PAVEMENT TEMPERATURE RESPONSE TO COLD FRONTS: A MODEL COLUMN STUDY IN A FREEZER BOX

BY

TARYN DILORENZO

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ABSTRACT

Pavement Temperature Response to Cold Fronts:

A Model Column Study in a Freezer Box

Taryn DiLorenzo

The University of Texas at Arlington

Supervising Professor: Dr. Xinbao Yu

The correlation of meteorological data and pavement conditions is crucial for winter pavement maintenance, this is the main reason that it is so important to understand in what ways pavement responds to cold fronts as well as when the formation of ice on a pavement surface can be expected. The pavement surface and its underlying subsurface layers combine to create a system with the behavior of the surface being influenced by both the air temperature above it, as well as the temperature and thermodynamic processes occurring in the sublayers below it. Both the pavement surface as well as the sublayers are influenced by precipitation as well, although the influence from precipitation is more readily apparent on the surface. This thesis presents a

specially designed model column, consisting of soil and a concrete slab, tested in a freezer box to investigate the pavement response to cold fronts.

Soil samples were collected from a site at Dallas Fort Worth International Airport (DFW). These samples were tested according to ASTM standards and classified using the United Soil Classification System. The samples were then compacted in the specially designed soil box, with thermistors and moisture sensors placed throughout the lifts of soil. A concrete slab was then placed on top of the soil with thermistors installed at different depths within the interior of the slab as well as thermocouples on the surface. The system was then moved into a freezer box where it was wrapped with R30 insulation and tested using several different weather scenarios, designed with historical data provided by DFW.

The sensors installed in the system recorded temperature changes, while instrumentation in the freezer box itself recorded the ambient temperature and the relative humidity in the freezer box. From the results of the various testing scenarios, it can be observed that there is a significant time difference between the rate of change in ambient freezer temperature and the slab response, this difference becomes even more prominent when observing the temperature trends of the soil. This difference can be attributed to the thermal capacity of both the soil and the concrete slab, with the thermal capacity of the soil having the most influence on how the slab behaves when exposed to variations in temperature.

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CHAPTER I

INTRODUCTION

1.1 Overview

The correlation of meteorological data and pavement conditions is crucial for winter pavement maintenance. This is one of the reasons for the importance of understanding in what ways pavement responds to cold fronts and when the formation of icing can be expected. Ambient temperature, relative humidity, wind speed, dew point, precipitation, both duration and intensity, as well as pavement temperature contribute to the potentiality of adverse driving conditions during cold weather (Qiu Xin, 2018). The ability to predict pavement temperature response is applicable in many fields including pavement design, the analysis of urban heat island effect as well as in the research and development of pavement materials.

Pavement temperature is governed by heat transfer theory. The thermal properties of the surface and the subsurface layers play a role in the pavement's response to temperature fluctuations, with the subsurface being the most important factor for determining the response. The main thermal properties that are influential here are: thermal conductivity, heat capacity, thermal diffusivity, and latent heat of fusion.

In this study a model column was designed, built, and installed into a freezer box to observe the response of both the pavement and the subsurface soil to simulated cold fronts of varying duration and intensity. The use of a misting system simulated precipitation events in an effort to record the conditions required for the potential of ice formation. Sensors were installed in the soil to record temperature and moisture. Sensors in the pavement slab recorded the temperature throughout its body as well as on the surface. Sensors to record the ambient temperature and relative humidity in the freezer box environment were used as well. This study provides detailed results of the factors influencing the response of pavement to cold fronts.

1.2 Objective

The objective of this research is to investigate the response of pavement to cold fronts and to explore the phenomena of icing on pavement under controlled weather scenarios. This is achieved by exposing a specially built model column system to 12 different testing scenarios designed to reproduce field conditions obtained from past cold weather events.

1.3 Problem Statement

Pavement and its immediate environment combine to form a microclimate system where the pavement temperature field is influenced by environmental factors, such as air temperature and wind speed (Chen, Wang, & Xie, 2019). Subsurface factors such as the thermal properties of the underlying soils also exert an influence. Although the ambient temperature effects the surface temperature, the surface temperature influences the ambient temperature of the air closest to it. This creates the need to understand not only the individual components of the system but also to understand how they each contribute to the system as a whole and how the system, specifically the pavement, responds to cold fronts. There is a lack of experimental studies performed under controlled environments examining the pavement surface temperature and icing that considers both meteorological factors as well as soil temperature. The winter maintenance of pavement is critical for the transportation of both people and goods. To maintain pavement efficiently, knowledge of how certain factors influence the response of the pavement is crucial.

1.4 Thesis Structure

This thesis is structured in the following manner.

Chapter 2 presents a description of heat transfer theory, meteorological factors related to winter weather events, the conditions required for the formation of ice based on previous studies, and an overview on the factors contributing to the influence of the subsurface on the pavement above.

Chapter 3 details the design and building of the model column used to contain the soil samples and the concrete slab. Included here are the dimensions of the column, location and types of sensors used in the study, as well as details of soil testing and classification. This chapter includes a description of the tests performed.

Chapter 4 presents the results of the tests performed where meaningful results were obtained and a discussion on the results. A description of the remaining tests are included in the Appendix.

Chapter 5 summarizes the research presented in this thesis and provides recommendations for the improvement of future experiments.

A list of references of any cited research is provided at the end of each chapter.

1.5 References

Chen, J., Wang, H., & Xie, P. (2019). Pavement Temperature Prediction: Theoretical Models and Critical Affecting Factors. *Applied Thermal Engineering, 158*.

Qiu Xin, X. J.-x.-q. (2018). *Journal of Highway and Transportation Research and Development*, 1-9.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

This chapter provides a summary of some contributing factors of pavement weather, including a brief overview of heat transfer theory, contributing meteorological factors, and a description of the pavement soil interaction. The main objective of this chapter is to detail how the weather, pavement surface, and the subsurface come together to form a dynamic system.

2.2 Heat Transfer in Pavement and at the Pavement-Air Interface

Energy in the form of heat is transferred by a system interacting with its surroundings. Heat transfer occurs whenever there is a temperature difference between two media hence, heat transfer requires thermodynamic nonequilibrium. The main modes of heat transfer are conduction, convection, and radiation.

Conduction is associated with heat transfer through molecular activity. Energy is transferred from the more active molecules to the less active molecules in a medium. It is important to note that this transfer takes place through direct contact between the molecules. Higher temperatures are associated with a greater degree of molecular activity. When there is a temperature gradient present, the energy is transferred from warmer regions to cooler regions (Incropera, DeWitt, Bergman, & Lavine, 2007). Conduction generally occurs in solids and liquids where the molecules are more closely oriented such as the exchange of energy between a pavement surface and its subsurface. Heat conduction can be expressed as heat flux or the rate of heat transfer per unit area, using Fourier's Law:

$$q_x^{"} = -k\frac{dT}{dx} \quad (2.1)$$

where $q_x^{"}$ is the heat transfer rate per unit area in the x direction perpendicular to the energy transfer in W/m^2, $\frac{dT}{dx}$ is the temperature gradient, and k is the thermal conductivity of the medium. It should be noted that the thermal conductivity is negative, indicating that the transfer is to the decreasing temperature regime (Incropera, DeWitt, Bergman, & Lavine, 2007).

Convection is defined as heat transfer that occurs through the movement of liquid or vapor molecules and a boundary when there is a difference in temperature. Latent heat exchange is a form of convection heat transfer associated with a phase change between liquid and vapor, such as the formation of condensation. Convection is quantified using the following equation:

$$q_x^{"} = h(T_s - T_\infty) \quad (2.2)$$

where $q_x^{"}$ is the convection heat flux in W/m^2, h is the convection transfer coefficient, T_s is the surface temperature in Kelvin and T_∞ is the fluid temperature in Kelvin (Incropera, DeWitt, Bergman, & Lavine, 2007).

Radiation is another mode of heat transfer. Unlike conduction and convection, the heat energy is emitted by electromagnetic waves, negating the need for any contact between the material media such as energy radiating off a pavement surface. Radiation can occur between all forms: solid, liquid, and gas. The equation that quantifies radiation is:

$$q_{rad} = \varepsilon\sigma(T_s^4 - T_{sur}^4) \quad (2.3)$$

where q_{rad} is the radiation heat flux in W/m^2, ε is emissivity between 0 and 1, σ is the Stefan-Boltzmann constant which is equal to $5.67 * 10^{-8}\ \frac{W}{m^2} * K^4$, T_s is the temperature of the surface in Kelvin and T_{sur} is the temperature of the surroundings in Kelvin (Incropera, DeWitt, Bergman, & Lavine, 2007).

2.3 Meteorological Factors

Pavement surface conditions are critical to understanding, predicting, and maintaining surfaces during winter events. Reliable information on future surface conditions are predicted using weather information provided by meteorological services as well as future surface temperature predictions (Nuijten, 2016).

Moisture can take all three physical forms when discussing the weather. Moisture can be considered a gas when in the form of condensation. Liquid in the form of rain and a solid in the form of ice and snow. All these forms of precipitation can influence the response of a surface based on the intensity, duration, and temperature (Tarleton, 2006). Cold precipitation that falls for a long period of time with a medium intensity will rapidly cool the surface to the point that it will not be able to maintain its current temperature and will lose heat in an attempt to reach equilibrium, increasing the potential for ice formation.

Relative humidity is the amount of water vapor that is in the air compared to how much of the vapor the air can hold at a particular temperature. Relative humidity is dependent on the temperature of the air: warm air can hold a greater amount of water vapor compared to cool air. Dew point is defined as the temperature that the air needs to be cooled to for complete saturation, the dew point is a function of both relative humidity and the air temperature. Relative humidity and dew point are commonly used to describe the amount of moisture in the air (Lawrence, 2005). When the air temperature reaches the dew point temperature, the air cannot hold its moisture any longer and releases it in the form of condensation. This condition is directly related to surface conditions. If a surface is at or below the freezing point, the condensation will be in the form of frost, this is typical in the formation of black ice.

For relative humidity greater than 50%, Lawrence (2005) finds that the dew point temperature will decrease approximately 1°C for every 5% decrease in the relative humidity. Lawrence’s (2005) simplified equation is used to calculate the dew point for this project:

$$t_d \approx t - \left(\frac{100-RH}{5}\right) \quad (2.4)$$

where t_d is the dew point temperature in degrees Celsius, RH is the relative humidity in percent, and t is the ambient temperature in degrees Celsius. This equation is valid for relative humidity greater than 50%, in this range the relationship between the relative humidity and the dew point temperature becomes close to linear. This equation is accurate to 1°C or 5% relative humidity for temperatures 0° to 30°C and relative humidity readings between 50% to 100% (Lawrence, 2005). The relative humidity in the freezer box did not drop below 50% at any time during the testing, validating the use of this equation.

Ice can form when precipitation in the form of freezing rain, drizzle, or fog fall onto a surface that is at or below freezing conditions. There are two primary scenarios for the formation of ice to occur. The first scenario involves precipitation that is close to 32°F falling through cool air onto a surface that is at or below freezing. The second scenario occurs when supercooled precipitation falls onto a surface that is close to freezing. In both scenarios the latent heat from the droplets plays a critical role (Jumikis, 1959). One gram of water releases 80 gram-calories of latent heat during the process of freezing. When the water droplet strikes a surface, either pavement or soil that is below freezing, the latent heat released by the droplet warms the surface until both the droplet and the surface have reached equilibrium. Once this occurs, whether the droplet solidifies or not depends on the surface being sufficiently cold to continue the freezing process when the droplet lands. Given these factors, it should be noted that the formation of ice is not an immediate process. The dissipation of the latent heat from the droplet to its surroundings takes time (Jumikis, 1959).

2.4 Pavement Soil Interaction

The factors associated with surface temperature variation are surface radiation, convection, evaporation, condensation, and the heat flow of the soil (in or out). For pavements and soil, conduction is the primary method of heat transfer with radiation and convection contributing to the pavement surface and shallow subsurface layers. Surface radiation is the summation of the heat fluxes that are involved at the ground surface (Fig 1). Using the heat balance approach developed by Scott (1964), the summation of the contributing fluxes at the surface must be equal to zero for equilibrium to be achieved. Heat directed to the surface is positive, while heat flow directed away from the surface is negative (Fig 1). Convection involving the heat flow exchanged between the air and the ground is dependent on the air temperature, wind speed, and turbulence (Andersland & Ladanyi, 2004). It is interesting to note that the air located within 5 inches of the surface has the most influence on the surface response, as opposed to the surrounding air. While the closer air influences the surface, the surface also exerts an influence over the air and by extension, the subsurface influences both. The heat flux within the soil plays an influential role in the pavement temperature as it is the flow path that combines the energy balance at the surface with that of the soil (Sauer & Horton , 2005). Water flowing in the soil through the action of evaporation and condensation, both of which involve latent heat, will also contribute to the energy balance.

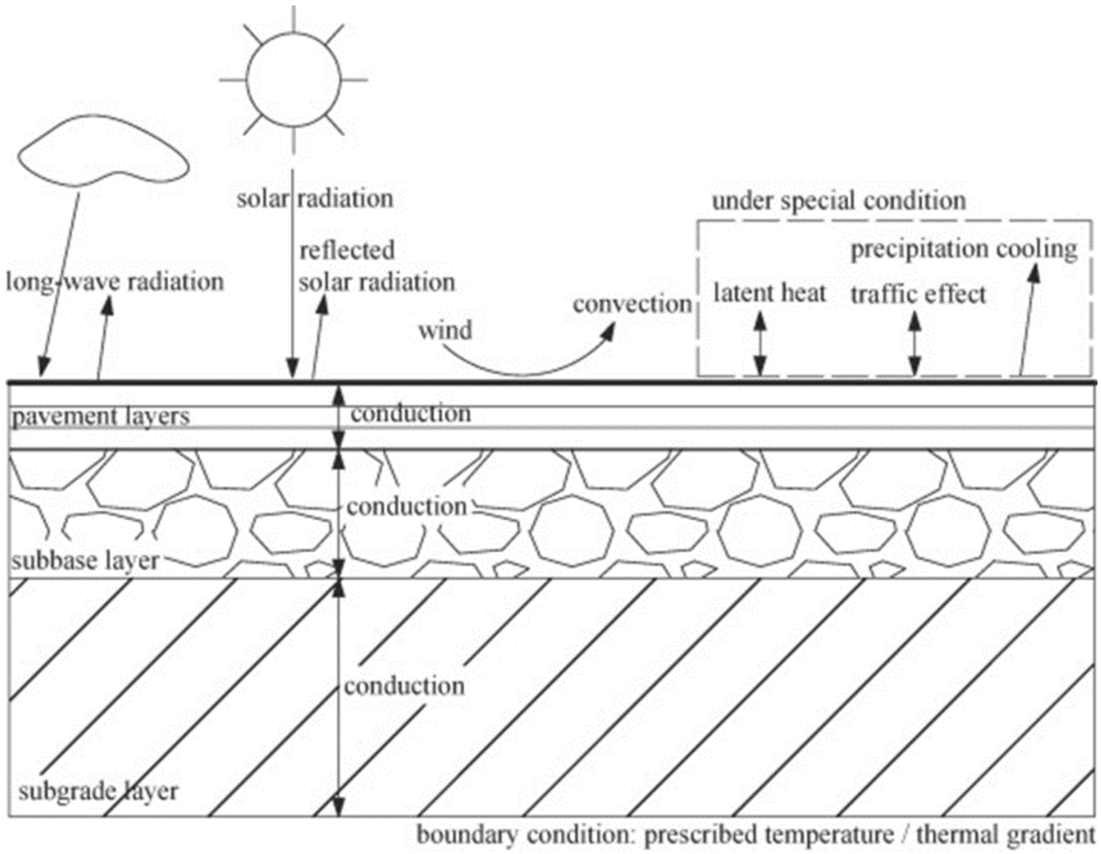

Figure 1. Heat transfer between the pavement and its environment (Source: Chen et al, 2019)

The thermal properties that influence the pavement and soil layers are thermal conductivity, heat capacity, and thermal diffusivity (Chen, Wang, & Xie, 2019). In this section, we will focus on the thermal properties as they relate to the soil. These thermal properties are a result of the relative properties and relations between the three soil phases: air, solids, and water. The conductivity of a material is based on its composition and is independent of temperature variation (Scott, 1964). Within soil, this variation can come from freeze and thaw cycles that can change the molecular composition of a soil, it can also vary within the same layer of soil (Andersland & Ladanyi, 2004).

Heat capacity is defined as the amount of heat required to raise the temperature of the soil by 1° Celsius. Heat capacity is calculated through the summation of all the heat capacities of each of the soil parts (Andersland & Ladanyi, 2004). Thermal diffusivity is the ratio of the thermal conductivity of the soil to that of its heat capacity. Diffusivity is a measurement of the soil's ability to conduct energy relative to its ability to store the energy (Chen, Wang, & Xie, 2019).

All these properties combine to dictate the soil's response to temperature change. Studies by Mann et al. (2003) found that in the Northern Hemisphere, ground surface temperature closely follows the air temperature only for the warm weather seasons. The soil retains this residual heat during the cooler months, slowing the freezing of the pavement surface during winter events. It has also been demonstrated that the temperature of the soil remains approximately constant at a depth of 9 to 15 meters below the ground surface, irrespective of the seasonal changes above (Andersland & Ladanyi, 2004). This illustrates the effectiveness of the thermal capacity of the subsurface.

2.5 References

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CHAPTER III

LABORATORY INVESTIGATION

3.1 Introduction

To conduct the experiments in the freezer box, a specially designed pavement box was built to contain the soil samples collected from a site at DFW. A misting system was also created using landscaping grade irrigation nozzles and a hose, which was installed in the freezer box where the testing would occur.

3.2 Design of the System

The box was constructed of wood with additional reinforcement provided using Simpson Strong Ties on the inside corners. This was due to the significant lateral force that would result from placing the pavement slab sample on top of the compacted soil. Vertical joists were placed on the outside of the box as additional external reinforcement. Further reinforcement was provided by placing rods of all thread at three different depths within the soil itself and increasing the tension on the rods by tightening nuts on both ends. The soil box is 2-feet wide, 3-feet tall, and 3-feet in length. Hand sketches of the box design provided by Dr. Andy Kruzic can be found in Appendix 2, Fig 75.

The misting system was created using landscaping grade irrigation nozzles and a hose, connected with brass fittings (Fig 2). The end of the hose connected to the water source was passed through an access hole in the freezer to the outside. The access hole was later sealed with foam insulation.

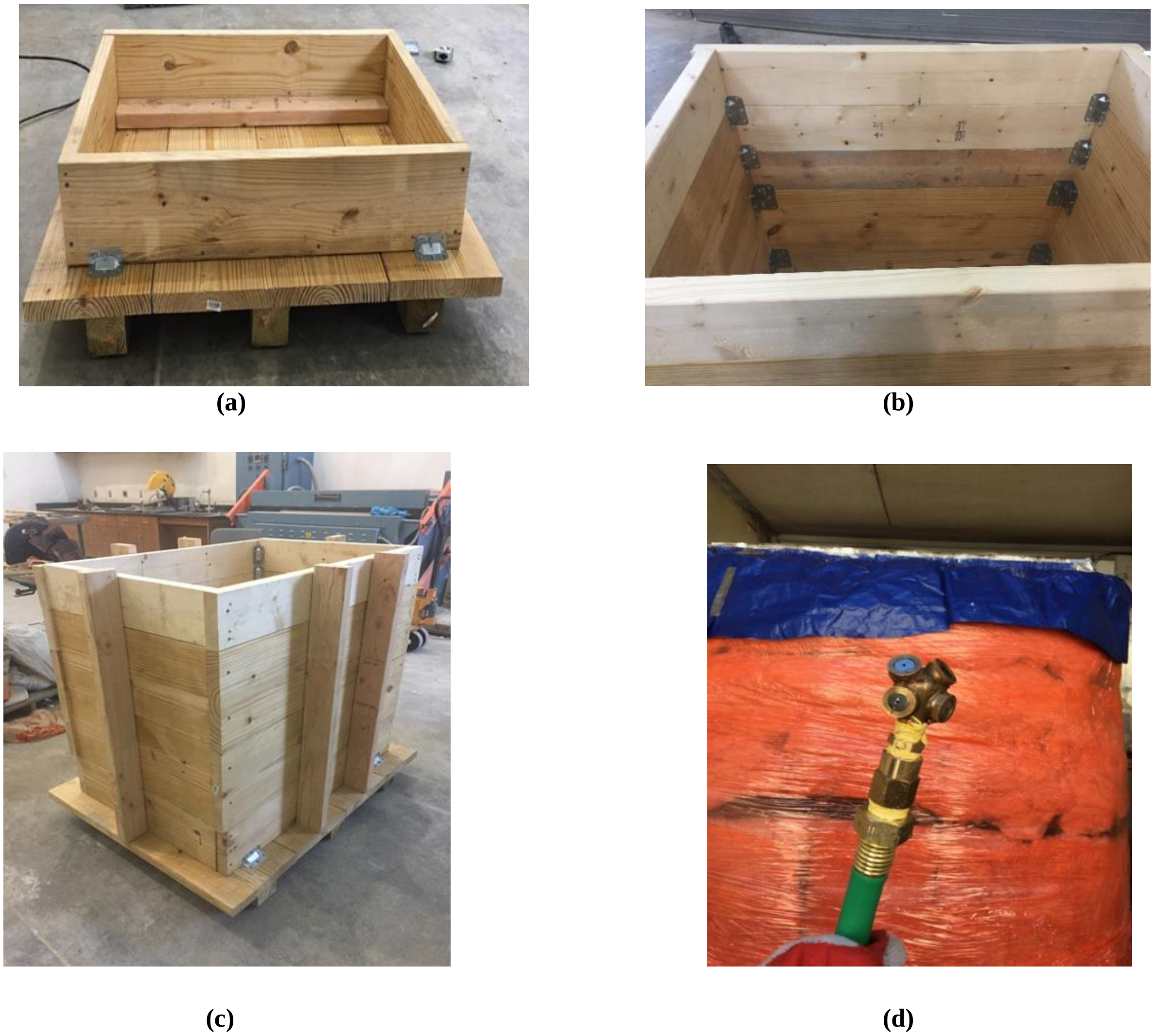
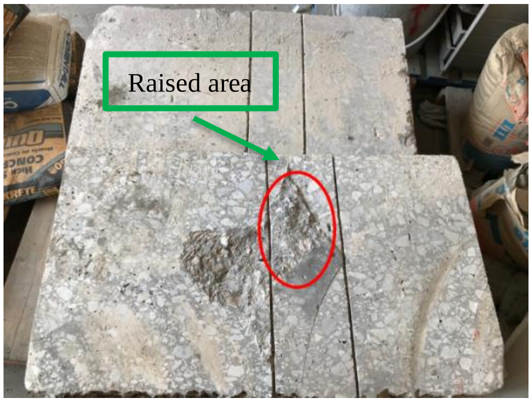


Figure 2. (a): Base of the soil box (b): Inside reinforcements (c): Completed soil box (d) Misting nozzle head

A sample of a piece of runway slab was provided to the University of Texas at Arlington (UTA) by DFW. Personnel at DFW divided the slab into two pieces and cut grooves into the faces of them to facilitate the installation of sensors. The slab needed modification to create two smooth contact surfaces. Higher portions of the slab were smoothed down, while lower portions were built up using commercial Mason Mix. The grooves were also made wider to accommodate the sensor cables. Six holes were drilled into the grooves at a depth of one-half inch for the sensor heads (Fig 3).



(a)

(b)

(c)

(d)

Figure 3. Retrofitting of slab: (a): Slab before repair (b): Slab after repair (c): Widening of the grooves for cables (d): Drilling holes for sensor heads

3.3 Instrumentation

Various sensors were used to monitor the temperature of the slab and the soil, as well as the ambient conditions in the freezer box (Table 1). Figures 4 and 5 illustrate the location of the sensors within the soil and the slab.

To monitor the temperature within the soil column and the pavement slab, thermistors Type YSI 44005 manufactured by GeoKon were used (Fig 5). The soil thermistors were installed at several depths throughout the column. T_1 is located at the interface of the first lift and the bottom of the wooden box to monitor the boundary conditions between the bottom of the box, the ambient freezer temperature, and the soil. T_2, T_4, T_6, and T_7 are installed directly above each other in various lifts to monitor the vertical temperature profile of the soil column. It should be noted that T_7 is in the fine sand layer just below the sand slab interface, T_7 serves to monitor the boundary conditions between the slab and the soil. T_3 is located at the interface of the wooden box and the soil in lift 4, which is at mid-depth (38.5-in below slab surface). T_4 and T_5 are also located in lift 4. These sensors monitor the lateral temperature profile of the soil column at mid-depth. The thermistors were placed in the lifts while they were being filled with loose soil, prior to compaction.

