Effect of Warmer Minnesota Winters on Freeze-Thaw Cycles

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Institute for Transportation
Iowa State University

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An increase in freeze-thaw events will result in detrimental impacts on pavement systems. However, the impacts of recent climate changes on freeze-thaw cycles have not been well studied, although they are of interest to a broad number of transportation agencies. In this study, the number of freeze-thaw events at typical air temperature sensor level (e.g., 6 feet above the earth’s surface) as well as at different pavement layers and critical sub-pavement locations such as saturated subgrade within the active zone were quantified. In response to global warming, current work resulted in rigorously quantified freeze-thaw events rooted in climate data from 1941 to 2020. Results indicated that in the recent 40 years (i.e., 1981-2020), Minnesota winters have become warmer by 1-2 °F daytime and 2-5 °F nighttime temperatures. With a decrease in freezing temperatures, the yearly number of freeze-thaw cycles tended to decrease at shallow pavement depths (< 6 inches), whereas remained sporadic at deeper pavement layers. The decreases in freeze-thaw events at shallower depths were significant during the early and late winter months. However, the annual freeze-thaw events at the air temperature sensor level were randomly distributed throughout the analysis period.
Effect of Warmer Minnesota Winters on Freeze-Thaw Cycles

FINAL REPORT

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<td>AASHO</td>
<td>American Association of State Highway Officials</td>
</tr>
<tr>
<td>ANOVA</td>
<td>Analysis of Variance</td>
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<tr>
<td>ASOS</td>
<td>Automated Surface Observing System</td>
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<td>AWOS</td>
<td>Automated Weather Observing System</td>
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<tr>
<td>AWS</td>
<td>Automatic Weather Station</td>
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<tr>
<td>CFI</td>
<td>Cumulative Freezing Index</td>
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<td>CTI</td>
<td>Cumulative Thawing Index</td>
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<td>COOP</td>
<td>Cooperative Observer Network</td>
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<tr>
<td>CPC</td>
<td>Climate Prediction Center</td>
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<td>CRREL</td>
<td>Cold Regions Research and Engineering Laboratory</td>
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<tr>
<td>CV</td>
<td>Coefficient of Variance</td>
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<td>DCPs</td>
<td>Data Collection Platforms</td>
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<td>Department of Natural Resources</td>
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<td>DSC</td>
<td>Differential Scanning Calorimetry</td>
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<td>EOSDIS</td>
<td>Earth Observing System Data and Information System</td>
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<td>ESS</td>
<td>Environmental Sensor Station</td>
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<td>FHDI</td>
<td>Fractional Hot-deck Imputation</td>
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<td>FHWA</td>
<td>Federal Highway Administration</td>
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<td>F/T</td>
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<td>GOES</td>
<td>Geostationary Operational Environmental Satellites</td>
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<td>GMAO</td>
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<td>LVR</td>
<td>Low-Volume Road</td>
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<td>Road Weather Information System</td>
</tr>
<tr>
<td>SE</td>
<td>Southeast</td>
</tr>
<tr>
<td>SLR</td>
<td>Spring Load Restrictions</td>
</tr>
<tr>
<td>SPS</td>
<td>Specific Pavement Studies</td>
</tr>
<tr>
<td>TAP</td>
<td>Technical Advisory Panel</td>
</tr>
<tr>
<td>USACE</td>
<td>United States Army Corps of Engineers</td>
</tr>
<tr>
<td>VMC</td>
<td>Volumetric Moisture Contents</td>
</tr>
<tr>
<td>VWS</td>
<td>Virtual Weather Station</td>
</tr>
</tbody>
</table>
EXECUTIVE SUMMARY

Freeze-thaw (F/T) events cause significant damage to the pavement structure in colder regions, including the midwestern areas located within the United States, Alaska, Canada, northern Europe, China, and Russia. These colder areas can be classified as either permafrost or seasonally frozen areas. The permafrost areas remain partially frozen during summer, whereas the seasonally frozen areas experience frequent freezing and thawing throughout winter and early spring (Zeinali et al., 2016). The pavements in seasonally frozen areas undergo substantial deterioration due to frost heaving and thaw weakening ensued by these cyclic F/T events (Satvati et al., 2020).

Over the last several decades, Minnesota’s winters have gotten warmer, even faster than the summers. It is possible that this warming trend could increase the time spent around the freezing point (32 °F) and thus increase the number of F/T cycles. However, it is also possible that the warming trend does not have any impact on F/T events. The supposition can only be verified by quantifying the F/T events occurring in Minnesota through a rigorous assessment of historical air, pavement, and subsurface temperatures, precipitation, and freezing-thawing depth data, and by investigating the correlations between air temperature, pavement and subsurface temperatures, and the occurrence of F/T events. Therefore, it is essential to examine the available historical weather data resources for Minnesota climate conditions. In this study, several weather data resources were reviewed to identify the availability of Minnesota climatological data focusing on the quantification of F/T events.

Minnesota climate trends were analyzed in several geographical extents (statewide, climate-division, and sub-divisional resolution) for multiple times, averaging monthly and annual data sources. Minnesota road test facility (MnROAD) measurements were used to determine the monthly and yearly F/T cycles from the air and pavement system and to develop correlations between air temperature, pavement and subsurface temperatures, and the occurrence of F/T events. Pavement F/T cycles were determined for multiple conditions of soil freeze and thaw durations and material-specified freezing temperatures. Air temperature F/T cycles were also quantified by two methods for soil freeze and thaw temperature.

F/T cycles were also determined from historical climate data measurements and reanalysis of air and soil temperatures. F/T events for subsurface data were calculated from two conditions for freezing and thawing temperature duration, also applied to the MnROAD pavement data. For air temperature data, F/T cycles were determined from multiple conditions of thaw temperatures. Historical data informed the regional representation of F/T events determined from the extensive observations of air, pavement, and subsurface temperatures at the MnROAD test facility and provided a preliminary assessment of statewide and regional changes in F/T cycles for past and current climate conditions. A summary of these findings was described with recommendations for future assessment of Minnesota F/T cycles from multiple roadway locations.

Analysis of Minnesota weather data indicated a 2° to 5° F warmer nighttime temperature in the most recent 40-year period. A 0.5- to 1-inch increase in precipitation was also determined before and at the end of the cold season. The National Aeronautics Space Administration’s (NASA) second version of the Modern-Era Retrospective analysis for Research and Applications (MERRA-2) data revealed delayed
freezing at shallow depths in November and December in response to warmer temperatures and increased precipitation. A further assessment of sensor data from MnROAD showed that the number of F/T cycles tended to decrease at shallower pavement depths during early and late winter and remained sporadic for other winter months and at higher depths. The annual F/T events at the air temperature sensor level were randomly distributed throughout the analysis period. Based on the findings from the Phase 1 study, the TAP recommended a Phase 2 study focusing on the implications of increased precipitation due to climate change and the performance of road foundations using weather stations and extensive instrumentation data available at MnROAD while also developing a vulnerability map for the state road network.
CHAPTER 1: INTRODUCTION

Over the last several decades, Minnesota’s winters have gotten warmer. In fact, winters have warmed significantly faster than summers. Such a trend is forecast to continue into the foreseeable future. It is possible that this warming trend has increased the length of time spent around the freezing point (32°F), thus also increasing the average number of freeze-thaw events. However, it is also possible that this warming trend has resulted in no change in the number of freeze-thaw events. The primary objective of this study was to investigate whether Minnesota’s warmer winters have increased the number of freeze-thaw cycles. A two-phase research approach was developed to achieve this objective. The specific objectives for the Phase 1 study were (1) to attempt to quantify the number of freeze-thaw events on monthly and annual bases from historical data resources and (2) to attempt to identify the current trend of freeze-thaw events in response to warming winter conditions. The research approach for the Phase 1 study was summarized in the Research Methodology (scope) section.

1.1 RESEARCH METHODOLOGY

To obtain the goals of this study, a comprehensive literature review was conducted to identify the possible definitions of the “freeze-thaw cycle” and determine which was most appropriate for application to pavement damage. For instance, a freeze-thaw cycle is meaningless if no moisture is present. Different excursions beyond the phase change temperature and different times between consecutive excursions will have different impacts on the volume of water and amplitude of volume expansion, which suggests that multiple definitions of the “freeze-thaw cycle” be used. The freeze-thaw day event at each location was defined as any time the temperature at each location crosses the freezing point (i.e., a daily low with a maximum temperature of 31°F and a daily high with a minimum temperature of 33 °F) in a 24-hour period (Hershfield 1974). Alternative definitions incorporating soil moisture content were explored when historical soil moisture content records were available in the weather data resources evaluated.

