45°F to 55°F, heat exchangers warm the fluids that circulate through the pipes (Wang et al. 2010, Adl-Zarrabi et al. 2016, Ho 2017, 2019, 2021, Raheb et al. 2018). However, the temperature of shallow ground is relatively low and, thus, more energy must be consumed in order to harvest the required heat. Although geothermal energy is considered to be environmental-friendly and efficient, the installation costs of geothermal hydronic heating systems are high.

The main challenge of a HHP system is the temperature of the fluid which circulates in the embedded pipes. The fluids carry the thermal energy that harvests shallow geothermal heat which has relatively low ground temperature. The shallow geothermal typically can be harvested through the geothermal loops or geothermal piles, then provides heat through heat exchangers. However, the act of melting snow requires higher surface temperatures than those to simply prevent ice formation (Eugster 2007). Thus, geothermally heated pavement using a heat exchanger may not be realistic for those areas having a high demand for heat (e.g., North Dakota). Because of the relatively low temperature of the shallow ground, the operation of the system becomes less efficient and more energy consuming. Direct-use of geothermal hot water can improve the heat supply on pavement surface for a HHP system (Ho 2018). The geothermal hot water pumped from deep aquifers usually has higher temperatures depending on depths and locations. Geothermal hot water for pavement heating has been used in the United States and Japan since 1948 and 1966, respectively (Lund 2000). The oldest HHP system was installed in Klamath Falls, Oregon (Lund 2000), with the supply water temperature varying from 100° to 130°F (37.8° to 54.4°C).

Chapter 3 Model Testing Plan and Data Collection

3.1 Model Testing Plans

The hydronic snow-melting concrete panels involves embedding pipes in concrete pavement panels several inches. This purpose of this study is to carry out the laboratory tests, further collect and simulate the piped pavements in terms of geomechanical behavior and assess their serviceability for concrete pavements. This study considered the time-dependent heating process of piped pavements, the final temperatures of heated pavements, the final temperature drops of the hot water in the embedded pipes, and the required flow rates of the water circulating through the pipes. The two concrete panels have been built and setup in December 2021 (see Fig. 3.1). One concrete panel containing no rebar is directly placed on the ground and the other panel containing rebar is lifted above the ground.

(a) (b)

Figure 3.1 Snow-Melting Concrete Panel (a) with rebar, and (b) without rebar

The model testing plan includes the following items:

3.1.1 Data Collection and analysis

The data collected through the semiautomatic system was recorded. The variables can be adjusted through the computer interface. The inlet water temperature can be controlled through the computer program. The inlet temperature of water is the same for both concrete panels and only one outlet temperature was recorded. Three temperature sensors were installed in each panel: top, middle and bottom surfaces. In addition, the air temperature was also recorded. The data analysis is to evaluate the snow-melting process under different snowfall events and air temperatures. The inlet and outlet temperature difference of water varies subjected to air temperature and snowfall intensity.

3.1.2 Numerical Analysis

The numerical analysis using finite element methods was conducted. The simulated models were created using COMSOL finite element software. The numerical analysis can be used to validate the collected data and conduct parametric studies. Several influential factors such as volumetric flow rate, inlet water temperature, air temperature, heated surface temperatures and pipe arrangements should be analyzed and calibrated. These numerical models can help the design in the future.

3.1.3 Geothermal Resource Analysis

The existing water production wells and aquifers to secure the geothermal hot water with the sufficient temperatures was identified. The inlet temperature of water considers the available temperature of water from the geothermal aquifers and the favorable snow-melting effectiveness. The water temperature was first focused on the range between 55 °F and 100 °F. However, the water temperature above 65 °F seems to overheat the pavement under most of the weather conditions. On the contrary, the water temperature below 55 °F is less efficient in melting snow and heat up the surface temperatures of two concrete panels under most weather conditions. Finally, the water temperature stabilized at 65 °F was investigated in most weather condition from Nov. 2021 to Feb. 2022.

3.2 Data Collection System

The data collection mainly focuses on the effectiveness of snow-melting while the snow-melting process is time dependent. The data was collected from Dec. 2020 to Feb. 2022. These data includes the air temperature snow-melting system operations heat supply, heating process, heated surface temperatures, circulating flow rate and inlet and outlet water temperatures. A semi-automatic system and computer program was developed and used to transmit the data to a database drive. The system can be activated according to the snowfall events through the acquisition system shown in Figure 3.2. The designed computer software is user-friendly and can monitor the system in the lab anytime. In Figure 3.2, the information shown includes the air temperature, top and bottom surfaces temperatures in the concrete panels and the sensors embedded in the middle of concrete records the temperature in the concrete panels. The inlet temperature of water can be controlled through the system and the outlet temperatures can also be recorded. The flow velocity can be adjusted based on the pressure in the pipes. These are the important factors affecting the effectiveness of the snow-melting process.

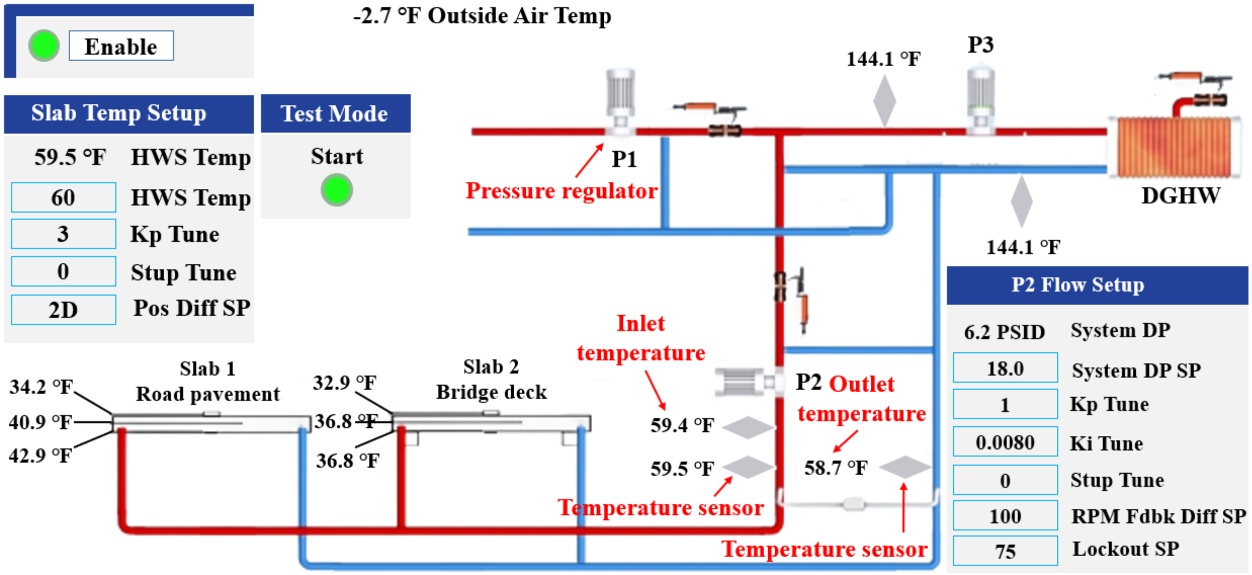
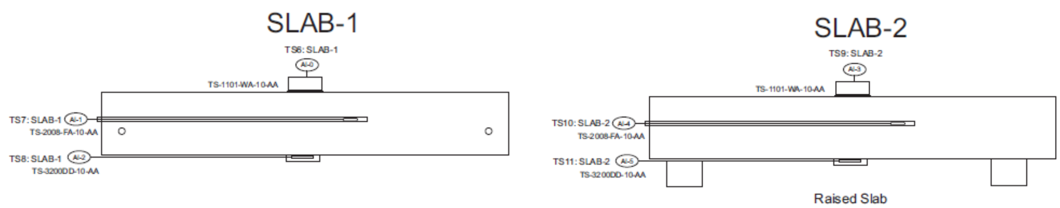


Figure 3.2 Concrete pavement data acquisition system

Chapter 4 Snow-Melting Panels Data Collection

4.1 Sensor Locations

Two concrete panels were built and setup in December 2021. One concrete panel containing no rebar is directly placed on the ground and the other panel containing rebar is lifted 2 inch above the ground. Each slab has three temperature sensors for surface temperatures. In addition, inlet and outlet temperature for the embedded pipes, air temperature, and fluid pressures were recorded. Fig. 4.1 shows the schematic diagrams for the positions of temperature sensors for both slabs. Three temperature sensors to measure top, middle and bottom temperatures were installed in each slab.