Six thermistors were installed in grooves that were cut into the body of the slab, these grooves are located 16-in and 22-in from the edge of the slab, one half inch deep holes were drilled into the grooves to accommodate the sensor heads (Fig 4). T_8, T_9, and T_10 are located 16-in from the edge of the slab, T_11, T_12, T_13 are 21-in from the edge of the slab oriented vertically and evenly spaced approximately 9-in from each other. The location of these sensors monitor the vertical temperature distribution of the slab and the horizontal temperature distribution as well.

Three Type T thermocouples manufactured by National Instruments are located on the surface of the slab, separated by approximately 8-in. T_Center is located directly above T_8, T_9, and T_10, it is 0.75-in above T_10. T_Center, along with the thermistors below it, illustrate the vertical temperature profile of the surface and the body of the slab, monitoring in what ways the reactions of the two differ in their response to temperature fluctuations, specifically cold fronts.

Two TDT SDI-12 temperature and moisture sensors manufactured by Acclima, Inc. are also installed in the soil column. TDT 1 is located at mid-depth in lift 4, in line with T_3 and T_4. TDT 2 is located in line with T_6, 10.5-in from the surface. The sensors are intended to confirm that the thermistors are reading temperature correctly. Through the monitoring the volumetric moisture content of the soil, it can be confirmed that the wrapping of the system in plastic has sufficiently kept moisture from infiltration during the various misting operations performed.

To monitor the relative humidity and the ambient temperature in the freezer box, an EE181-L air temperature and relative humidity sensor manufactured by Campbell Scientific was used, this sensor was suspended from the ceiling of the freezer box away from the air ventilation system.

Table 1. Instrumentation used during testing

Instrument	Manufacturer	Function	Accuracy
CR 1000X	Campbell Scientific	Control datalogger, operating range: -55°C to +70°C	+/- 0.04% at 0° to 40°C +/- 0.06% at -40° to +70°C
DataSnap SDI-12 Logger	Acclima, Inc.	Control datalogger, operating range: -20° to +60°C	
KD2 Pro	Decagon Devices, Inc.	Thermal properties analyzer	Conductivity: +/- 10%, 0.2 to 2 $\frac{W}{(m*K)}$ Diffusivity: +/- 10% @ conductivities above 0.1 $\frac{W}{(m*K)}$
EE181-L Air temperature and Relative Humidity sensor	Campbell Scientific	Temperature and relative humidity sensor, operating temperature range: -40°C to +60°C	Air temperature: +/- 0.2°C (at 23°C) Relative humidity: +/- (1.3 + 0.003* RH reading) % RH (-15°C to +40°C, 0 to 90% RH)
TDT SDI-12	Acclima, Inc.	Temperature and moisture sensor, operating range: 1° to +50°C for volumetric water content (VWC), -20° to +50°C for temperature	VWC: +/- 2% Temperature: +/- 2°C for 1° to 50°C

Instrument	Manufacturer	Function	Accuracy
CS100	Campbell Scientific	Barometric pressure sensor	+/- 1hPa at 0° to 40°C +/- 1.5hPa at -20° to +50°C
Thermocouple Type T	National Instruments	Temperature sensor, operating range: -270° to +370°C	+/- 1°C
Thermistor Type YSI 44005	GeoKon	Temperature sensor, operating range: -100° to +500°C	+/- 0.2°C

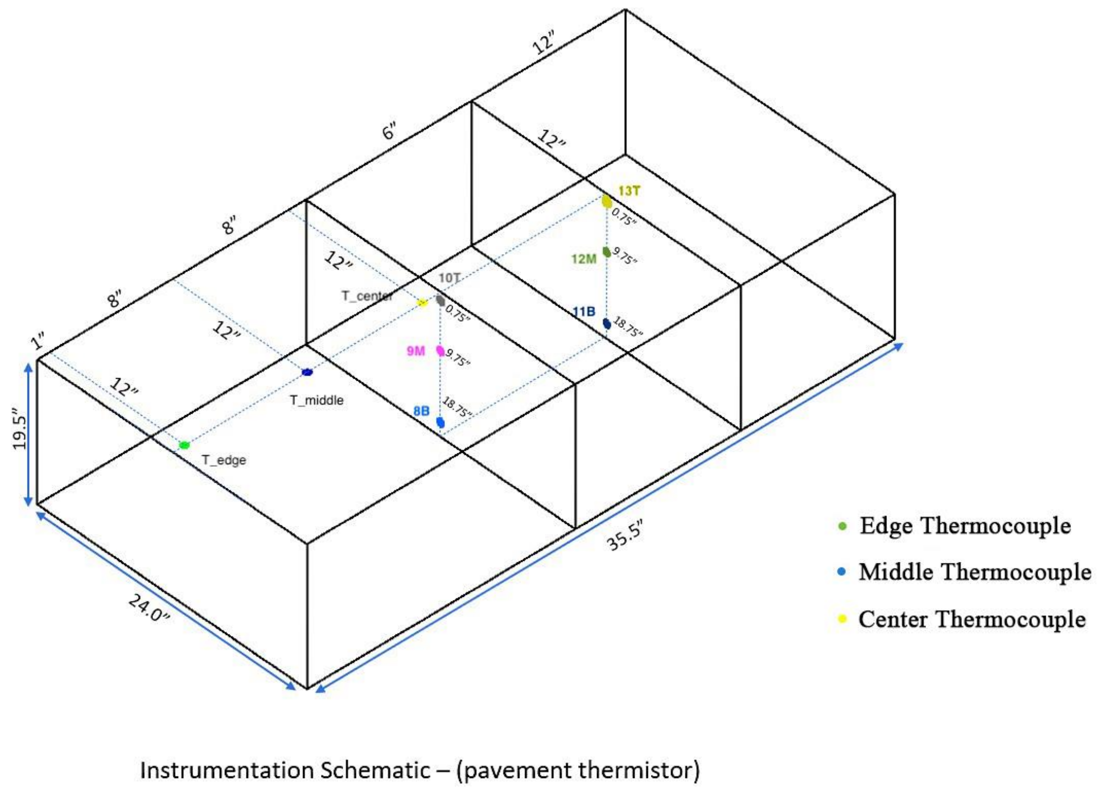


Figure 4. Pavement instrumentation schematic. (Source: Kothari, 2021)

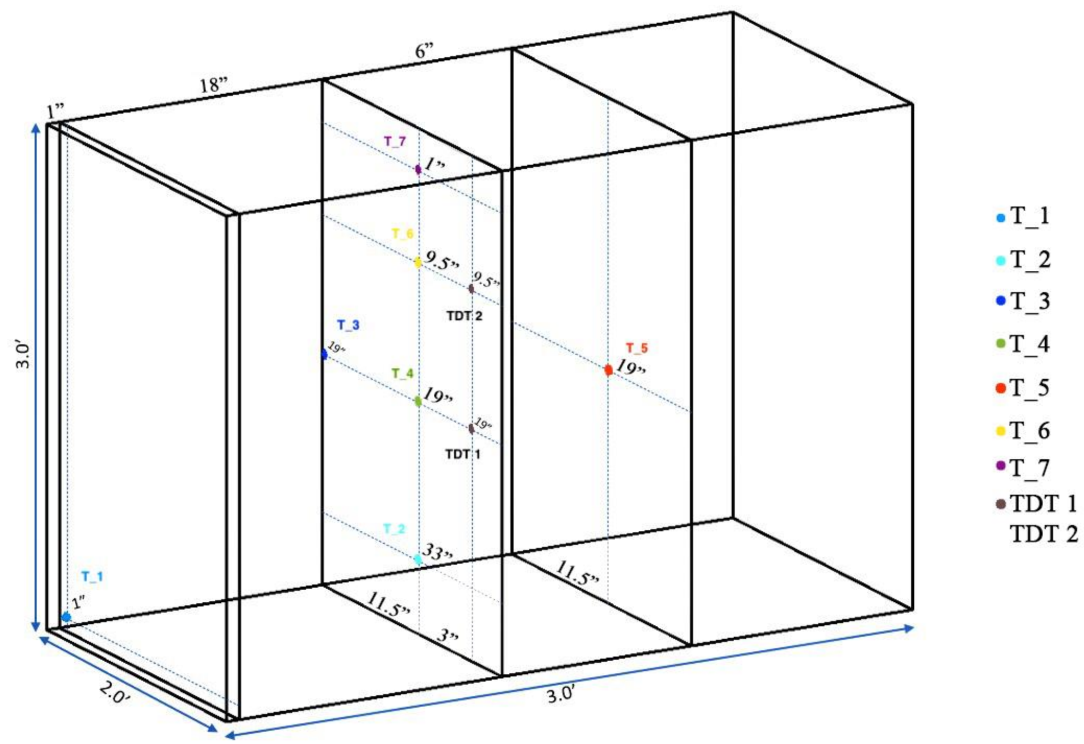


Figure 5. Soil instrumentation schematic. (Source: Kothari, 2021)

3.4: Soil Testing

Soil samples were collected from a site at DFW. Thirty-two samples were collected using 5-gallon buckets and transported to UTA. Several representative samples were taken to the laboratory for testing and classification. The samples were tested for moisture content according to the American Society for Testing and Materials (ASTM) standard designation D2216-19. The moisture content of the soil is found to be 12.68%. A dry sieve analysis was performed according to ASTM standard designation D6913. The result of the analysis (Fig 6) is reported as the soil being mostly sand however, the samples exhibited characteristics of clay and it was determined to perform a wet sieve analysis according to ASTM standard designation D1140-17. The result of the analysis (Appendix 2, Table 21) was reported as the soil containing 57.07% fines. As a result, Atterberg limit tests were performed according to ASTM standard designation D4318-17

(Figs 7 and 8), tabulated calculations can be found in Appendix 2, Tables 22 and 23. Specific gravity tests are also performed according to ASTM standard designation D854-14, the resulting specific gravity was 2.61 (Table 2). A more detailed table of the specific gravity calculations can be found in Appendix 2, Table 24. As a result of the tests performed, the soil is classified as a sandy lean clay (Table 2). Thermal conductivity readings were also taken for the soil (Table 3).

To determine the maximum dry density and optimum moisture content of the soil, the Standard Proctor Test for compaction was performed according to ASTM standard designation D698. The results of the compaction test are a maximum dry density of 94.92 pcf and an optimum moisture content of 25% (Fig 9). Tabulated calculations for the Standard Proctor Test results can be found in Appendix 2, Table 25.

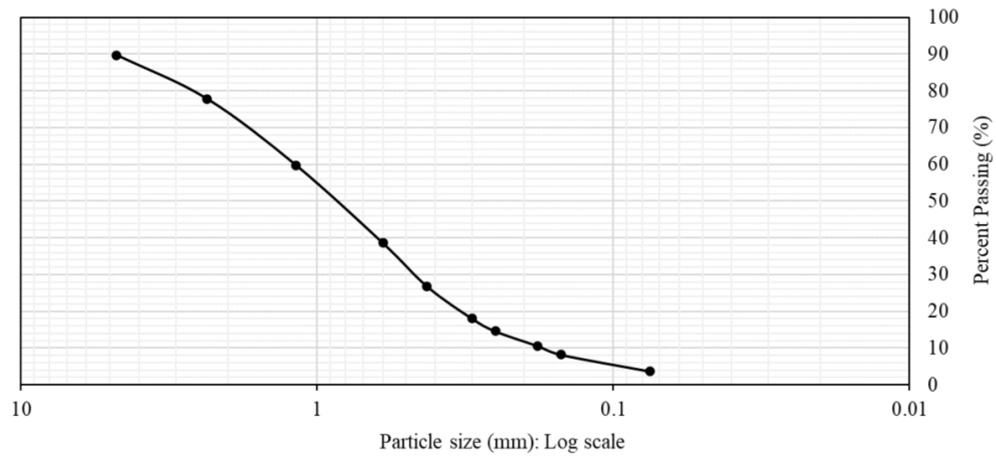


Figure 6. Gradation curve for dry sieve analysis

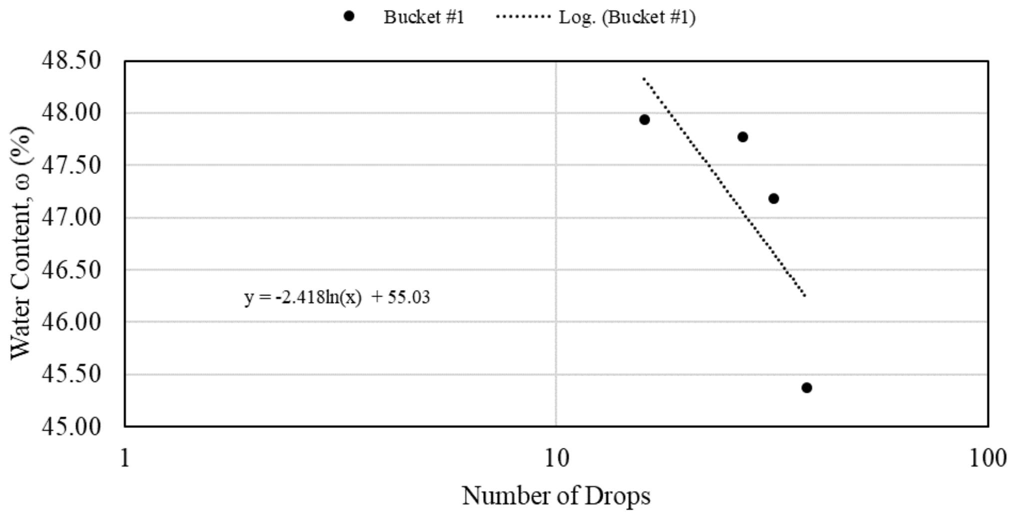


Figure 7. Flow curve, sample 1

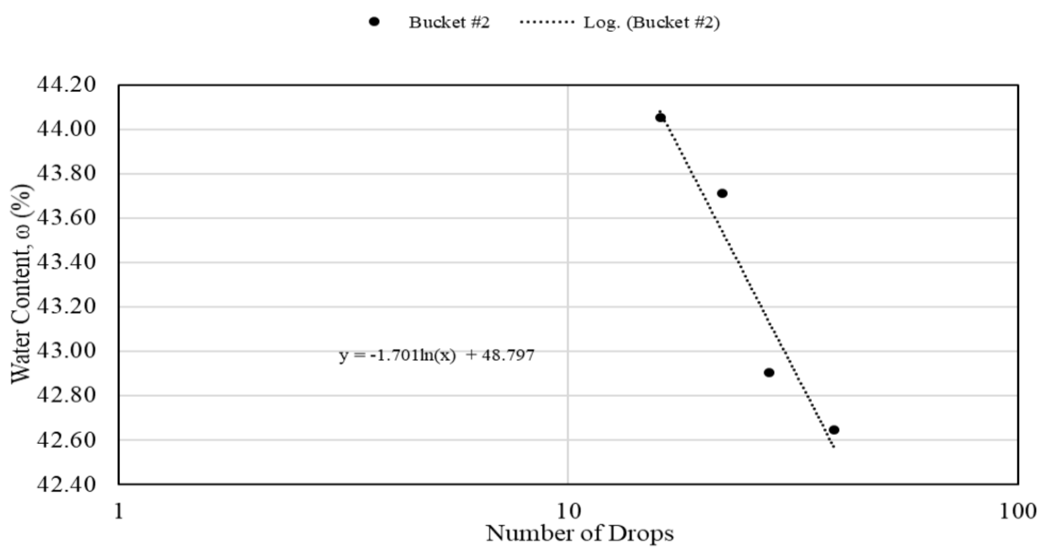


Figure 8. Flow curve, sample 2

Table 2. Summary and final soil classification

Sample	G_s	LL	PL	PI	Soil Classification
Bucket #1	2.59	47	25.91	21.09	CL- Sandy Lean Clay
Bucket #2	2.62	43	25.35	17.65	CL- Sandy Lean Clay

Table 3. Thermal conductivity results

Lift #3	
Thermal conductivity, K_{avg} (BTU/h-ft-°F)	0.80025
Thermal diffusivity, α_{avg} (in^2/s)	0.00058
Lift #5	
Thermal conductivity, K_{avg} (BTU/h-ft-°F)	0.57181
Thermal diffusivity, α_{avg} (in^2/s)	0.00054

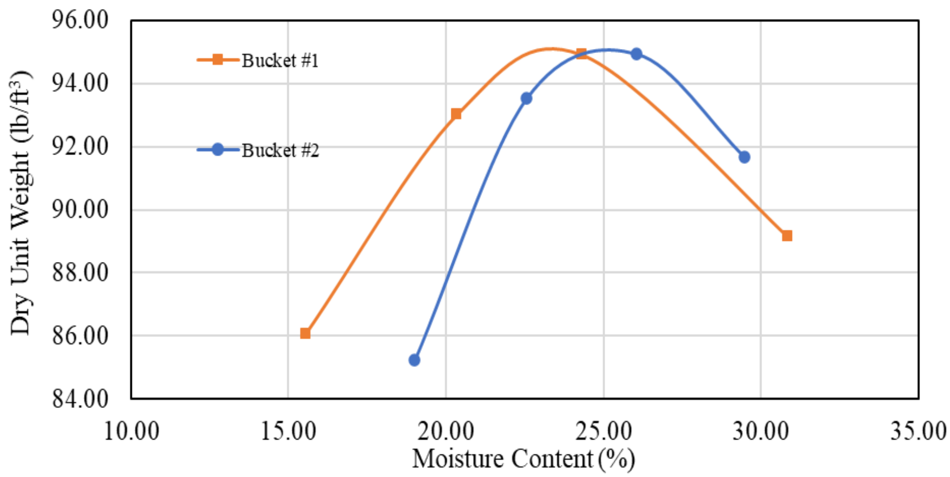


Figure 9. Proctor compaction curve

The soil samples were weighed and placed into a specially designed soil wetting box where water was added to achieve the desired moisture content. The soil was then covered with a plastic tarp and allowed to set for 24 hours before being placed into the soil column. After the 24 hours, samples of each batch of soil were tested for moisture content. The column was filled in 6-inch lifts and then compacted (Fig 10). The moist density of the compacted soil was 87.8 pcf.

(a) **(b)** **(c)**

Figure 10. Installation of soil (a): Wetting soil (b): Soil lift before compaction (c): Soil lift after compaction

Sensors were placed at various locations throughout the soil as the lifts were installed and compacted (Fig 11). After the lifts were installed, a thin layer of fine sand was placed on top and slightly compacted. Due to the bottom of the slab being very uneven, the fine sand was placed to create a more substantial mating surface between the sandy lean clay and the slab (Fig 12).

(a) **(b)**

Figure 11. Sensor installation. (a): T_1 thermistor (b): TDT moisture sensor and thermistors in mid-depth layer of soil

(a) **(b)**

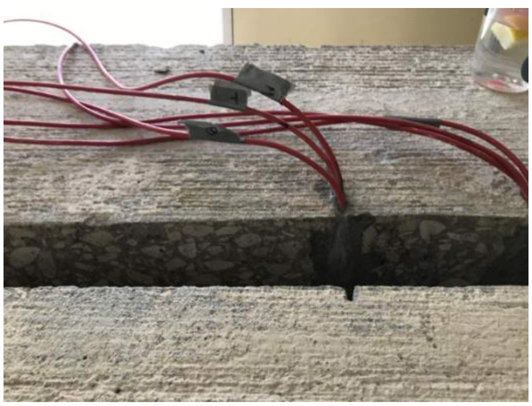
Figure 12. (a): Condition of bottom of slab (b): Fine sand layer

The slab was placed on top of the soil using a ceiling crane and the entire system was moved to the freezer box where the gap between the two slab halves was filled with commercial Mason Mix and allowed to cure. The system was wrapped in insulation and plastic to prevent interference from freezing temperatures and infiltration of water during testing. R30 insulation was used to insulate the soil as well as the slab. R30 was chosen for its ability to perform well in cold temperatures. This R value is recommended by the U.S. Department of Energy for attics in Northern Texas (Appendix 2, Fig 76). Given that the box would be in conditions similar to conditions of an attic (i.e.: no other surrounding structures to help provide insulation), it was determined that R30 would provide sufficient insulation. The insulation was wrapped around the box, as well as placed under it. After conducting an initial baseline test, an additional layer of insulation was added to the bottom 6 inches of the box to insulate the lower layers of the soil further. Insulation was placed around the perimeter of the slab, leaving space between the insulation wrapping and the edge of the slab surface. This space was later covered with a tarp and sealed with Gorilla Glue and silicone. Three thermocouple sensors were also affixed to the surface of the slab (Figs 13 and 14).

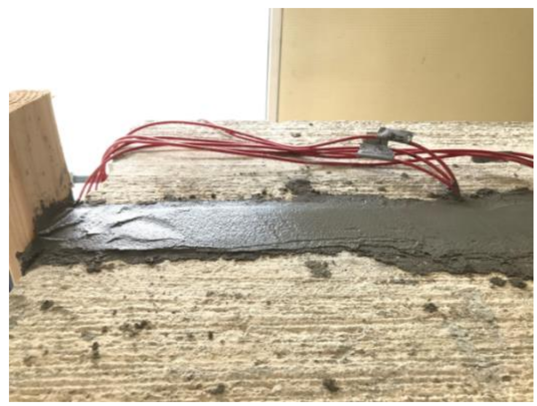
(a)

(b)

(c)



(d)



(e)

Figure 13. (a): Placing the slab onto the soil (b): Moving the system into the freezer box (c): Complete system installed into freezer box (d): Gap between slabs before filling (e): Gap after filling

(a) **(b)**

Figure 14. (a): System wrapped in insulation and plastic (b): Installation of surface thermocouples

3.5 Experimental Program

The table below outlines the testing program. The cases that yielded significant results are highlighted and detailed within this thesis. All other cases can be found in Appendix 1.

Table 4. Table of tests conducted

Test Number	Test Description
Baseline Cooling	Freezer start temperature was 60°F, freezer was set to 20°F where is remained for 48 hours.
Baseline Warming	Freezer start temperature was 32°F, the freezer was turned off and the temperature allowed to rise for 145 hours.
Case 1	Gradual temperature decrease from 40°F to 30°F, with misting occurring when the ambient temperature reaches 30°F.

Test Number	Test Description
Case 1.1	Gradual temperature decrease from 40°F to 25°F, with misting occurring when the slab surface reaches freezing conditions.
Case 2	Sharp temperature decrease from 40°F to 15°F, with misting occurring when the slab surface reaches 30°F.
Case 2.1	Sharp temperature decrease from 40°F to 15°F, with misting occurring when the slab surface reaches 30°F. Duration of misting increased to approximately 30 minutes.
Case 3	Sharp temperature increase from 25°F to 50°F accompanied by varying levels of relative humidity.
Case 3.1	Baseline test for Case 3, with both freezer doors being opened fully.
Case 3.2	Baseline test for Case 3, with one freezer door being opened slightly.
Case 3.3	Repeat of Case 3.2 with the introduction of additional moisture provided using a coffee pot.
Case 3.4	Repeat of Case 3.3
Case 3.5	Repeat of Case 3.2 with the introduction of additional moisture provided using an electric kettle.
Case 3.6	Repeat of Case 3.2, using the natural outside humidity to introduce moisture.
Case 4	Freezer box door opened during a cold snap to allow for the outside air to cool the freezer environment.

Baseline (Cooling trend)

This test was performed to obtain a cooling baseline for the system as well as to confirm that the sensors and dataloggers were operating correctly. The test was performed September-22-2020 to September-26-2020. The freezer box was set to a starting temperature of 60°F, remaining at this setting for several days to allow the system to reach a steady state. On September-22-2020 at 12:34 pm, the freezer was set to 20°F, remaining at this setting until September-26-2020 at 12:06 pm when the data was collected, and the freezer box returned to 60°F. Please note that the spikes in the ambient temperature are due to the defrost cycle of the freezer box. The slab temperature is plotted in Fig 15. The locations of the sensors in the body of the slab are: 0.75-in, 9.75-in, and 18.75-in from the surface, respectively. One can observe that the cooling of the slab is uniform however, there is a difference in the temperature of the slab and the temperature of the ambient freezer air, with the slab being anywhere from 10° to 15°F warmer than the ambient temperature, even after being in below freezing conditions for 89 hours. It can also be observed that the entirety of the slab did not reach freezing conditions, even after an extended period in below freezing conditions. This indicates that the soil is retaining heat and preventing the slab from reaching freezing conditions.

Figure 16 illustrates the sensors that have been placed horizontally at mid-depth (38.5- in below slab surface) of the soil. The mid-depth layer decreases in temperature uniformly by approximately 20°F. It should be noted that sensor T_3 is located at the interface of the soil column wall and the soil. The plot illustrates that despite the location of T_3 along the boundary, there is not a discernible temperature variation with the other sensors located further from the boundary. This shows that the insulation wrapping around the box is effective.