Several historical weather data resources for Minnesota climate conditions were identified and evaluated to collect immense information required for achieving project objectives. These weather data resources included the temperature and moisture sensor data and the weather station data from the MnROAD test facility, the temperature sensor data from the Long-Term Pavement Performance (LTPP) program sites in Minnesota, the Road Weather Information System (RWIS) and the Spring Load Restrictions (SLR) program at MnDOT, the climate data from the National Oceanic and Atmospheric Administration (NOAA), the Modern Era Retrospective Analysis Versions 1.0 and 2.0 (MERRA-1 and MERRA-2) data from the National Aeronautical and Space Administration (NASA), and Iowa State University Environmental Mesonet for Minnesota RWIS sites. An in-depth review and a critical evaluation of each data resource were conducted while considering various factors, including available data types (e.g., air/ground/pavement temperature records, freeze gauge readings, soil moisture content records, solar radiation, etc.); data collection years; the spatial distance of weather stations; environmental influences caused by land-use changes; spatial and temporal variability of weather conditions; measurement time interval; and availability of quality control (QC) procedures.
Based on the definitions of the “freeze-thaw cycle” determined, the number of freeze-thaw events (i.e., monthly and annually) at typical air temperature sensor level as well as at each of the pavement layers by using the available historical weather data (temperature moisture, etc.) resources were also determined. A detailed statistical analysis was also carried out on MnROAD test facility data to identify correlations between the number of freeze-thaw cycles at the air temperature sensor level and at different pavement layers. The raw data extracted from the MnROAD test facility was preprocessed and checked for engineering reasonableness and accuracy.

1.2 ORGANIZATION OF THE REPORT

This report includes five chapters. Chapter 1 describes the background, objectives, and research methodology of this study. Chapter 2 provides a comprehensive literature review identifying the possible definitions of freeze-thaw, factors influencing freeze-thaw events, and the impact of freezing and thawing on pavement structures. Chapter 3 provides the summary of historical data resources evaluated. The results of the associated review and evaluations are synthesized, tabulated, and used as a reference to determine the historical weather data resources. Chapter 4 provides the quantification of freeze-thaw events at air the temperature sensor level and at different pavement layer by using a number of historical data resources. Chapter 5 provides the key findings of this study, providing preliminary insights into the trend of freeze-thaw events in Minnesota at the face of climate change. All supporting materials are presented in the appendices.
CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

During winter, as the subsurface temperature drops below the freezing temperature, a portion of pore water turns into ice crystals resulting in undue heaving on the pavement surface. When water converts to ice, a volume expansion of approximately 9% is responsible for this undue heaving (Johnson, 2012). Due to capillary action, water movement from the underlying unfrozen layers to the freezing front exacerbates the situation by increasing the moisture contents in the top layers (Zhang et al., 2016). During spring, ice crystals melt at the top layers and become trapped by underlying frozen layers. Thus, the bearing capacity of the top pavement layers decreases significantly due to the presence of excess moisture (Rosa et al., 2017). If the pavement is subjected to traffic load during this thawing period, saturated subgrade could pump up through the points of least resistance, causing frost boils on the pavement surface (Mahedi et al., 2020). Doré and Zubeck (2009) reported that more than 60% of the pavement distresses at the American Association of State Highway Officials (AASHO) Road Test happened during the spring thawing period. Therefore, SLR are often enforced during the spring thawing periods to reduce pavement deterioration. However, SLR could be detrimental to the economy due to lower payloads, increased trip numbers, and reroutes (Kestler et al., 2007; Levinson et al., 2005). In Minnesota, the start and end dates of SLR are set according to the Minnesota climatic zones (MnDOT, 2020i). For the North and North-Central zones, the SLR start and end dates for the year 2020 were March 13 and May 08, respectively. Correspondingly, for the Metro, South, and Southeast zones, the SRL start date was March 6, whereas March 9 for the central zone. The SLR end dates for these zones were April 13, April 20, April 13, and May 4, respectively.

Annual precipitation and freezing index are two crucial climatic factors influencing the freeze-thaw damage of pavements in the United States (Chen et al., 2019). The pavement surface temperature, frost penetration, thawing depth, and the number of freeze-thaw cycles are dependent on these two parameters. A higher amount of precipitation could saturate the pavement subgrade, intensifying the damage during the thawing period. In addition, a shallow groundwater table is often associated with higher rainfall, which plays a crucial role during freeze-thaw events. The freezing index (°F–day) is defined as the area under the temperature curve during the frozen periods and usually is reset on July 1 of each year (Chen et al., 2019). Based on the annual precipitation and freezing index, the Federal Highway Administration (FHWA) divides the U.S. into four climatic zones (i.e., dry-freeze, wet-freeze, dry-non-freeze, and wet-non-freeze) (FHWA, 2016). The pavements in wet-freeze zones are the most susceptible to freeze-thaw actions. There are three primary conditions identified for ice-segregation and severe freeze-thaw actions (Johnson, 2012; Zhang et al., 2018):

- Presence of frost-susceptible soil,
- Freezing temperature penetrating the frost-susceptible soil, and
- Shallow groundwater table along with high subsurface moisture.
In the wet-freeze zones, two of these three conditions (i.e., moisture and freezing temperature) are present. Figure 2.1 shows the climatic regions identified by the FHWA. As shown in Figure 2.1, the state of Minnesota is located in the wet-freeze zone. In the wet-freeze climate, the annual precipitation is above 20 inches/year, along with a cumulative freezing index over 182 degree-Fahrenheit days (Oman and Lund, 2018).

![Climatic Zones in the United States](image)

**Figure 2.1 The climatic zones in the United States. Adopted from FHWA, (2016)**

### 2.2 FACTORS AFFECTING FREEZE-THAW EVENTS

#### 2.2.1 Frost-Susceptible Soil

Not all soils are frost-susceptible. Pore water in granular materials freezes in-place resulting in no or little frost action (Oman and Lund, 2018). Besides, the water absorbance and the moisture content of granular materials are often negligible to demonstrate acute freeze-thaw actions. In addition, the large pore sizes of granular materials may not contribute to the capillary rise of water, inhibiting the water supply to the frost fringe (Johnson, 2012). Similarly, clayey soils are considered low frost-susceptible due to finer soil particle size, higher surface area, and lower hydraulic conductivity (Mahedi et al., 2019). Although the freezing action is less severe in clay, extensive loss in pavement support is often encountered during the thawing period since water cannot dissipate due to the lower hydraulic conductivity. In addition, the frost-susceptibility of clayey soils is known to be influenced by mineralogy. Kaolinite is more frost-susceptible than montmorillonite, whereas the thaw weakening is severe for montmorillonite (Brandl, 2008). On the other hand, silt soils and silt loams are considered high frost-susceptible because of larger voids, higher capillary actions, and higher water permeability than the clayey soils (Oman and Lund, 2018).

Casagrande et al. (1931) recorded the total amount of heave and the temperature beneath square slabs placed over different soil types. He reported a considerable amount of frost heaving in non-uniform soils when more than 3% of the soil particles were smaller than 0.02 mm. Heaving could be expected for uniform soils when more than 10% of the soil was finer than 0.02 mm. No frost heave was observed for
soils with less than 1% passing 0.02 mm sieve size. Casagrande’s criteria are still widely accepted in identifying frost-susceptibility of soils, though the tests did not include the thaw weakening (Chamberlain, 1986; Johnson, 2012; Oman and Lund, 2018; Zhang et al., 2018). The United States Army Corps of Engineers (USACE) provides three criteria to determine the test requirements for frost-susceptible soil (USACE, 1984). The Type 1 criterion describes gravels and sands as non-frost-susceptible when the particle sizes smaller than 0.02 mm are less than 1.5% and 3%, respectively. Under the Type 2 criterion, a complete soil classification is required when the soil does not meet the Type 1 criterion. As described in the Type 3 criterion, a frost-heave test is needed for gravels containing 1.5% to 3% particles smaller than 0.02 mm, and for sands with 3% to 10% smaller than 0.02 mm. The USACE criteria to determine the frost-susceptibility of soil are summarized in Table 2.1.

Table 2.1 The USACE criteria for frost-susceptibility of soil. Adopted from USACE (1984)

<table>
<thead>
<tr>
<th>Frost-Susceptibility</th>
<th>Frost Group</th>
<th>Soil Type</th>
<th>Amount 0.02 mm (%) by weight</th>
<th>USCS Soil Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negligible to low</td>
<td>Non-frost-susceptible</td>
<td>Gravels</td>
<td>0 to 1.5</td>
<td>GW, GP</td>
</tr>
<tr>
<td>Possible</td>
<td>Possible-frost-susceptible</td>
<td>Sands</td>
<td>0 to 3</td>
<td>SW, SP</td>
</tr>
<tr>
<td>Low to medium</td>
<td>S1</td>
<td>Sands</td>
<td>1.5 to 3</td>
<td>GW, GP</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3 to 10</td>
<td>SW, SP</td>
</tr>
<tr>
<td>Very low to high</td>
<td>S2</td>
<td>Sands</td>
<td>6 to 10</td>
<td>GM, GW-GM, GP-GM, GP-GM</td>
</tr>
<tr>
<td>Very low to high</td>
<td>F1</td>
<td>Gravels</td>
<td>3 to 6</td>
<td>GW, GP, GW-GM, GP-GM</td>
</tr>
<tr>
<td>Medium to high</td>
<td>F2</td>
<td>Gravels</td>
<td>10 to 20</td>
<td>GM, GM-GC, GW-GM, GP-GM</td>
</tr>
<tr>
<td>Very low to very high</td>
<td>F2</td>
<td>Sands</td>
<td>6 to 15</td>
<td>GM, GM-GC, SW-SM, SP-SM</td>
</tr>
<tr>
<td>Medium to high</td>
<td>F3</td>
<td>Gravels</td>
<td>&gt; 20</td>
<td>GM, GC</td>
</tr>
<tr>
<td>Low to high</td>
<td>F3</td>
<td>Sands, except very fine silty sands</td>
<td>&gt; 15</td>
<td>SM, SC</td>
</tr>
<tr>
<td>Very low to very high</td>
<td>F3</td>
<td>Clays, PI &gt; 12</td>
<td>-</td>
<td>CL, CH</td>
</tr>
<tr>
<td>Low to very high</td>
<td>F4</td>
<td>All silts</td>
<td>-</td>
<td>ML, MH</td>
</tr>
<tr>
<td>Very low to high</td>
<td>F4</td>
<td>Very fine silty sands</td>
<td>&gt; 15</td>
<td>SM</td>
</tr>
<tr>
<td>Low to very high</td>
<td>F4</td>
<td>Clays, PI &lt; 12</td>
<td>-</td>
<td>CL, CL-ML, CL and ML; CL, ML and SM; CL, CH and ML; CL, CH, ML and SM</td>
</tr>
<tr>
<td>Very low to very high</td>
<td>F4</td>
<td>Varved clays and other fine-grained, banded sediments</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>
Note: G = Gravel, S = Sand, M = Silt, C = Clay, W = Well-graded, P = Poorly graded, H = High plasticity, L = Low plasticity, USCS = Unified soil classification system.