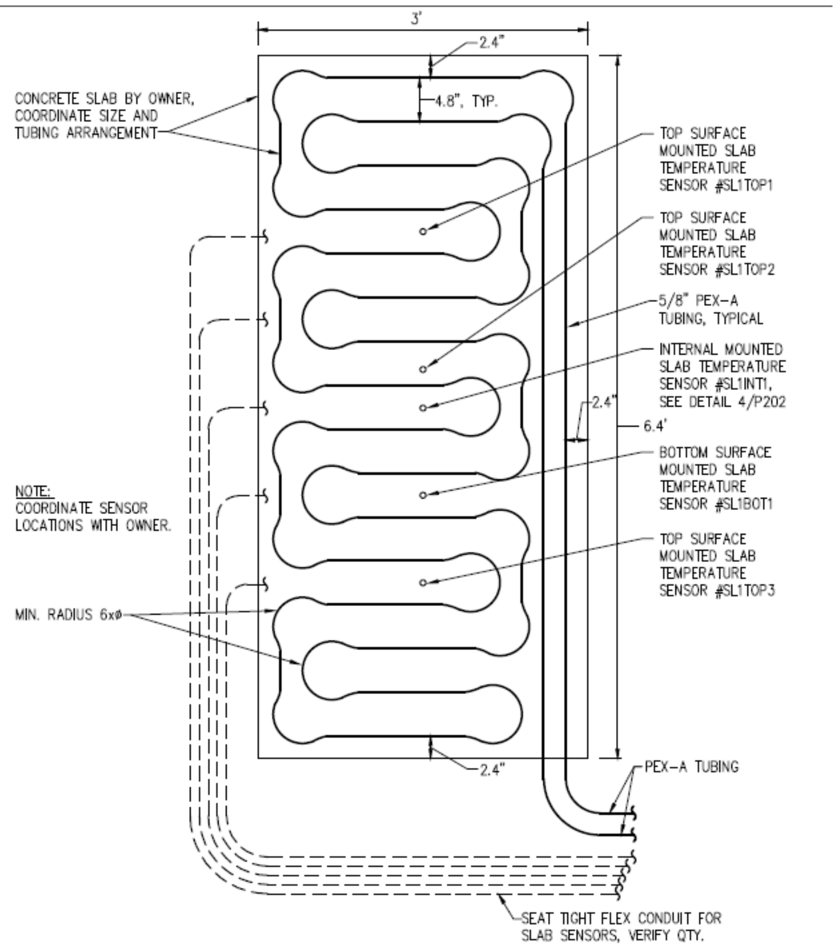
(a) (b)

Fig. 4.1 Sensors Locations for (a) Slab 1-no rebar, and (b) raised slab

Fig. 4.2 shows the pipes and rebars arrangements before pouring concrete. Fig 4.2(a) shows the panel without rebar and the steel net to withhold the pipes, and Fig.4.2(b) shows that the panel containing two layers of rebars. Fig. 4.3 shows the design of pipes, rebar and panel size for two concrete panels. Typical plastic pipes made of cross-linked polyethylene (PEX) were modeled because, according to ASTM standard, PEX pipe is able to carry water up to 200°F (93.3°C) at 80 psi or 180°F (82.2°C) at 100 psi.

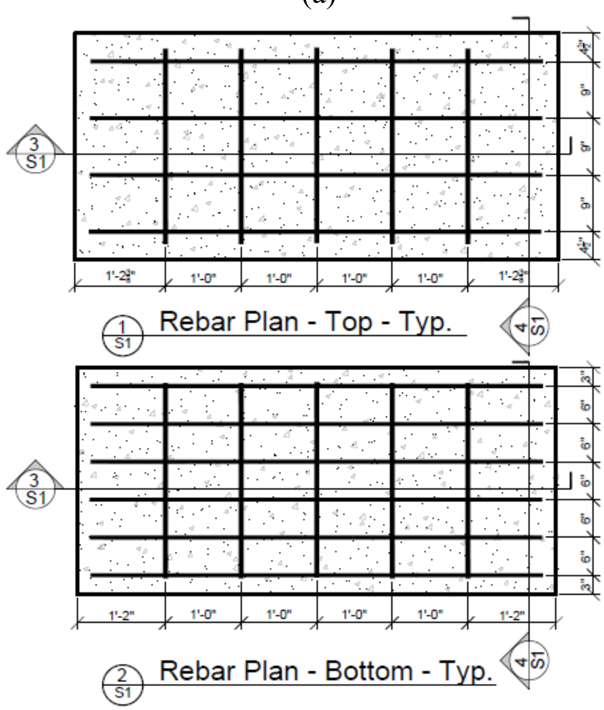
(a) (b)

Fig. 4.2 (a) panel without rebar, (b) panel with rebars before pouring concrete



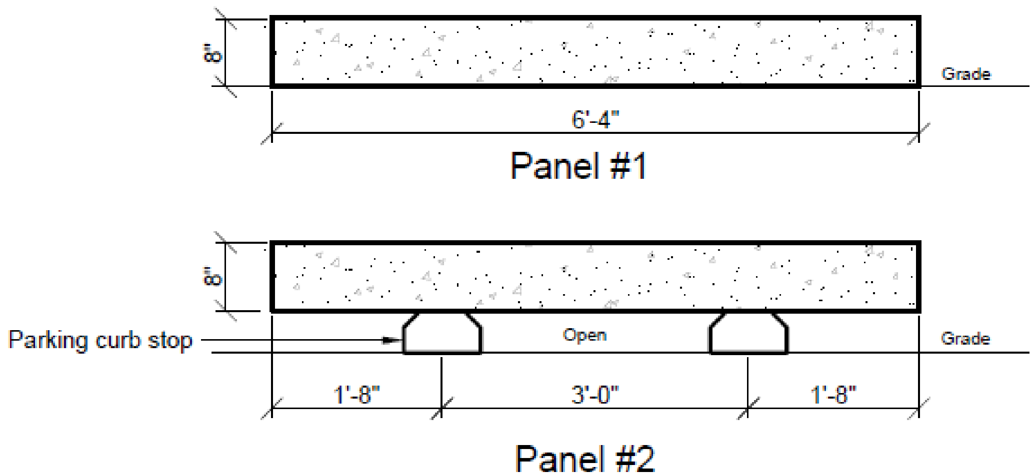
3'
2.4"
4.8", TYP.
CONCRETE SLAB BY OWNER, COORDINATE SIZE AND TUBING ARRANGEMENT
TOP SURFACE MOUNTED SLAB TEMPERATURE SENSOR #SL1TOP1
TOP SURFACE MOUNTED SLAB TEMPERATURE SENSOR #SL1TOP2
5/8" PEX-A TUBING, TYPICAL
INTERNAL MOUNTED SLAB TEMPERATURE SENSOR #SL1INT1, SEE DETAIL 4/P202
2.4"
6.4'
BOTTOM SURFACE MOUNTED SLAB TEMPERATURE SENSOR #SL1BOT1
TOP SURFACE MOUNTED SLAB TEMPERATURE SENSOR #SL1TOP3
NOTE:
COORDINATE SENSOR LOCATIONS WITH OWNER.
MIN. RADIUS 6xø
2.4"
PEX-A TUBING
SEAT TIGHT FLEX CONDUIT FOR SLAB SENSORS, VERIFY QTY.

(a)

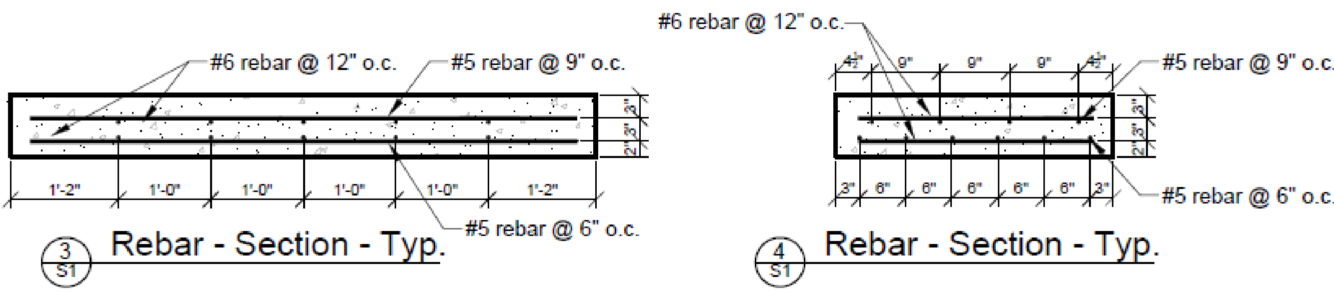


1'-0"
Rebar Plan - Top - Typ.
Rebar Plan - Bottom - Typ.
1'-2"

(b)



(c)



(d)

Fig 4.3 Schematic diagrams: (a) embedded pipe layout, (b) top and bottom rebar layouts, (c) panels placement, and (d) lateral and from side views of concrete panel containing rebars.