Figure 17 shows the sensors that have been placed vertically throughout the depth of the soil. T_6, T_7 are located in the upper layers of the soil, 29 and 20.5-in from the surface respectively, T_2 is located 52.5-in from the slab surface, and T_4 is located at approximately mid-depth 38.5-in from the slab surface. From the plot, it can be observed that although T_2 is located in the bottom layer, it follows the same cooling trend as T_7 which is located 1-in from the surface. This indicates that although the bottom of the box is wrapped with insulation, it is not sufficient to protect the bottom-most layers of the soil from immediate reaction to the freezer box conditions.

Figure 18 illustrates the greater influence the ambient temperature has on the upper-most layer of soil as opposed to the mid-depth layer. The vertical temperature profile shown in Fig 19 illustrates the temperature change of the system at 24-hour increments throughout the test. The highlighted legend entries indicate the start and end of the test. It can be observed that at the beginning of the test the system has reached a steady state. By the end of the test, the slab decreased by 30°F while the soil at 38.5-in below the slab surface decreased by 20°F.

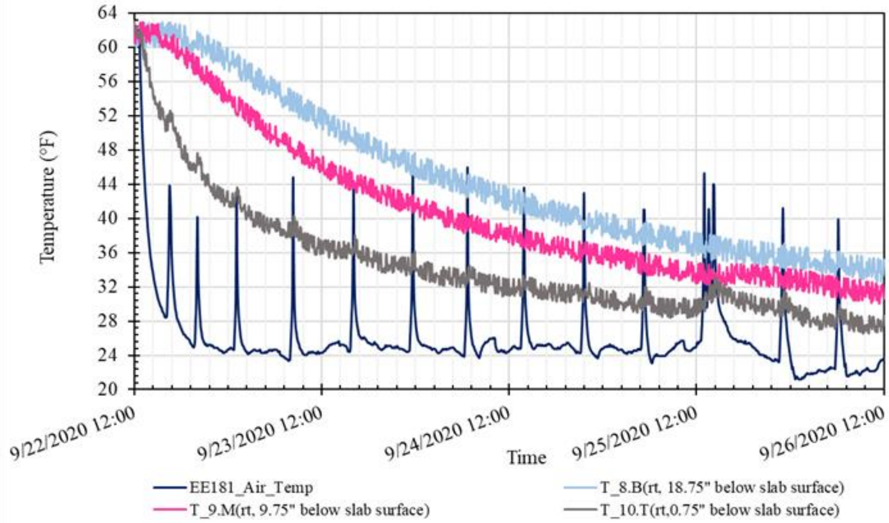


Figure 15. Variation of ambient freezer temperature and slab surface

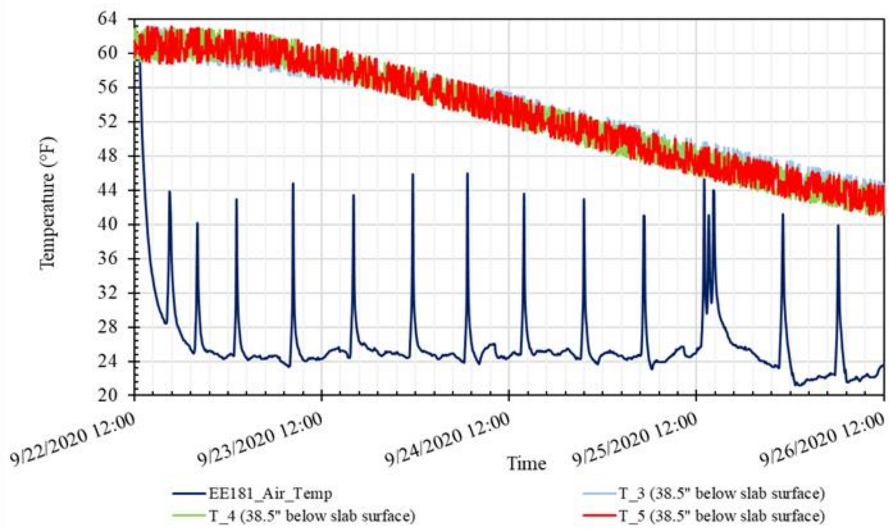


Figure 16. Variation of ambient freezer temperature and horizontal soil section 38.5" below slab surface

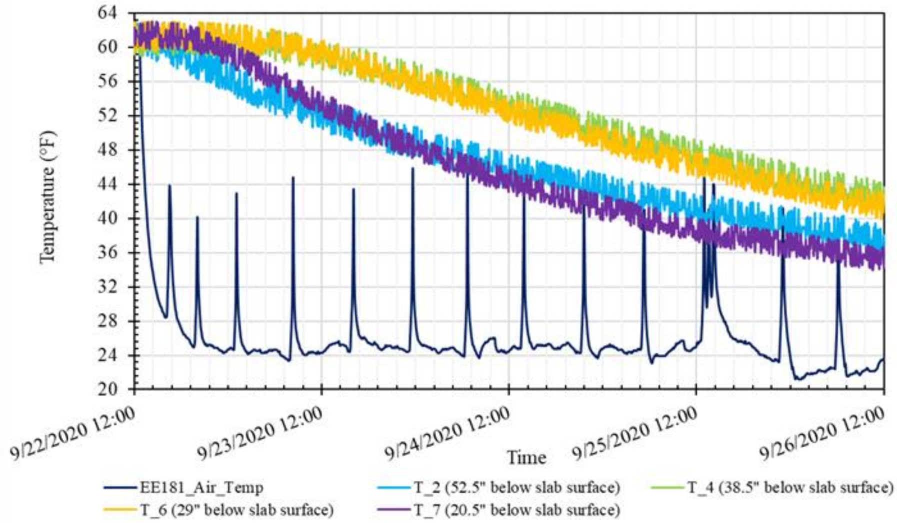


Figure 17. Variation of ambient freezer temperature and vertical soil section

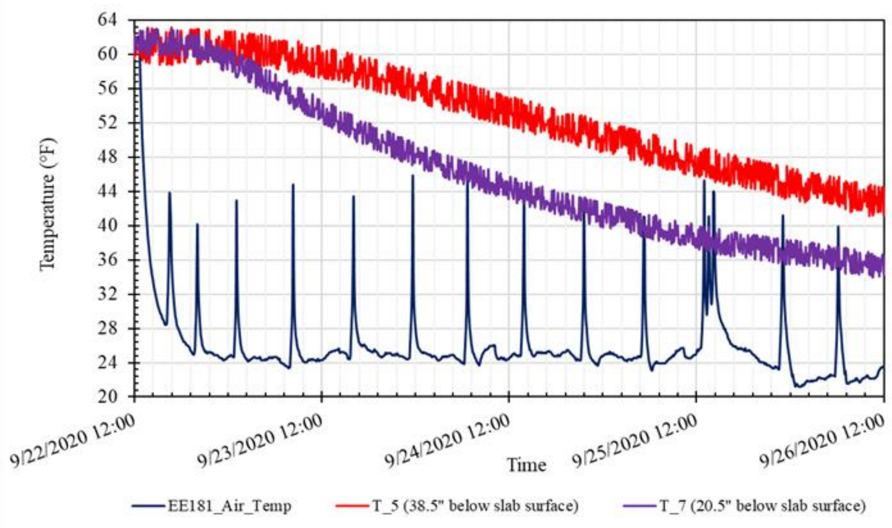


Figure 18. Variation of ambient freezer temperature, soil at 38.5" below slab surface, and soil at the slab-soil interface

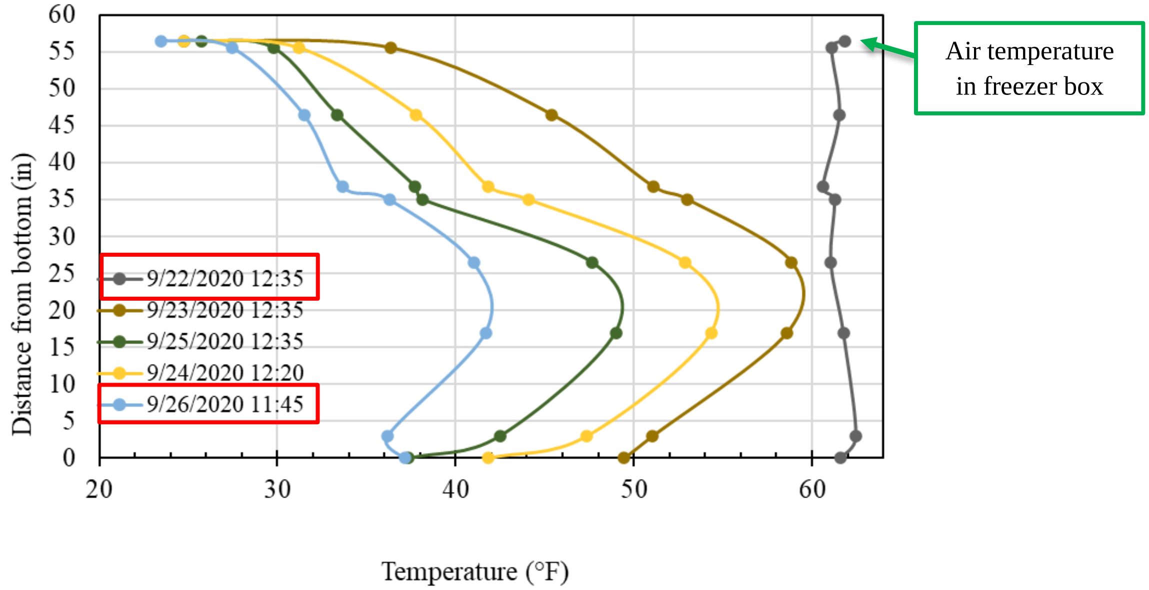


Figure 19. Vertical profile of temperature variation in the system (24-hour increments)

<u>Baseline (Warming trend)</u>

This test was performed to obtain a warming baseline for the system, to confirm that the sensors and dataloggers were operating correctly and to allow the system to return to a steady state prior to the start of testing. The test was performed September-29-2020 to October-05-2020. The freezer box began at a starting temperature of 37°F, the freezer was turned off to allow for the collection of data for a warming trend baseline. On September-29-2020 at 7:38 am, the freezer was turned off, remaining off until October-05-2020 at 8:30 am when the data was collected. The slab temperature is plotted in Fig 20. The locations of the sensors in the body of the slab are: 0.75-in, 9.75-in, and 18.75-in from the surface, respectively. It can be observed from the plot that while the slab follows the same general warming trend of the ambient air, there is a significant temperature difference between them. The slab temperature does not begin to converge on the ambient temperature until six days after the freezer box was turned off. Figure

21 illustrates the sensors that have been placed horizontally at 38.5-in below the slab surface. This mid-depth layer only increases in temperature by approximately 15 degrees, illustrating not only that the insulation is effective, but also that the soil will take more time to warm after being exposed to freezing conditions. Fig 22 shows the sensors that have been placed vertically throughout the depth of the soil. T_6, T_7 are located in the upper layers of the soil, 29 and 20.5-in from the slab surface, T_2 is located 52.5-in from the slab surface, and T_4 is located at approximately mid-depth 38.5-in from the slab surface. It is interesting to note that although T_2 and T_7 follow the same warming trend, despite being separated by the entirety of the soil column. There is a larger temperature difference between the two, with T_2 being colder which we also would have expected from the cooling trend as well. This could be a result of the layers of soil above acting as insulation for T_2. Figure 23 illustrates the large influence the ambient temperature has on the upper-most layer of soil as opposed to the mid-depth layer. It can be observed from the plots of the ambient temperature and the soil that unlike the slab, the middle layers of the soil do not approach convergence with the ambient temperature even after six days. This illustrates how efficient the soil is when holding temperature. The vertical temperature profile shown in Fig 24 illustrates the temperature change of the system at 24-hour increments throughout the test. The highlighted legend entries indicate the start and end of the test. It can be observed that by the end of the test, the slab is approximately 8°F warmer than the soil at mid-depth.

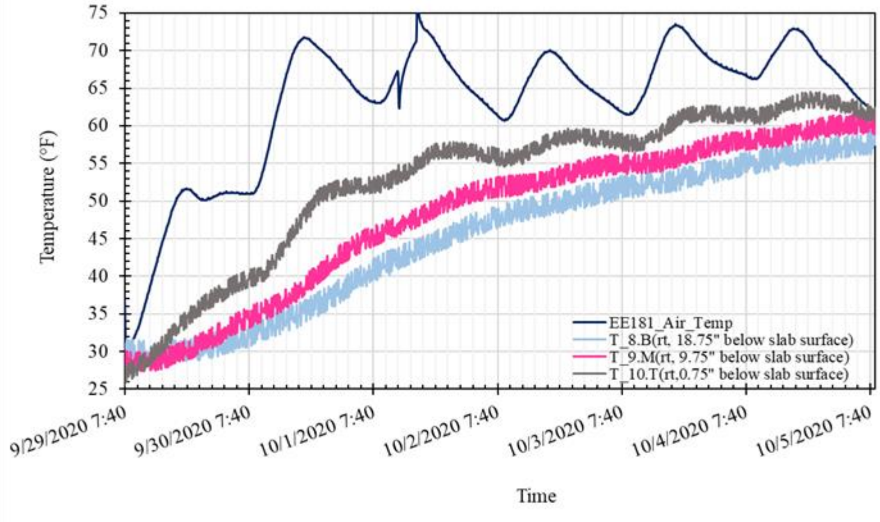


Figure 20. Variation of ambient freezer temperature and the slab surface

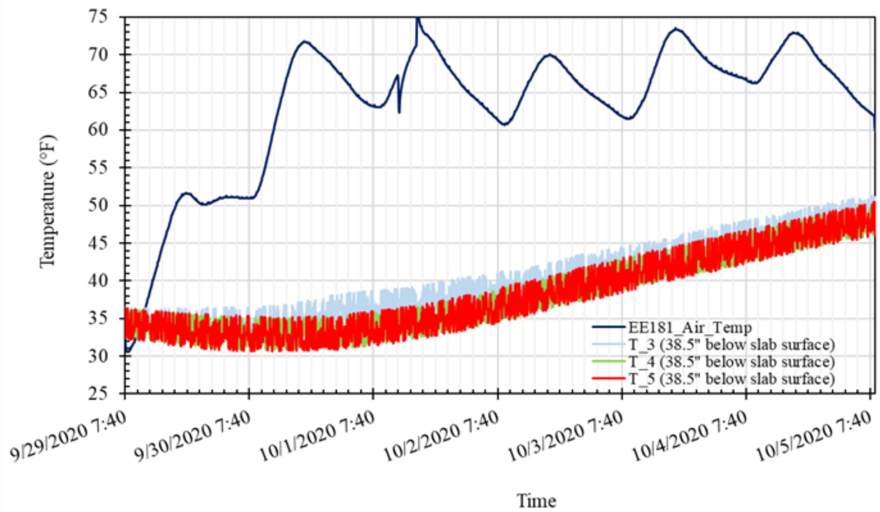


Figure 21. Variation of ambient freezer temperature and horizontal soil section 38.5" below slab surface

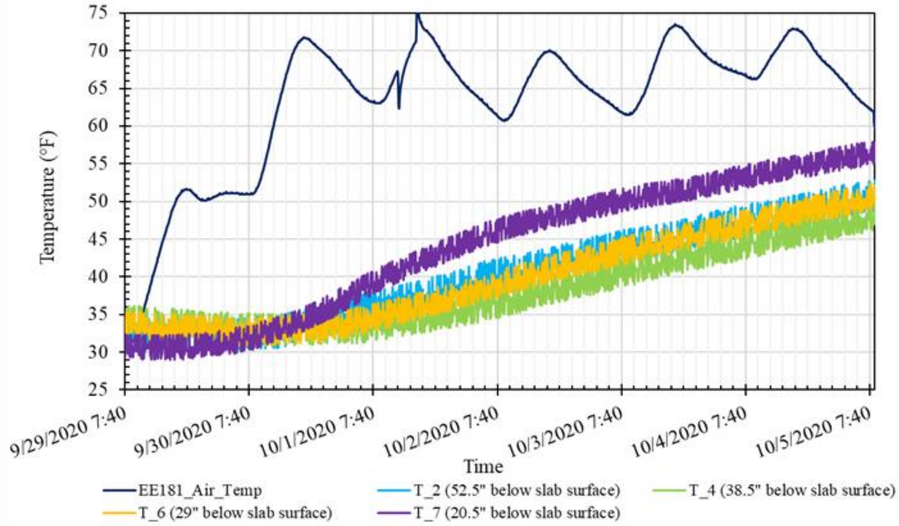


Figure 22. Variation of ambient freezer temperature and vertical soil section

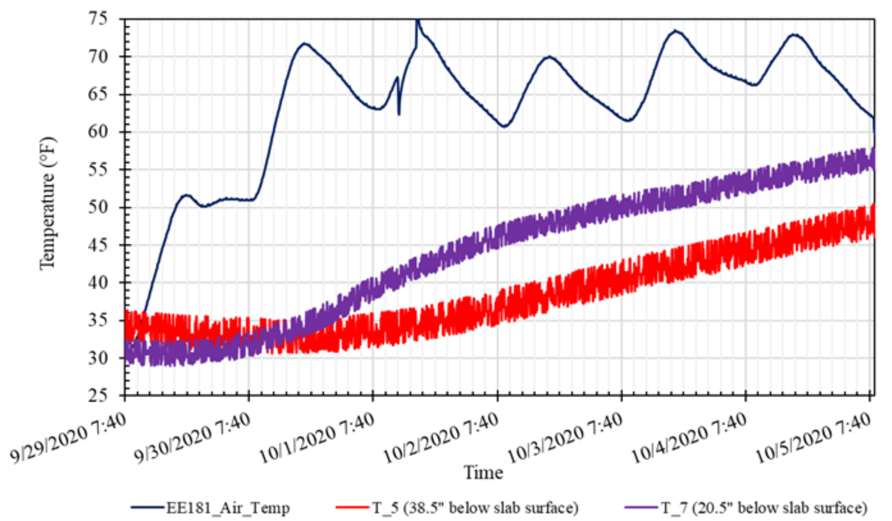


Figure 23. Variation of ambient freezer temperature, soil at 38.5'' below slab surface and soil at the soil-slab interface

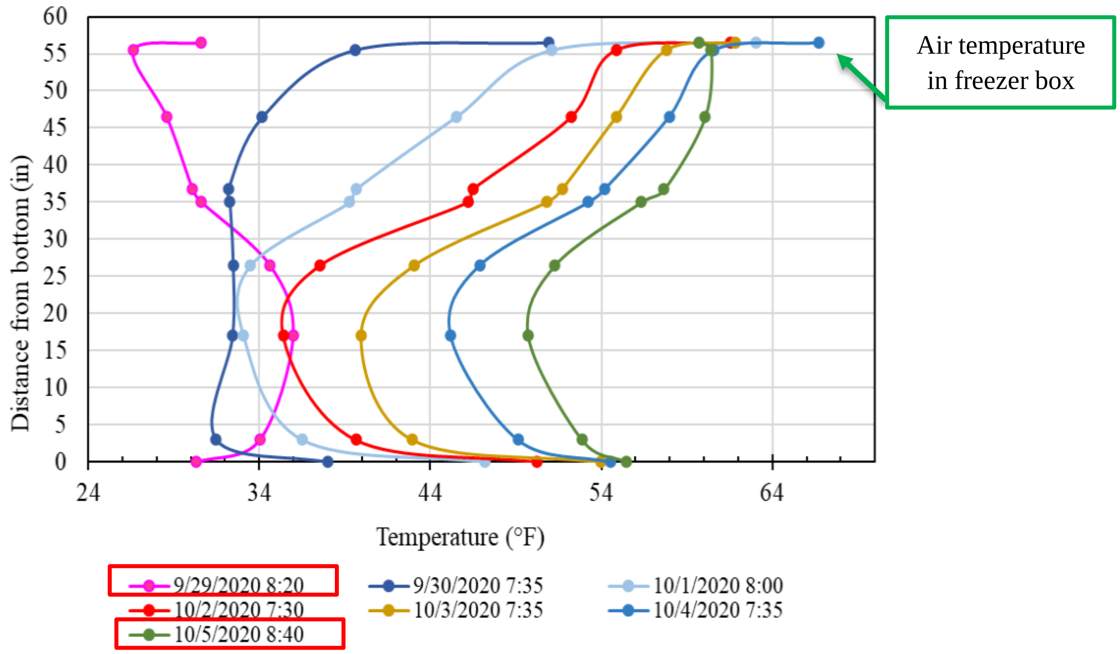


Figure 24. Vertical profile of temperature variation in the system (24-hour increments)

<u>Case 1</u>

The weather scenario being tested for case 1 is a gradual temperature decrease from 40°F to 30°F with misting occurring when the air temperature was 30°F. This scenario was designed using historical field observation data provided by DFW. The duration of the historical event used to design the test is 16 hours (Fig 25). The objective of the case 1 test was to monitor the behavior of the pavement and to determine the conditions for icing to occur on the slab surface. The case 1 test was performed on November-20-2020 on the campus of UTA. The duration of the test was 22 hours, the misting operation utilized 18-20 gallons of a water/ice mixture with the duration of the misting operation beginning when the air temperature reached 30°F and remained there for approximately 6 hours. The misting operation was 8 minutes long (Fig 26). Please refer to Table 10 for the time log of the test procedure, -24 hours denotes the time that the freezer box was set to 40°F and allowed to remain for 24 hours to allow the freezer box conditions to reach steady state. The temperature of the water/ice mixture was monitored using a thermistor located on the outside of the freezer box, connected to the data logger (Fig 27). Once the misting operation was completed, the freezer box remained at a setting of 30°F for an additional five hours before concluding the test.

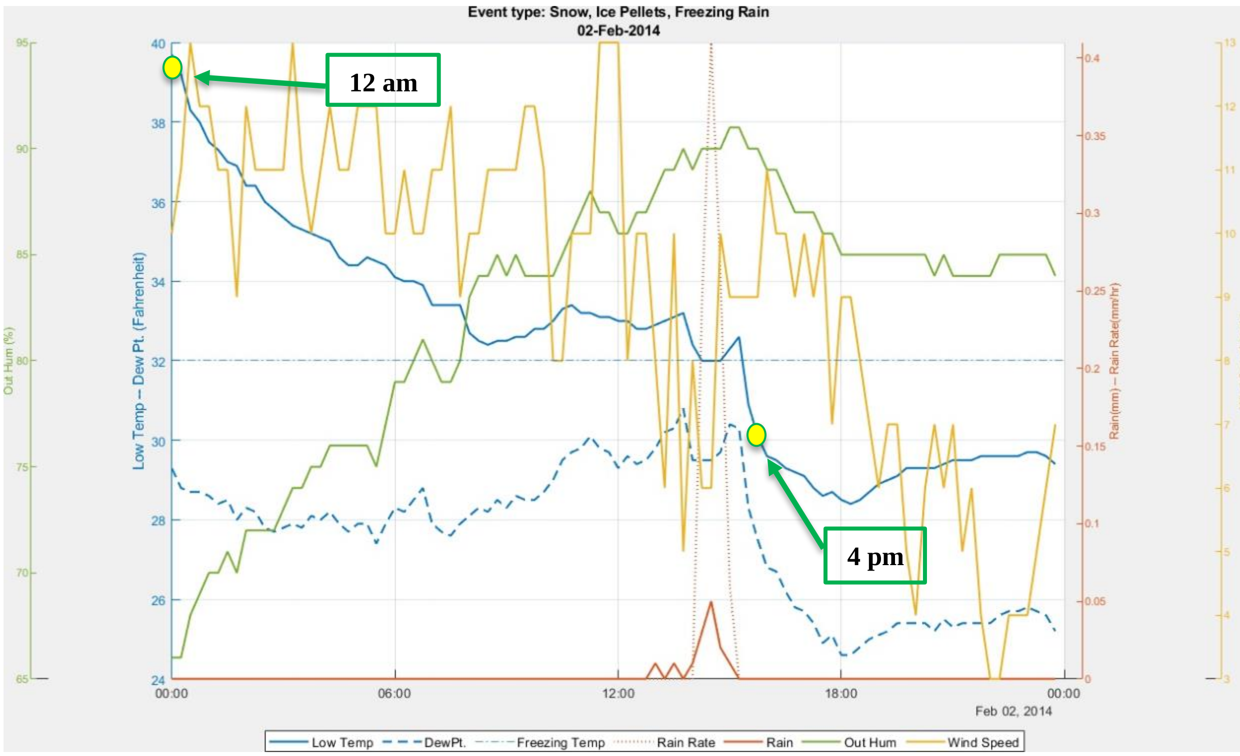


Figure 25. Historic event used to design case 1 test. (Source: Li, 2020)

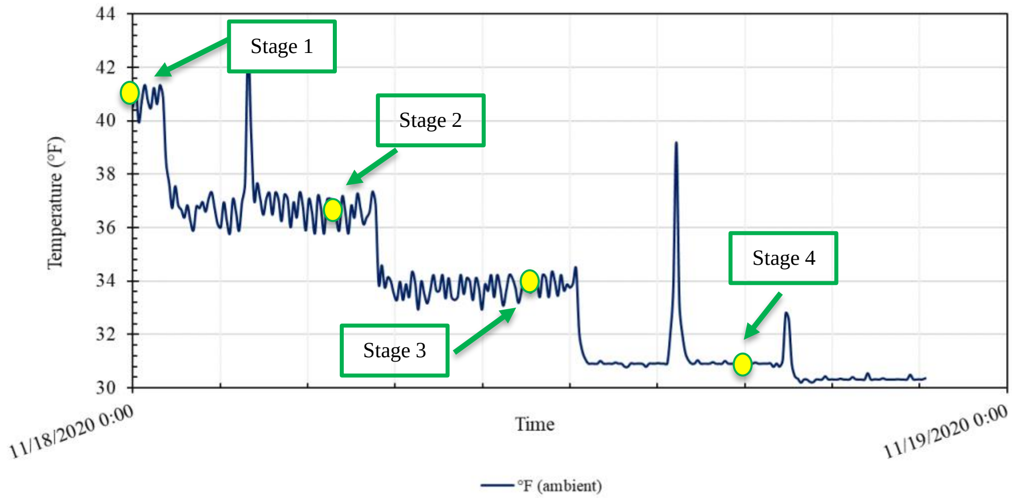


Figure 26. Ambient freezer temperature during case 1 testing

Table 5. Time log for case 1 testing procedure

Stage	Time (hr.)	Action	Description
Initial Condition (IC)	-24	Set Temperature to 40 °F	24 hours allowed for freezer box to reach steady state
#1	0	Set Temperature to 36 °F	Temperature set to 36 °F @ 11:50 pm
#2	6	Set Temperature to 33 °F	Temperature set to 33 °F @ 5:37 am
#3	11	Set Temperature to 30 °F	Temperature set to 30 °F @ 11:09 am
#4	17	Mist/Rain	Misting 4:51 – 4:59 pm
End	22	Set Temperature to 40 °F	Temperature set to 40 °F @ 9:45 pm

(a) **(b)** **(c)**

Figure 27. (a): Water/ice mixture (b): Monitoring temperature of water/ice mixture (c): Temperature of water/ice mixture at time of misting

<u>Case 1.1</u>

Case 1.1 is a repeat of case 1 with several modifications, it was performed March-11-2021 to March-15-2021. The repeated test was needed due to the lack of ice formation during case 1 testing. The scenario for case 1.1 is a gradual decrease from 40°F to 25°F, with misting occurring when the slab surface had reached freezing conditions. The duration of the test was 4 days. A new misting system and a new pump were used in this test (Appendix 2, Figs 77, 78). The new misting system was created using a patio misting system and discharged ¼ inch of water every 20 minutes, creating a much finer mist than in the previous tests. This finer mist allowed for more even coverage over the surface of the pavement. The duration of the misting operation was 38 minutes. Figure 28 shows the ambient temperature in the freezer box throughout the test. Table 8 presents the time log for case 1.1 testing procedure.