Though the USACE criteria are widely used in identifying the frost susceptible soils, the maximum of 3% < 0.02 mm for non-frost-susceptibility is too strict and may prove uneconomical by rejecting a wide range of materials commonly used in pavement construction. Depending on the mineralogy, the frost-susceptibility of the minerals listed by Brandl (2008) in ascending order were carbonates, quartz, and feldspars except for several silicate groups such as weathered iron hydroxide, kaolinite, chlorite, mica, and vermiculite. In general, the freezing of the pavement base and subbase materials is ignored since these materials are typically non-frost susceptible. However, depending on the amounts of fines, the frost-susceptibility of these materials could vary within a wide range.

### 2.2.2 Temperature and Freezing Point of Soil

The presence of freezing temperature is the most crucial factor influencing the freeze events. The freezing temperature is commonly characterized by the cumulative freezing index (CFI) calculated from the weather station data. The Minnesota Department of Transportation (MnDOT) provides specific guidelines for calculating the CFI under the Technical Memorandum No. 14-10-MAT-02, which is used to determine the start and end dates of the winter load increase and spring load restriction periods (MnDOT, 2014b). Freezing of pavement subgrade significantly increases the bearing capacity, and thereby the pavements are capable of carrying large weights. On the other hand, top-to-bottom thawing traps excess moisture in upper pavement layers, decreasing the bearing capacity, and requiring load restrictions. The MnDOT schedules the winter load increase when the 3-day weather forecast indicates that the CFI exceeds 280 °F-days with an extended freezing temperature forecast. The CFI is calculated as follows:

$$ CFI_n = \sum_{i=1}^{n} \text{(Daily Freezing Index)} $$

1. When, $CFI_{n-1} + \left( T_{\text{reference}} - \frac{T_{\text{maximum}} + T_{\text{minimum}}}{2} \right) \geq 0 \degree F$

   $\text{Daily Freezing Index} = \left( T_{\text{reference}} - \frac{T_{\text{maximum}} + T_{\text{minimum}}}{2} \right) \degree F$-day

2. When, $CFI_{n-1} + \left( T_{\text{reference}} - \frac{T_{\text{maximum}} + T_{\text{minimum}}}{2} \right) < 0 \degree F$

   $\text{Daily Freezing Index} = 0 \degree F$-day

where,

- $CFI_n$ = Cumulative freezing index calculated over ‘n’ days (°F-day),
- $CFI_{n-1}$ = cumulative freezing index for the previous day,
- $T_{\text{reference}}$ = Reference air temperature (°F),
- $T_{\text{maximum}}$ = Maximum daily air temperature (°F), and
- $T_{\text{minimum}}$ = Minimum daily air temperature (°F).

(CFI resets to zero on July 1)
Following North Dakota, Minnesota is the second coldest state in the contiguous United States, with minimum and maximum 10-year frequency CFI of 2,101 and 3,846, respectively (NOAA, 2020b). The NOAA provides the 100-year return period CFI map of the U.S. As indicated in Figure 2.2, The north-west corner of Minnesota could have a CFI value over 4,000 °F-days, whereas south-east Minnesota has the minimum CFI in the range of 2,000 to 3,000 °F-days.

The winter load increase is ended when the forecasted air temperature predicts daily thawing as determined by the cumulative thawing index (CTI). However, the winter load increase is not typically removed before February 1, and the enactment of spring load restrictions may not coincide with the conclusion of the winter load increase. MnDOT schedules the load restrictions when the 3-day weather forecast indicates a CTI over 25 °F-days, and the long-range weather forecast indicates continual warmth. The MnDOT Technical Memorandum No. 14-10-MAT-02 also provides specific guidelines for the CTI calculation as the running total of daily thawing index starting from 0 °F-days.

![AIR-FREEZING INDEX (°F Days)](image)

A simplified analysis of the 100-year return period

As per the MnDOT Technical Memorandum No. 14-10-MAT-02, the calculation of CTI is as follows:

\[
CTI_n = \sum_{i=1}^{n} (\text{Daily Freezing Index} - 0.5 \times \text{Daily Freezing Index})
\]

\[CTI_n = \frac{T_{\text{maximum}} + T_{\text{minimum}}}{2} - T_{\text{reference}} < 0 \text{ °F}\]

\[\text{And, } CTI_{n-1} \leq 0.5 \times \left(T_{\text{reference}} - \frac{T_{\text{maximum}} + T_{\text{minimum}}}{2}\right)\]

Daily Thawing Index = 0 °F-day and,

Daily Freezing Index = 0 °F-day
• When, \(\frac{T_{\text{maximum}} + T_{\text{minimum}}}{2} - T_{\text{reference}} > 0 \degree F\)

\[\text{Daily Thawing Index} = \left(\frac{T_{\text{maximum}} + T_{\text{minimum}}}{2} - T_{\text{reference}}\right) \degree F\text{-day}\]

\[\text{Daily Freezing Index} = 0 \degree F\text{-day}\]

• When, \(\frac{T_{\text{maximum}} + T_{\text{minimum}}}{2} - T_{\text{reference}} < 0 \degree F\)

And, \(CTI_{n-1} > 0.5 \times \left( T_{\text{reference}} - \frac{T_{\text{maximum}} + T_{\text{minimum}}}{2} \right)\)

\[\text{Daily Thawing Index} = 0 \degree F\text{-day and,}\]

\[\text{Daily Freezing Index} = \left( T_{\text{reference}} - \frac{T_{\text{maximum}} + T_{\text{minimum}}}{2} \right) \degree F\text{-day}\]

where,

\(CTI_n = \text{Cumulative thawing index calculated over ‘n’ days (°F-day)},\)

\(CFI_{n-1} = \text{cumulative thawing index for the previous day},\)

\(T_{\text{maximum}} = \text{Maximum daily air temperature (°F)},\)

\(T_{\text{minimum}} = \text{Minimum daily air temperature (°F)},\) and

\(T_{\text{reference}} = \text{Reference air temperature (°F)}.\)

(CTI resets to zero on January 1)

Instead of using a fixed reference temperature, the MnDOT Technical Memorandum No. 14-10-MAT-02 uses a floating reference temperature in assessing the CFI and CTI to address the increase in solar gain and daily sun duration during the thawing period. As shown in Table 2.2, a decrease of 2.7 °F (-1.5 °C) is used during the first week of February, and thereafter, a decrease of 0.9 °F (-0.5 °C) is applied per week. It is noted that the floating reference temperature is the air temperature at which thawing may occur, disregarding the subsurface temperature. An additional freezing point depression in the subsurface is very likely due to the presence of ions in the soil pore solution.

The conclusion of load restriction is determined using the forecasted air temperature, frost depths, and other key indicators, such as the soil moisture, maximum frozen depth, and weather patterns. However, the MnDOT intends to limit the spring load restriction within eight weeks. In recent times, the notable rise in Minnesota winter temperature may induce early thawing, requiring a complete assessment of winter load increases and spring load restrictions. An earlier study indicated that Minnesota’s winter temperature is increasing twice as faster as the annual average temperature, with significant warming in over-night low temperatures (MnDOH, 2014). As indicated in Figure 2.3, starting from the 1970s’, the annual average temperature in Minnesota has risen by 2 °F. This warming trend could increase the length of time spent around the freezing point, thus increasing the average number of freeze-thaw events. In this project, the number of freeze-thaw events could be quantified at the typical air temperature sensor level (e.g., 6 feet above the earth’s surface) as well as at each of the pavement layers (e.g., 1 inch beneath the surface layer, 6 inches beneath the surface layer, 12 inches beneath the surface layer, or some other
critical sub-pavement location where the temperature transition is more relevant) to answer if Minnesota’s warm winters are increasing the freeze-thaw events in pavements.

