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Laboratory simulation of frost on a pavement column inside a freezer under a controlled environment

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ABSTRACT
Meteorological factors like air and dew point temperature and relative humidity levels influence a pavement surface's response to rapidly increasing air temperature combined with freezing conditions. This scenario can result in black ice. Black ice is dangerous due to its thinness and transparency. Understanding the conditions for black ice development benefits winter pavement maintenance by limiting chemical overuse and forming a basis for warning systems. However, limited experimental data on this weather scenario exists. A fully instrumented model column was built using soil and a concrete pavement slab obtained from the Dallas Fort Worth (DFW) airport. The column duplicated the airport pavement structure and subgrade. The system was placed in a freezer box and wrapped in insulation. The weather scenarios simulated historic airport weather involving freezing temperatures followed by rapid temperature increases and high relative humidity. After multiple baseline tests, two successfully replicated the rapid temperature increase scenario. The formation of frost on the pavement surface occurred 40 min after condensation developed combined with a surface temperature of −2°C and dew point temperatures above 0°C. The results of this study provide insight into frost development on pavement and is useful in implementing proactive winter pavement maintenance for black ice.

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Black ice; frost formation; pavement temperature; road weather

1. Introduction

Correlating pavement surface conditions and meteorological data is central to winter road maintenance. This determines the response of the pavement to cold fronts and when ice formation can be expected. More than 70% of the roads in the United States are in areas affected by winter weather. Vehicle crashes due to icy pavement conditions account for 24% of accidents annually, with an average of 700 fatalities and over 65,000 injuries. Wintry road conditions increase travel time and fuel consumption and decrease business profits. Winter road maintenance accounts for 20% of local Department of Transportation (DOT) annual budgets (Snow & Ice- FHWA Road Weather Managment 2020), with a direct cost of 2.3 billion dollars and an infrastructure cost of approximately 5 billion dollars (Veneziano *et al.* 2018). The chemicals that are applied to the pavement surface have detrimental effects on soil, water, vegetation, and wildlife through runoff (Dai *et al.* 2012, Usman *et al.* 2012). De-icing salts have been found to increase the salinisation of freshwater and contaminate drinking water sources (Hintz *et al.* 2021). The damage applied chemicals and abrasives inflict affect more than just the natural environment. Corrosion caused by chemicals used for winter road maintenance damages not only infrastructure but vehicles as well (Sutter *et al.* 2006).

Reactive winter road maintenance operations are initiated based on the current weather conditions and include de-icing and sanding of the pavement. Proactive winter road maintenance operations are initiated ahead of a forecasted winter weather event and include the application of anti-icing chemicals to the pavement surface. To minimise the numerous adverse effects caused by reactive winter road maintenance, a combination of knowledge of the pavement temperature response and proactive application of anti-icing measures is necessary (O'Keefe and Shi 2005). The current practice is for DOTs to apply chemicals and abrasives to roads and bridges in advance of a forecasted winter storm. In general, this practice focuses on weather that will also bring precipitation. However, this practice does not address the conditions that can lead to the formation of black ice on the roadways. A number of field studies and models on the prediction of pavement surface temperature response have been conducted (Chen *et al.* 2019, Qiu *et al.* 2018, Zhao *et al.* 2020). These studies were performed under dry field conditions, neglecting the effects of humidity, dew point temperature, and the formation of surface condensation. Pavement response involving cold fronts with relative humidity and the development of frost have not been studied extensively. There is a deficit of controlled experimental studies that examine the combination of meteorological factors required for the formation of frost on a pavement surface (Chen *et al.* 2019).

The objective of this study is to investigate the conditions required for frost to form on a pavement surface in a model pavement column tested inside a freezer box under controlled weather scenarios. The aim is to examine the relationship between relative humidity, air temperature, and dew point temperature and how they relate to the formation of frost on

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a pavement surface during a rapid increase in air temperature. In this study, a pavement model column was designed, built, and installed into a freezer box to observe the temperature response of the pavement surface to simulated cold fronts combined with a rapid air temperature increase and high levels of relative humidity. Sensors in the pavement body and on the surface measured temperature. The temperature and the relative humidity of the freezer box were also monitored.

1.1 Background on frost formation

Frost is a thin layer of ice that forms when atmospheric water vapour that is above freezing temperatures encounters a surface that is below freezing. The amount of water vapour in the air is measured by both relative humidity and the dew point temperature, although the dew point temperature is preferred as it relates directly to the surface condition (Tarleton 2006). Relative humidity is the amount of water vapour present in the air in relation to the amount of vapour the air can hold at a given temperature. Warmer air holds a greater amount of water vapour compared to cooler air. Relative humidity is a function of air temperature. Dew point is the temperature that the air needs to reach for complete saturation and is a function of both relative humidity and air temperature. When the air temperature reaches the dew point temperature, the air is completely saturated and releases moisture in the form of condensation. The development of frost during this release of moisture is entirely dependent on the surface condition. If a surface is at or below the freezing point, condensation is released in the form of frost. Frost forms slowly and the thickness is generally less than 1.6 mm (Mass and Steed n.d.). As the frost layer continues to develop and thicken, the formation of black ice will occur.

Figure 1 illustrates the conditions required for the formation of black ice from a recorded airport temperature graph (Toronto Pearson International Airport 2014). Here, the airport pavement temperature converges on the dew point temperature and then drops below it. When this scenario occurs, the condensation of water vapour occurs on the freezing pavement surface and becomes ice crystals. As a result, black ice is formed on the pavement surface.