4.2 Data Collection and Analytical Solutions

According to the previous research, the heat requirements for different months are shown in Table 4.1. The estimations of the heat required for melting snow must account for the climatic conditions at the locations of the pavements using Chapman and Katunich's equation (1956). These weather conditions include the snowfall rate, ambient air temperature, humidity, and wind speed, which are considered in the equation. For this research, because the study is applicable to the locations in western North Dakota, the climatic conditions for western North Dakota were used for the heat requirement estimations. Weather data, including air temperature, wind speed, and snowfall rate during the five coldest months with heaviest snowfalls in a year, were used for the estimations. Because the differences among those weather data for the four cities were small, averaged values were used for the estimations of the heat requirements. That is, the weather data were averages for a 15- year period for the four major cities in western North Dakota.

In addition to the weather conditions, the snow-free area ratio, A_r. needed to be assumed in order to estimate the heat requirements for a snow-melting pavement panel. The snow-free area ratio, A_r, represents how the snow can be melted during a snowfall event when the snow-melting system is activated. The snow-free area ratio, A_r, can reasonably be assumed to be a value between 0.5 and 1.0. This analysis used two snow-free area ratios, $A_r = 0.5$ and 0.75. Also, 25 percent heat loss at other boundaries of a concrete panel was assumed. Table 4 provides a summary of the estimated heat requirements for melting snow. Table 4.1 (a) summarizes the heat estimations for the snow-free area ratio, $A_r = 0.5$, and Table 4.1 (b) summarizes the estimations for $A_r = 0.75$.

Table 4.1 Heat requirements for melting snow on pavement panels in western North Dakota

(a) Area ratio, $A_r = 0.5$

	January	February	March	November	December
Temperature, °F	14	15.3	30.2	30.6	17.2
Wind Speed, ft/s	14.76	13.78	14.76	13.78	14.76
Snowfall, in/hr	0.021	0.021	0.014	0.011	0.017
Snow Ratio, A_r	0.5	0.5	0.5	0.5	0.5
q_0, Btu/hr/ft^2	48.66	45.36	19.81	13.38	46.5
Q_0, Btu/hr/ft^2	60.83	56.71	24.76	16.71	58.14

(b) Area ratio, $A_r = 0.75$

	January	February	March	November	December
Temperature, °F	14	15.3	30.2	30.6	17.2
Wind Speed, ft/s	14.76	13.78	14.76	13.78	14.76
Snowfall, in/hr	0.021	0.021	0.014	0.011	0.017
Snow Ratio, A_r	0.75	0.75	0.75	0.75	0.75
q_0, Btu/hr/ft^2	71.2	65.46	25.45	16.36	64.26
Q_0, Btu/hr/ft^2	89.01	81.85	31.83	20.45	80.3

4.2.1 Temperature of Geothermal Hot Water

The geothermal hot water in the reservoir adjacent to Minot is in the Dakota Aquifer. The water temperatures are between 93.2 °F and 111.2 °F at depths between 2093 ft and 2788 feet. Even deeper, the geothermal hot water in the Pennsylvanian Aquifer is about 140 °F at approximately 4,265 ft deep. In the Bismarck area, hot water at about 104 °F can be obtained at depths between 2200 ft and 2645 ft from the Dakota Aquifer. Water at about 140 °F can be extracted from the Pennsylvanian and Madison Aquifers at the depth of 4,265 feet. As for Dickinson and Williston, the underlying aquifers contain water above 176 °F. Because water temperatures ranging between 86 °F and 140 °F were technically available for all the studied locations, the numerical analysis for the proposed snow-melting system focused on that range of temperatures.

As shown in Table 4.1(a), the least amount of heat that is needed to melt snow is 13.38 Btu/hr/ft^2 in November and the greatest amount is 48.66 Btu/hr/ft^2 in January. When taking into account 25% heat loss at the boundaries of the concrete pavement panel, the heat requirements are 16.71 Btu/hr/ft^2 and 60.83 Btu/hr/ft^2, respectively. Table 4.1(b) shows that the heat needed to melt snow is 16.36 Btu/hr/ft^2 in November and 71.2 Btu/hr/ft^2 in January. When 25% heat loss is considered, the heat requirements are 20.45 Btu/hr/ft^2 and 89.01 Btu/hr/ft^2, respectively. In addition to using averaged weather data, the parametric study also considered that the temperatures varied from -13 °F to 23 °F, wind speeds varied from 8.2 ft/s to 16.4 ft/s, and the snowfall rate varied from 0.007 in/hr to 0.035 in/hr.

Table 4.2 provides a summary of the heat requirements in terms of climatic variables. The heat requirement estimations are based on controlling one variable at a time, and 25 percent heat loss was considered in all cases. Table 4.2 (a) shows that air temperature varies from -13 °F to 23 °F, whereas the wind speed and snowfall rate are considered to be fixed at 14.76 ft/s and 0.011 in/hr, respectively. The lowest and highest heat requirements are 38.36 Btu/hr/ft^2 and 122.01 Btu/hr/ft^2 for A_r = 0.5, respectively, and 52.15 Btu/hr/ft^2 and 176.92 Btu/hr/ft^2 for A_r = 0.75, respectively. Table 4.2 (b) shows that the wind speed varies from 16.40 ft/s to 8.2 ft/s, whereas the air temperature and snowfall rate are fixed at 14 °F and 0.011 in/hr, respectively The highest and lowest heat requirements are 66.09 Btu/hr/ft^2 and 44.03 Btu/hr/ft^2, respectively, for A_r = 0.5 and 93.58 Btu/hr/ft^2 and 60.48 Btu/hr/ft^2, respectively, for A_r = 0.75. Table 4.2 (c) shows that the heat requirements are subject to snowfall rate variations by fixing the air temperature at 14 °F and the wind speed at 14.76 ft/s. The highest and lowest heat requirements are 85.43 Btu/hr/ft^2 and 57.5 Btu/hr/ft^2, respectively, for A_r = 0.5 and 110.66 Btu/hr/ft^2 and 82.74 Btu/hr/ft^2, respectively, for A_r = 0.75.

Table 4.2 Heat requirements subject to climatic variables

(a) Temperature

Temperature, °C	-13	-4	5	14	23
Wind Speed, ft/s			14.76		
Snowfall, in/hr			0.011		
Q_0, Btu/hr/ft^2, A_r = 0.5	122.01	103.06	83.05	49.36	38.36
Q_0, Btu/hr/ft^2, A_r = 0.75	176.92	148.64	118.84	86.95	52.15

(b) Wind Speed

Wind Speed, m/s	16.4	13.1	11.48	9.84	8.2
Temperature, °F			14		
Snowfall, in/hr			0.011		
Q_0, Btu/hr/m^2, A_r = 0.5	66.09	57.28	52.88	48.44	44.03
Q_0, Btu/hr/m^2, A_r = 0.75	93.58	80.33	73.7	67.08	60.48

(c) Snowfall

Snowfall, in/hr	0.035	0.021	0.014	0.011	0.0071
Temperature, °F			14		
Wind Speed, m/s			14.76		
Q_0, Btu/hr/ft^2, $A_r = 0.5$	85.43	71.45	64.48	60.99	57.50
Q_0, Btu/hr/ft^2, $A_r = 0.75$	110.66	96.72	89.74	86.26	82.74

4.3 Model Data Collections and Analysis

The data collection mainly focuses on the effectiveness of snow-melting while the snow-melting process is time dependent. We have collected data from Dec. 2020 and this winter (from November). The data will include weather conditions (air temperature, humidity, and precipitation), snow-melting system operations (heat supply, heating process, heated surface temperature, circulating flow rate), We will analyze the collected data for optimization and economic feasibility. Currently, the data is achieved and will be downloaded for analysis and numerical analyses.

We design a friendly interface to control the system and collect the data. The inlet temperature of water can be controlled through the system and the outlet temperatures can also be recorded. The flow velocity can be adjusted based on the pressure in the pipes. These are the important factors affecting the effectiveness of the snow-melting process. Figure 4.4 shows the relationship between the temperature and the elapsed time for a 48-hour period for the panel without the rebar. The system was activated at the 12th hour. In this collected data, the air temperature was below 0 F and as low as -14˚F. Four hours after activation, the bottom surface temperature increase to 32˚F which can start to melt snow or de-ice and the top surface needs 12 hours to achieve 32˚F. However, the operation time does not consider the decrease of air temperature. The flowrate was stabilized at 3.5 gpm and inlet temperature of water was 65˚F.