Table 2.2 Reference temperature as per the MnDOT Technical Memorandum No. 14-10-MAT-02

<table>
<thead>
<tr>
<th>Date</th>
<th>Reference Temperature (°F)</th>
<th>Reference Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January 1 – January 31</td>
<td>32.0</td>
<td>0</td>
</tr>
<tr>
<td>February 1 – February 7</td>
<td>29.3</td>
<td>-1.5</td>
</tr>
<tr>
<td>February 8 – February 14</td>
<td>28.4</td>
<td>-2.0</td>
</tr>
<tr>
<td>February 15 – February 21</td>
<td>27.5</td>
<td>-2.5</td>
</tr>
<tr>
<td>February 22 – February 28</td>
<td>26.6</td>
<td>-3.0</td>
</tr>
<tr>
<td>March 1 – March 7</td>
<td>25.7</td>
<td>-3.5</td>
</tr>
<tr>
<td>March 8 – March 14</td>
<td>24.8</td>
<td>-4.0</td>
</tr>
<tr>
<td>March 15 – March 21</td>
<td>23.9</td>
<td>-4.5</td>
</tr>
<tr>
<td>March 22 – March 28</td>
<td>23.0</td>
<td>-5.0</td>
</tr>
<tr>
<td>March 29 – April 4</td>
<td>22.1</td>
<td>-5.5</td>
</tr>
<tr>
<td>April 5 – April 11</td>
<td>21.2</td>
<td>-6.0</td>
</tr>
<tr>
<td>April 12 – April 18</td>
<td>20.3</td>
<td>-6.5</td>
</tr>
<tr>
<td>April 19 – April 25</td>
<td>19.4</td>
<td>-7.0</td>
</tr>
<tr>
<td>April 26 – May 2</td>
<td>18.5</td>
<td>-7.5</td>
</tr>
<tr>
<td>May 3 – May 9</td>
<td>17.6</td>
<td>-8.0</td>
</tr>
<tr>
<td>May 10 – May 16</td>
<td>16.7</td>
<td>-8.5</td>
</tr>
<tr>
<td>May 17 – May 23</td>
<td>15.8</td>
<td>-9.0</td>
</tr>
<tr>
<td>May 24 – May 30</td>
<td>14.9</td>
<td>-9.5</td>
</tr>
<tr>
<td>June – December 31</td>
<td>32.0</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 2.3 Average annual temperature in Minnesota with 10-year running average: 12 months ending is in December (MnDOH, 2014)
Under normal conditions, freezing and melting of pure water happen on the ice-water interface at 32 °F (0 °C). However, the soil pore water freezes at a temperature lower than the 32 °F (0 °C) depending on pressure, presence of the solute (i.e., cation and anions from the soil and deicing salts), and pore diameter (Kozlowski, 2009). Freezing involves nucleation and crystal formation, typically associated with a temperature lower than the theoretical freezing point of water. Nucleation occurs as the prerequisite of ice crystal formation when the liquid water molecules spontaneously gather in clusters defining the crustal structure of ice (Kozlowski, 2009). In addition, freezing is not a reversal of thawing. Thawing is initiated as a single step (pulse-like process) when the temperature rises to the melting point (Kozlowski, 2016). During the thawing process, temperature becomes stable due to the latent heat of fusion. On the other hand, water remains at a non-equilibrium/metastable state when the freezing point is reached. The crystallization is a continual process, and not all the pore water may get frozen in the soil-water system.

Figure 2.4 depicts the cooling curve of pure water and soil. As indicated in Figure 2.4, purified water started to freeze when the temperature drops below 32 °F (0 °C). However, the crystallization process (A’B’) was completed at a lower temperature, as indicated by the B’ on the cooling curve. As shown by line B’C’, melting of pure water was initiated when the temperature was raised to 32 °F (0 °C). The temperature of water remained constant throughout the melting process (C’D’). A similar observation was made for the freezing of soil, despite that fact that the freezing was introduced at a temperature lower than 32 °F (0 °C). The supercooling of soil was prominent compared to pure water, and thereby, a smaller temperature for spontaneous nucleation (Point B) was observed. The thawing process was also associated with a temperature lower than 32 °F (0 °C). Moreover, the distance between C to D is smaller than pure water since not all the water could get frozen in soil.

![Figure 2.4 Cooling curves of soil and pure water. Note: $T_f =$ Freezing point of soil and $T_{sn} =$ Spontaneous nucleation temperature (Kozlowski, 2009)](image_url)
Considering the lower freezing point of soil, Zhang et al. (2018) considered -0.5 °C (31.1 °F) in quantifying the number of freeze-thaw cycles in asphalt and concrete pavements. The results reported by Zhang et al. (2018) were verified by using in-situ soil moisture and temperature measurements for several years. Mahedi et al. (2019) applied differential scanning calorimetry (DSC) to determine the freezing point of loess soil in the temperature range of -15 °C to 20 °C (5 °F to 68 °F). The freezing point of the soil was determined to be -0.87 °C (30.4 °F) at a soil moisture content of 16.5%. Nagare et al., (2012) monitored the freezing effects on soil temperature and moisture redistribution through the laboratory investigation on large-scale peat mesocosms. The result showed that with a decrease in soil moisture, the freezing point of soil tended to decrease. Nagare et al., (2012) determined the soil freezing temperature between -0.4 °C and -1.13 °C (31.3 °F and 30 °F). Zheng et al. (2020) observed the in-situ soil moisture and temperature changes during the freeze-thaw events at multiple depths. This study indicated that the unfrozen water content decreased as the soil temperature decreased below 0 °C (32 °F). Zheng et al. (2020) identified the temperature range of 0 °C to -2 °C (32 °F to 28.4 °F) as the phase change temperature for soil pore solution. In addition, results indicated that, even at a temperature below -10 °C (14 °F), some of the soil moisture remains unfrozen. As shown in Figure 2.5, the unfrozen/residual moisture content of soil remained in the range of 10% to 20% depending on soil type.

![Figure 2.5](image)

**Figure 2.5** The unfrozen moisture content of the soil at different freezing temperatures. Adopted from Zheng et al. (2020)

In addition, the freezing of soil is primarily influenced by soil type. Coarser soils have relatively higher freezing temperatures and lower residual moisture content compared to finer soils. As shown in Figure 2.6, coarser silica had a freezing point of around -0.5 °C (31.1 °F), which decreased in the range of -1.5 °C to -2 °C (29.3 °F to 28.4 °F) when mixed with kaolinite. This is because of the smaller pore radius and higher suction values in finer soils. Kozlowski (2016) indicated that the unfrozen water content decreased with a decrease in soil pore diameter.
2.2.3 Role of Moisture

A freeze-thaw cycle is meaningless if no moisture is present in the pavement subgrade. Previous studies demonstrated that soil moisture content is a crucial factor in controlling the freezing temperature (Kozlowski, 2009, 2016). Kozlowski (2009) performed DSC experiments on homogeneous kaolinite and bentonite between -28 °C and 10 °C (-18.4 °F and 50 °F) to determine the effects of initial soil moisture on soil freezing point depression. Results showed that the equilibrium freezing temperature of soil monotonically decreased with a decrease in soil moisture content (Figure 2.7). The influence of soil moisture was more prominent for bentonite compared to kaolins. This signifies that moisture plays a significant role in the freezing and thawing of expansive soils than those with sandy and silty soils. Based on the experimental results, Kozlowski (2009) presented an empirical equation correlating the soil freezing temperature, plastic limit, and moisture content as follows:

$$T_f = -0.0729 \ w_p^{2.462} w^{-2}$$  \hspace{1cm} (3)

Where, $T_f$ is the soil freezing temperature in °C, $w_p$ is the plastic limit (%), and $w$ is the soil moisture content (%). The degree of correlation of the equation is 0.933, indicating a good distribution of the experimental results around the fitted line.
The intrusion of moisture in pavement foundations could happen in several ways. Among these, water infiltration through the surface cracks and other discontinuities could contribute to more than 40% of the rainfall to infiltrate into pavement structures (Oman and Lund, 2018). A higher groundwater table could significantly contribute to the adverse freeze-thaw effects on the pavements in low-lying areas. A study conducted by the ARA (2004) concluded that the groundwater table within five feet of pavement foundation provides adequate free moisture for ice crystallization. Compiled with a higher groundwater table, capillary action caused by the surface tension and the soil suction exacerbate the freezing and thawing of pavement subgrade soil by ensuring adequate water supply to the freezing front. Capillarity is controlled by the pore distribution and pore diameter in soil. The most significant capillary actions are associated with the smallest pore sizes (Johnson, 2012). However, the lower permeability of soils related to smaller pore diameters could negate the capillary actions during the soil freezing periods. Therefore, clayey soils are considered low frost-susceptible due to lower permeability, though the clay capillary actions are the highest. Vapor movement and lateral flow of water along the pavement edges and ditches can also contribute to the subgrade moisture noticeably.