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

$$t_d \approx t - \left(\frac{100 - RH}{5}\right) \quad (1)$$

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. For this study, the ambient temperature is defined as the temperature of the freezer box. This equation is valid for relative humidity greater than 50%. In this range the relationship between the relative humidity and the dew point temperature approaches linear. This equation is accurate to 1°C or 5% relative humidity for temperatures 0° – 30°C and relative humidity readings between 50% and 100% (Lawrence 2005). The relative humidity in the freezer box remained above 50% throughout testing, validating the use of this equation.

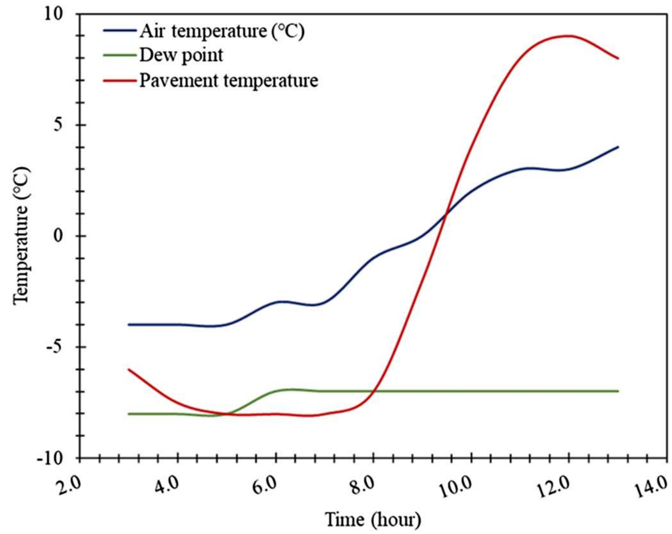

Figure 1. Conditions required for frost formation on pavement surface (modified from Toronto Pearson International Airport 2014).

2. Materials and methods

2.1 Pavement model column

The model column was constructed using a concrete slab and soil obtained from the DFW airport. The column would be used to duplicate the airport pavement structure and its subgrade. A unique wood box (0.60 m × 0.90 m × 0.90 m) was built for housing the model.

2.1.1 Soil and concrete slab

Thirty-two soil samples were collected from DFW property. Representative soil samples were tested and classified according to American Society for Testing and Materials (ASTM) standards and the resulting soil classification was CL-sandy lean clay.

A sample of concrete runway slab provided by DFW Airport was used for the pavement. Thermal conductivity tests were conducted on the slab with a KD2 Pro. The thermal conductivity was 2.74 W/m·K. The slab was cut into two halves with grooves cut into the faces to assist in the placement of sensors in the slab body. The halves were uneven and were made level by grinding the high spots and filling low spots with commercial mason mix to create an even surface. Six holes were drilled into the grooves at a depth of 2 cm to accommodate the sensor heads of thermistors. The space around the sensor heads was filled with the same commercial mason mix (Figure 2a and b).

2.1.2 Assembly of the pavement column

The two halves were installed on the soil with a cantilever crane and the column was transported to the freezer box by forklift. Once inside, the void between the halves was closed with the same commercial mason mix used to fill the gaps

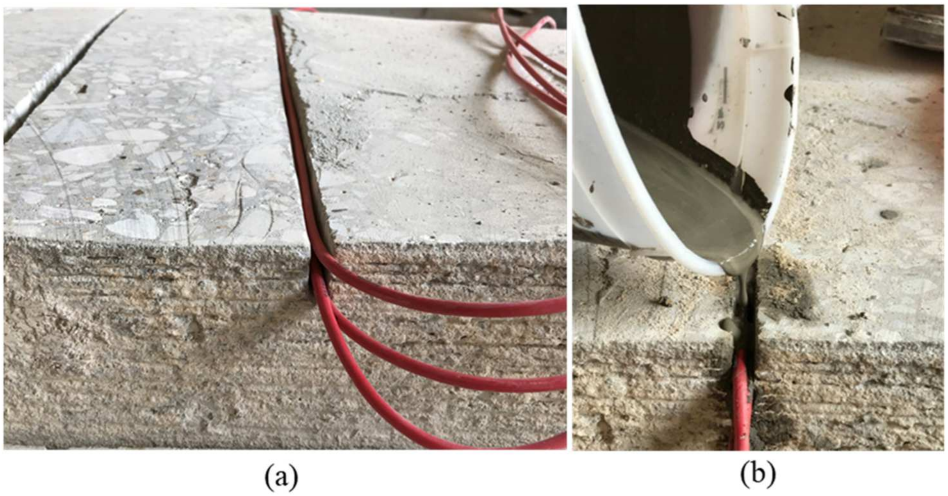

Figure 2. (a): Sensor cables in grooves of slab (b): Filling grooves with mason mix.

around the sensor heads in the slab body. Baseline testing for cooling and warming was performed and the temperature response of the slab body was found to be uniform, affirming no interfering effect from the mason mix. The box was wrapped in R30 insulation and commercial-grade plastic wrap. The edges of the slab body were wrapped in R30 insulation and roof tarping. It was then sealed with silicone and Gorilla Glue to prevent water infiltration during precipitation operations that occurred during ice formation testing (DiLorenzo *et al.* 2022). The pavement column was used to study the formation of icing on a pavement surface due to a precipitation event in DiLorenzo *et al.* 2022. R30 insulation material was used to fill the gap between the box and the floor and surface instrumentation was installed at this time (Figure 3a through 3d).

2.2 Instrumentation

Table 1 presents a summary of the instrumentation used to record the temperature of the pavement slab. For the locations of the instrumentation, please refer to Figure 4. Thermistors placed at different locations in the column monitored the boundary conditions between the freezer box temperature, the slab, and the soil.