Figure 4.5 shows the relationship between the temperature and the elapsed time for a 48-hour period for the panel with two layers of rebar. In this collected data, less than four hours after activation, the bottom surface temperature increase to 32˚F which can start to melt snow or de-ice and the top surface needs less than 12 hours to achieve 32˚F. Compared to the panel without rebar, the heat conduction for the panel with rebars are found to be better because of the rebars. Figure 4.6 shows the water temperature difference between inlet and outlet. The results show that the temperature difference was about 0.8˚F. Thus, the efficiency of the snow-melting panel can work very well in a low temperature using 65˚F (18.3˚C) of inlet water.

In the heated concrete pavement panel, when the top surface was heated to or above 32 ˚F, there is no cumulative snow presents. Due to the limitation, the outlet temperature of water for both panel were combined. However, the separate sensors should be installed to monitor the outlet temperature of water separately so that the heated process of the panel with rebar can be validated.

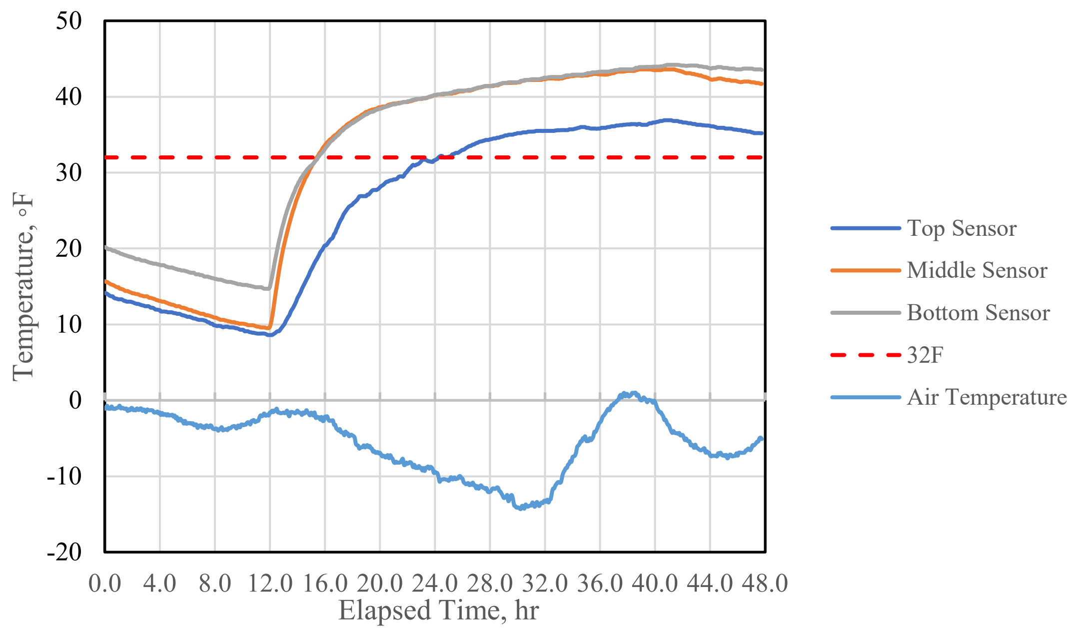


Fig. 4.4. Heated pavement panel without rebar (Slab-1)

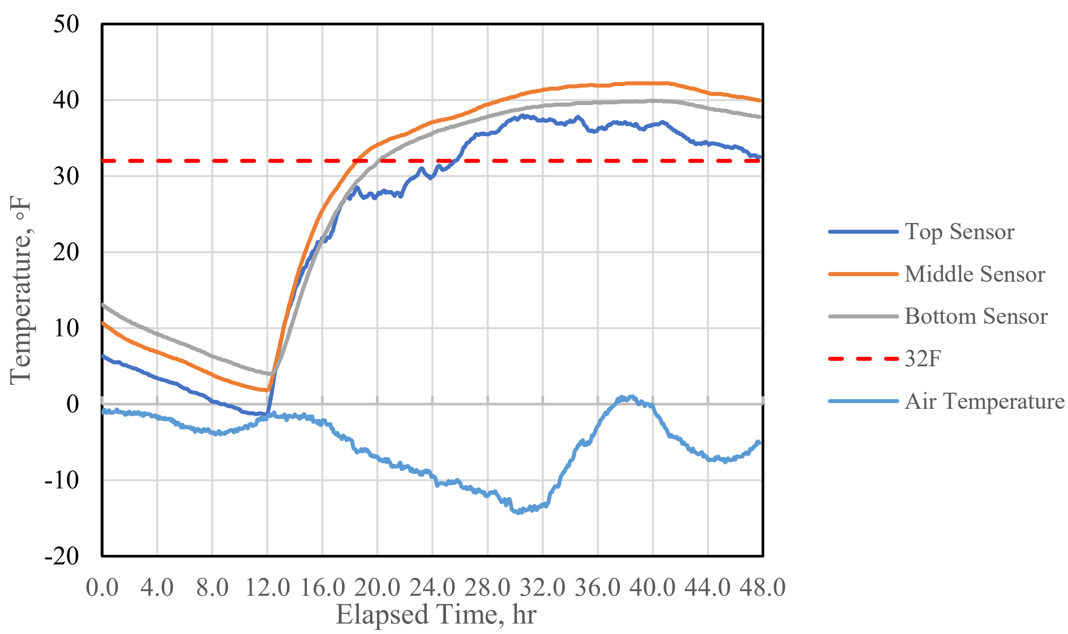


Figure 4.5 Heated pavement panel with rebar (Slab-2)

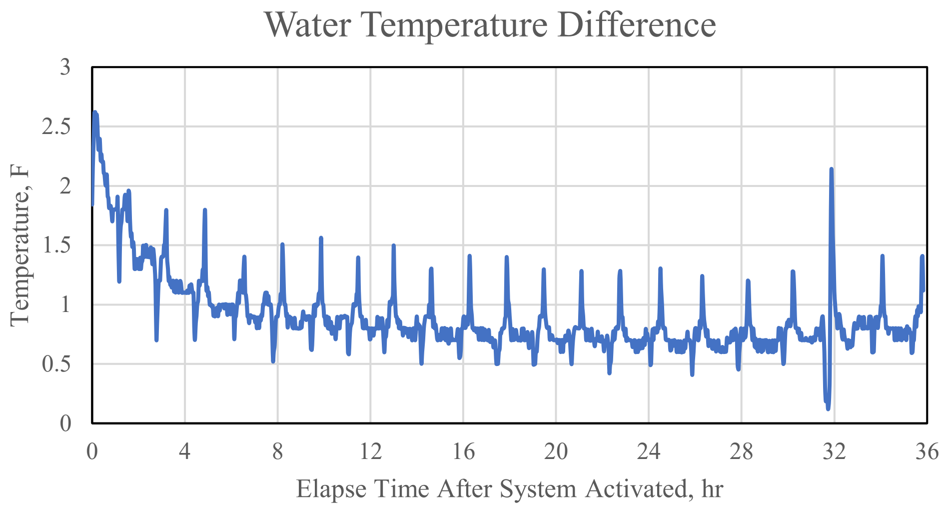


Figure 4.6 Water Temperature Difference after system activation from two slabs (refer to Figure 3.2)

Chapter 5 Numerical Simulations

5.1 Parametric Study and Principles of Snow Melting

5.1.1 Modeling of Heat Equilibrium for Hydronic Heating Pavement

Hydronic Heating Pavement (HHP) involves two heat-transfer mechanisms: heat diffusion in the pavement slab and the mass and heat transfer between the slab surface and the environment (Liu 1998). The principles of the snow-melting process are based on raising the level of heat that is needed to melt snow on a pavement surface to 32°F (0°C) or above. The two primary heating mechanisms for a hydronic pavement system are heat transfer and ambient factors (Chiasson and Spitler 2000). The Chapman and Katunich equation (1956) has been widely used to estimate the heat requirements for melting snow based on climatic conditions. Most similar snow-melting designs that have been proposed consider steady-state conditions. Given ambient variables such as snowfall rate, ambient air temperature, and wind speed for weather data compiled over several years, this data can be used to estimate the amount of heat that is needed to melt snow. Also, the snowfall rate and layout (arrangement) of the embedded pipes in the concrete are significant factors for the heat requirement calculations. The intensity of the snowfall typically is based either on the average or upper level of the intensity during a snowfall event.