A literature review was performed to assess the influence of moisture during the freezing and thawing of pavement structures. Al-Omari et al. (2015) performed freeze-thaw tests on two different limestone aggregates to determine the role of moisture and pore distribution in freeze-thaw damage. Specimens prepared at eight different saturation levels were subjected to 50 freeze-thaw cycles under controlled laboratory conditions. Results from this study revealed that the freeze-thaw damage was the most acute when the degree of saturation of the limestone samples exceeded 80% to 85% (Figure 2.8a). In addition, Al-Omari et al. (2015) showed that the number of freeze-thaw cycles did not influence the critical degree of saturation. Critical saturation could be considered an intrinsic property, and the pore size distribution mostly controlled the frost damage of limestone. Liu et al. (2019) assessed the influence of moisture on the freezing and thawing of silty clay samples. Frost shrinkage was noted by Liu et al. (2019) at lower soil saturation levels. Segregation of water as ice crystals, along with ice-cementation, were identified as the prominent reasons for the observed frost shrinkage. Liu et al. (2019) reported frost heaving of silty clay at a saturation higher than 75% (Figure 2.8b). With an increase in soil degree of saturation, frost-induced swelling increased due to the conversion of pore water into ice lenses. It is noted that moisture migration to the frost front from the underlying unfrozen layers results in excess moisture in the subgrade during
the freezing of soil. Therefore, frost heaving is most likely to overshadow the frost shrinkage and cause undue heaving on the pavement surface. Smith et al. (2019) discussed the service-life of concrete under freezing-thawing conditions focusing on the critical degree of saturation. Smith et al. (2019) indicated that, regardless of concrete mixture compositions, fiber contents, and air contents, the freeze-thaw damage on concrete was significant when the degree of saturation was above 86%. This study concluded that freeze-thaw damage is unlikely if the degree of saturation is below the critical saturation point. The fact is further illustrated in Figure 2.8c, where the damage rate is measured as the rate of decrease in concrete dynamic modulus for each freeze-thaw cycle. For asphalt concrete, the effect of moisture on the freeze-thaw damage has not been well studied. This is because the intrusion of moisture in hot-mix asphalt leads to the stripping of asphalt from the aggregates (Kim et al., 2009). Therefore, the residual moisture content of hot-mix asphalt is often restricted to less than 0.3% (IDOT, 2017). In addition, to reduce the moisture damage of asphalt pavements, anti-strip additives are added. However, the freeze-thaw events could impact the top layer of asphalt pavements in various ways, as discussed in the following section.

Based on the aforementioned discussion, it was identified that moisture availability could exacerbate the freeze-thaw damage of the pavements. In addition, the freeze-thaw damage is connected to the degree
of saturation rather than specific moisture contents. Therefore, moisture content, coupled with the degree of saturation, is required to assess the role of moisture during the freeze-thaw damage of the pavement systems.

2.3 FREEZE-THAW IMPACT ON PAVEMENTS

Though the pavement subgrade is the most vulnerable to freeze-thaw events, pavement surface layers could also be severely impacted. Mei et al. (2010) indicated a strong correlation between the fatigue damage in asphalt pavements and winter weather conditions. This study also noted the fracture of asphalt cement at the asphalt-aggregate interface due to freeze-thaw actions. Feng et al. (2010) studied the indirect tensile strength tests on asphalt after 0, 2, 4, 6, and 8 freeze-thaw cycles and concluded that the splitting tensile strength of asphalt decreased with an increase in freeze-thaw events due to the loss of asphalt adhesion. In a separate study, Tarefder et al. (2018) performed bending beam rheometer test, beam fatigue characterization, and indirect tensile strength test of asphalt mixtures after 0, 5, 10, 15, and 20 freeze-thaw cycles. As shown in Figures 2.9(a) to 2.9(c), the initial stiffness, the number of cycles required for fatigue failure, and the tensile strength ratio of hot-mix asphalt decreased significantly with an increase in freeze-thaw events. Si et al. (2014) performed compressive strength and resilient modulus test on asphalt concrete to investigate the impact on freeze-thaw. Results showed the compressive strength and resilient modulus of asphalt mixes decreased monotonically with an increase in the number of freeze-thaw cycles (Figures 2.9d and 2.9e). In addition, Si et al. (2014) investigated the pavement reliability during the freeze-thaw events using a range of coefficient of variance (CV). Analyses revealed that the asphalt pavement reliability declined due to freeze-thaw action (Figure 2.9f).

Figure 2.9 Impact of freeze-thaw on the hot-mix asphalt: (a) Stiffness, (b) number of cycles required for fatigue failure, (c) indirect tensile strength ratio, (d) compressive strength, (e) resilient modulus, and (f) reliability. Adopted from Tarefder et al. (2018) and Si et al. (2014)
The MnDOT studied the relations between the potholes and freeze-thaw events (MnDOT, 2006). The pothole season in Minnesota was recognized to coincide during the thawing period, later winter. The daytime thawing and nighttime freezing were credited for the increased number of potholes during the early spring of 2006. The MnROAD data supported the hypothesis, showing that the highest number of freeze-thaw events occurred in January 2006, whereas between 1994 and 2005, the maximum number of freeze-thaw cycles occurred in February and March (Figure 2.10).

In addition, the International Roughness Index (IRI) measurements in Cell 1 of the MnROAD test facility indicated that the IRI of the pavement surface increased as the pavement aged (Figure 2.11a). The IRI calculation process estimates the total cumulative amount of vertical movement between a vehicle wheel and the vehicle body over some fixed distance. The IRI data of Cell 1 was further analyzed to address the seasonal contributions. The general trend indicated that the increase in IRI inclines to be higher during the winter than the summer seasons (Figure 2.11b).

Moreover, distress surveys were conducted in Cell 1 during the fall and spring to allow a more direct comparison between the pavement distresses developed during summer and winter. Figure 2.12 shows...
the total top-down cracks in linear footage in Cell 1 between 1994 and 2005. As illustrated in Figure 2.12a, the majority of the top-down cracking appeared over the winter months. In addition to the top-down cracking, transverse cracks were also developed in Cell 1. The transverse crack severity level increased to medium severity from a low severity rating during the winter months. As depicted in Figure 2.12b, most of the transverse cracking was identified to be a one winter event distress (1996-1997). The coldest air-temperature (-39.7 °C or -39.5 °F) at the MnROAD was recorded during this winter on February 2, with a pavement subsurface temperature of -31 °C (-23.8 °F) at a depth of 0.96 inches.

The MnROAD test facility also measures the air temperature and pavement subsurface temperature at multiple depths. The pavement layer temperature measured in Cell 1 during February 1996 indicated that after the cold spell, the upper part of the pavement moved back and forth across the 0 °C (32 °F) line almost on a daily basis. The daily excursions between the high and low temperatures were more than 10 °C (50 °F), while the lower depth temperatures remain below freezing. Therefore, the thawed water on the top pavement layers became trapped with no or little drainage. A similar observation was made in January 2006, and the trapped moisture in pavement top layers could have acted as the trigger points of pothole development.
CHAPTER 3: HISTORICAL WEATHER DATA RESOURCES

3.1 INTRODUCTION

Several weather data resources were reviewed to identify the availability of Minnesota climatological data focusing on the quantification of freeze-thaw events. These weather data resources include the weather station data and embedded sensor data in pavement test sections from the MnROAD, MnDOT Seasonal Load Limits program, the RWIS sites from the MnDOT VAISALA/SCAN website and the IEM, the NOAA, the Modern-Era Retrospective Analysis Versions 1.0 and 2.0 (MERRA-1 and MERRA-2) database from the National Aeronautics and Space Administration’s (NASA) website, and the Virtual Weather Station (VWS) and the MERRA-1 and MERRA-2 databases in the FHWA LTPP program for active LTPP test section in Minnesota. An in-depth review and critical evaluation of each data resource were performed, focusing on the available data type, data collection year, spatial and temporal variability of weather conditions, measurement intervals, etc. A summary table was developed incorporating the available data types in various weather data resources to identify the most appropriate data resources for assessing freeze-thaw events in Minnesota.

3.2 REVIEW OF WEATHER DATA RESOURCES

3.2.1 Weather Station and Sensor Data in Pavement Test Sections from MnROAD

MnDOT has been utilizing several on-site weather stations to monitor and record the weather conditions at the MnROAD facility. The weather station data, along with the traffic and sensor data, are stored in the MnROAD oracle database. Between September 26, 1990, and February 17, 1997, the MnROAD facility used the Automatic Weather Station (AWS) data. Much of the missing data was often supplemented with the weather station data from the Buffalo Minnesota Regional Airport. Along with the AWS, weather data from the Cold Regions Research and Engineering Laboratory (CRREL) was used between October 30, 1990, and April 18, 1997. Currently, much of the data comes from the Northwest (NW) and Southeast (SE) weather stations in Minnesota RWIS sites. The NW weather station has been utilized since March 21, 1997, whereas the SE weather station is being used starting from April 30, 1998 (MnDOT, 2014a).

All the historical weather station data were combined in the MnDOT database in 2013. The current database includes air temperature (Celsius), atmospheric pressure (Millibars), heated rain gauge precipitation (100th inch), relative humidity (%), net radiation (Watts/square meter), net shortwave radiation (Watts/square meter), net longwave radiation (Watts/square meter), wind direction (Degrees from North), wind average speed (Meter/second), maximum wind gust (Meter/second), and wind gust direction (Degrees from North). All the data were reported to be collected in every 15 minutes intervals. The earliest data is reported from April 17, 1991, and the most recent data is reported on February 09, 2020. In the database, relative humidity and average wind speed data are missing until March 25, 1991. Wind gust direction data is available from November 23, 2010, whereas the net radiation data is accessible from April 12, 2013. The shortwave and longwave radiation, average wind speed, and wind gust direction data are missing intermittently. The temperature, atmospheric pressure, precipitation, wind direction,
and maximum wind gust are more regularly reported in the database. In addition, the weather station database does not provide data in chronological order.