Six thermistors were installed in the slab body at 2, 25 and 48 cm below the slab surface. The sensors were placed in two vertical rows with each row containing three thermistors to record the temperature distribution in the vertical and horizontal direction. Three thermocouples were installed on the surface of the slab. The center surface sensor was installed over a row of slab body thermistors to monitor the vertical temperature distribution of the slab (Figure 4). A detailed description of the instrumentation can be found in DiLorenzo *et al.* 2022.

2.3 Pavement frost test program

After performing initial baseline cooling and warming tests for the entire system, extensive baseline testing was performed to determine how the temperature and the relative humidity in the freezer box would react when outside air was introduced into the freezer box. These multiple baseline tests were performed because the introduction of the outside air into the freezer box created a variable whose effect on the freezer box environment was unknown. The introduction of warm outside air into the freezer box was required because the historic weather scenarios being replicated involved a sharp temperature increase with varying levels of relative humidity. The best way to accomplish this scenario was through the introduction of warm outside air into the freezer box. After the baseline was established, two tests were performed to simulate the weather scenarios provided by DFW airport. Table 2 provides a description of the tests performed for the formation of frost on pavement. The two tests, frost case 1 and frost case 1.1, both involved a sharp temperature increase with a starting freezer box temperature of −4°C. To achieve this temperature increase, one of the doors of the freezer box was opened slightly to allow warmer outside air into the freezer box. During this time the freezer box temperature, slab surface temperature, dew point temperature, and relative humidity were monitored for both test cases and the condition of the slab surface was physically monitored.

3 Baseline testing

3.1 Initial baseline for cooling and warming of the model column

Initial baseline cooling and warming tests were used to confirm operation of the data acquisition system and to determine a baseline temperature response for the pavement column. These initial baseline cooling and warming tests are not reported in Table 2. A description of these initial baseline tests and the results can be found in DiLorenzo *et al.* 2022. The plot in Figure 5 shows the hourly temperature variation during testing. Please note that the freezer box temperature spikes on the plots are due to the defrost cycle of the freezer box. At the start of testing, the pavement column had an approximately uniform temperature distribution and was in equilibrium with the freezer box temperature. At the end of testing, the

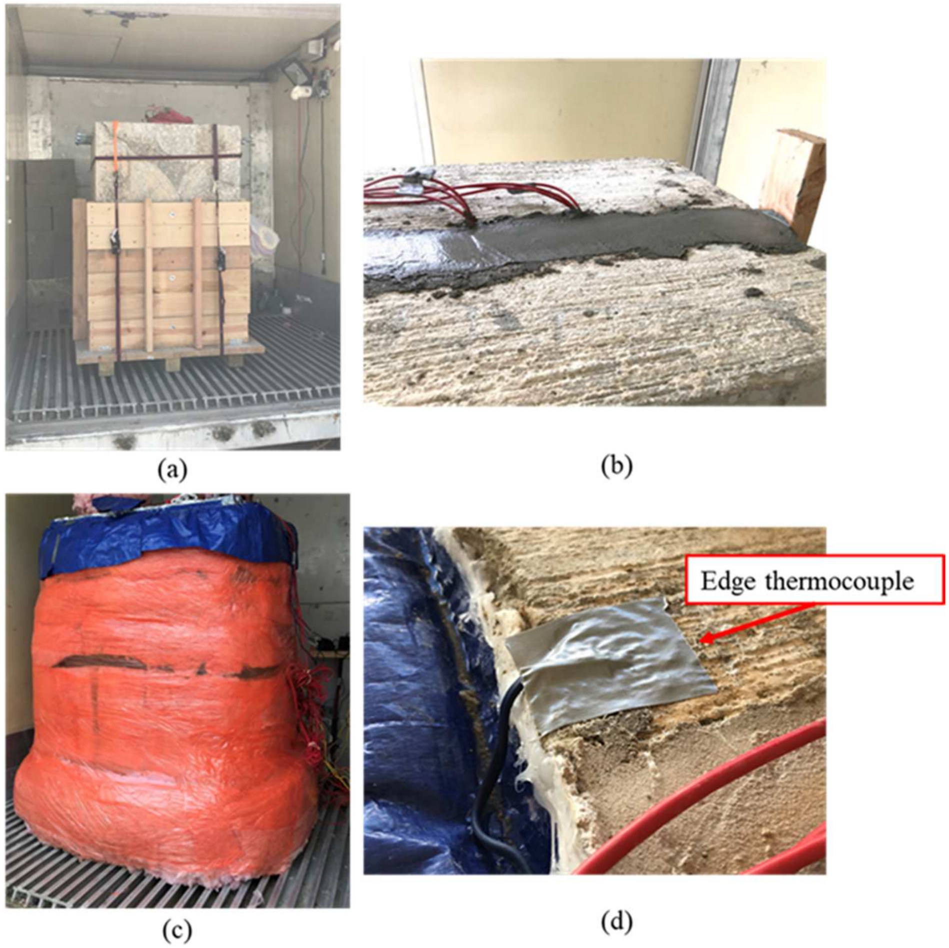

Figure 3. (a): Model column inside freezer box (b): Gap between slab halves filled (c): Model column wrapped in insulation and plastic (d): Installed edge surface thermocouple (after: DiLorenzo *et al.* 2022).

pavement surface temperature decreased by 17°C and the subgrade at 74 cm below the slab surface decreased by 11°C. Maximum temperature was located between 70 and 100 cm below the slab surface. Maximum temperature depth increased with time. This observation agrees with the trend observed in temperature profiles of pavements in the field. Previously observed temperature trends were obtained after repeated baseline cooling tests.

Table 1. Model column instrumentation.