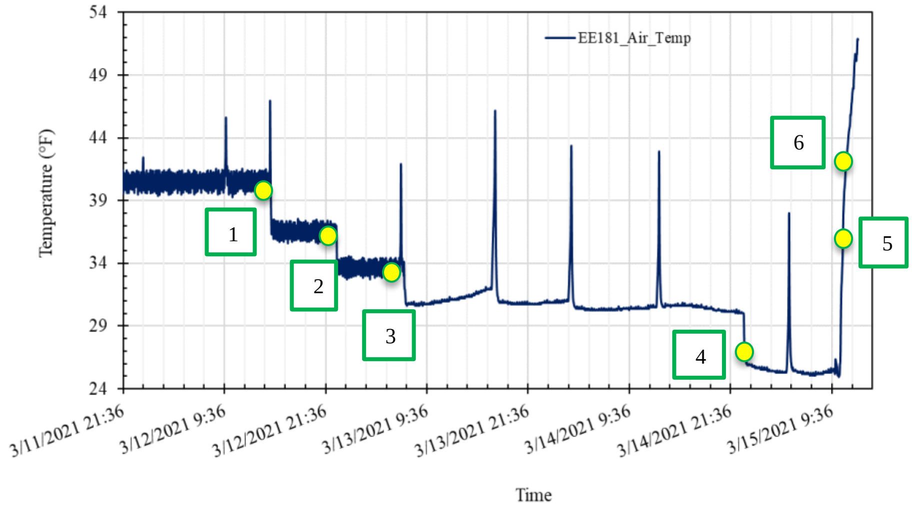


Figure 28. Ambient freezer temperature during case 1.1 testing

Table 6. Time log for case 1.1 testing procedure

Stage	Time (hr:min)	Action	Description
Initial Condition (IC)	-27:31	Set to 40 °F	At 11:30 am, 03/11/2021
#1	00:00	Set to 36 °F	At 03:01 pm, 3/12/2021
#2	7:48	Set to 33 °F	At 10:49 pm, 3/12/2021
#3	15:47	Set to 30 °F	At 6:48 am, 3/13/2021
#4	57:04	Set 25 °F	At 12:05 am, 3/15/2021
#5	67:51	Misting	At 10:52 am, 3/15/2021
#6	68:29	End misting and freezer off	At 11: 30 am, 3/15/2021; door crack open, freezer off

<u>Case 2</u>

The weather scenario tested for case 2 is a sharp decrease from 40°F to 15°F with misting occurring when the slab surface reaches 30°F. This scenario was designed using historical field observation data provided by DFW. The duration of the historical event used to design the test is 4 hours (Fig 29). The objective of case 2 was to monitor the behavior of the system and to determine the conditions for icing on the slab surface. The case 2 test was performed on December-03-2020 on the campus of UTA. The duration of the test was 41 hours. The misting operation utilized 18-20 gallons of a water/ice mixture with the duration of the misting operation being 8 minutes (Fig 30). Please refer to Table 9 for the time log of the test procedure. The temperature of the water/ice mixture was monitored using a thermistor located on the outside of the freezer box, connected to the data logger. Once the misting operation was completed, the freezer box was set to 15°F where it remained for 16.37 hours before concluding the test.

Figure 29. Historic event used to design case 2 test. (Source: Li, 2020)

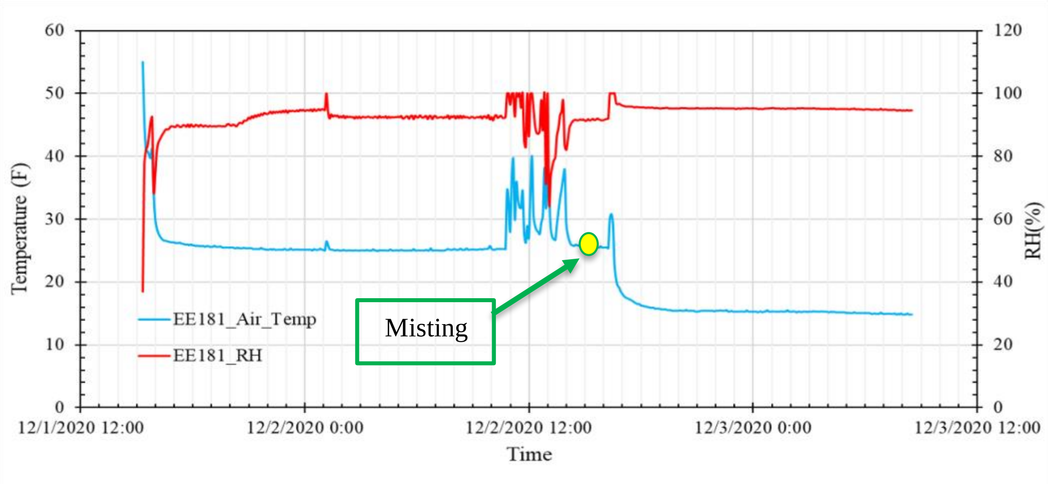


Figure 30. Ambient temperature and relative humidity of freezer during case 2 testing

Table 7. Time log for case 2 testing procedure

Stage	Time (hr.)	Action	Description
Initial Condition (IC)	-24	Set Temperature to 40 °F	24 hours allowed for freezer box to reach steady state
#1	0	Set Temperature to 25 °F	Set air temperature to 25 °F at 12/01/2020 2:47 PM.
#2	24.5	Mist/Rain	Started misting at 12/02/2020 3:17 PM; Slab surface temperature was 30 °F.
#3	24.63	Set Temperature to 15 °F	Set air temperature to 15 °F at 12/02/2020 3:25 PM.
#4	41	Set Temperature to 40 °F	Set air temperature to 40 °F at 12/03/2020 7:47 AM.

<u>Case 2.1</u>

Case 2.1 was performed as a modification of case 2. The weather scenario, objective and procedure were the same as for case 2 apart from an increase in the duration of the misting operation. This increase was implemented to provide enough precipitation coverage for the formation of ice to be observed on the surface of the pavement. The case 2.1 test was performed on December-14 to 16-2020. The duration of the test was 49 hours, the misting operation utilized

54-60 gallons of a water/ice mixture with the duration of the misting operation being 27.5 minutes (Fig 31). Please refer to Table 13 for the time log of the test procedure. The temperature of the water/ice mixture was monitored using a thermistor located on the outside of the freezer, connected to the data logger. Once the misting operation was completed, the freezer box was set to 15°F where it remained for 24 hours before concluding the test.

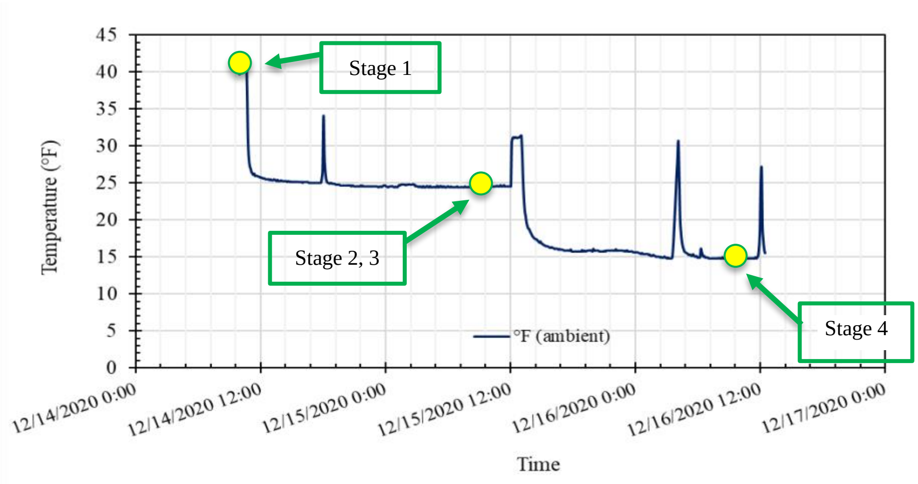


Figure 31. Ambient temperature and relative humidity of freezer during case 2.1 testing

Table 8. Time log for case 2.1 testing procedure

Stage	Time (hr.)	Action	Description
Initial Condition (IC)	-24	Set temperature to 40°F	24 hours allowed for freezer box to reach steady state
#1	0	Set temperature to 25°F	Set freezer temperature to 25°F at 12/14/2020 9:36 AM
#2	24.5	Mist/Rain	Misting began 12/15/2020 at 11:01 AM, slab surface temperature was 28°F
#3	25	Set temperature to 15°F	Set freezer temperature to 15°F on 12/15/2020 at 11:30 AM
#4	49	Set temperature to 40°F	Set air temperature to 40°F on 12/16/2020 at 11:29 AM

Case 3

The weather scenario tested for case 3 is a sharp temperature increase from 25°F to 50°F accompanied by varying levels of relative humidity inside the freezer box. This scenario was designed using historical field observation data provided by DFW. The duration of the historical event used to design the test was 6 hours (Fig 32). The objective of case 3 test was to monitor the behavior of the system and to determine the conditions for the occurrence of frost on the slab surface. Six different tests were performed for the case 3 scenario.

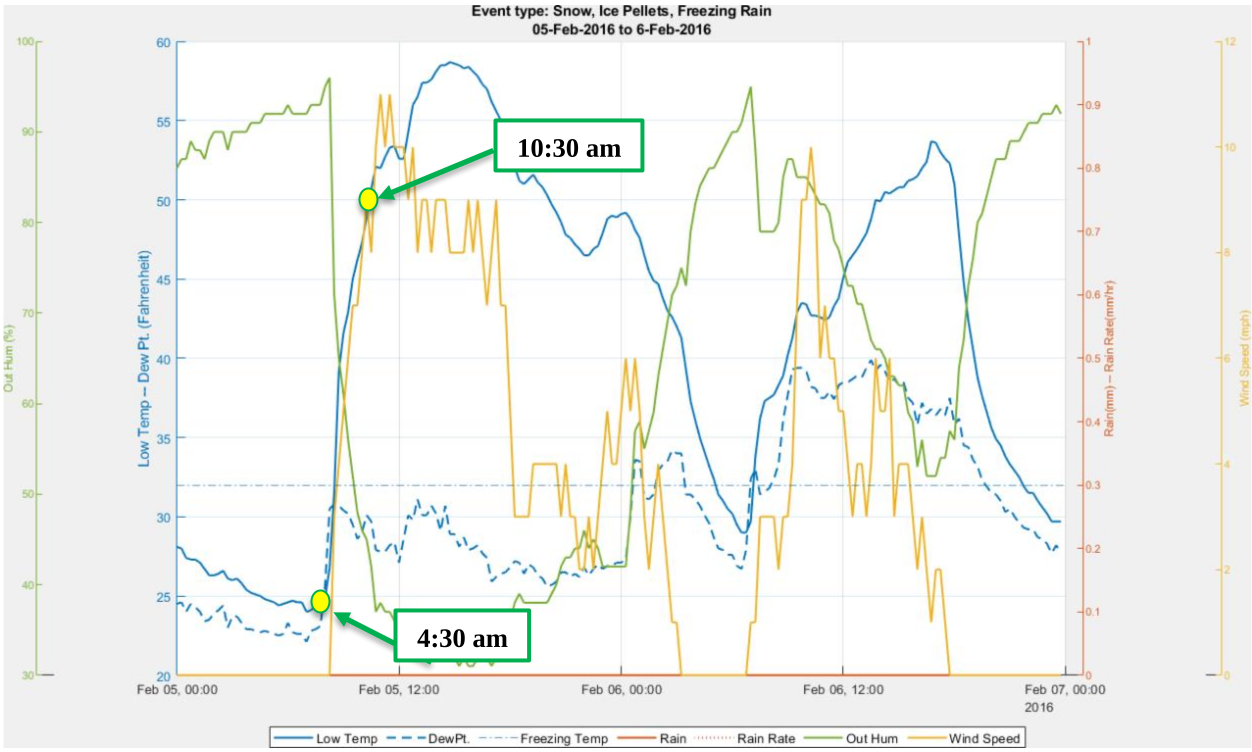


Figure 32. Historic event used to design case 3 test. (Source: Li, 2020)

Case 3.1

Case 3.1 was performed as a baseline test to determine how the ambient temperature and the relative humidity in the freezer box would react when outside air was introduced into the freezer box. The case 3.1 test was performed on December-22-2020, the outside relative humidity ranged from 36% to 31% during the test. The temperature of the outside air was 56°F at the start of the test and 66°F at the end. For this test, the freezer box attained a steady state condition of 25°F, at which point the freezer was turned off and both doors were opened fully. Relative humidity, ambient temperature, and the slab surface temperature in the freezer box were monitored. The duration of the test was 1.32 hours (Fig 33). Upon completion of the test, the freezer box was turned on and set to 25°F.

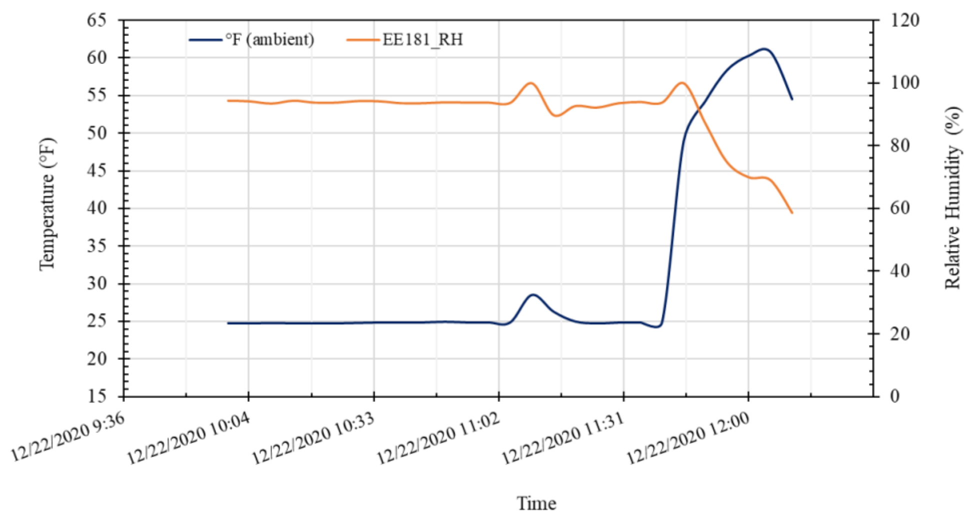


Figure 33. Ambient temperature and relative humidity in freezer during case 3.1 testing

<u>Case 3.2</u>

Case 3.2 was performed as a modification of baseline case 3.1. The scenario, objective, and procedure were the same as for case 3.1 except for only one door of the freezer box being opened slightly. This was done to slow the temperature increase in the freezer box. The case 3.2 test was performed on December-22-2020, the outside relative humidity ranged from 32% to 27% during the test. The outside air temperature was 66°F at the beginning of the test and 68°F at the end. Relative humidity, ambient temperature, and the slab surface temperature in the

freezer box were monitored, the duration of the test was 2.17 hours (Fig 34). Upon completion of the test, the freezer box was turned on and set to 25°F.

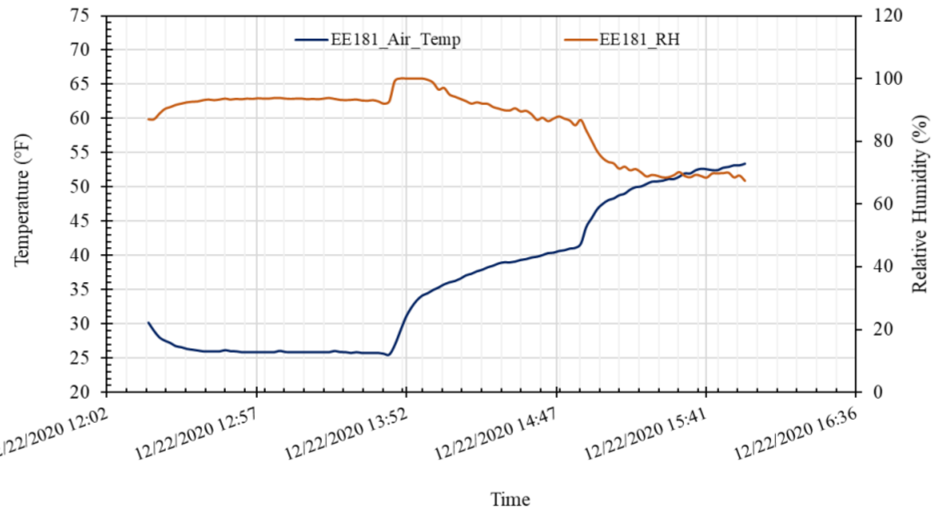


Figure 34. Ambient temperature and relative humidity in freezer during case 3.2 testing

<u>Case 3.3</u>

Case 3.3 was performed as a repeatability test of case 3.2 to further understand how the inside conditions of the freezer box react to the addition of the outside air. The weather scenario, objective, and procedure were the same as for case 3.2. The case 3.3 test was performed on January-11-2021, the outside relative humidity ranged from 49% to 46% during the test. The outside temperature was 37°F at the beginning of the test and 38°F at the end. Relative humidity, ambient temperature, and the slab surface temperature in the freezer box were monitored, the duration of the test was 7.67 hours (Fig 35). Please refer to Table 11 for the time log of the test procedure

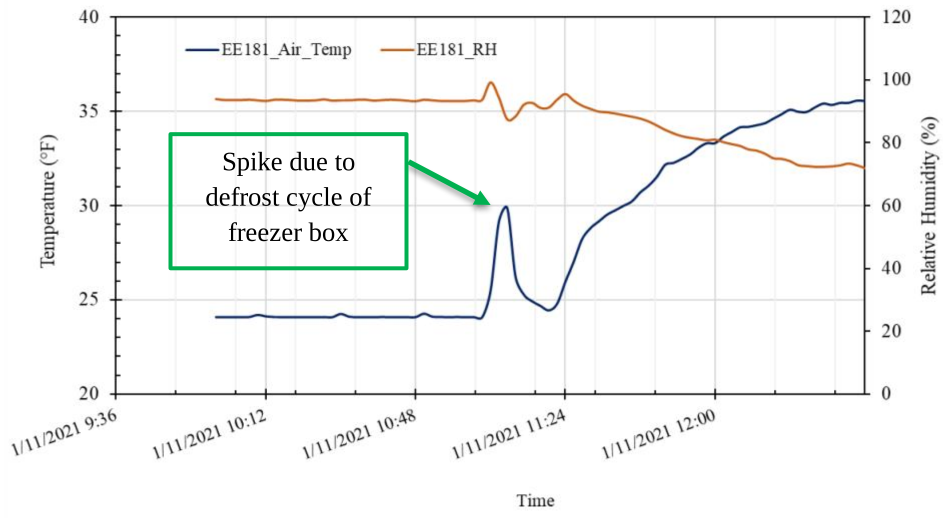


Figure 35. Ambient temperature and relative humidity in freezer during 3.3 testing

Table 9. Time log for case 3.3 testing procedure

Stage		Time (hr.)	Action	Description
Initial conditions (IC)		-24	Set temperature to 25 °F	24 hours to allow the freezer box to reach steady state
Case 3.3	Step 1	0	Installed Cameras	Opened the door and installed the cameras at 1/11/2021 10:50 AM. Then closed the door at 1/11/2021 10:52 AM.
		0.5	Turned off the freezer & opened the door slightly	Turned off the freezer, opened the door slightly at 1/11/2021 11:20 AM.
		3.67	Set temperature to 25 °F	The first step was finished at 1/11/2021 3:00 PM.
	Step 2	7.67	Closed the door & Set Temperature to 25 °F	Closed the door and set temperature to 25 °F at 1/11/2021 3:00 PM. The second step was finished at 1/11/2021 7:00 PM.

Case 3.4

Case 3.4 was performed as a modification of case 3.3. The scenario, objective, and procedure were the same as for case 3.3 except for the addition of a coffee maker which was used to introduce more moisture into the freezer box environment. The case 3.4 test was performed on January-14-2021, the outside relative humidity ranged from 20% to 18% during the test. The outside temperature was 61°F at the beginning of the test and 56°F at the end. Relative humidity, ambient temperature, and the slab surface temperature in the freezer box were monitored, the duration of the test was 2.17 hours (Fig 36). Table 12 shows the time log for case 3.4 testing procedure. The temperature spike combined with the drop in relative humidity in Fig 36 occurs when both doors to the freezer box were opened. This allowed warm dry air into the freezer box. The dip in the temperature accompanied by the rise in the relative humidity occurs when the amount of warm dry air allowed into the freezer box was decreased. This was done by allowing only one door to remain open slightly.