The MnROAD test facility houses over 92 test cells to study the pavement materials and the design methods (MnDOT, 2020f). Initially constructed in 1990-1993, the facility is located on westbound I-94, consisting of 2.7 miles two-lane I-94 mainline; 2.5 miles two-lane closed-loop Low-Volume Road (LVR), 1,000 feet two-lane roadway in stockpile area, and a series of asphalt overlay and spall repair section on the original westbound of I-94 (Van Deusen et al., 2018). Along with the pavement deformation data, the MnROAD staff installed a wide range of sensors in each test cell. Among these, a number of sensors were installed to monitor the pavement layer and subsurface conditions. The most commonly installed environmental sensors are thermocouples and moisture sensors. Almost all the cells contained temperature and moisture sensors. Thermocouples are installed at various depths of the pavement sections ranging from 0.004 to 8.82 feet from the pavement surface. On the other hand, the moisture sensors are installed mainly in pavement base and subgrade layers. The temperature data availability varies from 1993 to 2019, whereas the Decagon moisture data (EW) is available from 2008 to 2015. In general, the temperature and moisture data are recorded in 15 minutes intervals at the MnROAD test facility (MnDOT, 2020a). Besides, 44 cells in the MnROAD test facility contain groundwater monitoring systems. The open standpipe tubes are installed to the depth of 15 feet to monitor the water table elevations (MnDOT, 2020a). In addition, some of the cells are installed with multiple resistivity probes to observe the frost depth penetration. In general, the resistivity probes are installed between the depth of 0.5 and 14 feet, thus only being in pavement base and subgrade layers. Furthermore, the MnROAD facility monitors the pore water pressure in the pavement base and sub-base at 11 different cells. The pore pressure is measured by using the static pore water pressure gauges. The pore water pressure gauges are installed between the depths of 0.6 and 4.5 feet.

In collaboration with the FHWA and I-Engineering, the MnROAD has developed an LTPP-InfoPave system by incorporating the MnROAD data (MnDOT, 2020e). The data is scheduled to update twice a year, and the system provides the search, view, and download options. While the information on the study area, weather station data, traffic data, and field data on pavement performance are accessible; the LTPP-InfoPave system does not provide information on pavement and subgrade temperature, moisture content, depth of groundwater table, and frost penetration (FHWA, 2020c).

3.2.2 MnDOT Seasonal Load Limits Program

The MnDOT provides specifications and detailed procedures on the winter load increases and the start of spring load restrictions through the seasonal load limits program (MnDOT, 2020h). Under this program, the state of Minnesota is divided into six frost zones (i.e., north, north-central, central, south, metro, and southeast) and identifies specific dates, locations, routes, and weight information for the winter load increases and spring load restrictions (MnDOT, 2020d). The tool generates subsurface temperature maps at 18 inches depths, freezing index maps, thawing index maps, maps for freeze-thaw depths, and county weight information. The statewide subsurface temperature maps could be generated from November to May, starting from 2005-2006. The freezing and thawing index maps are available from 2001-2002 winter for north and south zones, whereas from 2003-2004 winter for other zones. The MnDOT seasonal load
limits use RWIS and National Weather Service (NWS) to generate subgrade temperature, freezing index, and thawing index maps. In addition, the MnDOT incorporates 16 independent frost and thaw depth monitoring sites (MnDOT, 2020b). The maps available for the frost and thaw depths vary from site to site. The earliest maps are available for the Norman Ada and Wright Otsego sites, starting from 1998-1999 winter, whereas the latest addition is the Washington Marine site (2020-2021). The MnDOT seasonal load limits program provides a comprehensive assessment of the spatial and temporal distribution of subsurface temperature, moisture, and freeze-thaw depths, along with the traffic load criteria. However, the web-based tool does not provide the option to access the raw temperature, freezing depth, and thawing depth data. These data are available through the MnROAD database.

### 3.2.3 MnDOT Road Weather Information System (RWIS)

The RWIS is an environmental sensor station (ESS) deployed to collect atmospheric, pavement surface and subsurface, and visibility-related information (MnDOT, 2020c). In addition, camera images are gathered to support maintenance decisions. To facilitate the acquisition of night-time pavement images, infrared illuminators are also available. In accordance with the MnDOT VAISALA/SCAN website, the MnDOT RWIS consists of 108 sensor stations providing the near real-time atmospheric, surface, and subsurface information (MnDOT, 2020g). MnDOT also plans to add 53 systems statewide to expand the current capabilities. The MnDOT RWIS also reports climatological data from 82 Automated Weather Observing System (AWOS) stations and 17 Automated Surface Observing System (ASOS) stations (RWIS, 2020b, 2020a). The AWOS and ASOS data that RWIS reports include air temperature, relative humidity, dew point, air pressure, wind speed, wind direction, gust, gust direction, precipitation, and visibility. These AWOS data are reported in 20-second intervals, whereas the ASOS data interval is 1 minute. Both the AWOS and ASOS database in MnDOT RWIS starts from June 2015. The RWIS sites report air temperature, relative humidity, dew point, wind speed, wind direction, gust, precipitation rate, intensity, and type, visibility, pavement surface temperature, pavement layer temperature, subsurface temperature, freezing point, chemical saturation, chemical factor, water layer depth and thickness on the sensors, ice percentage, conductivity, and salinity. The temperature of the pavement layers is reported for the depths of 0.8 to 4 inches, whereas the subsurface temperatures are obtained at a depth of 17 inches from the top of the pavements. The freezing point of moisture is reported based on the specific chemical in use, thus considering the freezing point depression. In general, the data is described in 5-second intervals. Depending on the installation of the RWIS sites, the data archive start date varies.

### 3.2.4 Iowa Environmental Mesonet (IEM)

Iowa State University collects and archives weather data into IEM to gather, compare, and disseminate environmental data into a single collection point (ISU, 2020b). The data in IEM comes in a variety of formats along with the GIS data sources. The IEM data for the State of Minnesota include Minnesota ASOS, Minnesota Cooperative Observer Program (COOP), Minnesota Geostationary Operational Environmental Satellites (GOES) Data Collection Platforms (DCPs), and Minnesota RWIS data. The IEM archives RWIS data from 98 stations as a direct feed from MnDOT starting from October 15, 2010. According to the IEM, some of the data could be missing for the years 2000 and 2001 (ISU, 2020a). The IEM RWIS data for the State of Minnesota archives air temperature, dew point, precipitation, relative humidity, wind speed, wind...
direction, gust, visibility, pavement surface and layer temperature, and subsurface temperature. The IEM RWIS outputs are available at 15 minutes or 25 minutes temporal resolutions. Thus, there are discrepancies in the data measurement resolution reported in the IEM RWIS and MnDOT VAISALA/SCAN RWIS databases. These are dependent on the type of sensors’ measurement: air temperature (hundredths of decimal for IEM vs. integer for MnDOT RWIS), pavement surface temperature (hundredths of decimal vs. tenths), subsurface temperature (tenths vs. whole). Data could be missing either in the IEM RWIS and MnDOT RWIS, specifically for the pavement layers. For instance, the Alexandria station in the MnDOT RWIS reported only the surface and air temperature on December 01, 2017, 0:00 CST, whereas the IEM RWIS database provides pavement level temperatures at two different depths and subsurface temperature, along with the air and pavement surface temperatures. Conversely, there are other situations in which IEM RWIS data is missing sensor information. For example, on January 01, 2020, 0:00 CST, the Duluth Blatnik Bridge site in the MnDOT VAISALA/SCAN RWIS reports pavement surface temperature, along with the pavement layer temperatures at two different depths, whereas the IEM RWIS reports only the pavement surface and pavement temperatures at a single depth (depth unspecified). Table 3.1 summarizes the differences between the MnDOT VAISALA/SCAN RWIS and IEM RWIS databases.
### Table 3.1 Differences between the MnDOT VAISALA/SCAN RWIS and IEM RWIS databases

<table>
<thead>
<tr>
<th>Criteria</th>
<th>MnDOT VAISALA/SCAN RWIS</th>
<th>IEM RWIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Availability</td>
<td>2015 to current</td>
<td>2010 to current</td>
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<tr>
<td>Temporal Resolution</td>
<td>5 sec to 1 min</td>
<td>15 min to 26 min</td>
</tr>
<tr>
<td>Station Available</td>
<td>108</td>
<td>98</td>
</tr>
<tr>
<td>Weather Data Types</td>
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<td>Air temperature, road surface temperature, pavement layer temperature, subsurface temperature, precipitation, humidity, wind speed, wind direction, gust, visibility, and dew point</td>
</tr>
<tr>
<td>Pavement Data</td>
<td>Pavement temperature at two depths for some stations</td>
<td>One pavement layer temperature could be missing for those stations</td>
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<tr>
<td>Subsurface Data</td>
<td>Could be missing</td>
<td>Could be missing</td>
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<td>Pavement Sensor Depth</td>
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<tr>
<td>Subsurface Sensor Depth</td>
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<tr>
<td>Data Accessibility</td>
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<td>Yes</td>
</tr>
<tr>
<td>Data Interoperability</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

### 3.2.5 National Oceanic and Atmospheric Administration (NOAA)

The National Oceanic and Atmospheric Administration (NOAA) within the U.S. Department of Commerce aims to provide information on weather and the nation’s major waterways and oceans. NOAA created the National Environmental Satellite, Data, and Information Service (NESDIS) to operate the U.S. environmental satellites, manage the NWS data, and the data from other departments and governmental agencies. NESDIS’s National Centers for Environmental Information (NCEI), previously known as the National Climatic Data Center (NCDC), archives the weather data collected by NOAA (NOAA, 2020d).