Instrument	Function	Accuracy
CR 1000X	Control datalogger, operating range: − 55°C to +70°C	+/ − 0.04% at 0° to 40°C +/ − 0.06% at − 40° to +70°C
EE181-L Air temperature and Relative Humidity sensor	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)
Thermocouple Type T	Temperature sensor, operating range: − 270° to +370°C	+/ − 0.5°C
Thermistor Type YSI 44005	Temperature sensor, operating range: − 100° to +500°C	+/ − 0.2°C

The initial warming test was performed at the end of the initial cooling test by turning off the freezer for a period of six days. During this time the outside average daily temperature was 21.1°C, resulting in an increase in the freezer box temperature. The starting temperature of the freezer box was 2.8°C. Figure 6 shows the hourly temperature variation of the system during testing. The slab is warmer than the mid-depth soil by approximately 5°C. The pavement follows the warming trend of the freezer box air but takes much longer to warm. The temperature of the slab does not show convergence with the freezer temperature until the completion of the test.

3.2 Initial baseline frost condition testing

To create the weather conditions for frost illustrated in Figure 1, several baseline test cases were performed to evaluate the response of the test environment to simulated weather scenarios. The temperature rise and humidity variation inside the freezer box were obtained by opening the freezer door and exposing the test system to the outside air. Base case A was performed as a baseline test to determine how the temperature and the relative humidity in the freezer box would change when warmer outside air was introduced into the freezer box. During the test, the air outside the freezer had a relative

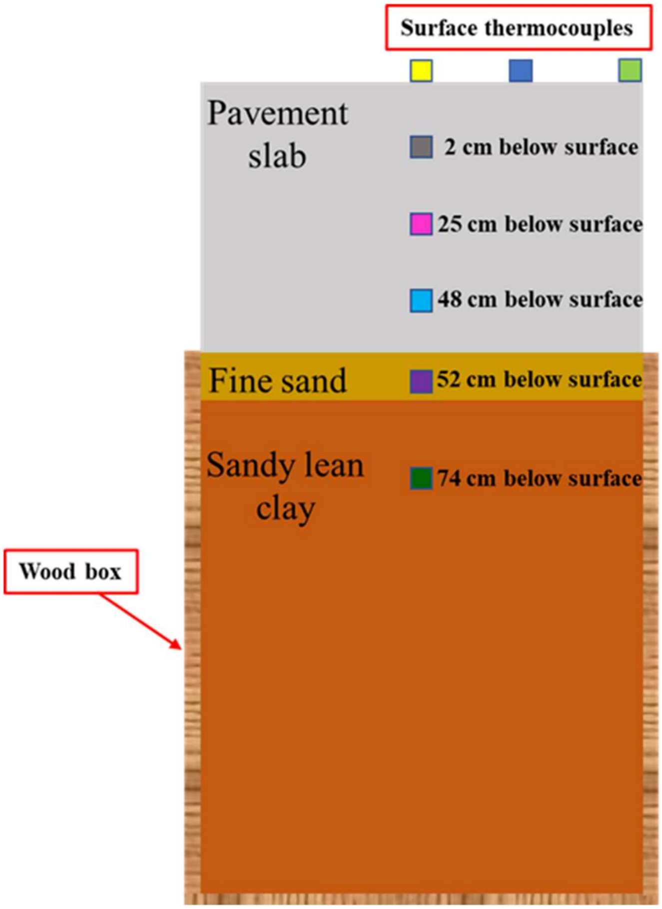

Figure 4. Instrumentation for pavement column.

Table 2. Description of testing program.

Test Name	Description of Test
Base Case A	Baseline test for frost case. Starting freezer box temperature was – 4°C and both freezer doors were opened fully. Outside relative humidity during the test was 36–31% and outside temperature range was 13–19°C. Duration of test was 1.3 h.
Base Case B	Second baseline test for frost case. Starting freezer box temperature was – 4°C and one freezer door was opened slightly. Outside relative humidity during test was 32–27% and outside temperature range was 19–20°C. Duration of the test was 2.2 h.
Base Case C	Third baseline test for frost case. Starting freezer box temperature was – 4°C and one freezer door was opened slightly. Outside relative humidity range for the test was 49–46% and the outside temperature was 2.8°C at the start and 3.3°C at the end of the test. The duration of this test was 7.7 h.
Base Case D	Additional baseline test for frost. This test followed the same procedure as base case C, but with the addition of a coffee maker inside the freezer to add moisture to the air. The relative humidity outside was 20–18% and the temperature outside was 16°C at the start and 13°C at the end of the test. The duration of the test was 2.2 h.
Frost Case 1	Modification of base case D with the introduction of additional moisture provided using a boiling electric kettle. Outside relative humidity during the test was 90–86% and outside start and end temperatures were 9.4°C and 10°C, respectively. Duration of the test was 3.5 h.
Frost Case 1.1	Modification of frost case 1, using the natural outside humidity to introduce moisture. The outside relative humidity at the start of the test was 58% and 47% at the end. Outside start and end temperatures were 8.3°C and 12.8°C, respectively. Duration of the test was 2.15 h.

humidity in the range of 36–31%. The temperature of the outside air was 13°C at the start of the test and 19°C at the end. For this test, the freezer box attained a steady state condition of −4°C, at which point the freezer was turned off and both freezer doors were opened fully. The conditions in the freezer box including temperature, relative humidity, and dew point temperature, along with the slab surface temperature were monitored. The duration of the test was 1.30 h. During the test it was observed that with both doors open, the temperature inside the freezer increased too quickly to achieve the conditions necessary for the formation of frost. 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 for frost formation.