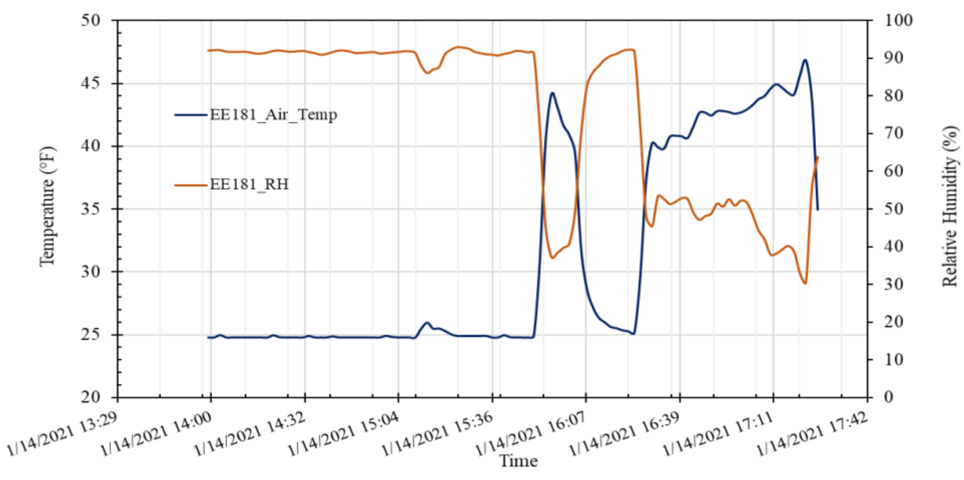


Figure 36. Ambient temperature and relative humidity in freezer during case 3.4 testing

Table 10. Time log for case 3.4 testing procedure

<table>
<tr><th colspan="2">Stage</th><th>Time (hr.)</th><th>Action</th><th>Description</th></tr>
<tr><td colspan="2">Initial conditions (IC)</td><td>-24</td><td>Set temperature to 25 °F</td><td>24 hours to allow the freezer box to reach steady state</td></tr>
<tr><td rowspan="5">Case 3.4</td><td rowspan="3">Step 1</td><td>0</td><td>Installed Cameras</td><td>Opened the door and installed the cameras at 1/14/2021 3:10 PM. Then closed the door at 3:12 PM.</td></tr>
<tr><td>0.6</td><td>Turned off the freezer, opened the door completely, then opened the door slightly and put a boiling kettle inside the box</td><td>Turned off the freezer, opened the door completely at 1/14/2021 3:50 PM. After two minutes, opened the door slightly and put a boiling kettle inside the box at 3:52 PM. The kettle kept boiling for 3 minutes (until 3:55 PM).</td></tr>
<tr><td>0.67</td><td>Closed the door and set temperature to 25 °F</td><td>Closed the door and set temperature to 25 °F at 3:56 PM
The first step was finished at 1/14/2021 3:55 PM.</td></tr>
<tr><td rowspan="2">Step 2 (repeat Step 1)</td><td>1.17</td><td>Turned off the freezer, opened the door completely, then opened the door slightly and put a boiling kettle inside the box</td><td>Turned off the freezer, opened the door completely at 4.24 PM. After two minutes, opened the door slightly and put a boiling kettle inside the box at 4:26 PM. The kettle kept boiling for 8 minutes (until 4:34 PM).</td></tr>
<tr><td>2.17</td><td>Closed the door and set temperature to 25 °F</td><td>Closed the door and set temperature to 25 °F at 5:22 PM.
The second step was finished at 1/14/2021 5:26 PM.</td></tr>
</table>

Case 3.5

Case 3.5 was performed as a modification to case 3.4. The weather scenario, objective, and procedure were the same as for case 3.4 with two exceptions: an electric kettle was used to introduce additional moisture into the freezer box environment and the slab was physically observed during the test for the formation of frost. The electric kettle was chosen because it would introduce a greater amount of moisture into the freezer box environment than the coffee maker. The case 3.5 test was performed on January-22-2021, the outside relative humidity ranged from 90% to 86% during the test. The outside temperature was 49°F at the beginning of the test and 50°F at the end. Relative humidity, ambient temperature, and the slab surface temperature were monitored. The duration of the test was 3.50 hours (Fig 37). Please refer to Table 13 for the time log of the test procedure. Upon completion of the test, the freezer box was turned on and set to 25°F.

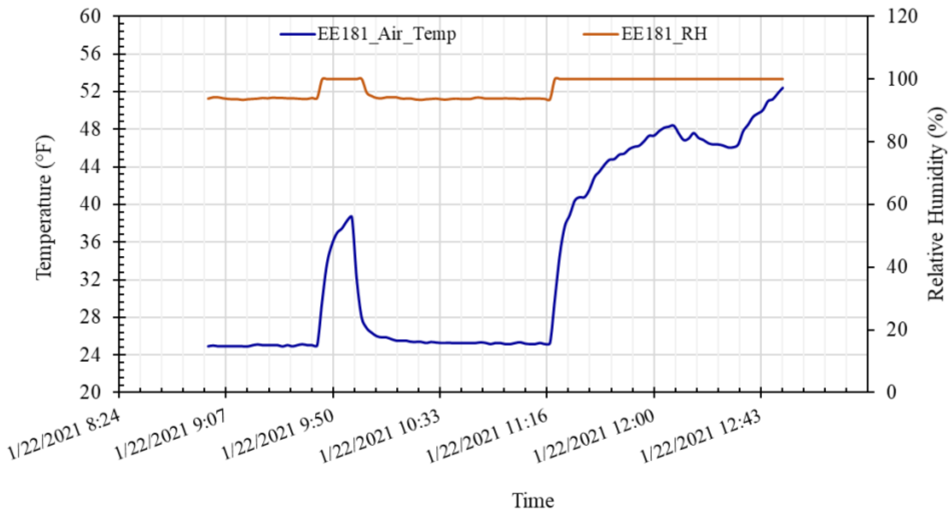


Figure 37. Ambient temperature and relative humidity in freezer during case 3.5 testing

Table 11. Time log for case 3.5 testing procedure

Stage		Time (hr.)	Action	Description
Initial conditions (IC)		-24	Set temperature to 25 °F	24 hours to allow the freezer box to reach steady state
Case 3.5	Step 1	0	Installed Cameras	Opened the door and installed the cameras 1/22/2021 at 9:44 AM. Then closed the door 1/22/2021 at 9:48 AM.
		1.50	Turned off the freezer & opened the door slightly	Turned off the freezer, opened the door slightly, turned on kettle 1/22/2021 at 11:18 AM.
	Step 2	3.0	Closed the door & Set Temperature to 25 °F	Closed the door and set temperature to 25 °F 1/22/2021 at 12:50 PM.

Case 3.6

Case 3.6 was performed as a repeatability test for case 3.5 with the objectives of observing frost formation with a lower relative humidity level in the freezer box than previously recorded. The case 3.6 test was performed on January-29-2021. The outside relative humidity ranged from 58% to 47% during the test. The outside temperature was 47°F at the beginning of the test and 55°F at the end. Relative humidity, ambient temperature, and the slab surface temperature were monitored, and the slab surface was physically observed for the formation of frost. The duration of the test was 2.15 hours (Fig 38). Please refer to Table 14 for the time log of the test procedure. Upon completion of the test, the freezer box was turned on and set to 25°F.

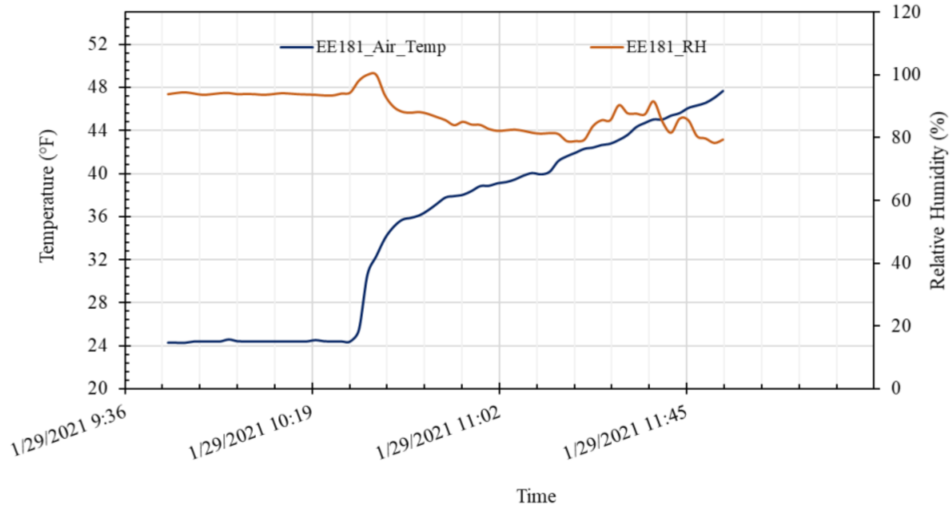


Figure 38. Ambient temperature and relative humidity in freezer during case 3.6 testing

Table 12. Time log for case 3.6 testing procedure

Stage		Time (hr.)	Action	Description
Initial conditions (IC)		-24	Set temperature to 25 °F	24 hours to allow the freezer box to reach steady state
Case 3.6	Step 1	0	Freezer off, door opened slightly	Opened door 1/29/21 at 10:28 am, monitored RH in freezer
		0.75	Turned kettle on	Turned kettle on at 11:13 am, boiling began at 11:21 am
	Step 2	2.15	Closed the door & Set Temperature to 25 °F	Closed the door and set temperature to 25 °F on 1/29/21 at 11:53 am

Case 4

The weather scenario being tested for case 4 was to open the freezer box door to allow the outside air to influence the freezer box environment. This test was performed during a cold snap experienced in Texas. The objective of the test was to observe how the system reacts to conditions that are similar to field conditions and to observe how long it takes for the formation of ice to occur when a misting operation is performed at freezing conditions. The outside air temperature was 31°F at the start and 26°F at the end of the test. The test was performed on Febuary-12-2021 and the duration of the test was 46 hours (Fig 39). The misting operation used 36-40 gallons of water. The water was kept outside for the complete duration of the test and was 32°F when the misting began. The duration of the misting operation was 21 minutes. Please refer to Table 15 for the time log of the test procedure. Once concluded, the freezer was closed and returned to a setting of 40°F.

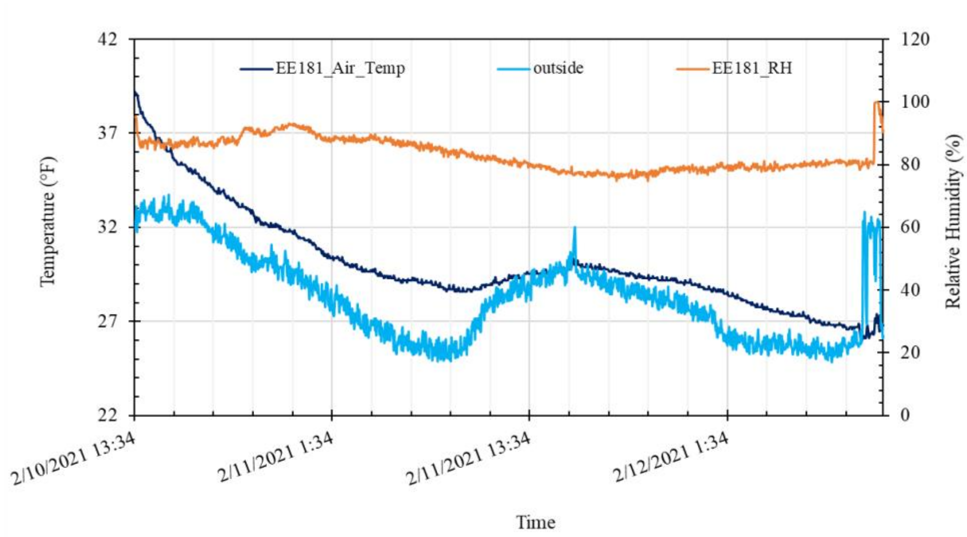


Figure 39. Ambient temperature in freezer, relative humidity in freezer, and outside air temperature during case 4 testing

Table 13. Time log for case 4 testing procedure

Stage	Time (hr.)	Action	Description
1	0	Freezer door opened	Freezer door opened slightly 2/10/21 @ 1:34PM
2	45.5	Misting	Misting 2/12/21 @ 10:29 to 10:50AM
3	46	Freezer set to 40°F	Test ends

CHAPER IV

RESULTS AND DISCUSSION

4.1 Introduction

Analysis of the test results illustrates the difference in the time that the temperature decreases and how the soil and the pavement respond. Additionally, a time frame for the expectancy of the formation of ice is uncovered for winter events involving precipitation as well as the events that do not involve precipitation.

4.2 Results by Test Cases

An investigation into the results of the highlighted cases presented in Table 6 of chapter 2 are presented here. A summary table of the cases presented here is located at the end of the results section.

Case 1

During case 1 test, the freezer box temperature was gradually decreased to a final temperature of 30°F. The freezer box remained at this setting for 5.70 hours, at which time the misting operation began. The ambient temperature of the freezer box was 30.9°F at the start of the misting operation. However, the slab surface did not reach freezing conditions at any point during the testing of case 1. Please refer to Fig 40 and Fig 41.

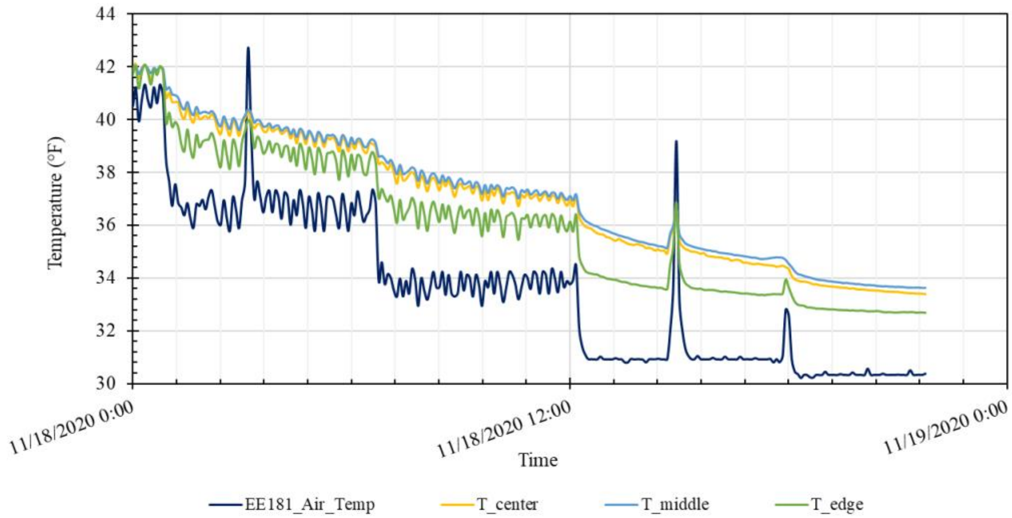


Figure 40. Variation of ambient freezer temperature and slab surface

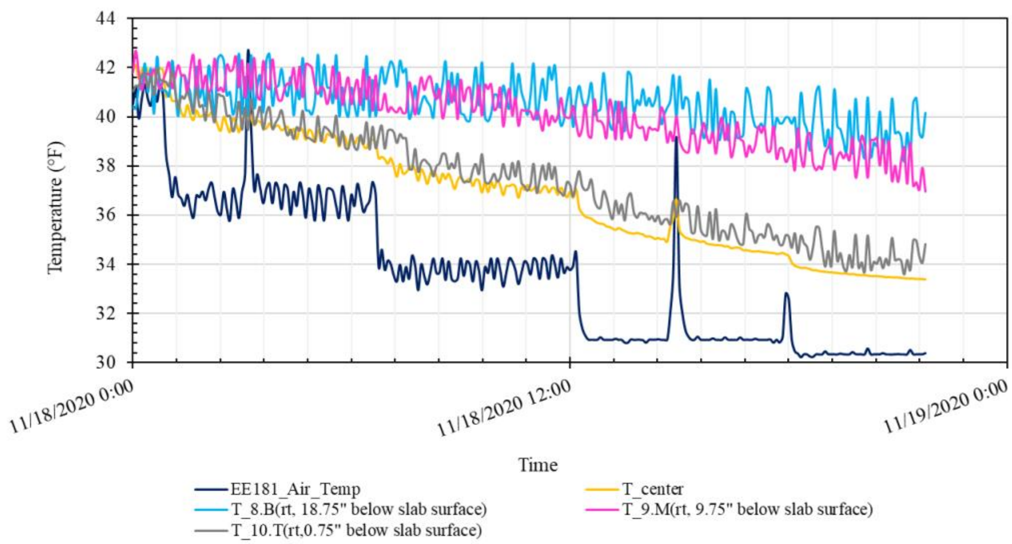


Figure 41. Variation of ambient freezer temperature and slab body

The vertical profile shown in Fig 42 illustrates the temperature variation throughout the system. The soil maintains a significant amount of heat. This demonstrates that not only is the insulation wrapping is effective, but the degree of the thermal capacity of the soil is evident and quite influential on the response of the slab.

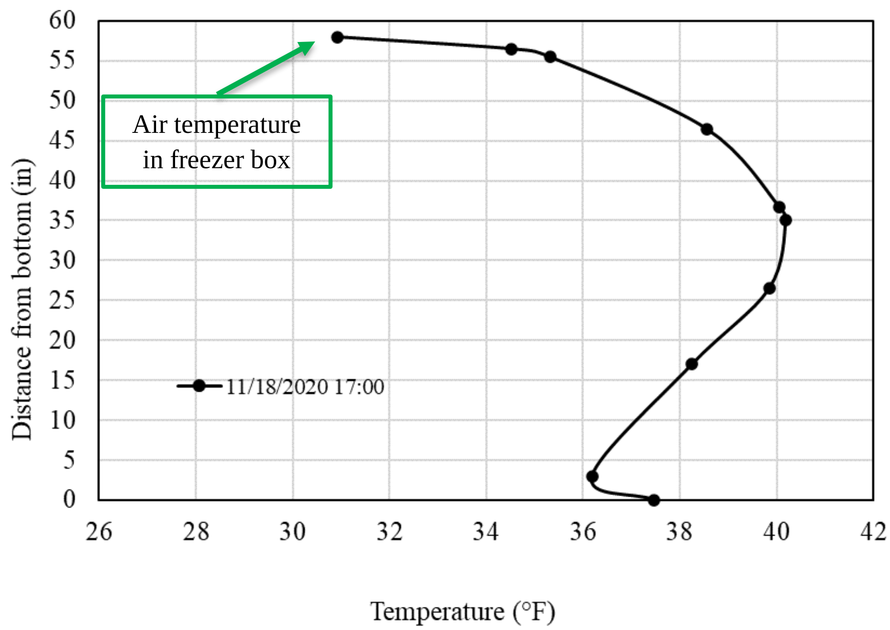


Figure 42. Vertical profile of temperature variation in the system

Final Slab Condition

Photos of the slab throughout the test (shown in Fig 43) indicate that although the ambient temperature in the freezer was below 32°F, no ice formation was observed on the surface of the slab. The temperature of the slab remained at approximately 33°F, even as the ambient temperature reached below freezing for a period of nine hours. This is an indication of how effectively the soil retains heat, preventing the slab from reaching freezing conditions. As a result, there is a time lag between the ambient temperature of the freezer box reaching below freezing and the slab surface reaching freezing conditions. The air temperature in the freezer decreases at a rate of 0.44°F per hour while the slab surface decreases at a rate of 0.34°F per hour. The formation of ice was not observed and is not a concern for the weather scenario tested in case 1.

(a) **(b)** **(c)**

Figure 43. (a): Slab surface at start of misting (b): Slab surface at midpoint of misting (c): Slab surface at end of misting

Case 1.1

During case 1.1 test, the freezer box temperature was gradually decreased to a final temperature of 25°F. The freezer box remained at this setting for 10 hours, at which time the misting operation began. Based on previous tests, it was observed that the slab surface does not respond immediately to a change in ambient air temperature. During this test it was observed that the air in the freezer box took 48 hours to reach 31°F, but the surface of the slab took an additional 36 hours to reach 32°F. Hence, extra time was allotted before beginning the misting operation. The surface temperature of the slab was 30°F at the start of the misting operation. Figure 44 shows the ambient freezer temperature and the slab surface temperature throughout the test. It can be observed in Fig 45 that the surface sensor and T_10 (located 0.75 inches from the slab surface) follow the ambient temperature closely. While the sensors deeper into the body of the slab take much longer to cool and do not reach freezing conditions until the end of the misting operation. Three thermistors were placed in the soil at mid-depth (38.5 inches from the slab surface) to record any lateral temperature variations. Figure 46 shows that the temperature decrease within the soil at mid-depth is minimal and uniform and that the soil layer does not reach freezing conditions. Likewise, Fig 47 shows the comparison of the soil temperature at mid-depth to that at the soil/slab interface. The soil at the interface cooled at a more rapid rate, but failed to reach freezing, even after 52 hours in freezing conditions. Figure 48 shows the ambient freezer temperature, slab surface and slab body during the misting operation. The red dot denotes the beginning of the misting operation. The formation of ice was observed 12 minutes after the beginning of the misting operation.

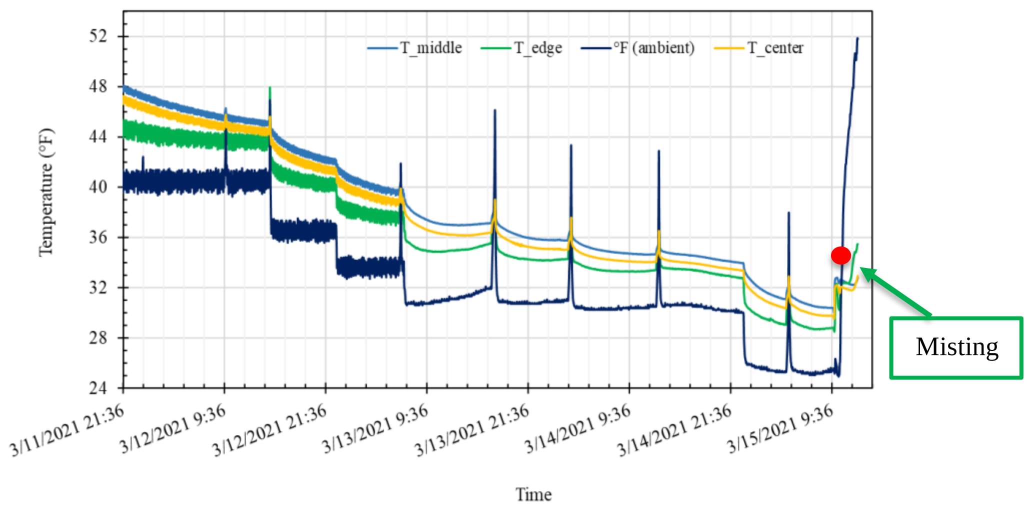


Figure 44. Variation of ambient freezer temperature and slab surface during case 1.1 testing

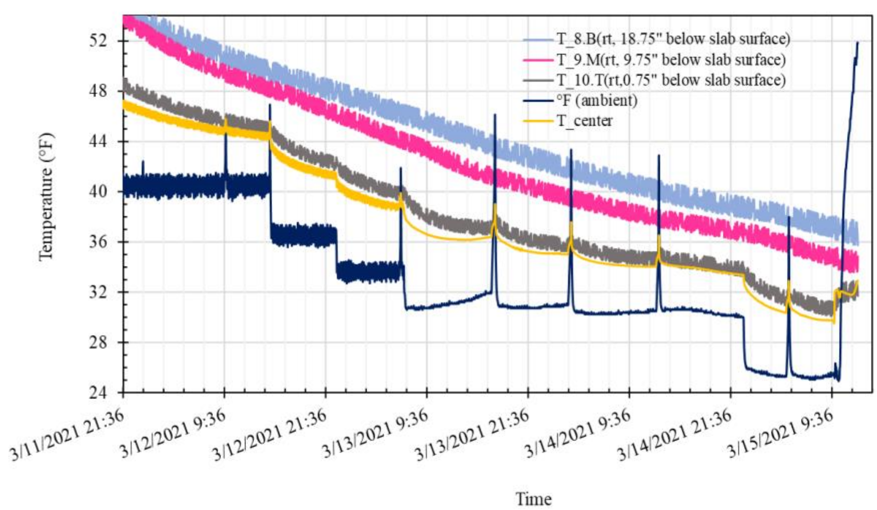


Figure 45. Variation of ambient freezer temperature, slab surface, and slab body during case 1.1 testing

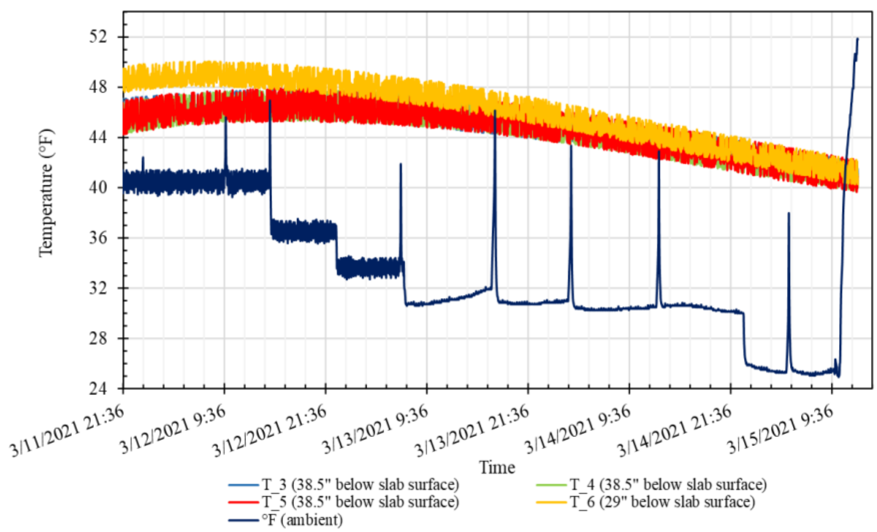


Figure 46. Variation of ambient freezer temperature and soil at mid-depth during case 1.1 testing

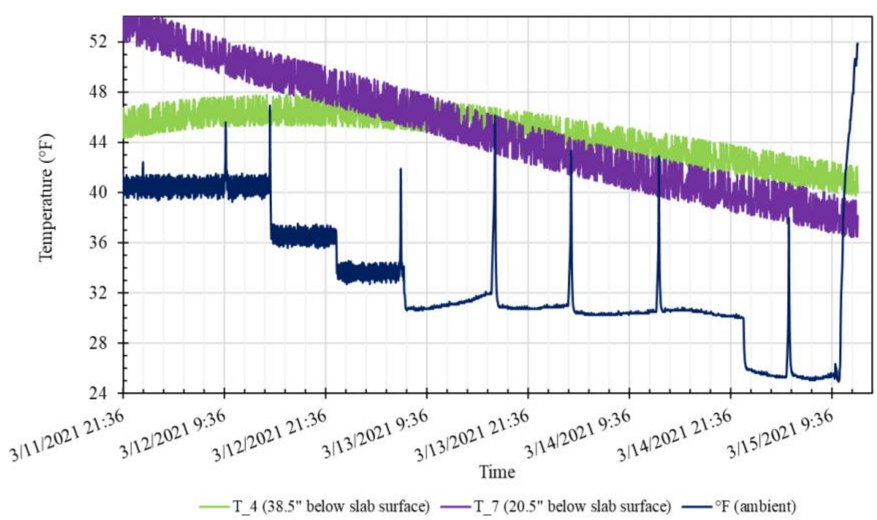


Figure 47. Variation of ambient freezer temperature, soil at mid-depth, and soil at the surface interface during case 1.1 testing

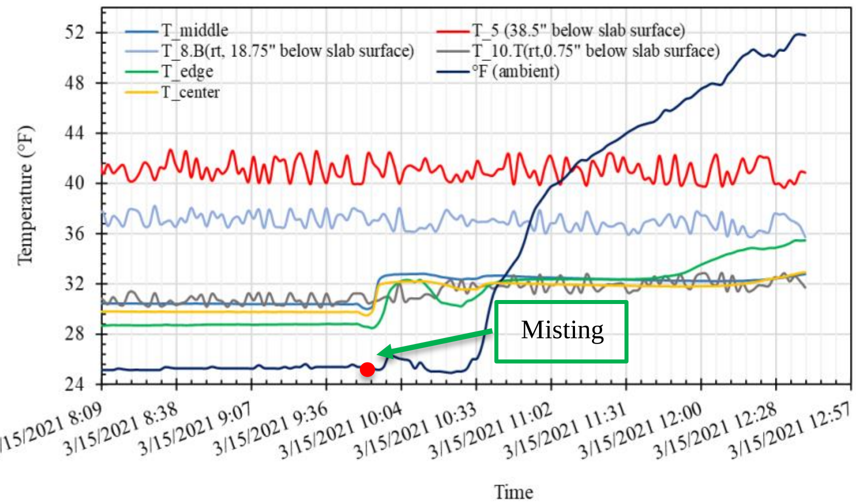


Figure 48. Variation of ambient freezer temperature, slab surface, and 0.75-in below slab surface during case 1.1 misting operation

Final Slab Condition

Photos show the final slab condition for case 1.1. Due to the very fine mist and the slower rate of water droplet deposit onto the slab surface, the formation of a thin glaze of ice covering the entirety of the slab surface was observed to occur 12 minutes after the start of the misting. This glaze is similar to the icing glaze that forms during a freezing rain, drizzle, or fog event.