NOAA gathers the daily weather data from 1,286 sites in Minnesota, providing daily summaries on air temperature, evaporation, soil temperature, precipitation, sky condition, sunshine, frost depth, wind speed, wind direction, gust, and gust direction. Data is reported on an hourly basis, starting from the date of installation of the stations (NOAA, 2020a). The monthly summaries are generated by compiling data from 1,198 stations in Minnesota (NOAA, 2020c). The sky condition and frost depth data are not included in monthly summaries. In addition, 102 stations are providing local climatological data for Minnesota. These stations provide information on dew point temperature, relative humidity, sky condition, and
visibility. The summaries are a product of surface observations from manual and automated stations (e.g., COOP, AWOS, and ASOS). The data are reported in 20 minutes intervals, and the archive start dates depend on the installation dates of the stations.

3.2.6 Modern-Era Retrospective Analysis Versions 1.0 and 2.0 (MERRA-1 and MERRA-2)

The National Aeronautics Space Administration (NASA) evaluates remote sensing data derived from satellites to simulate past atmospheric and surface environmental conditions. The first version of the Modern-Era Retrospective analysis for Research and Applications (MERRA) is available from January 1979 to February 2016, whereas the 2nd version of this product, MERRA-2, extends these capabilities to the most recent decade (data available up to October 2020) (Gelaro et al., 2017; Holmes et al., 2012). MERRA Land Data Product provides an understanding of past trends in soil temperature (Holmes et al. 2012) and soil moisture (Reichle et al. 2011) at multiple depths. Soil temperatures are reported between the depths of 0.2-0.5 ft, 0.5-1.2 ft, 1.2-2.4 ft, 2.4-4.9 ft, 4.9-9.8 ft, and 9.8-43 ft, whereas soil moisture contents are between the depths of 0-0.2 ft, 0-3.3 ft, and 0-43 ft (Holmes et al., 2012; Reichle et al., 2011). In addition to soil temperature and moisture, the other data available in MERRA-1 and MERRA-2 are air temperature, air pressure, humidity (atmospheric moisture), sky condition (cloud fraction and properties), evaporation, solar radiation (net radiation, lateral radiation, incident radiation, and air and soil heat flux), precipitation, snow and ice parameters, surface temperature (surface type not specified), vegetation fraction, wind speed, and gust (maximum wind speed).

MERRA and MERRA-2 have similar grid spacing with slightly higher resolution with the recent version in MERRA-2 (34 miles×44 miles) compared to MERRA (34 miles×46 miles). Reanalysis data are available hourly, on the half-hour, 3-hourly (20 minutes interval), 8-daily (3 hours interval), daily, and monthly intervals (Bosilovich et al., 2016). Due to the large volume of information generated from these reanalysis datasets, the files are extremely large and complicated to analyze from multiple years without specialized software to extract critical information (e.g., soil temperature and soil moisture) from the remaining parameters.

3.2.7 Long-Term Pavement Performance (LTPP)

The FHWA LTPP program provides research quality pavement and weather data across the U.S. and Canada (FHWA, 2020b). Starting from 1987, the LTPP program studies the in-service pavement performance focusing on how and why the pavements perform. The program collects data related to climate, material properties, loading conditions, and pavement performance. To ensure the quality of the collected data, personnel training and certification, regular calibration and maintenance of data collection equipment, and post-collection data checks are performed. All the LTPP test section data are accessible through the LTPP InfoPave system.

There are 2,581 LTPP sites across the U.S. and Canada. Among these, 82 sites are located in Minnesota (FHWA, 2020d). All these sites in Minnesota are distributed in 20 counties. Beltrami County has the highest number of LTPP sites (25 LTPP test sites). Among these 82 sites in Minnesota, 35 sites are for the General Pavement Studies (GPS), and 47 sites are for the Specific Pavement Studies (SPS). The GPS sites are located
on existing pavements, whereas the SPS sites are built to specific design and pavement layer thicknesses (Elkins & Ostrom, 2019; FHWA, 2020e, 2020a). However, only one GPS LTPP test site (i.e., GPS-6S) is currently active in the state of Minnesota. This site is located (LTPP Section ID 27-6251) at US-2, Westbound, Mile Post 113.8 at Beltrami County for the GPS-6S study of Asphalt Concrete Overlay of Asphalt Concrete Pavement with structural milling and fabric. The Minnesota climatological data in the LTPP program is available either through the VWS or MERRA. The VWS provides the average monthly and annual precipitation (rainfall and snowfall), temperature (average temperature, freezing index, and freeze-thaw days), humidity (maximum and minimum), and wind speed for the sites. The VWS uses up to five nearby weather station data and the $1/R^2$ weighting scheme interpolation technique to estimate climatological data without any physical station (Franco et al., 2020). The availability of the VWS data varies widely. The earliest VWS data is reported from 1947. The MERRA offers precipitation, evaporation, temperature (average and mean temperature, freezing index, freeze-thaw days, degree days, and coldest air temperature), pavement surface temperature (50% and 90% reliability), pavement subsurface temperature (50% and 90% reliability), wind speed, relative humidity, cloud cover, and shortwave surface radiation on a monthly and annual basis. The MERRA data is available from 1980, hence compiling both the MERRA-1 and MERRA-2 data from NASA.
CHAPTER 4: FREEZE-THAW ASSESSMENT FOR MINNESOTA

4.1 INTRODUCTION

Over the last several decades, Minnesota’s winters have gotten warmer, even faster than the summers. This warming trend could increase the time spent around the freezing point (32 °F) and thus increase the number of freeze-thaw (F/T) cycles. However, it is also possible that the warming trend does not impact freeze-thaw events. For example, in recent years, winter conditions have been highly variable in-between extreme warmth and cold and/or wet and dry conditions in the U.S. Upper Midwest. These fluctuations in temperature and precipitation may contribute to an increase or decrease in freeze-thaw events at different portions of the cold season (e.g., October through May) for a single year. Late fall or early winter warmth transported by strong winds reduces nighttime radiational cooling, and precipitation may occur more in the form of rain instead of snow. Increases in liquid vs. solid precipitation penetrate the subsurface and reduce the likelihood of soil freezing for the duration of the cold season. Conversely, a reduction in snow cover may also increase deep soil freezing as the subsurface is less insulated from cold events (Baker and Ruschy, 1995; Friesen et al., 2021). Additionally, in the late winter to early spring, cold surges promote sudden freeze events when subsurface temperatures are otherwise warming to begin the growing season. These variations in extreme temperatures and precipitation are also dependent on the north-south and east-west gradients of heat/cold and/or moisture across the state that change from the cold season into the warm season. These additional contexts to the observed climate trends in Minnesota winters are important for interpreting the change in F/T cycles that will be determined in Minnesota pavement systems. Historical climate data provide a long-term assessment of changes in Minnesota air and soil temperatures, precipitation, and freezing/thawing dates and depths to quantify F/T cycles for periods in which pavement measurement data are unavailable. These data resources have the best potential to confirm or reject the supposition that Minnesota warmer winters have increased freeze/thaw cycles by comparing climate conditions in the 20th century as a baseline to more recent conditions.

4.2 HISTORICAL ASSESSMENT OF MINNESOTA CLIMATE DATA

Historical climate data were evaluated to examine the temporal statewide and regional variability of climate trends of increasing temperature and precipitation for Minnesota winters. This assessment provides additional context for understanding how climate changes have modified concurrent Freeze/Thaw cycles and the depth of the freezing layer for soil and the pavement system. Monthly composites of mean maximum and minimum air temperature, mean surface temperature, mean soil temperatures, and total precipitation among multiple decades beginning in the 20th century and for longer-term composites of two or more consecutive decades indicate representative shifts in climate conditions starting in the 1980s.

4.2.1 Minnesota Climate Data from Cooperative Observer Network (COOP)

The National Oceanic Atmospheric Administration (NOAA) National Center for Environmental Information (NCEI) features long-term climate observations (starting in the late 1890s) from COOP station reports of
monthly mean daily high temperature, daily low temperature, and total precipitation. The measurements from these stations are influenced by decadal environmental changes in land use and changes in instrumentation reporting in the mid to late 20th century. These observations were utilized from two primary sources outside of NOAA-NCEI: (1) the Minnesota Department of Natural Resources Climate Trends Tool and (2) the COOP measurement archive automated plotting application on the Iowa IEM.

4.2.1.1 Minnesota Department of Natural Resources Climate Trends Tool

The MN Department of Natural Resources (DNR) provides a Climate Trends Tool web-applet (https://arcgis.dnr.state.mn.us/ewr/climatetrends/) for determining decadal trends in COOP monthly averages of daytime maximum and nighttime minimum temperature and monthly total precipitation. These trends were calculated by compositing COOP station measurements across different spatial regions, including statewide and the nine climate divisions represented in the state. These climate divisions represented regional cropland and drainage system boundaries and were adopted for climate data use since the late 1990s (Guttman and Quayle, 1996). Statewide trends in these variables were investigated for potential freeze-thaw conditions occurring in months September, October, November, December, January, February, March, April, and May for each decade, beginning in 1901 and ending in the most recent decade of 2020. Super decadal period averages were also determined for the long-term 20th century mean (1901-1980) corresponding to baseline climate conditions before the most recent 40-year period (1981-2020) of observed climate trends over the U.S. with higher mean temperatures and increased precipitation. The sensitivity of climate trends to staggering the start and end years of the decadal or super decadal periods by ±5 years (e.g., 1996-2005) were inconsequential, and so these composites were kept at the start of every new decade ending on the tenth year (e.g., 1991-2000). Monthly composites of statewide decadal trends were evaluated with spatial maps of monthly mean high and low temperature and monthly total precipitation of the MN 1981-2010 Climate Normal from the Minnesota DNR Climate Normal Map Tool:

(https://www.dnr.state.mn.us/climate/summaries_and_publications normalsportal.html).