Base case B was performed as a modification of base case A. Instead of opening both doors to the freezer box, only one door was opened slightly to slow the rate of temperature increase inside the freezer box. During the test, the outside relative humidity ranged from 32% to 27%. The outside air temperature was 19°C at the beginning of the test and 20°C at the end. Relative humidity, dew point temperature, freezer box temperature, and the slab surface were monitored. The duration of the test was 2.20 h. By only opening one door of the freezer slightly, the rate of temperature increase inside the freezer box was better controlled. During this test, the slab surface temperature did drop below the dew point temperature however no frost formation was observed. It was determined that this was due to the low humidity of the outside air lacking the moisture needed to create condensation inside the freezer box.

Base case C was performed to further understand what effects the introduction of outside air would have on the freezer box environment. For this test, a day was chosen where the relative humidity of the outside air was higher than during base case B in an effort to introduce more moisture into the freezer box. The relative humidity for the test ranged from 49% at the start to 46% at the end. The outside temperature was 2.8°C at the start and 3.3°C at the end of the test. During this test, the slab surface temperature did not drop below the dew point temperature and the formation of frost was not observed. The duration of this test was 7.70 h. It was determined that the lack of frost formation was due to the outside air being too cold and dry, leading to the conclusion that additional moisture would need to be added into the freezer box environment through mechanical means to create the conditions required for condensation to occur. It was also decided that a day with warmer forecasted temperatures would be optimal to create the rapid freezer box temperature increase needed without causing the slab surface to rise above freezing.

Base case D was a repeat of base case C, but a coffee maker was installed in the freezer box to add additional moisture into the freezer box environment. The relative humidity of the outside air was 20–18% during the test with a temperature range of 16–13°C. 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

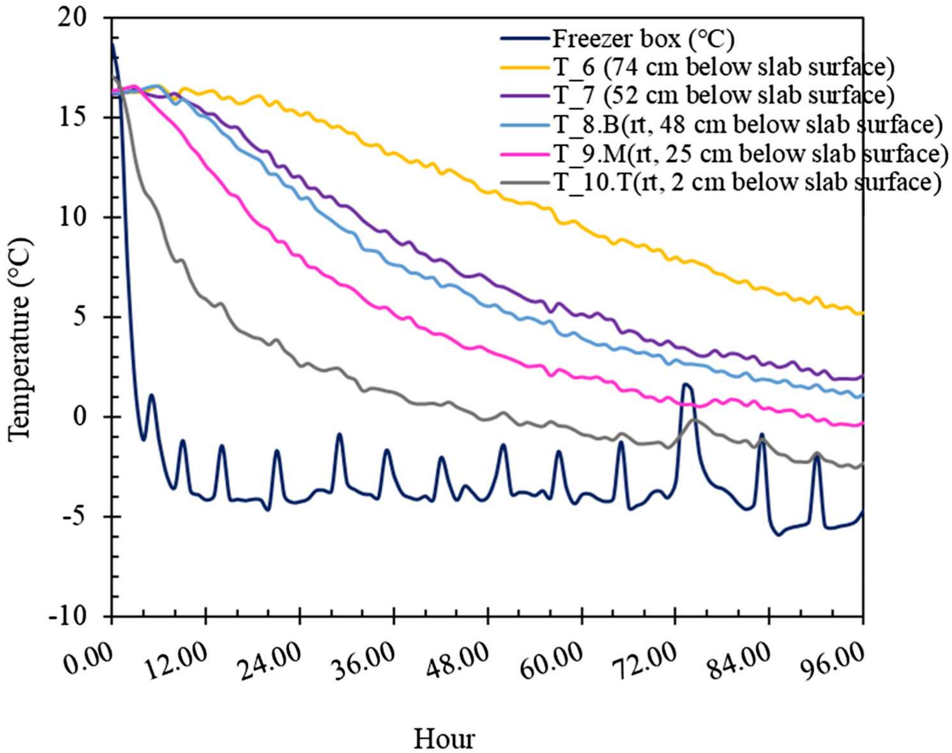

Figure 5. Hourly temperature trend for cooling baseline testing.

above the dew point as well, indicating that frost formation is not a possibility for this scenario. The duration of the test was 2.20 h. From this test, it was determined that the coffee maker would not provide enough moisture to create the condensation needed for frost formation.

Frost case 1 was designed based on the lessons learned from the previous tests performed in the freezer box. It was determined that to create enough moisture in the freezer box environment to have condensation form, an electric kettle would be used as it would create a greater amount of moisture