The Chapman and Katunich equation (1956) assumes a steady-state condition and is used to compute the amount of heat that is needed per square foot to melt snow. The Chapman and Katunich equation can be expressed mathematically as shown in Equation 5.1:

$$q_o = q_s + q_m + A_r*(q_h + q_e) \tag{5.1}$$

where q_o is the total heat flux per unit area of the surface, Btu/h·ft^2 (W/m^2); q_s is the total sensible heat flux to bring snow to a melting point, Btu/h·ft^2 (W/m^2); q_m is the melting load, Btu/h·ft^2 (W/m^2); A_r is the ratio of the snow-free area to the total area (i.e., the snow-free area ratio); q_h is the sum of the convection and radiation losses, Btu/h·ft^2 (W/m^2); and q_e is the evaporative loss, Btu/h·ft^2 (W/m^2).

In order to use the Chapman and Katunich equation to estimate the heat needed to melt snow, a few assumptions must be made concerning precipitation, area ratio, etc. Nonetheless, even though the equation may involve assumptions and may have some limitations, it still provides a good estimation of the heat required for a snow-melting system. Details regarding use of the equation to estimate heat requirements can be found in papers by Lund (2000) and Liu (1998). In this study, the estimations of the required heat are based on the transient weather conditions and climatic conditions in four major cities in western North Dakota: Bismarck, Minot, Dickinson, and Williston. Details are provided in the following sections.

The heat transfer that takes place and is needed to melt snow can be expressed as Equations 5.2 through 5.6:

$$q_s = \rho s c\ (t_f - t_a) \tag{5.2}$$

where ρ is the density of the liquid water equivalent of snow, 62.4 lb/ft^3; s is the snowfall rate in cm of water equivalent; c is the specific heat of ice, 0.48 Btu/lb-°F; and t_f and t_a are the water film temperature and ambient temperature, respectively, °F.

$$q_m = \rho\ s\ h_f \tag{5.3}$$

where ρ is the density of liquid water; s is the snowfall rate in cm or inches of water equivalent; and h_f is the heat of fusion, 141.87 Btu/lb.

$$q_e = (c_1 V + c_2)(P_{wv} - P_{av})\ h_{fg} \tag{5.4}$$

where c_1 is a constant of 49.36 s^2/ft^2; c_2 is a constant of 198.05 s/ft; V is wind speed, ft/s; P_{wv} is the partial pressure of water vapor in the saturated air film on the surface, 13.3 psf; P_{av} is the partial pressure of water vapor in ambient air, 12.91 psf; and h_{fg} is the heat of the vaporization of water (0.00097 Btu/lb).

$$q_h = c_3(c_1 V + c_2)(t_f - t_a) \tag{5.5}$$

where c_3 is a constant, 0.003168 BTU/(ft·hr·°F).

Of particular interest is the ratio of the snow-free area to the heated area. Snow has an insulating effect on the pavement, thereby reducing the amount of heat that is lost to convection. Although this model assumes that the snow cover remains constant, the snow cover would, of course, be changing throughout the snow-melting process.

Heat is required to melt snow and for evaporation (Zwarycz 2000). If the pavement surface is free of snow, the heat will be transferred from the surface to the atmosphere by convection and radiation. When the snow on the surface is being warmed, but before it has melted, the snow acts as insulation. Thus, the ratio of the snow-free area, A_f, to the total area, A_t, is defined as the snow-free area ratio, A_r. This ratio equation can be written as Equation 6 (Chapman and Katunich 1956, Ho and Dickson 2017):

$$A_r = \frac{A_f}{A_t} \tag{5.6}$$

where $A_r = 1$ represents that the snow is totally melted on the pavement surface, whereas $A_r = 0$ represents that the surface is completely covered with snow. In practical terms, the snow-free area ratio can reasonably be assumed to be a value between 0.5 and 1.0.

Q_o is the total heat requirement adjusted for 25% conductive heat loss at the bottom and edges of the boundaries of concrete pavement heat panels. The heat requirement for snow-melting for design purposes, Q_0, is mathematically expressed as Equation 7:

$$Q_0 = q_o \cdot (1.25) \tag{5.7}$$

5.1.2 Class of Snow-Melting Pavement

Three types of design and installation of hydronic snow-melting pavement are classified by Chapman (1957) according to different applicable infrastructure. The details are described below:

- Class I (minimum): residential walks or driveways, interplant ways or paths
- Class II (moderate): commercial sidewalks and driveways, steps of hospitals.
- Class III (maximum): toll plazas of highways and bridges, aprons and loading areas of airports, hospital emergency entrances.

The ASHRAE Applications Handbook, published in 1995 and 2003, suggests the design output data for each of the three classes for selected cities in the United States. The examples of the heat outputs of the four cities are converted to SI units and listed in Table 5.1.

Table 5.1. Design outputs of heat for four selected cities

City	Design Output (Btu/hr/ft^2)		
	Class I	Class II	Class III
New York City	121.03	298.04	342.04
Chicago, IL	89.0	165.03	350.06
Reno, NV	98.02	164.01	155.01
Portland, OR	86	98	111

5.2 Numerical Analysis

This research focuses on assessing the effectiveness of hydronic pavement heating using geothermal hot water. This study considered the time-dependent heating process of piped pavements, the final temperatures of heated pavements, the final temperature drops of the hot water in the embedded pipes, and the required flow rates of the water circulating through the pipes. The feasibility of hydronic pavement heating using DDU geothermal hot water is addressed through the numerical modeling of the pavement heating process using the finite element technique.

Numerical analyses were conducted to study the heat transfer mechanisms and time-dependent heating process for the proposed hydronic snow-melting system. COMSOL Multiphysics software using the finite element method was employed to carry out the computations. In this snow-melting system, the heat is transferred from circulating hot water in embedded pipes to the concrete and from the concrete to the pavement surface. Thus, two built-in laws of physics, non-isothermal pipe flow (nipfl) and heat transfer in solids (ht), were used to study the heat transfer that occurs in these two "Physics". When water circulates through pipes embedded in concrete, the temperature of the flowing water decreases due to the cold environment in which the pavement will be heated. Thus, the analysis focused on the final temperature reduction of the hot water between the inlets and outlets and the temperature of the heated pavement panels. Although heat transfer is time-dependent, stationary results were examined to assess the effectiveness and feasibility of this hydronic snow-melting technique. This study controlled several influential factors, such as heat requirement, air temperature, inlet temperature of water, and volumetric flow rate, to examine the effectiveness of the proposed snow-melting system. The assessment of the hydronic snow-melting system is based on the finite element analysis results regarding the heated pavement temperatures and outlet temperatures of the water after circulating through the pavement panel.

The finite element analysis for the HHP is to simulate the actual panel size and pipe layout. Fig. 5.1 shows the pipe layout for the pavement panels design and Fig. 5.2 shows the model established using COMSOL. The numerical analysis is verified with the collected data. The validated results of numerical analysis can be used for future designs of HHP.