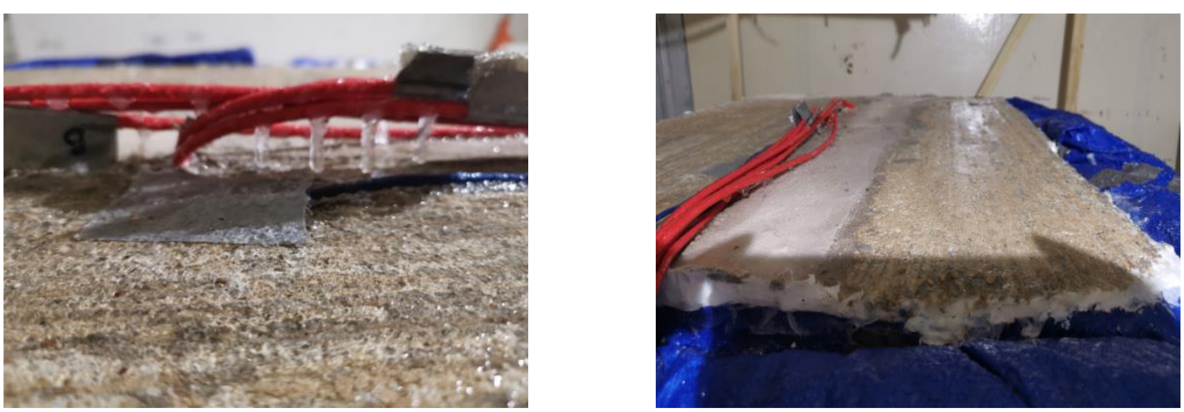


Figure 49. Final slab condition with the formation of glaze after case 1.1 testing

Case 2.1

During this test, the freezer temperature was decreased quickly to a final temperature of 25°F, where it remained for 24.5 hours before the misting operation began. At the start of misting, the temperature of the slab surface was 28°F and the ambient temperature in the freezer box was 24.5°F. The duration of the misting operation was 27.5 minutes, utilizing 54-60 gallons of an ice/water mixture. Ice formation was observed approximately 19 minutes after the start of misting. The chart in Fig 50 illustrates the close relationship of the slab surface temperature and the ambient temperature of the freezer box. Figure 51 indicates the time lag between the surface and the body of the slab reaching freezing conditions. From the figure, it can be observed that the sensor located on the edge of the surface follows the temperature profile of the ambient temperature much closer than the sensors at the center of the slab surface. This indicates that the edge is much more responsive to changes in the surrounding outside environment rather than the internal slab or soil temperature. The vertical profile in Fig 52 shows that after being at a setting of 15°F for a period of 12 hours, the temperature of the slab decreased an average of approximately three degrees, while the soil decreases an average of approximately two degrees.

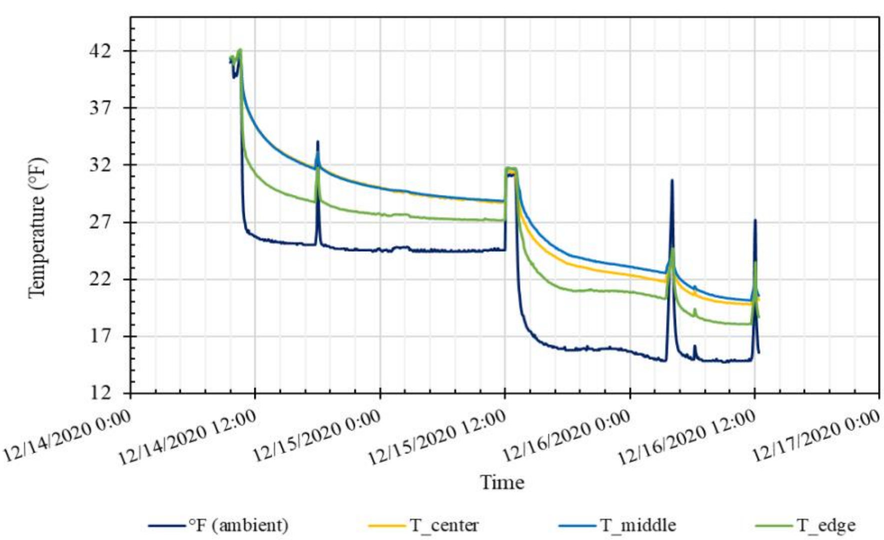


Figure 50. Variation of ambient freezer temperature and slab surface

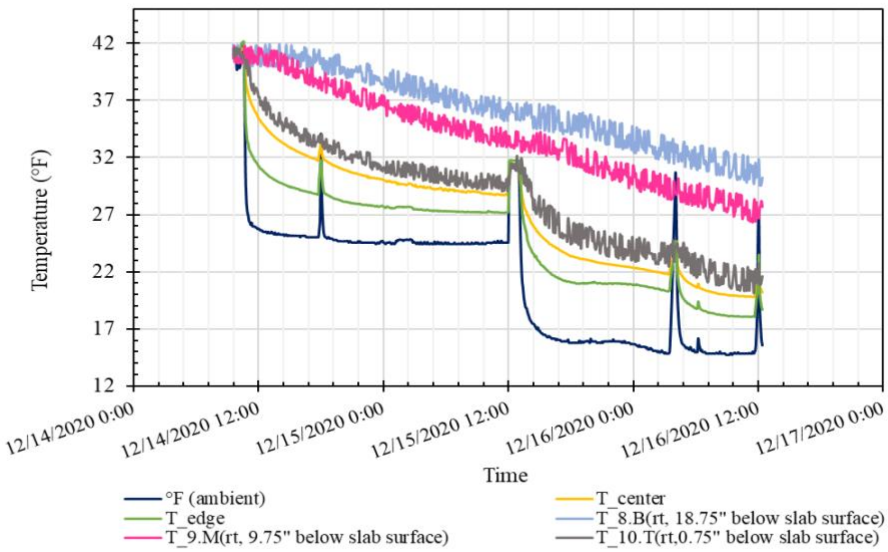


Figure 51. Variation of ambient freezer temperature and slab body

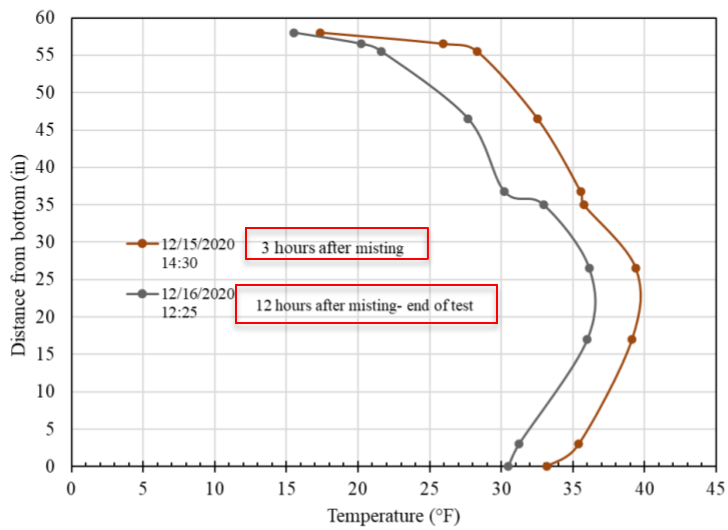


Figure 52. Vertical profile of temperature variation in the system

Photos taken during the testing indicate the formation of ice. This occurred 19 minutes after the beginning of the misting operation, with observation of the ice solidifying further 15 minutes after the misting operation ended (Fig 53).

(a) **(b)** **(c)**

Figure 53. (a): Slab surface under dry conditions (b): Slab surface 20 minutes into misting (c): Slab surface 15 minutes after misting

Final Slab Condition

As a result of the longer misting duration, ice formation was observed not only along the slab edges and corners, but also further down the length of the body of the slab as well as toward the middle. When physically observed, the coating of ice was found to be non-uniform with the thickest ice forming on the portion of the slab closest to the misting nozzles. As the distance from the nozzles increased, the surface ice decreased in both thickness and occurrence (Fig 54).

(a) **(b)**

Figure 54. (a): Ice formation on the slab surface (b): Thicker ice formation closer to the misting nozzle

Case 3.2

During this test, the freezer box was at a steady state condition of 25°F. The freezer was turned off and one door was slightly opened. The relative humidity of the outside air was 32% to 27% during the test. The outside air temperature was 66°F at the beginning of the test and 68°F at the end. Figure 55 shows the ambient freezer box temperature, the relative humidity in the freezer, the slab surface temperature, as well as the dew point during testing. For frost conditions to occur, the surface temperature of the slab must converge or drop below the dewpoint while the surface is at or below freezing. As indicated in the figure, there is a period of time during the test where the slab surface temperature drops below the dewpoint. Although this occurs while the slab surface is below freezing, the formation of frost is not observed. This can possibly be attributed to the relatively low humidity in the outside air lacking the moisture needed for condensation to occur.

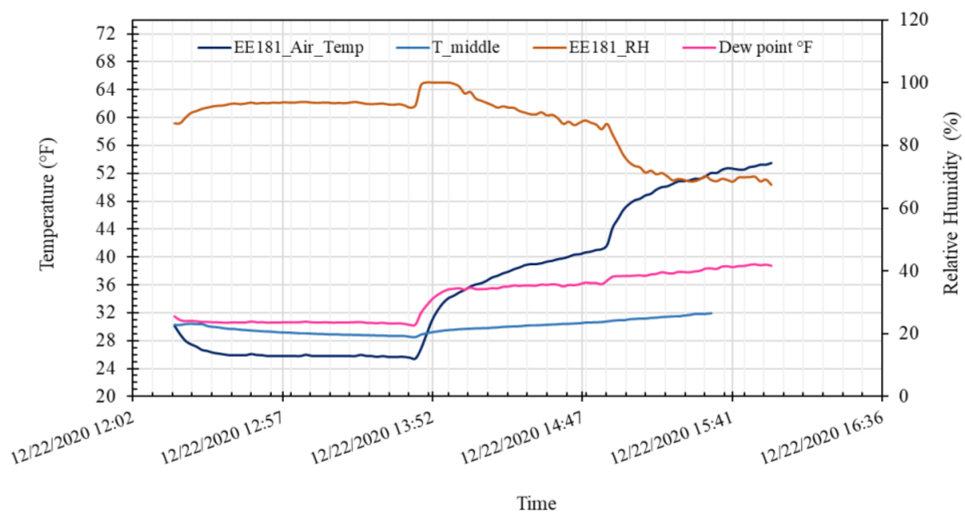


Figure 55. Variation of ambient freezer temperature, slab surface, relative humidity, and dew point during testing

Case 3.5

During this test, the freezer box began at a steady state condition of 25°F. The freezer was turned off, one door was opened slightly, and an electric kettle was used to introduce additional moisture into the freezer box. The relative humidity of the outside air at the start of the test was 90%, and 86% by the end of the test. .The outside temperature was 49°F at the beginning of the test and 50°F at the end. Figure 56 shows the ambient temperature, the relative humidity in the freezer, slab surface temperature, as well as the dew point during testing. For frost conditions to occur, the surface temperature of the slab must converge or drop below the dewpoint while the surface is at or below freezing. As indicated in the figure, the slab surface temperature was below the dewpoint when the electric kettle begins to boil. Approximately 40 minutes after the introduction of the additional moisture, the formation of a light frost was observed.

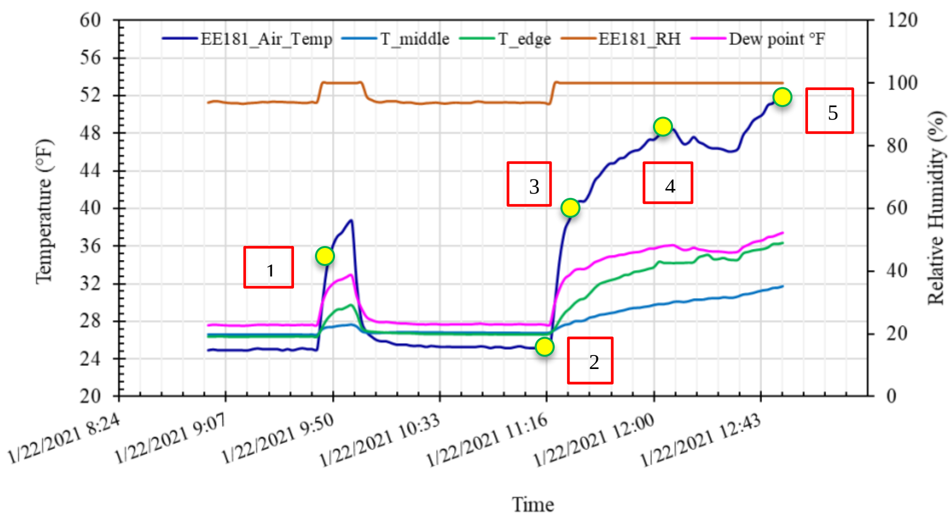


Figure 56. Variation of ambient freezer temperature, slab surface, relative humidity, and dew point during testing

Table 14. Test log corresponding to Fig 56

Stage	Time (hr.)	Action	Description
1	9:44 am	Cameras installed	Freezer is opened for camera installation and then closed and allowed to return to 25°F for 1.50 hours.
2	11:18am	Installation of kettle into freezer	Freezer is turned off, one door opened slightly, electric kettle is introduced into freezer, relative humidity of the freezer is monitored.
3	11:32am	Moisture introduced	Introduction of moisture via the kettle boiling.
4	12:07pm	Frost observed	The formation of a light frost on the slab surface is visually observed.
5	12:50pm	End of test	The test concludes, freezer turned back to 25°F.

Final Slab Condition

A light coating of frost was observed along the edges as well as toward the center of the slab approximately 40 minutes after the kettle begins to boil. This can be attributed to the introduction of the steam from the boiling kettle creating enough moisture in the air for condensation resulting in frost formation to occur (Fig 57).

Figure 57. Light coating of frost on the surface of the slab

Case 3.6

During this test, the freezer box began at a steady state of 25°F. The freezer was turned off and one door was opened slightly, and the electric kettle was installed. However, the formation of frost was observed due to the natural humidity creating sufficient moisture in the air for condensation to occur prior to the kettle boiling. The relative humidity of the outside air was 58% at the start of the test and 47% at the end the test. The outside temperature was 47°F at the beginning of the test and 55°F at the end. Figure 58 shows the ambient freezer box temperature, the relative humidity in the freezer, the slab surface temperature, as well as the dew point during testing. As indicated in the figure, the slab surface temperature dropped below the dewpoint while the slab was at freezing conditions. As previously observed in case 3.5, the formation of frost occurs approximately 40 minutes after the dewpoint and slab surface temperature converge with the surface temperature dropping below the dew point temperature. It should be noted that although the conditions in the freezer box differ from the conditions in case 3.5, the time duration required for the formation of frost is almost identical. From these two cases, it can be inferred that when the temperature of a surface converges on or falls below the dew point and freezing conditions are present, the formation of frost can be expected within a 35 to 45 minute time frame.

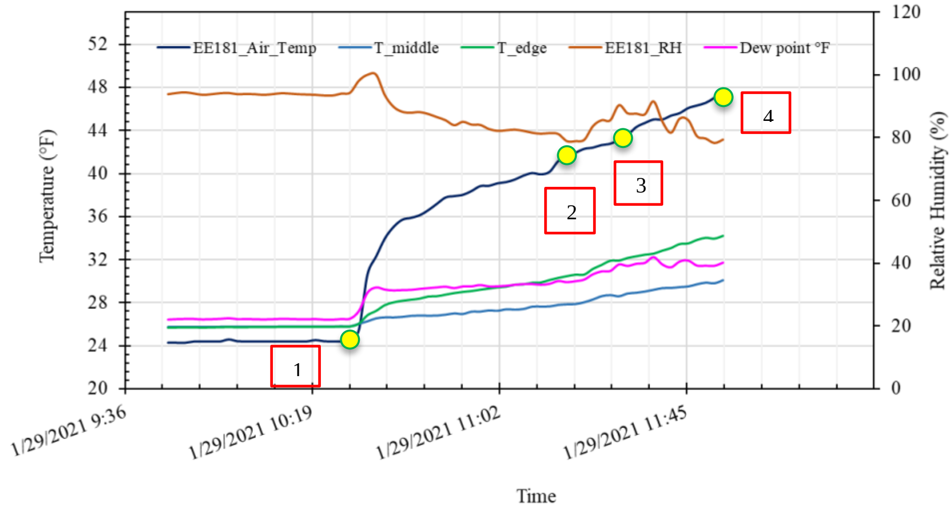


Figure 58. Variation of ambient freezer temperature, slab surface, relative humidity, and dew point during testing

Table 15. Test log corresponding to Fig 58

Stage	Time (hr.)	Action	Description
1	10:28am	Freezer off	Freezer is turned off, one door is opened slightly, relative humidity in the freezer is monitored.
2	11:16am	Frost observed	The formation of a light frost on the slab surface is visually observed.
3	11:21am	Moisture introduced	Introduction of moisture via the kettle boiling.
4	11:53am	End of test	The test concludes, freezer turned back to 25°F.

Final Slab Condition

A layer of frost was observed along the edges as well as into the center of the slab surface as indicated in Fig 59. The formation of the frost layer was observed approximately 40 minutes after the introduction of the humid outside air. When visually observed, this layer appeared to be slightly thicker than the one produced in case 3.5 with the moisture from the electric kettle.

Figure 59. Fine layer of frost on the slab surface

Table 16 provides a summary of the case results presented within this chapter that involve precipitation. Table 18 provides a summary of the case results that did not involve precipitation. Results and observations from the baseline tests are also included for completeness (Table 17).

Table 16. Summary of results for tests with precipitation

Case 1 22 hours	**Initial Conditions**	**Final Conditions**	**Temperature Change**	**Rate of Change (per hour)**
Ambient	40°F	30.4°F	-9.6°F	-0.44°F
Slab Surface	41.7°F	33.4°F	-8.3°F	-0.34°F
Slab Body	41.8°F	37.3°F	-4.5°F	-0.21°F
Soil	38.5°F	37.6°F	-0.9°F	-0.04°F
Observation	The soil cools at a much slower rate than the ambient air, preventing the slab from reaching freezing conditions. As a result, no ice formation is observed.			

Table 16 cont: Summary of results for tests without precipitation

Case 1.1 96 hours	**Initial Conditions**	**Final Conditions**	**Temperature Change**	**Rate of Change (per hour)**
Ambient	70°F	43.8°F	-26.2°F	-0.27°F
Slab Surface	57.7°F	31.9°F	-25.8°F	-0.27°F
Slab Body	51.9°F	34.4°F	-17.5°F	-0.18°F
Soil	40.7°F	39.3°F	-1.4°F	-0.02°F
Observation	Due to the surface being exposed to freezing conditions for such a long duration, the ambient temperature overcomes the soil's influence on the surface. The formation of glaze is observed 12 minutes after the beginning of the misting operation.			
Case 2.1 49 hours	**Initial Conditions**	**Final Conditions**	**Temperature Change**	**Rate of Change (per hour)**
Ambient	41°F	15.5°F	-25.5°F	-0.52°F
Slab Surface	41.4°F	20.2°F	-21.0°F	-0.43°F
Slab Body	41.4°F	34.7°F	-14.9°F	-0.30°F
Soil	40.2°F	26.5°F	-5.5°F	-0.11°F
Observation	The ambient air has more of an effect on the slab temperature, due to the longer duration of cold temperature exposure. The formation of ice is observed 19 minutes after the beginning of the misting operation.			

Table 17. Summary of results for baseline tests

Baseline Cooling Case 95.5 hours	**Initial Conditions**	**Final Conditions**	**Temperature Change**	**Rate of Change (per hour)**
Ambient	68.7°F	23.7°F	-45.0°F	-0.47°F
Slab Body	61.8°F	31.5°F	-30.3°F	-0.32°F
Soil	61.6°F	39.4°F	-21.7°F	-0.23°F
Observation	The ambient temperature decreases at a faster rate than the soil by double, allowing for a slower cooling rate of the slab body. It should be noted here that the surface thermocouples were not yet installed for this baseline test.			
Baseline Warming Case 145 hours	**Initial Conditions**	**Final Conditions**	**Temperature Change**	**Rate of Change (per hour)**
Ambient	37.0°F	59.7°F	+22.7°F	+0.16°F
Slab Body	27.9°F	59.4°F	+31.5°F	+0.22°F
Soil	32.6°F	51.8°F	+19.2°F	+0.13°F
Observation	The slab body experiences a larger temperature increase than the ambient temperature, coming close to converging with it by the end of the test. It should be noted here that the surface thermocouples were not yet installed for this baseline test.			

Table 18. Summary of results for tests without precipitation

Case 3.2 3.50 hours	**Initial Conditions**	**Final Conditions**	**Temperature Change**	**Rate of Change (per hour)**
Ambient	25°F	52.4°F	+23.2°F	+10.7°F
Slab Surface	26.5°F	33.2°F	+6.0°F	+2.77°F
Slab Body	26.9°F	28.1°F	+1.2°F	+0.1°F
Soil	26.9°F	26.8°F	-0.8°F	-0.4°F
Observation	The surface is influenced by the warmer ambient air entering the freezer, but it is still evident that the cooler soil affects the rate of the temperature change by observing that the surface cools at a rate that is one fifth of the ambient rate. No frost formation was observed for this test.			
Case 3.5 3.50 hours	**Initial Conditions**	**Final Conditions**	**Temperature Change**	**Rate of Change (per hour)**
Ambient	25°F	52.4°F	+27.4°F	+7.80°F
Slab Surface	26.5°F	33.2°F	+6.7°F	+1.90°F
Slab Body	26.9°F	28.1°F	+1.2°F	+0.34°F
Soil	26.9°F	26.8°F	-0.1°F	-0.29°F
Observation	The effects of the ambient air are not as evident here, although it is interesting to note that at the end of the test, the edge sensor was 36.3°F while the middle of the surface was only 31°F. This illustrates that the edge of the slab is influenced to a large extent by the surrounding environment rather than the system's internal environment. Frost is observed approximately 40 minutes after the introduction of moisture in the form of steam.			