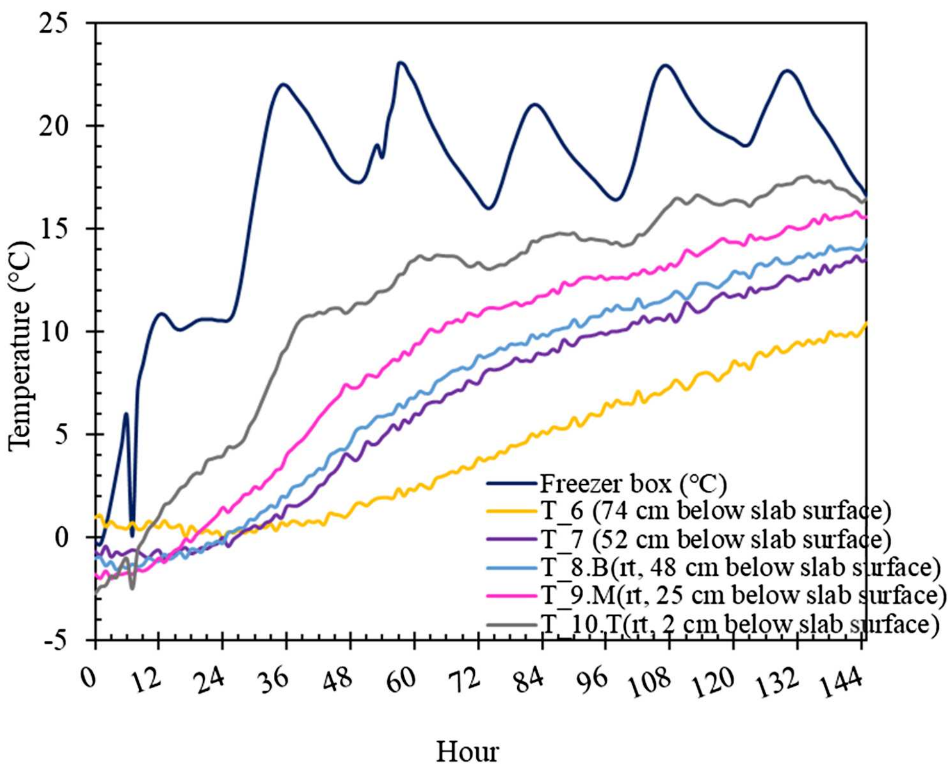

Figure 6. Hourly temperature trend for warming baseline testing.

Table 3. Summary of test results.

	Measured data	Initial conditions (°C)	Final conditions (°C)	Temperature change (°C)	Rate of change (per hour)
Frost case 1 (3.50 h)	Freezer Box	−4.0	11.3	+15.3	+4.4
	Slab Surface	−3.0	1.0	+4.0	+1.1
	Slab Body (8B)	−2.8	−2.2	+0.6	+0.17
	Soil (T6)	−2.1	−1.9	−0.2	−0.06
	At the end of the test, the edge surface thermocouple was 2.4°C and the middle of the surface was −0.56°C. This indicates the high degree of influence exerted on the edge of the slab by the surrounding environment as opposed to the system's internal environment. Frost is observed approximately 40 min after the introduction of moisture in the form of steam from an electric kettle.				
Frost case 1.1 (2.15 h)	Freezer Box	−4.0	8.7	+12.7	+5.9
	Slab Surface	−3.5	−0.3	+3.2	+1.5
	Slab Body (8B)	−3.6	−3.1	+0.5	+0.23
	Soil (T6)	−3.0	−3.0	0.0	0.0
	Here it can be noted that the edge surface thermocouple read 1.2°C, while the middle was −1.0°C. The difference can be attributed to the influence of the freezer box temperature on the boundaries of the slab versus the inner portions. The formation of a light frost is observed approximately 40–47 min after the introduction of moisture via the humid outside air.				

as opposed to the coffee maker. The outside temperature during this test was 9–10°C with a relative humidity of 90–86%. For this test the air temperature, dew point temperature, and relative humidity inside the freezer box, as well as the slab surface temperature were all observed, with the surface of the slab being physically monitored.

Frost case 1.1 was performed as a repeatability test for frost case 1. The outside temperature during the test was 8–13°C and the relative humidity was 58–47%. For this test, the temperature of the freezer box, dew point, relative humidity inside the freezer box, and the slab surface temperature were all observed with the surface of the slab being physically observed.

4. Results and discussion

This section presents the results of the frost test cases; a summary table of the results can be found below (Table 3). Sensor locations noted in Table 3 can be found in Figure 4.

4.1 Frost case 1

The weather scenario for this test was a rapid freezer box temperature increase from a starting temperature of −4°C. The freezer box was at a steady state condition when it was turned off and one door of the freezer was opened slightly. The relative humidity and dew point as well as the temperature of the freezer box were monitored. When the dew point temperature was higher than the slab surface temperature, the electric kettle was turned on to boil the water to introduce additional moisture into the freezer box environment. 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 9.4°C at the beginning of the test and 10°C at the end. The duration of the test was 3.50 h.

Figure 7 shows the freezer box temperature, the relative humidity in the freezer, slab surface temperature, and the dew point during testing. The spike in freezer box temperature on the plot is due to the freezer box being open during the electric kettle and camera installation. The freezer box was then completely closed for approximately one hour. After the hour had passed, the freezer box and slab temperatures converged to their original temperatures prior to the freezer being opened. Once this occurred, one door of the freezer box was opened slightly to increase the temperature inside. It can be observed from the plot that the freezer box temperature and the dew point converge when the relative humidity in the freezer box reaches 100%. The relative humidity increased from the additional moisture created by the boiling kettle. It should be noted that for frost conditions to occur, the surface temperature of the slab must converge on or drop below the dew point temperature while the surface remains below freezing temperatures. This condition was met a few minutes after the door was opened slightly. Although the conditions for frost formation were met, this is not an indication of immediate frost development. About 40 min after this frost condition was met, in combination with the additional moisture from the kettle, a light frost was observed. It can be seen from Figure 7 that when the frost was observed, the dew point temperature was greater than the slab surface which was approximately −2°C. It can be observed from Table 3 that the soil did not experience any type of appreciable temperature change. This can be attributed to the short duration of the test.

4.1.1 Final slab condition

A light coating of frost was observed along the edges as well as toward the center of the slab approximately 40 min after the kettle begins to boil. This can be attributed to the introduction of the steam from the boiling kettle creating enough additional moisture in the air for condensation, resulting in frost formation to occur (Figure 8).