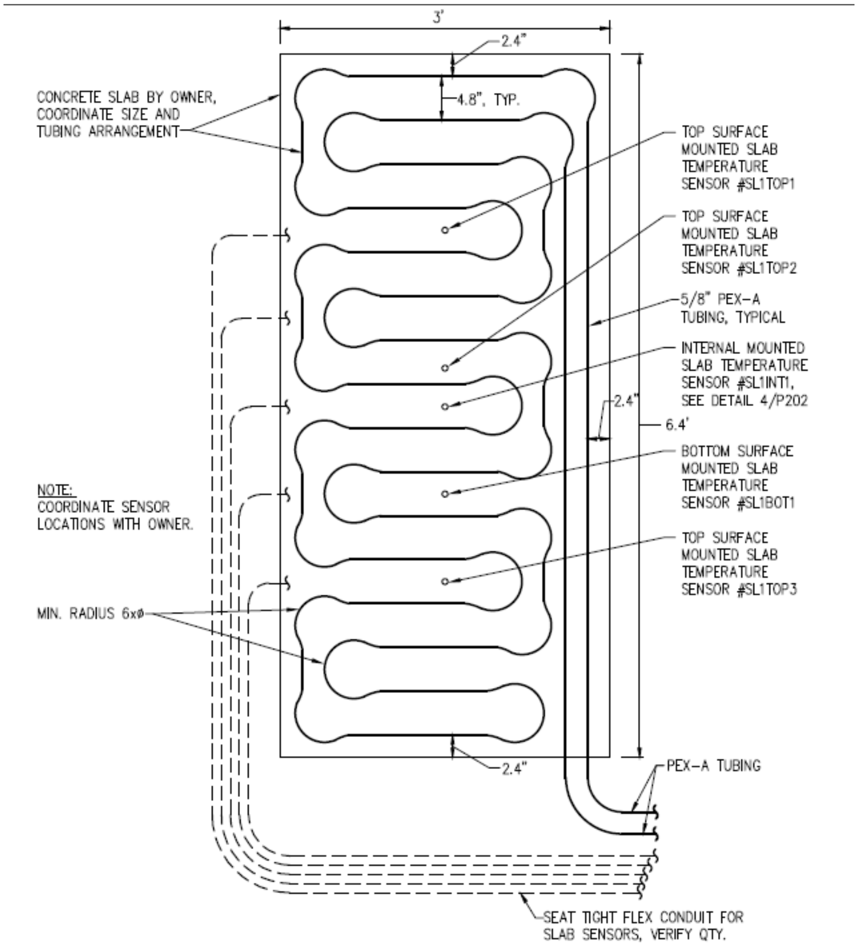


Fig. 5.1 Pipe layout for hydronic heating pavement in design

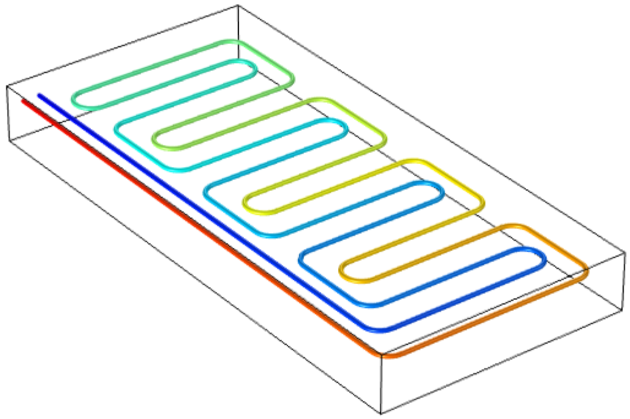


Fig. 5.2 Model establishment in COMSOL Multiphysic Software

To model a hydronic snow-melting system using COMSOL, the properties of the three materials, i.e., concrete, pipe, and water, need to be well defined. Because the numerical analysis focused on the heat transfer mechanisms, the thermal properties of the materials needed to be included as well as their mechanical properties. For the concrete, heavyweight concrete with a unit weight of 143.58 lb/ft^3 and thermal conductivity of 0.94 Btu/(h-ft-°F) was assumed. For the pipe, typical PEX plastic pipes were modeled and the diameter is 5/8 inch. For the water, the density and thermal conductivity were assumed to be 62.4 lb/ft^3 and 0.347 Btu/(h-ft-°F), respectively. The volumetric flow rate was defined according to actual model tests for the water in the embedded pipes.

The flowrate circulate in the embedded pipes was stabilized at 3.5 gpm and the diameter of the PEX pipes is 5/8”. The results of the finite element analysis were assessed based on the surface temperatures of the heated pavement panel and the outlet temperatures of the water that circulates through the pipes. The lowest temperature of the circulating water is found at the outlet. After conducting a series of finite element analyses for hydronic pavement heating, the results indicate that the heat requirements for heating pavement can be satisfied using these temperatures of water (i.e., 65°F to 95°F). Hot water at 65°F is found to be able to effectively melt snow under most weather conditions in western North Dakota, whereas water below 55°F may have some limitations in melting snow under extremely low air temperatures. Nonetheless, the results show that the outlet temperatures of the water only reduces 0.8°F to 1 °F. The outlet temperatures are still high and can be used in another panel if water temperatures at 65°F or higher are used. Previously, the circulating flow rate of water between 3.17 gpm (0.2 l/s) and 15.85 gpm (1 l/s) is able to respond to most weather conditions from finite element analysis. However, the flow rate at or below 3.17 gpm may not work efficiently for low air temperatures (-4°F or lower) and will result in a higher temperature difference in the same pavement panel. The analysis focused on the flowrate similar to the actual models that is between 3.5 and 4.0 gpm. The results are presented in the following sections.

The finite element analysis is used to calibrate the collection of data. The analysis focused on investigating the inlet temperature water, water temperature difference between inlet and outlet of embedded pipes, and top surface pavement heating. The heating process is time-dependent.

1. Inlet temperature of water
   The inlet temperature can be controlled. Although the higher temperatures of inlet water (up to 95°F) were investigated. However, the effectiveness of heated panel was mainly focused on lower temperature water which is able to heat the concrete panel in winter. Thus, the inlet water in the numerical analysis is stabilized at 65°F
2. Surface Temperature
   Compared the top surface temperatures of two panels, the two top surface temperatures are very close. However, the slab-2 containing rebars is found to have slightly higher temperatures compared to slab-2 without rebars. The data make good agreements with numerical analysis results (see Fig. 5.3). Fig. 5.4 shows the three-dimensional model of heating process at the 4^{th} hour after the system is activated.
3. Temperature different between inlet and outlet water
   The temperature difference determines the heat needed for snow-melting or de-icing. The temperature difference was found between 0.8 °F and 1.3 °F depending on the air temperature. The results shown in Fig. 5.5 make good agreement with the collected data. Although the temperature shown in the numerical analysis is slightly higher. This is because the air temperature in the finite element analysis is stable at -13 °F, however, the actual air temperature fluctuated. Thus, it is reasonable to have the heated surface temperatures slightly lower compared to the collected data.

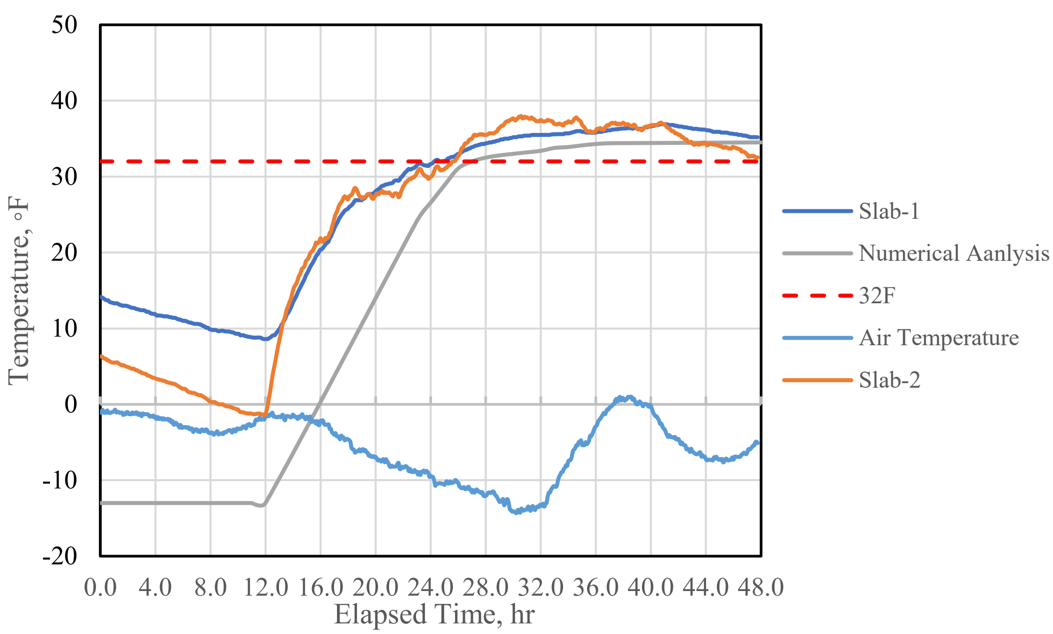


Fig. 5.3 Top surface temperature of heated panel, inlet water temperature = 65◦F, flowrate = 3.5 gpm (slab-1: no rebar panel, and Slab -2: panel containing rebar)