Table 18 cont: Summary of results for tests without precipitation

Case 3.6 2.15 hours	**Initial Conditions**	**Final Conditions**	**Temperature Change**	**Rate of Change (per hour)**
Ambient	24.3°F	47.7°F	+23.4°F	+10.9°F
Slab Surface	25.7°F	31.5°F	+5.8°F	+2.7°F
Slab Body	25.6°F	26.4°F	+0.8°F	+0.37°F
Soil	26.7°F	26.5°F	-0.2°F	-0.09°F
Observation	Here it can be noted that the edge surface sensor read 34.2°F, while the middle was 30.2°F. The difference of four degrees can be attributed to the influence of the ambient temperature on the boundaries of the slab versus the inner portions. The formation of a light frost is observed approximately 40-47 minutes after the introduction of moisture via the humid outside air.			

CHAPTER V

SUMMARY AND CONCLUSIONS

5.1 Summary

Pavement response to cold fronts is influenced by both meteorological and subsurface factors. This makes it crucial to understand both to prepare for winter pavement maintenance as well as to have a reasonable time frame for the expectancy of the formation of ice as it relates to weather conditions. Heat transfer taking place within the subsurface layers has a direct effect on the surface above. The surface is also impacted by environmental factors, although it is observed that the subsurface has a more influential effect. There has not been extensive testing in a controlled environment, which is the focus of the work presented in this thesis.

A model column consisting of collected soil samples and a pavement sample was used to replicate a pavement structure with sub soil. The soil was tested according to ASTM standards and classified as sandy lean clay using the USCS guidelines. The soil was compacted in lifts into the column, with thermistors and moisture sensors installed throughout. The slab was fitted with 6 thermistors inside its body and 3 thermocouples on the surface. The system was installed into a freezer box where it was wrapped in R30 insulation and plastic to prevent any moisture from seeping into the system during simulated precipitation events. R30 insulation was also installed between the bottom of the soil column and the freezer box floor to protect the lower soil layers. Twelve different tests designed using historic local weather information were performed and extensive data was collected.

The laboratory investigation is followed by an analysis and discussion of the results obtained. The pavement response to cold fronts was analyzed by simulating several different winter weather scenarios. A gradual temperature decrease to freezing conditions, a rapid temperature decrease to freezing conditions, and a rapid increase in temperature from freezing to above freezing. Some scenarios involved precipitation while others relied on the moisture in the freezer environment to create condensation to explore the phenomena of the formation of black ice.

5.2 Conclusions

The conclusions drawn from the analysis of the data collected during the laboratory investigation and the results obtained are as follows:

Performance in Simulated Field Conditions

A model column was built to replicate a slice of an airport runway and its subsoil. R30 insulation was wrapped around the column and placed underneath it to create a one-dimensional system. After a baseline test, it was discovered that the bottom most layers of the soil column were not sufficiently protected from the freezer conditions and an additional layer of insulation was added. Although this additional layer was not effective, the layers of interest in the soil column are located 38.5-in below the slab surface. Due to this fact, the testing results were not adversely effected. The lateral temperature variation within the mid-layer (38.5-in below slab surface) was monitored to determine if the conditions in the field were being replicated. From the data it was found that the lateral temperature variation was less than 1°F, illustrating that the lateral heat transfer was negligible, and replication of field conditions was successful. Analysis of the volumetric moisture content shows that the variation is negligible. This illustrates that the plastic wrap around the system and the sealing of the tarp were effective measures to keep the moisture in the soil constant.

Surface Temperature Response to Cold Fronts

The scenarios tested were designed using weather scenarios based on historic field observation data provided by DFW. Initially, testing scenario procedures were designed based on the ambient temperature of the freezer box. After analysis of both the baseline tests and case 1 test results, it was observed that the response of the system to temperature changes is not immediate. When compared to the field data, the rate of the surface temperature change is much slower than that of the ambient temperature change. Based on this observation, the remaining scenarios placed a greater emphasis on the temperature of the slab surface as the deciding factor for when to proceed to the next stage in a testing procedure. The difference in this rate of change can be attributed to the thermal capacity of both the pavement slab and the soil beneath. However, upon further analysis of the results it is evident that the thermal inertia of the soil is much greater than that of the slab and exerts more influence on the response behavior of the slab surface.

Formation of Ice Due to Precipitation

Icing is controlled by the pavement surface temperature and the moisture condition. It is important to note that the degree of icing is dependent on the intensity and the duration of a precipitation event. The simulated precipitation events ranged from 20 to 40 minutes in duration and the precipitation did not begin until the pavement surface temperature had reached a minimum of 32°F. The water used for the precipitation was cooled using 20 lb. bags of ice and the temperature was monitored to ensure that it was close to 32°F before beginning any misting operation. Analysis of the results from these tests show that if freezing conditions on the slab surface are present and there is sufficient precipitation coverage, the formation of ice can be expected to occur on the surface 12 to 20 minutes after the start of the precipitation event. This time frame is observed to repeat under different testing conditions for cases 1.1, 2.1, and 4.

Formation of Ice Due to Condensation

Icing can occur due to the formation of condensation. This is typical in the formation of frost and black ice. For tests that relied on the moisture in the freezer air to create condensation, it is observed from the data that when there are freezing conditions present and the slab surface temperature falls below the dew point temperature, the development of a frost layer can be expected to form starting 40 minutes after the beginning of the formation of condensation accompanied by the surface temperature falling below the dew point temperature. This condition was observed during two of the case 3 tests. One test was performed using the boiling kettle as the source for condensation, while the second test used only the moisture from the outside air to create condensation. It should also be noted that each of these successful tests were conducted with differing outside temperatures and relative humidity levels.

5.3 Recommendations

This section provides a list of recommendations that may improve the laboratory investigation and subsequent analysis of the pavement response to cold fronts.

1. It would benefit the laboratory investigation to devise a method for considering solar radiation, perhaps through the use of a sunlamp to explore the warming effects of the radiation waves when the air and pavement surface are both cold.
2. The installation of both a fan and heater in the freezer box would be beneficial to examine the role that wind plays when there is a layer of warm air present.

3. The manipulation of the relative humidity in the freezer box for the investigation of the formation of black ice at lower humidity levels may benefit from the utilization of a commercial desiccant dehumidifier.
4. A final recommendation would be to install some type of air temperature sensor suspended approximately 5 inches above the surface of the pavement to observe what effects that pavement surface has on the air immediately above it.

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Appendix 1

Test Results for Other Cases

Table 19 provides a summary of the tests performed involving misting operations. Table 20 provides a summary of tests performed that did not involve any precipitation. A more comprehensive analysis of the results for the tests, including plots and photographs, follows.

Table 19. Summary of results for tests with precipitation

Case 2 41 hours	**Initial Conditions**	**Final Conditions**	**Temperature Change**	**Rate of Change (per hour)**
Ambient	55°F	14.8°F	-40.2°F	-0.98°F
Slab Surface	46.3°F	21.3°F	-25.0°F	-0.61°F
Slab Body	41.9°F	28.1°F	-13.8°F	-0.34°F
Soil	40.4°F	36.0°F	-4.4°F	-0.11°F
Observation	The soil responds to the decrease in temperature at a slower rate than the slab surface or body. No ice formation is observed during the misting operation as a result of evaporation occurring before the droplets could freeze. At the end of the test, some non-uniform icing is observed where puddling may have occurred, most prominently at the edges of the slab in close proximity to the misting nozzles.			

Table 19 cont: Summary of results for tests with precipitation

Case 4 46 hours	**Initial Conditions**	**Final Conditions**	**Temperature Change**	**Rate of Change (per hour)**
Ambient	39.2°F	26.8°F	-12.4°F	-0.27°F
Slab Surface	40°F	32.0°F	-8.0°F	-0.17°F
Slab Body	37.7°F	32.0°F	-5.7°F	-0.12°F
Soil	32.2°F	31.4°F	-0.8°F	-0.02°F
Observation	During the test, the soil response to the decrease in temperature is negligible, illustrating the influence of the soil's thermal capacity on its response. This influence can also be observed when considering the difference in the change between the ambient temperature and the slab temperature. Ice formation is observed 10 minutes after the start of the misting operation, with the layer continuing to thicken throughout the remaining duration of the test.			

Table 20. Summary of results for tests without precipitation

Baseline Cooling Case 95.5 hours	**Initial Conditions**	**Final Conditions**	**Temperature Change**	**Rate of Change (per hour)**
Ambient	68.7°F	23.7°F	-45.0°F	-0.47°F
Slab Body	61.8°F	31.5°F	-30.3°F	-0.32°F
Soil	61.6°F	39.4°F	-21.7°F	-0.23°F
Observation	The ambient temperature decreases at a faster rate than the soil by double, allowing for a slower cooling rate of the slab body. It should be noted here that the surface thermocouples were not yet installed for this baseline test.			

Table 20 cont: Summary of results for tests without precipitation

Baseline Warming Case 145 hours	Initial Conditions	Final Conditions	Temperature Change	Rate of Change (per hour)
Ambient	37.0°F	59.7°F	+22.7°F	+0.16°F
Slab Body	27.9°F	59.4°F	+31.5°F	+0.22°F
Soil	32.6°F	51.8°F	+19.2°F	+0.13°F
Observation	The slab body experiences a larger temperature increase than the ambient temperature, coming close to converging with it by the end of the test. It should be noted here that the surface thermocouples were not yet installed for this baseline test.			
Case 3.1 1.32 hours	**Initial Conditions**	**Final Conditions**	**Temperature Change**	**Rate of Change (per hour)**
Ambient	24.8°F	54.5°F	+29.7°F	+22.5°F
Slab Surface	26.0°F	34.0°F	+8.0°F	+6.1°F
Slab Body	28.7°F	29.9°F	+1.2°F	+0.91°F
Soil	31.9°F	31.4°F	-0.5°F	-0.38°F
Observation	The rapid increase in ambient temperature did not translate fully to the system, although the surface increase is substantial, the body of the slab did not reach above freezing conditions. The formation of frost is not observed during this test. It is interesting to note that an increase or no change in the soil temperature is expected, but the soil temperature decreased slightly. This decrease is negligible.			

Table 20 cont: Summary of results for test without precipitation

Case 3.3 7.67 hours	**Initial Conditions**	**Final Conditions**	**Temperature Change**	**Rate of Change (per hour)**
Ambient	24.1°F	24.3°F	+0.20°F	+0.03°F
Slab Surface	25.0°F	26.0°F	+1.0°F	+0.13°F
Slab Body	26.2°F	27.4°F	+1.2°F	+0.16°F
Soil	28.8°F	29.0°F	+0.20°F	+0.03°F
Observation	There is not a significant change in temperature for the system or the ambient freezer during this test. It is interesting to note that the slab experiences a faster rate of temperature increase than the ambient temperature. The formation of frost is not observed for this test.			
Case 3.4 2.17 hours	**Initial Conditions**	**Final Conditions**	**Temperature Change**	**Rate of Change (per hour)**
Ambient	24.8°F	34.9°F	+10.1°F	+4.70°F
Slab Surface	26.3°F	29.3°F	+3.0°F	+1.40°F
Slab Body	26.7°F	27.2°F	+0.5°F	+0.23°F
Soil	29.0°F	29.0°F	+0°F	+0°F
Observation	The ambient temperature experiences a rapid temperature increase, while the slab does not and the soil temperature remains unchanged. The formation of frost is not observed during this test.			

<u>TDT Moisture Sensors</u>

The moisture sensors are located at mid-depth, 38.5-in from the slab surface, and 29-in from the slab surface. Figures 58 and 59 illustrate the variation in volumetric moisture content at mid-depth (38.5-in below the slab surface) for the time period of 09/14/20 to 10/02/20 and

10/26/20 to 12/16/20. It can be observed that there is a slight loss of moisture in September when the system was first installed in the freezer, shortly after the completion of compaction, which is to be expected. The plots show that throughout the testing where misting operations were involved, there was no discernible gain or loss of moisture in the middle layer of the soil column. Likewise, Figs 60 and 61 illustrate the variation in volumetric moisture content 29-in from the slab surface. It can be observed from these figures that the moisture content remained virtually unchanged in this layer of the soil column. These plots illustrate that the plastic wrapping around both the column and the slab kept the system from being infiltrated with moisture during any of the testing that involved a precipitation event.

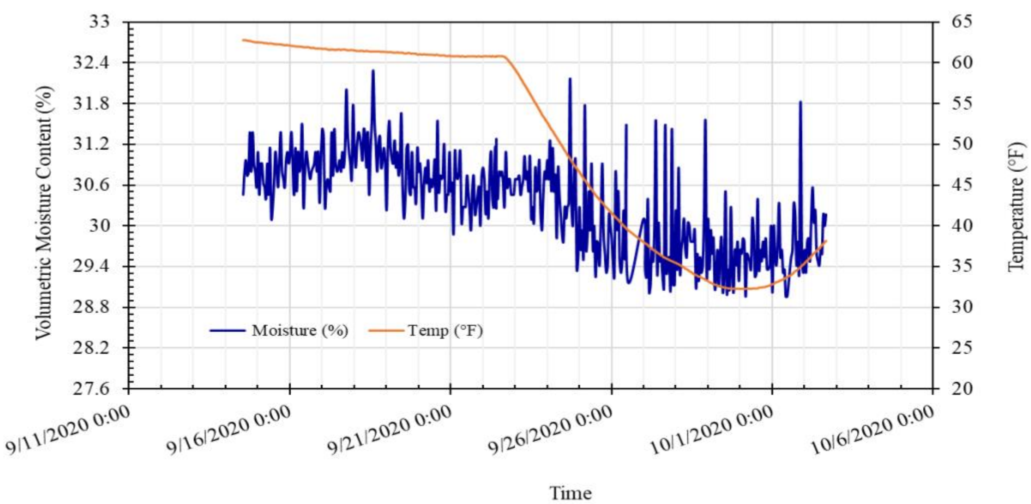


Figure 60. Volumetric moisture content 38.5-in from slab surface 09/14/20 to 10/02/20

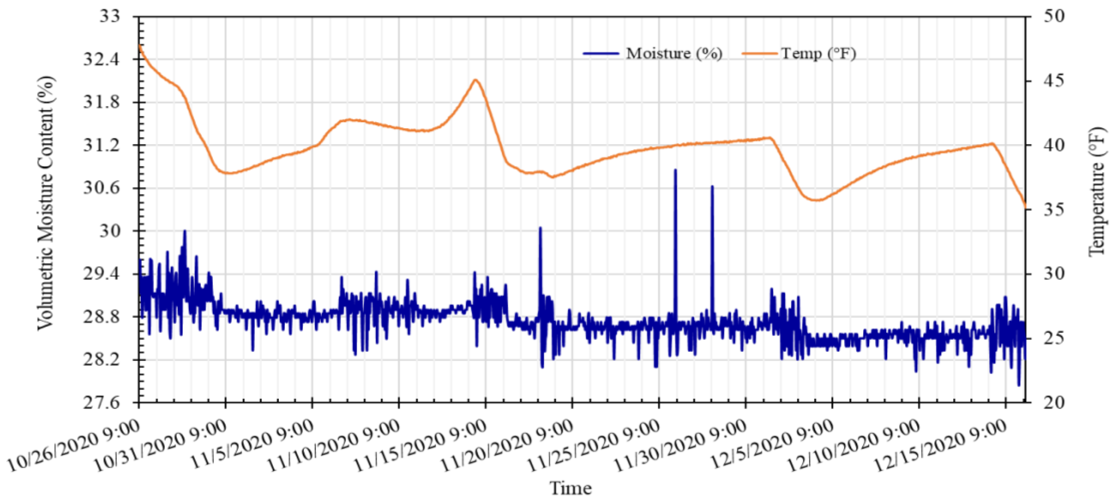


Figure 61. Volumetric moisture content 38.5-in from slab surface 10/26/20 to 12/16/20

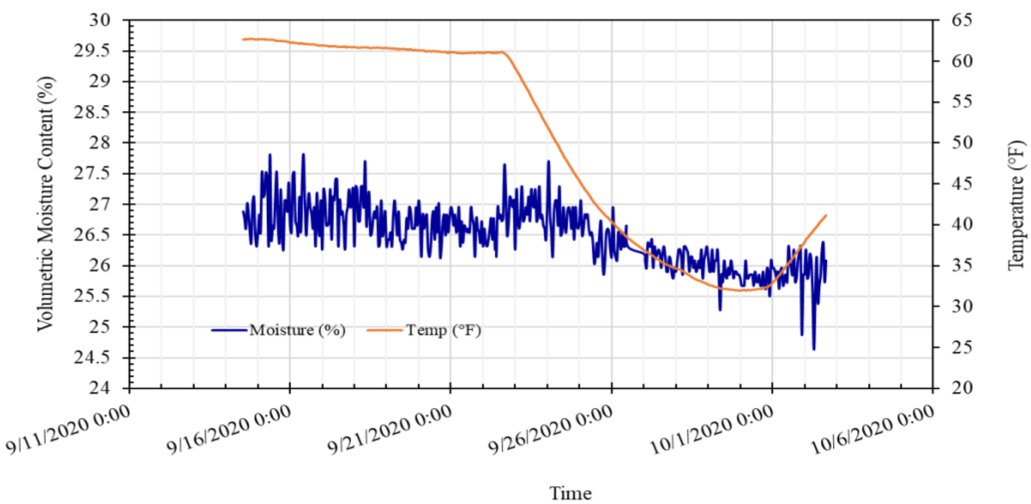


Figure 62. Volumetric moisture content 29-in from slab surface 09/14/20 to 10/02/20

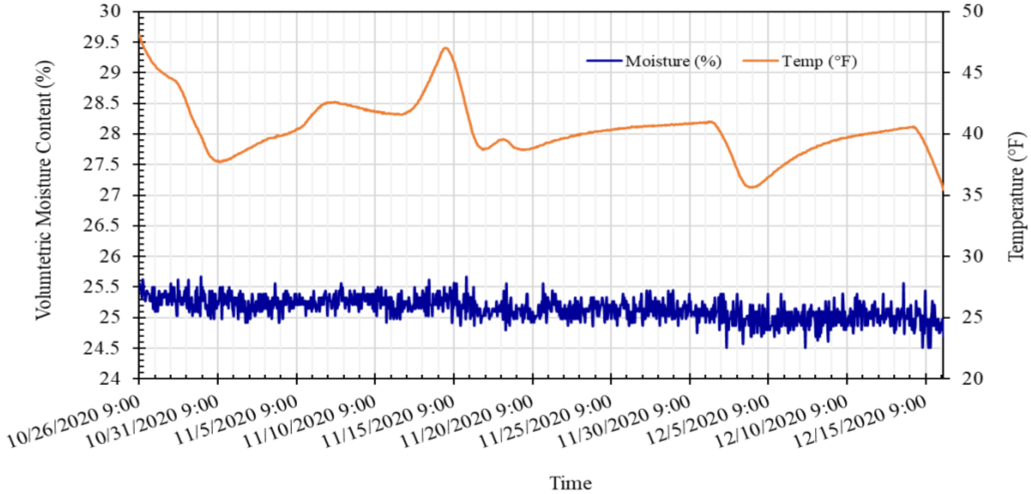


Figure 63. Volumetric moisture content 29-in from slab surface 10/26/20 to 12/16/20

<u>Case 2</u>

During this test, the freezer temperature was decreased rapidly to a final temperature of 25°F, where it remained for 24.5 hours before the misting operation began. At the start of misting, the ambient temperature was 25.6°F and the slab surface temperature was 30.3°F. The misting operation utilized 18-20 gallons of a water/ice mixture with the duration of the misting operation being 8 minutes. Although the slab surface reached freezing conditions, the formation of ice was not observed during misting. Please refer to Fig 64, 65.

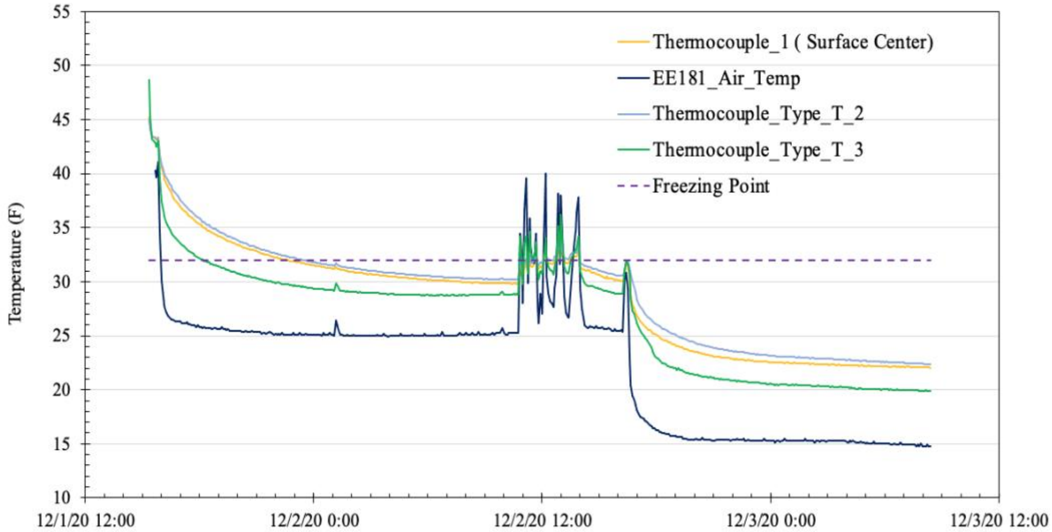


Figure 64. Variation of ambient freezer temperature and slab surface

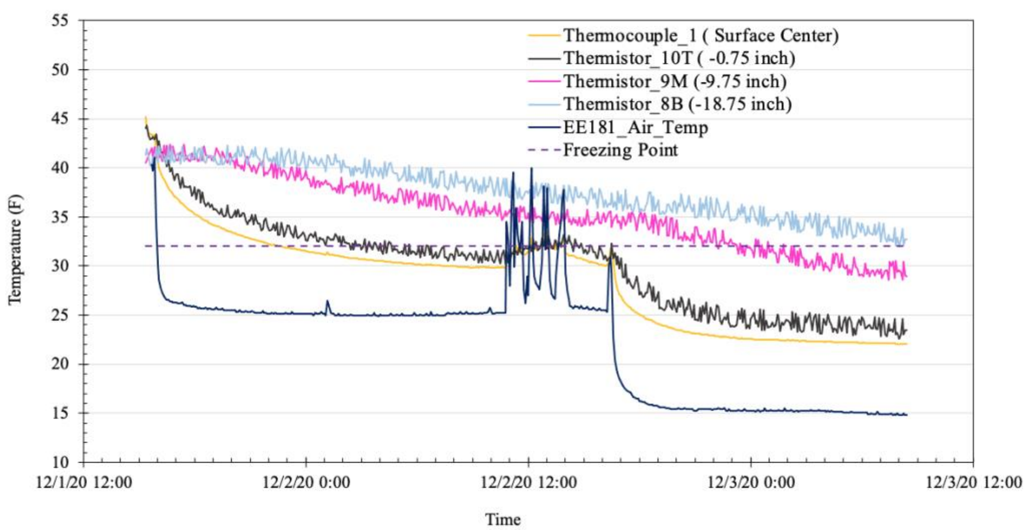


Figure 65. Variation of ambient freezer temperature, slab body, and center slab surface

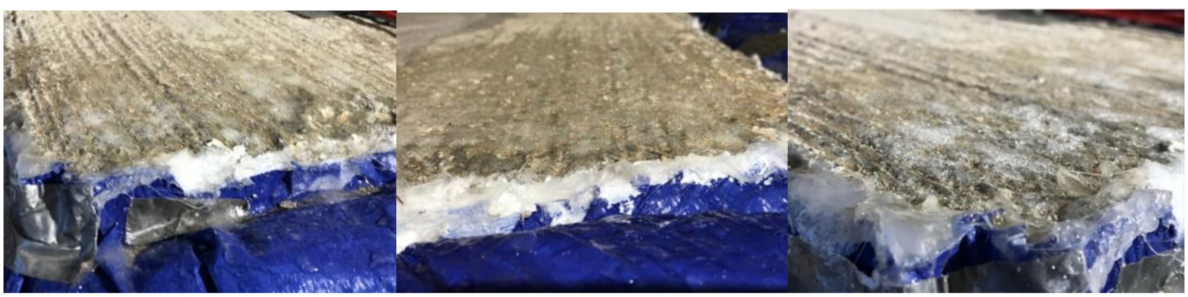
Photos taken during testing indicate that most of the water applied to the surface evaporated before icing could occur (shown in Fig 66).