4.2 Frost case 1.1

This test was performed as a repeatability test for frost case 1, but the electric kettle was not used for additional moisture. Instead, the moisture came from the outside air being introduced into the freezer box. During this test, the freezer box began at a steady state of −4°C. The freezer was turned off and one door was opened slightly. The relative humidity and temperature of the freezer box as well as the dew point and the slab surface temperature were monitored. 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 8°C at the beginning of the test and 13°C at the end. The duration of the test was 2.15 h. Figure 9 shows the freezer box temperature, relative humidity in the freezer, slab surface temperature, and the freezer box dew point temperature during testing. In this plot, there is not a spike in freezer box

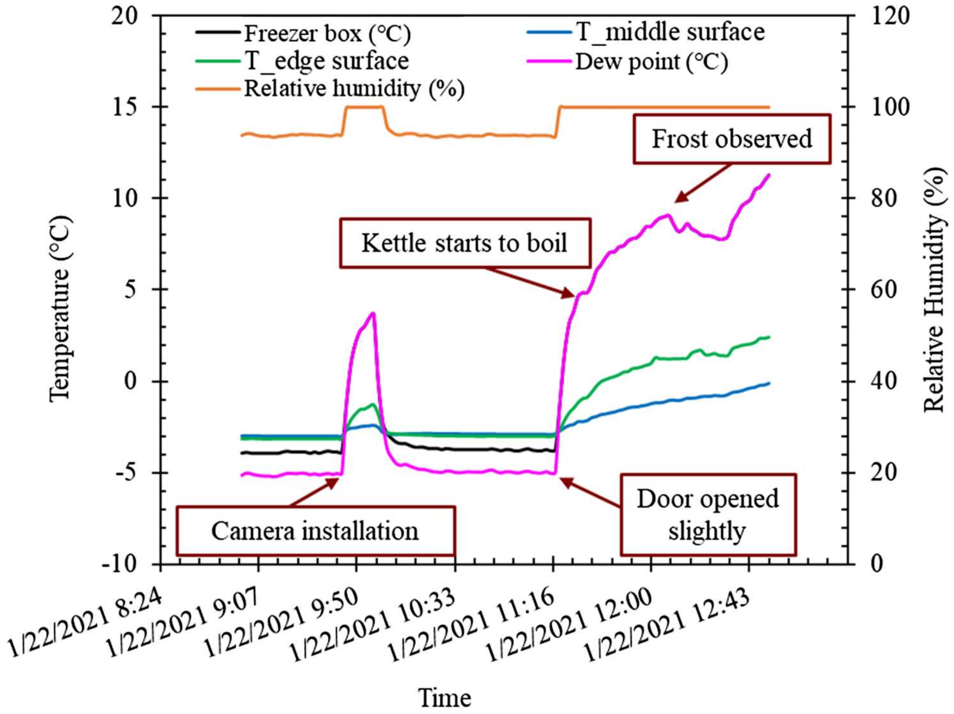

Figure 7. Variation of freezer box temperature, freezer box relative humidity, freezer box dew point temperature, and slab surface temperature.

temperature as in Figure 8 because the camera and electric kettle were not used for this test. It was found from the previous test that the frost layer was so fine that a human observer needed to be in the freezer box to properly document the timing for the development of frost on the slab surface. Unlike frost case 1, the dew point temperature and the temperature in the freezer box diverge as a result of the decrease in relative humidity in the freezer box environment. As indicated in the figure, the slab surface temperature dropped below the dew point a few minutes after the door was opened slightly. As before, frost conditions were met but there was no immediate formation of frost because more moisture needed to accumulate in the freezer box environment for condensation to occur. Here, it can be observed that the relative humidity in the freezer box continues to decrease after the door was opened. This differs from case 1 where the relative humidity increased to 100% as the boiling kettle created extra moisture in the freezer box environment. This decrease is due to the lack of the boiling kettle and relying solely on the relative humidity of the outside air for moisture. The warmer outside air being introduced into the freezer box held a greater amount of moisture as opposed to the colder outside air present in previous tests. This resulted in a smaller decrease in the relative humidity levels of the freezer box itself. The warmer air allowed for enough moisture to be present in the air of the freezer box for condensation to occur. The success of this test, as opposed to previous baseline tests performed without the mechanical addition of moisture, can be attributed to the higher relative humidity of the outside air combined with a 4°C increase in outside air temperature during testing at a rate that allowed the freezer box temperature to rise without increasing the temperature of the slab surface to the point where it was above freezing.

As previously observed in frost case 1, the development of frost occurs approximately 40 min after the slab surface temperature converges on and then drops below the dew point temperature. It should be noted that although the inside

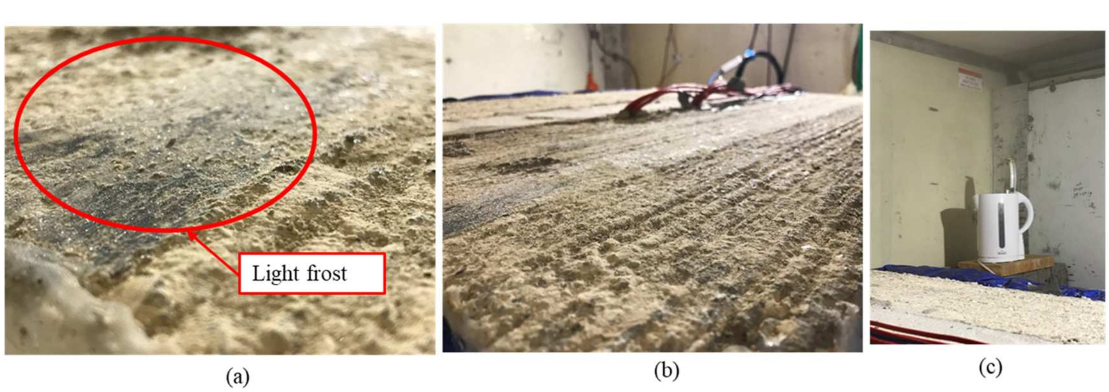

Figure 8. (a): Light frost coating on surface of slab (b): Entirety of slab surface with light frost coating (c): Kettle used for additional moisture in freezer box.