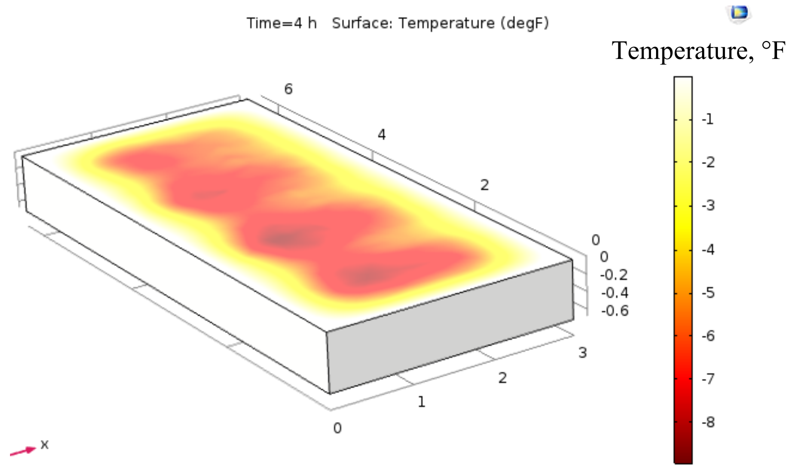


Figure 5.4 Time-dependent heating process of heated concrete panel (t=4h after the system is activated)

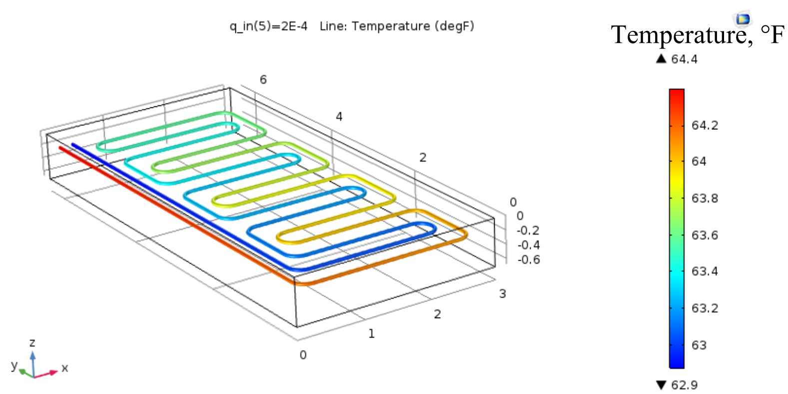


Figure 5.5 Three-dimensional pipe model with temperature of circulating water in numerical analysis

Chapter 6 Feasibility and Economic Analysis

6.1 Heat Resource

In North Dakota, the geothermal energy has been widely studied as the heat source for the hydronic snow-melting system used in heating bridge decks and pavements in recent years. Although the geothermal energy is abundant in western North Dakota, however, the application is still limited. The energy piles are used to harvest the shallow geothermal energy to warm up the fluids for the hydronic system through a heat exchanger. In the United States, the oldest geothermal pavement snow-melting system was installed in Klamath Falls, Oregon, in 1948 by the Oregon Highway Department (Lund 1999). Typically, the heat supplies at the original artesian flow of 20 gpm (1.26 L/s) are 3.5×10^5 Btu/hr (102585 watts) and 9.0×10^5 Btu/hr (263790 watts) at the pumped rate of 50 gpm (3.15 L/s). The latter energy supply rate can melt snow efficiently when the air temperature is −10°F (−23°C) with a snowfall up to 3 inches per hour. According to previous studies (Ho and Dickson 2016, 2017), the temperature in North Dakota in winter is extremely low; therefore, using the energy piles and GSHP to harvest the shallow geothermal may not be practical and may be less efficient. However, the deep geothermal hot water, which has higher temperatures, can supply the needed heat for HHP subjected to low temperatures and an intense snowfall rate.

6.1.1 Profile of Geothermal Hot Water

Several geothermal aquifers have been identified in western North Dakota that can produce abundant, quality, and high-economic hot water at temperatures for power generation or direct use. Importantly, the aquifers can be accessed easily under two scenarios: via coproduction wells used by the petroleum industry or by repurposing abandoned oil wells. Therefore, in western North Dakota, geothermal hot water conceptually can be applied to hydronic systems for melting snow. Generally speaking, these known hot-water reservoirs in western North Dakota are located 2,300 to 11,500 ft below the ground surface (Gosnold et al. 2015). The temperature of the hot water can be as high as 130°C. Bismarck, Minot, Williston, and Dickinson, are located over these geothermal aquifers and each has high heat demands in winter. The water temperature in the aquifers near Dickinson is 266 °F at the depth of about 11,500 feet. Near Minot, the aquifer temperatures are 104 °F at 2300 ft and 140 °F at 4265 feet. Near Bismarck, the aquifer temperatures are about 104 °F at 2600 ft and 140 °F at 4265 feet. The aquifers near Dickinson contain geothermal hot water at higher temperatures (178 °F to 279 °F) than the Minot and Bismarck aquifers.

Currently, the main applications of geothermal hot water are focused on power generation. However, the demand for using geothermal hot water to melt snow is massive in North Dakota. According to Lund (2000), the construction cost of 22,000 ft^2 of pavement that covers a heated bridge deck and the design for heat output of 50 $Btu/ft^2/hr$, which is equivalent to 538 W/m^2, is $430,000. The estimated annual maintenance cost is $500 and the operational cost is $3000 for a circulating pump. The implication of this estimation indicates that the direct-use geothermal hot water is more economical when compared to other heat sources.

In North Dakota, the extreme continental climate of the north-central United States leads to high demands for heating year round. The mean annual temperature in western and central North

Dakota is 39.7 °F, and temperatures in the winter (December–March) average 9.7 °F. Although the winter heat demands are high, geothermal hot water has not been widely applied to transportation infrastructure, despite the fact that the existence of geothermal aquifers and the good-quality water that contains low total dissolved solids (TDS) are well documented.

Currently, two scenarios of geothermal hot-water production have been demonstrated in North Dakota: coproduced water (Scenario 1, see Fig. 1) and deep direct-use (DDU) (Scenario 2, see Figure 6.1) (Ho et al. 2019). These two water wells are able to supply a combined flow of 875 gpm (55.2 L/s) at 208 °F. Fig. 6.2 shows the drilling profile to secure hot water in a reservoir. The drilling costs of these two horizontal wells are about $2,000,000 each according to Gosnold et al. (2015). Considering a 4% of inflation, the current price is estimated to be 2,600,000. The produced water temperature was 217.4 °F at the wellhead and 208.4 °F at the inlets to the power plant; the wellhead and inlets were approximately 1300 ft apart. The water was transported through uninsulated pipes buried below the frost line (Gosnold et al. 2016). Hence, capturing the heat that is contained in the large volumes of fluids produced from oil and gas operations has been a promising concept for geothermal development for the past decade (Swift and Erdlac 2004, McKenna et al. 2005, Blackwell 2006, Johnson and Schochet 2007, Augustine and Falkenstern 2012, Gosnold et al. 2015).

The third scenario of geothermal hot water production and use, therefore, involves the cascading use of geothermal hot water, which has drawn much attention recently. The 208 °F (98 °C of water after being used for power generation returns (refer to UND-CLR Binary Geothermal Power Plant) at temperatures between 140 °F (60 °C) and 158°F (70 °C), whereas this temperature of water is more suitable for heating purposes.

Theoretically, through the available geothermal aquifers in western North Dakota and a feasible drilling technique, coproduced water from oil and gas operations or newly drilled wells can be applied to HHP systems as the heat sources. Because of improvements in drilling techniques for the oil and gas industry in western North Dakota, accessing and using geothermal hot water is more feasible and cost-saving compared to decades ago.