(a) **(b)** **(c)**

Figure 66. (a): Slab surface 1 hours prior to misting (b): Slab surface during misting (c): Slab surface 3 hours after misting

Final Slab Condition

The test concluded after the freezer box remained at a setting of 15°F for 16.37 hours, upon which time the slab was physically observed. Although most of the water applied during misting had evaporated, non-uniform ice formation was observed along the slab edges and corners located closest to the misting nozzles as indicated in Fig 67. This implies that a longer duration misting operation is needed for better coverage of water on the slab surface to mitigate evaporation.



(a) **(b)** **(c)**

Figure 67. Ice formation along the slab edges and corner

Case 3.1

During this baseline test, the freezer box was at a steady state condition of 25°F. The freezer was turned off and both doors opened completely. The relative humidity of the outside air was 36% at the start and 31% at the end of the test. The outside air temperature was 56°F at the start and 66°F at the end of the test. Figure 68 shows the ambient freezer box temperature, the relative humidity in the freezer, the slab surface temperature, as well as the dew point during testing. For frost conditions to occur, the surface temperature of the slab must converge on or drop below the dew point while the surface is at or below freezing. As indicated in the figure, the ambient temperature increases too quickly to achieve a condition for the possibility of frost formation. By the time the temperature of the slab surface converged or dropped below the dew point, the surface of the slab had already reached a temperature above freezing, negating the opportunity of frost formation.

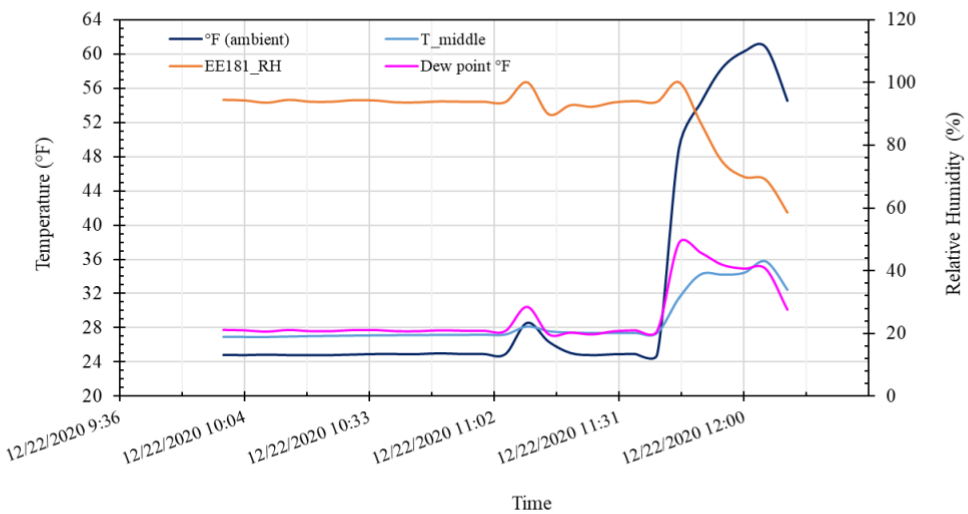


Figure 68. Variation of ambient freezer temperature, slab surface, relative humidity in freezer, and dew point during testing

Case 3.3

During this test, the freezer box was at a steady state condition of 25°F. The freezer was turned off and one door was slightly opened. The relative humidity of the outside air was 49% at the beginning of the test and 46% at the end. The outside air temperature was 37°F at the start and 38°F at the end of the test. Figure 69 shows the ambient freezer box temperature, the relative humidity in the freezer, the slab surface temperature, as well as the dew point during testing. As indicated in the figure, the slab surface temperature remained above the dew point temperature. As a result, conditions for the possibility of frost formation were not met during this test.

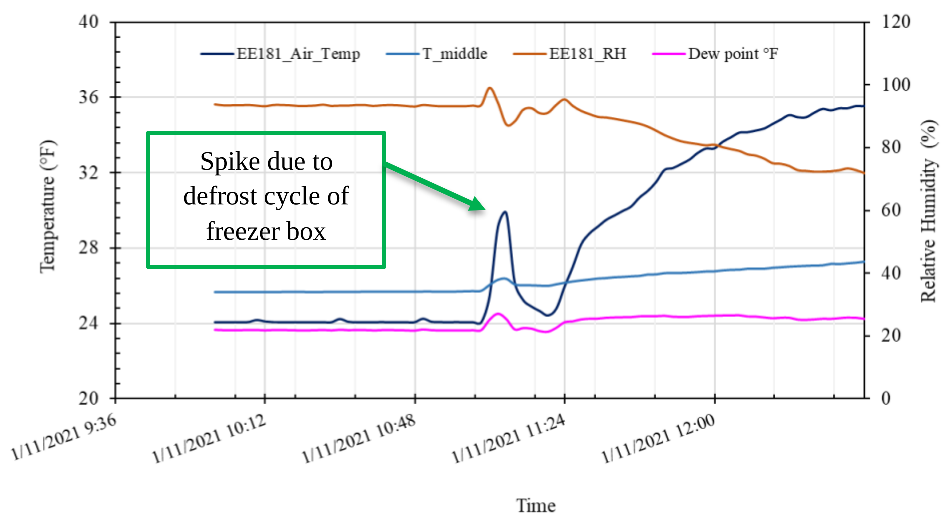


Figure 69. Variation of ambient freezer temperature, slab surface, relative humidity in freezer, and dew point during testing

Case 3.4

During this test, the freezer box began at a steady state condition of 25°F. The freezer was turned off, one door was opened slightly, and a coffee maker was used to introduce additional moisture into the freezer box. The relative humidity of the outside air was 20% at the start and 18% at the end of the test. The outside air temperature was 61°F at the start and 56°F at the end of the test. Figure 70 shows the ambient temperature, relative humidity in the freezer, slab surface temperature, as well as the dew point during testing. After the freezer door was opened, the relative humidity in the freezer box decreased rapidly and remained around 50%, this can be attributed to the very low humidity of the outside air. The slab surface temperature remained above the dew point as well, indicating that frost formation is not a possibility for this scenario.

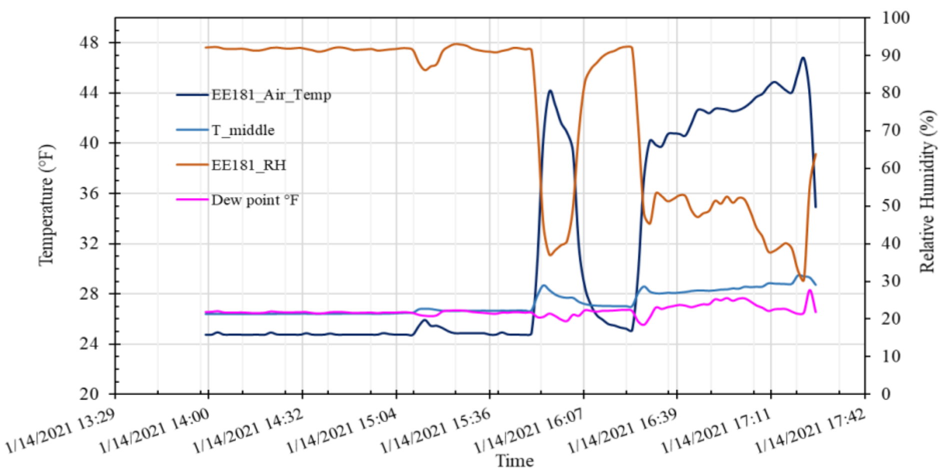


Figure 70. Variation of ambient freezer temperature, slab surface, relative humidity in freezer, and dew point during testing

<u>Case 4</u>

During this test, one freezer door was opened slightly to allow the cold outside air to influence the inside temperature of the freezer box to create a field-like condition, the door remained opened for a period of approximately 45 hours before misting began. The outside air temperature was 31°F at the start and 26°F at the end of the test. The duration of the misting operation was 21 minutes, ice formation was observed 10 minutes after misting began with the ice layer continuing to solidify after the misting ended. Figure 71 shows the variation between the ambient freezer temperature, the outside temperature, and the slab surface. It can be observed that the surface of the slab did not reach freezing conditions until 24 hours after the freezer box ambient temperature had reached below freezing conditions, even then the slab barely achieved a temperature below 32°F. Figure 72 shows the difference in time that it takes for the surface of the slab to cool in comparison with the body of the slab. T_10 is approximately 0.75 inches from the surface of the slab, and it exhibits the same cooling trend as that of T_center which is directly over T_10. Further into the body of the slab, there is little temperature decrease and the body of the slab does not reach freezing conditions at any point during the 46-hour test. Figure 73 shows the soil temperature at mid-depth (T_4 and T_5) as well as 20.5-in from the slab surface (T_7), it can be noted that the mid-depth layer remained at a constant temperature, while the soil at the interface experienced only a slight decrease in temperature. This can be attributed to the thermal capacity of the soil in the subsurface.

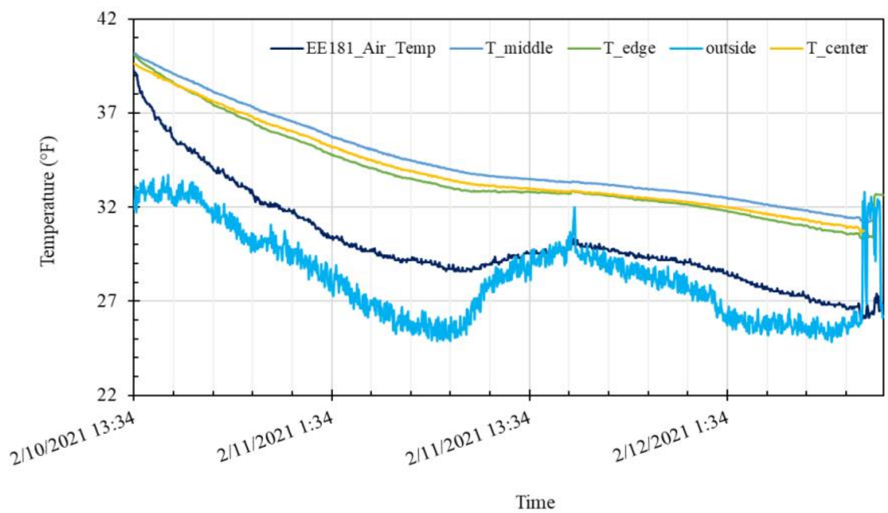


Figure 71. Variation of outside air temperature, ambient freezer temperature, and slab surface

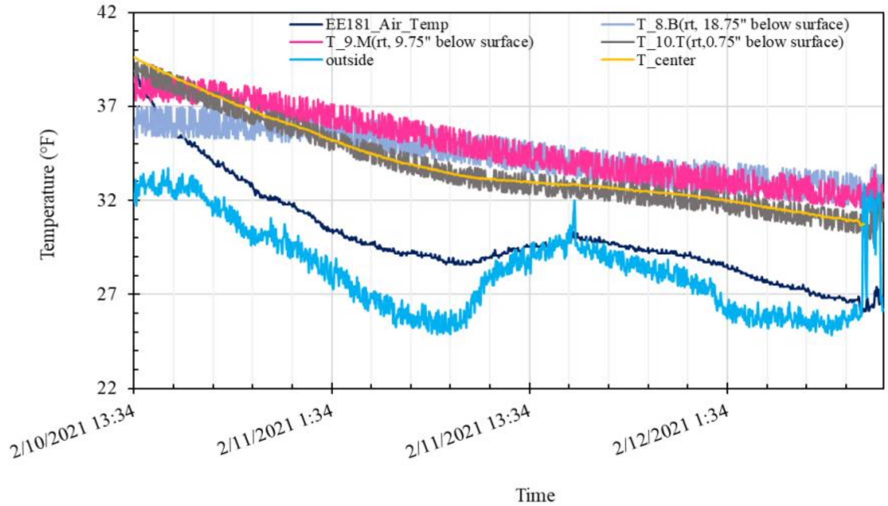


Figure 72. Variation of outside air temperature, ambient freezer temperature, slab surface, and slab body

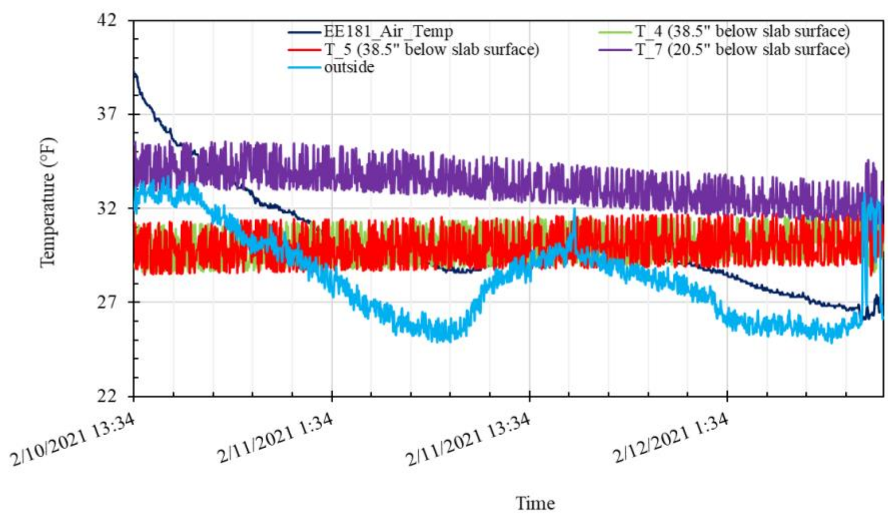


Figure 73. Variation of outside air temperature, ambient freezer temperature, soil at mid-depth, and soil at interface

Final Slab Condition

Ice formation was observed approximately 10 minutes after the start of the misting operation. Figure 74 below shows the final slab condition after testing. A thick layer of ice formation was observed.

Figure 74. Ice formation on slab surface after Case 4 misting operation

Appendix 2

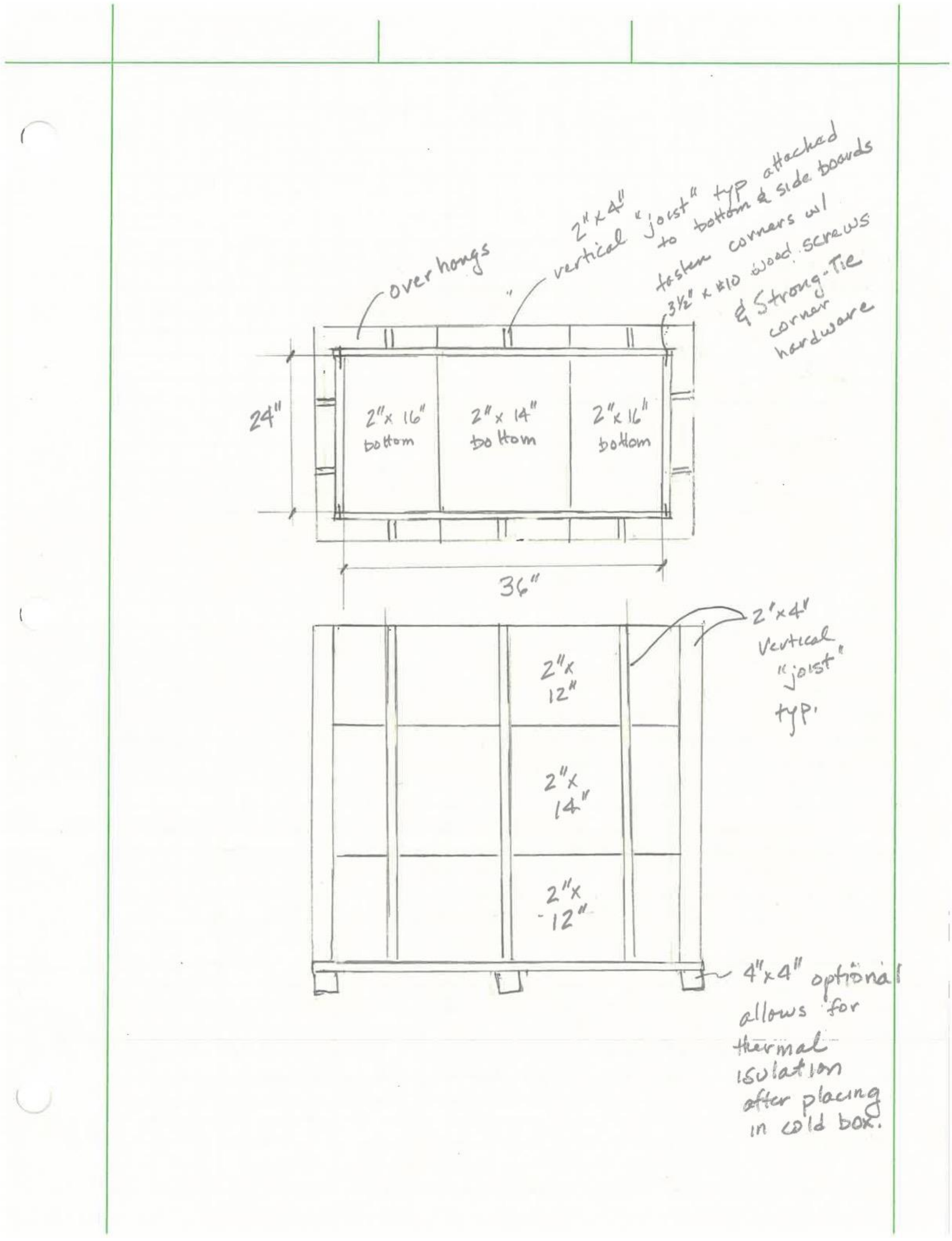


Figure 75. Hand sketch of soil box design (Source: Kruzic, 2020)

Table 21. Results of wet sieve analysis

Bucket #1	
Total Weight of Sample (g)	456.11
Mass Dry Passing $M_{dry\ pass}$ (g)	193
Percent Passing #200 (%)	57.69
Bucket #2	
Total Weight of Sample (g)	505.1
Mass Dry Passing $M_{dry\ pass}$ (g)	220
Percent Passing #200 (%)	56.44
Avg Percent Passing #200 (%)	**57.07**

Table 22. Liquid limit results for sample 1

Bucket #1					
Liquid Limit	Test 1	Test 2	Test 5	Test 4	Test 3
Tin #	2	12	7	1	3
Mass of Tin, M_{tin} (g)	35.08	35.01	26.44	26.3	26.68
Mass of Tin + Wet Soil, $M_{tin+wet}$ (g)	47.27	46.18	41.72	37.78	38.31
Mass of Tin + Dry Soil, $M_{tin+dry}$ (g)	43.32	42.7	36.78	34.1	34.68
Moisture Content, ω (%)	47.94	45.25	47.78	47.18	45.38
# of Drops	16	21	27	32	38
LL	47				

Table 23. Liquid limit results for sample 2

Bucket #2					
Liquid Limit	Test 1	Test 2	Test 3	Test 4	Test 5
Tin #	2	1	7	5	8
Mass of Tin, M_{tin} (g)	35.06	26.29	35.25	26.51	35.24
Mass of Tin + Wet Soil, $M_{tin+wet}$ (g)	50.69	42.4	48.84	40.54	47.85
Mass of Tin + Dry Soil, $M_{tin+dry}$ (g)	45.91	37.5	44.76	36.2	44.08
Moisture Content, ω (%)	44.06	43.71	42.90	44.79	42.65
# of Drops	16	22	28	32	39
LL	43				

Table 24. Specific gravity calculations

	Bucket #1			Bucket #2	
Specific Gravity	Test #1	Test #2	**Specific Gravity**	Test #1	Test #2
Pycnometer #	3	5	Pycnometer #	3	5
Mass of Pycnometer, M_{pyc} (g)	179.2	179	Mass of Pycnometer, M_{pyc} (g)	179.5	178.8
Temperature of Water, T_1 (°C)	21.7	21.7	Temperature of Water, T_1 (°C)	21.7	21.7
Density of Water at $T_{1,}$ ρ_{w1} (g/cm^3)	0.99784	0.99784	Density of Water at $T_{1,}$ ρ_{w1} (g/cm^3)	0.99784	0.99784
Mass of Pycnometer + Water, $M_{pyc+water}$ (g) [at T_1]	676.2	675.8	Mass of Pycnometer + Water, $M_{pyc+water}$ (g) [at T_1]	676.2	675.7
Volume of Pycnometer, V_{pyc} (ml)	498.1	497.9	Volume of Pycnometer, V_{pyc} (ml)	497.8	498.0
Mass of Soil, M_{soil} (g)	95.9	105	Mass of Soil, M_{soil} (g)	95.2	105.4
Mass of Pycnometer + Water + Soil, $M_{pyc+water+soil}$ (g)	735.5	741.1	Mass of Pycnometer + Water + Soil, $M_{pyc+water+soil}$ (g)	733.8	738.9
Temperature of Water and Soil, T_2 (°C)	21.7	21.7	Temperature of Water and Soil, T_2 (°C)	21.7	21.7
Density of Water at T_2, ρw_2(g/cm^3)	0.99784	0.99784	Density of Water at T_2, ρw_2(g/cm^3)	0.99874	0.99874
Mass of Pycnometer + Water, $M_{pyc+water}$ (g) [at T_2]	676.2	675.8	Mass of Pycnometer + Water, $M_{pyc+water}$ (g) [at T_2]	676.2	675.7
Mass of Container, M_{con} (g)	164.1	163.9	Mass of Container, M_{con} (g)	164.1	163.9
Mass of Container + Oven Dried Soil, $M_{con+dry}$ (g)	260.7	269.8	Mass of Container + Oven Dried Soil, $M_{con+dry}$ (g)	257	266.5
Mass of Oven Dry Soil, M_{dry} (g)	96.6	105.9	Mass of Oven Dry Soil, M_{dry} (g)	92.9	102.6
Specific Gravity, G_s	2.59	2.61	Specific Gravity, G_s	2.63	2.60
Temperature Coefficient, K	0.99963	0.9963	Temperature Coefficient, K	0.99963	0.99963
Specific Gravity at 20 °C, $G_{20°C}$	2.59	2.60	Specific Gravity at 20 °C, $G_{20°C}$	2.63	2.60
Average Specific Gravity, $G_{s, avg}$	2.59		**Average Specific Gravity, $G_{s, avg}$**	2.62	
			Total Average Specific Gravity, $G_{s, avg}$	2.61	

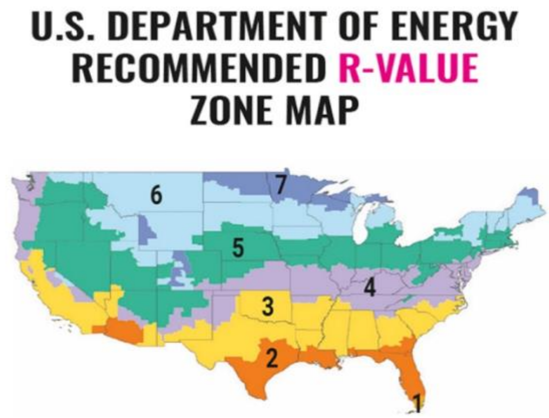
Table 25. Standard Proctor test results

Bucket #1		
Test #	ω_{avg} (%)	$\gamma_{dry, avg}$ (lb/ft^3)
1	15.55	86.07
2	20.35	93.01
3	24.30	94.91
4	30.85	89.15
Bucket #2		
Test #	ω_{avg} (%)	$\gamma_{dry, avg}$ (lb/ft^3)
1	19.00	85.23
2	22.55	93.52
3	26.05	94.93
4	29.48	91.66

RECOMMENDED R-VALUES

Zone	Attics	WALLS 2x4	WALLS 2x6	Floors	Crawl Spaces
7	R-49 to R-60	R-13 to R-15	R-19 to R-21	R-25 to R-30	R-25 to R-30
6	R-49 to R-60	R-13 to R-15	R-19 to R-21	R-25 to R-30	R-25 to R-30
5	R-49 to R-60	R-13 to R-15	R-19 to R-21	R-25 to R-30	R-25 to R-30
4	R-38 to R-60	R-13 to R-15	R-19 to R-21	R-25 to R-30	R-25 to R-30
3	R-30 to R-60	R-13 to R-15	R-19 to R-21	R-25	R-19 to R-25
2	R-30 to R-60	R-13 to R-15	R-19 to R-21	R-13	R-13 to R-19
1	R-30 to R-49	R-13 to R-15	R-19 to R-21	R-13	R-13

(a)



(b)

Figure 76. (a) Recommended R-values for insulation (b) Location map corresponding to recommended values (Source: U.S. Dept of Energy 2020)

Figure 77. New misting system for case 1.1

(a) **(b)**

Figure 78. (a) New pump for case 1.1 test (b) New pump and ice/water mixture set up for case 1.1 misting operation