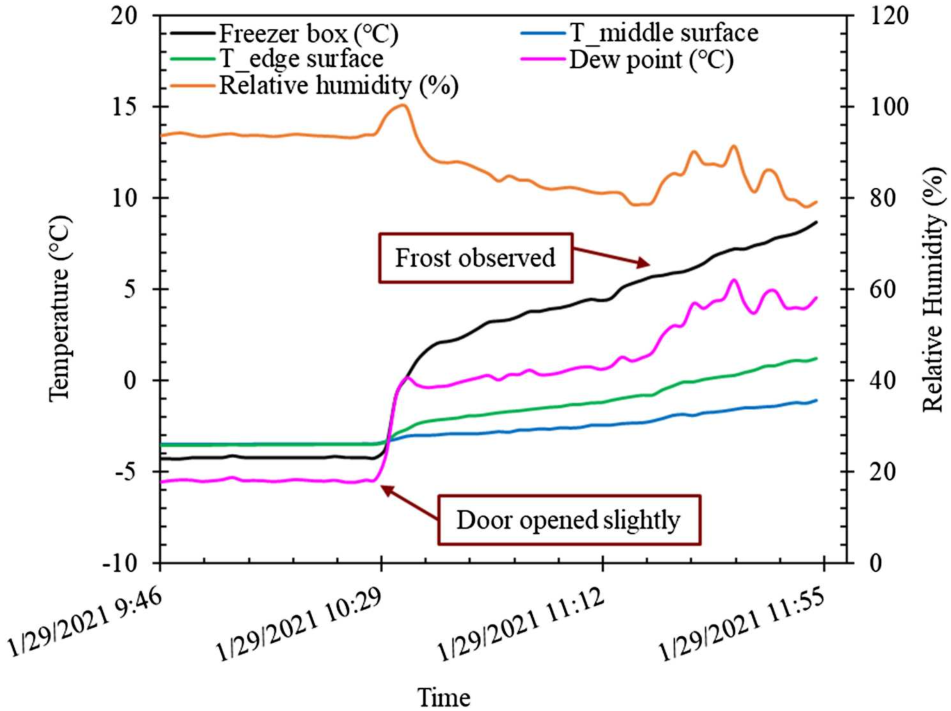

Figure 9. Variation of ambient freezer box temperature, freezer box relative humidity, freezer box dew point temperature, and slab surface temperature.

conditions of the freezer box environment differed from the conditions in frost case 1, 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 is −2°C and the dew point is above 0°C, the formation of frost on a pavement surface can be expected within a 35-to-45-minute time frame. As with frost case 1, the change in temperature of the soil was negligible and not considered to influence the slab temperature.

4.2.1 Final slab condition

A layer of frost was observed along the edges and into the center of the slab surface as indicated in Figure 10. The formation of the frost layer was observed approximately 40 min after the introduction of the humid outside air. When visually observed, this layer appeared to be slightly thicker than the layer produced in frost case 1 with the moisture from the boiling kettle.

5. Conclusions

This paper documents a series of tests performed in controlled conditions on a model column in a freezer box to further understand the timing and conditions necessary for the formation of frost on a pavement surface. The study validates in a controlled environment the specific conditions required for this formation to occur. The formation of frost can occur when moisture from the air is released as condensation of water vapour which then becomes ice crystals on a pavement surface with a temperature at or below 0°C combined with a dew point temperature that is higher than the pavement surface temperature. The necessity for multiple baseline testing in the freezer box illustrates the need to tightly control the temperature of the pavement surface as well as the level of moisture present in the surrounding air in order to achieve the formation of frost.

Results from this study show that when freezing conditions are present, combined with a pavement surface temperature of – 2°C and a dew point temperature above 0°C, the

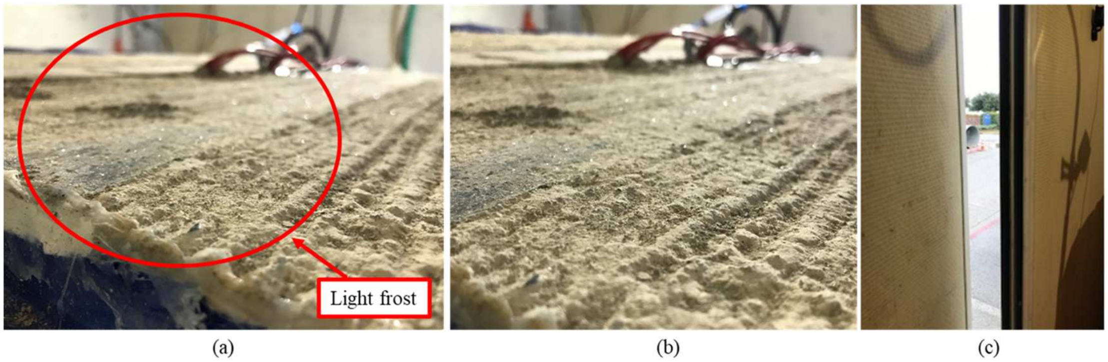

Figure 10. (a): Light frost coating on surface of slab (b): Entirety of slab surface with frost coating (c): Freezer door opened slightly.

development of a frost layer can be expected to form starting approximately 40 min after these conditions are met. This condition was observed during the two frost case tests. One test was performed using the boiling kettle as the source for moisture, while the second test used only the moisture from the outside air to create condensation. It is important to note that each of these successful tests were conducted with differing outside temperatures and relative humidity levels. It is interesting to note that although the conditions for the development of frost may exist, the development of frost on a pavement surface is not immediate.

The results from this study can be used to further advance the understanding of the relationship between meteorological factors and the response of a pavement surface. This relationship can be used in the development of nowcasting models for transportation agencies. Further study is needed to explore the effects that wind and cloud cover have on the timing and extent of frost formation.

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