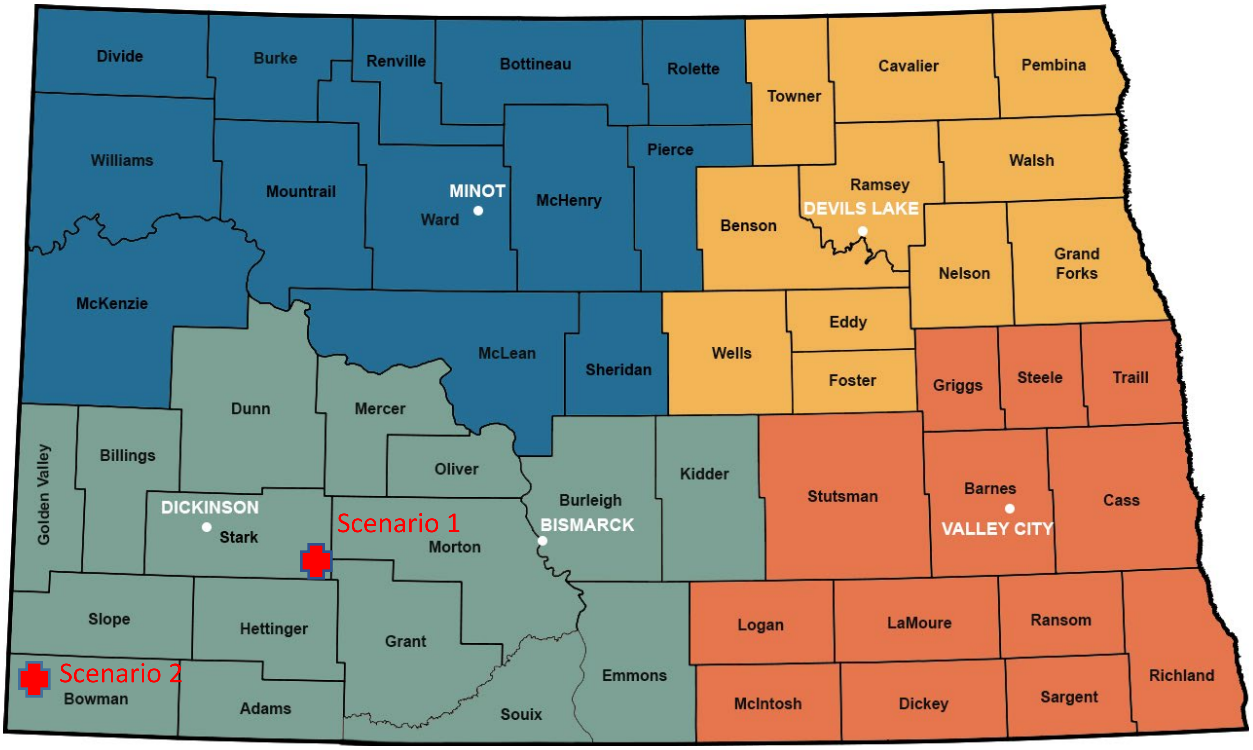


Figure 6.1 Locations of the University of North Dakota geothermal demonstration projects (modified from Gosnold et al. 2015).

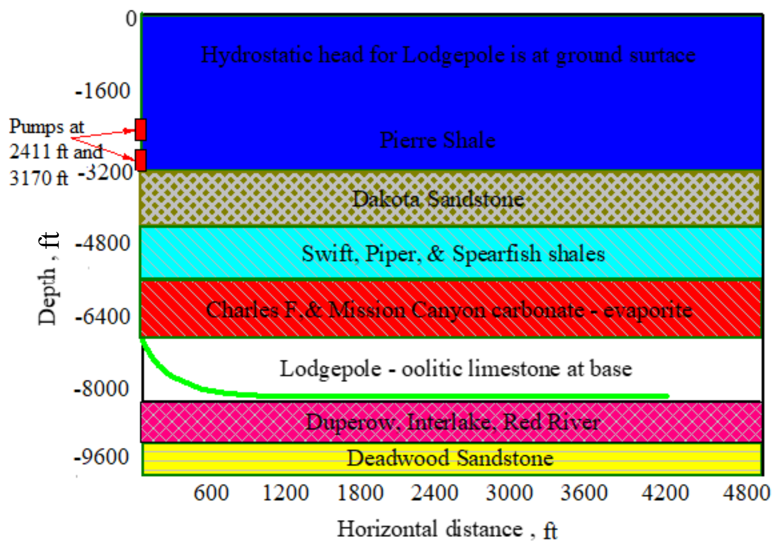


Figure 6.2 Cross section of horizontal well drilling in Lodgepole Formation (modified from Gosnold et al. 2015)

The temperatures of water studied is between 65 to 95 °F, However, the feasible temperature 150 °F which considers the exit water from geothermal power plant and the feasibility of drilling new wells. Although the water temperature at the exit of the heated panel is the same, the final temperature of heated pavement is slightly different.

Influencing factors that control the efficiency of the HHP were investigated. Considering the available temperature of water which can be accessed in the existing aquifers and the temperature of water returns after power generation, geothermal water at temperature = 150°F is available in all four studied locations. Meanwhile, the cost of drilling new wells and the feasible technique indicates the water temperature = 150°F or higher in the Williston Basin can be obtained. Thus, regardless of accessible scenarios of hot water in western North Dakota, the available temperature range of water between 65°F to 95°F is reasonable.

The pipes embedded in the HHP can heat the pavement surface to an ultimate temperature after about 4 to 8 hours of activation with a constant volumetric flow rate. However, to use water with higher temperature can shorten the heated time, the pavement can be heated to above 0°C in the second hour even under the lowest air temperature assumed in this study (e.g., 0°F) of water temperature = 95 °F is used. The HHP system can also prevent snow or ice from forming in extremely low temperature and severe weather conditions.

In addition, a lower volumetric rate can improve the utilization of thermal energy for hot water (e.g., 3gpm). The final temperature of pavement surface is found to be closer to the outlet temperature of water if a lower volumetric rate is used. Meanwhile, a lower flow rate used in the HHP can increase the total applicable area using the same temperature of water at outlet (e.g., 65°F). Using a higher flow rate (e.g., 7.9 gpm or 15.85 gpm) will result in small temperature drops of water between inlet and outlet. Therefore, the returned temperature can be used to heat the subsequent areas.

Although the direct use of geothermal hot water for the HHP is not a new technique, this method has not been widely used in the United States. The geologic formations, climatic conditions, and petroleum industry enable western North Dakota to directly utilize geothermal hot water based on the three scenarios described in this study. This technique directly applies the high temperature of geothermal hot water stored in accessible aquifers to the HHP. The efficiency of the HHP depends on a few influential factors besides available temperature of water. The lower volumetric flow rate, 4.0 gpm is recommended for using in the HHP and is able to heat the pavement surface efficiently if inlet water temperature = 65ºF. Assuming water temperature drops 1 ºF for a 3ft by 6.4 ft of concrete panel, considering the current scenario of pumping hot water (875 gpm and 150 ºF), the total applicable area can be up to 361,200 ft^2. In addition, using higher thermal conductivity of concrete is favorable to pavement heating and optimizes using circulating hot water in the embedded pipe. To enhance the HHP, using higher conductivity of concrete needs to be considered.

Chapter 7 Summary and Recommendations

The HHP containing heat pipe is a sustainable and effective alternative to melt snow and ice. The shallow geothermal heat to warm the fluids that circulate through the pipes has been widely used according to previous studies. In western North Dakota, due to the geologic formations, severe climatic conditions in winter, and the petroleum industry make the direct-use of geothermal hot water feasible according to the previous project at UND. The higher temperature of geothermal hot water can be explored and secured. Several influential factors including available water temperature should be investigated. Based on the feasibility and economic analysis, the hydronically heated pavement (HHP) is recommended to melt snow or de-ice for bridge decks and sidewalks. More influential factors which govern the effectiveness of the HHP still need to be optimized to improve the snow-melting performance. Some relevant influential factors include the embedded pipe patterns, embedment depth, volumetric flow rate, thermal conductivity of concrete need to be further studied before the HHP can be used more efficiently. Based on the results of this research, several conclusions and recommendations can be made accordingly:

1. In the HHP, several influential factors, including inlet water temperature, volumetric flow rate, and air temperature, were examined with regard to hydronic pavement heating. The time-dependent heating process is significantly related to these influential factors. An optimal design for a hydronic snow-melting pavement thus needs to consider these variables carefully.
2. Considering the flow rate = 4 gpm and feasible flow rate of DDU hot water, the applicable area for snow-melting can be up to 361,200 ft^2 for the current scenario.
3. All the volumetric flow rates used for the analysis can be used to heat pavement to the desired temperatures to melt snow in western North Dakota. Suitable volumetric flow rate can be used subjected to different heat requirements (air temperature) for snow-melting.
4. Based on the required temperature of geothermal hot water, the depth of the aquifers, the necessary circulating flow rates, and heat requirements, the three scenarios for the DDU of geothermal hot water (i.e., cascading use, newly-drilled wells, and co-production water from the oil industry) are all conceptually feasible.
5. According to the statistical weather conditions, the computed heat requirement for snow melting or deicing in western North Dakota is below 95.1 Btu/ft^2/hr for most conditions. The results show that the pavement still can be heated to temperatures above 32°F even when the required heat increases to 158.5 Btu/ft^2/hr. This result implies that the HHP can handle most weather conditions and snowfall events in western North Dakota in winter.
6. The thermal conductivity of concrete significantly influences the heat transfer between the embedded pipes and the concrete surfaces. The higher thermal conductivity can minimize the temperature difference between the ultimate surface temperature of pavement and water temperature at outlet.
7. High thermal conductivity is favorable to pavement heating and optimizes using circulating hot water in the embedded pipe. To enhance the HHP, using higher conductivity of concrete needs to be considered in the design if possible.

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