4.2.1.2 Iowa Environmental Mesonet Auto-plot Tool

The ISU IEM generates automated plots of georeferenced Minnesota COOP measurements of monthly mean high temperature, monthly mean low temperature, monthly total precipitation, and the number of days below freezing based on high and low temperatures for a particular climate period. The applet provided a comparison of statewide conditions for the two super-decadal trends represented the 20th century long-term climate mean (1901-1980) and the most recent 40-year mean (1981-2020): https://mesonet.agron.iastate.edu/plotting/auto/?q=151. Plots generated in March 2021 comprise the available COOP measurements determined from the starting year to the ending year. For the baseline, 20th century super-decade data from 51 stations were composited into the analysis, whereas for the recent 40-year super-decade, data from 103 stations were represented. The auto-generated plots were modified to include a state overlay of the Minnesota climate divisions found from the NOAA Climate Prediction Center:
The monthly differences between the two super-decadal periods were evaluated in the context of the baseline 20th century long term climate mean for monthly low temperature, monthly high temperature, monthly total precipitation, and the number of freeze days (air temperature below 0 °C) annually and for each month of the freeze/thaw cycle season (October, November, December, January, February, March, April, and May).

4.2.2 Minnesota Soil Temperature Data from Modern-Era Retrospective Reanalysis Application, Version 2 (MERRA-2)

The National Aeronautics Space Administration (NASA) MERRA-2 is available from January 1979 to the most recent decade. Climate trends in soil temperature and soil moisture were determined for multiple depth layers: 0.2-0.5 ft, 0.5-1.2 ft, 1.2-2.4 ft, 2.4-4.9 ft, 4.9-9.8 ft, and 9.8-43 ft for soil, whereas soil moisture data are available in the 0-0.2 ft, 0.0-3.3 ft, and 0.0-43 ft layers.

Due to the large volume of information generated from these reanalysis datasets, the files are extremely large and difficult to analyze from multiple years without specialized software to extract key information (e.g., soil temperature and soil moisture) from the remaining parameters. The NASA data portal Giovanni: https://giovanni.gsfc.nasa.gov/giovanni/ (Acker and Leptouky 2007; Berrick et al. 2009; Liu et al. 2017) plots geospatial variability of any subsurface or surface-level parameter that influences freeze-thaw conditions. Giovanni, access by subscription, is restricted to users in federal and academic organizations from the NASA Earth Observing System Data and Information System (EOSDIS) EarthData log-in system: https://urs.earthdata.nasa.gov/.

This report focuses on climate trends only in soil temperature due to spatial uncertainty in soil moisture data and relating volumetric water content to soil saturation conditions, which are dependent on the subgrade material properties of the soil and unknown to the MERRA-2 modeling system. Monthly output identified decadal trends in monthly mean soil temperature with depths for 1981-1990, 1991-2000, 2001-2010, and 2011-2020. The Giovanni interface generated a georeferenced image centered on the state of Minnesota for each month of the freeze/thaw season for the six soil temperature layers over each decadal period. Trends in soil temperature were also compared to trends from the surface (skin temperature) and 6 ft (air temperature) data from the same model. Automated plots were modified to remove unnecessary text or latitude and longitude gridlines and to improve the usability of the legend by resetting the maximum and minimum limits of the variable. A static image was saved for additional modification by overlaying the MN-climate divisional map generated by NOAA Climate Prediction Center (CPC):

4.2.3 Statewide Trend of Minnesota Monthly Minimum Temperature

Long-term climate trends in Minnesota's monthly minimum temperature were determined with the statewide and climate divisional output from the Minnesota DNR climate trends tool, as described in Section 4.2.1.1. Figure 4.1 indicates statewide warmer nighttime temperatures of 2-5 °F in the decades after 1980 vs. the decades before 1980, especially for winter months (December, January, February) and March. For most months, the interannual variability of warmer or cooler nighttime temperature is similar before 1980 vs. after 1980, with the largest fluctuations in the transition months of November and March. These statewide trends are consistent among the nine climate divisions, with warmer nighttime temperatures occurring for the Northern, Central, and Eastern divisions, especially in the winter months (Figure not shown for brevity). Subregional variations to climate division trends are represented with the composite difference of mean monthly minimum temperature of 1981-2020 from the long-term 20th century mean (1901-1980) using the IEM auto plot feature in Figure 4.2. The North Central, Northeast, East Central, and Central climate divisions indicate the largest nighttime temperature increase of > 2 °F for December, January, and February. However, sub-regions of the Southern third of the state have much lower increases or a slight decrease (< ±1 °F) in nighttime temperature from the long-term mean. These plots represent the importance of interpreting climate data with accounting for the influence of microclimate changes relating to site location and heterogeneity of surface features (forest, agricultural fields, proximity to metropolitan areas and/or land elevation transitions, etc.).

4.2.4 Statewide Trend of Minnesota Monthly Maximum Temperature

Long-term climate trends in Minnesota’s monthly maximum temperature were determined with the statewide and climate divisional output from the Minnesota DNR climate trends tool. Figure 4.3 indicates statewide warmer daytime temperatures of 1-2 °F in the decades after 1980 vs. the decades before 1980, especially for the transition months of November and March and the winter months of December, January, and February. Interannual variability of warmer or cooler daytime temperature is similar before 1980 vs. after the 1980 decade for most months, with the largest fluctuations occurring in the transition months of November and March. These statewide trends are consistent among the nine climate divisions, with larger increases in high temperature occurring for the Northern, Central, and Eastern divisions, especially in the winter months with higher interannual variability of warm and cold events for the Southern climate divisions (Figure not shown for brevity). Subregional variations to the climate division trends are represented with the composite difference of mean monthly maximum temperature of 1981-2020 from the long-term 20th century mean (1901-1980) using the IEM auto plot feature in Figure 4.4. The North Central, Northeast, East Central, and Central climate divisions indicate the largest daytime temperature increase of 1-2 °F for the winter months of December, January, and February and transition month March. However, sub-regions of the Southern third of the state have much lower increases or a slight decrease (< ±1 °F) in daytime temperature from the long-term mean for September, March, April, and May.
Figure 4.1 Minnesota statewide long-term decadal distributions of monthly average nighttime minimum air temperature for (a) September, (b) October, (c) November, (d) December, (e) January, (f) February, (g) March, (h) April, and (i) May. In each panel, climate trend is denoted by comparing the 20th century long-term mean (1901-1980) and the most recent 40-year period (1981-2020). Error bars represent one-standard deviation of the interannual variability for each decade.
Figure 4.2 IEM spatial distribution of Minnesota COOP monthly mean low air temperature difference of the most recent 40-year mean (1981-2020) to the long-term 20th century climate mean (1901-1980) for (a) September, (b) October, (c) November, (d) December, (e) January, (f) February, (g) March, (h) April, and (i) May. Climate division overlay adapted from NOAA CPC U.S. state maps of climate divisions.
Figure 4.3 Minnesota statewide long-term decadal distributions of monthly average daytime maximum air temperature for (a) September, (b) October, (c) November, (d) December, (e) January, (f) February, (g) March, (h) April, and (i) May. In each panel, climate trend is denoted by comparing the 20th century long-term mean (1901-1980) and the most recent 40-year period (1981-2020). Error bars represent one-standard deviation of the interannual variability for each decade.
4.2.5 Statewide Trend of Minnesota Freeze Days (Annually and Monthly)

A comparison of freeze dates in the 20th century means before 1980 vs. the most recent 40-years is determined from the IEM auto plot application. In Figure 4.5, baseline 1901-1980 mean number of days with partial (nighttime only) freezing (Figure 4.5a) and complete (daytime and nighttime) freezing (Figure 4.5b) indicate the highest number of annual frozen days (above 100) near the international border and the lowest number of annual frozen days (below 70) in the southcentral climate division. These baselines' 80-year climate means were compared with the most recent 40-year mean number of freezing days with a high temperature below 0 °C annually and for each of the months of October-May (Figure 4.6). These trends revealed a small decrease in thaw days statewide at the start of the freezing season in November but a consistent increase in thaw days (2-3 added per month) over the northern two-thirds of the state during the winter (December, January, and February). For March, thaw days increased over most of the state, but subregions within each climate division exhibited higher variability in thaw days (decrease in 1 day vs. increase in 3 days).
Figure 4.5 IEM spatial distribution of Minnesota COOP mean freeze days annually for the period of 1901-1980 based on the number of days with (a) min. temperature < 32 °F (0 °C) and (b) max. temperature < 32 °F (0 °C).

Figure 4.6 IEM spatial distribution of MN COOP climate trends in freeze day differences determined from the difference (1981-2020) mean-(1901-1980) mean freeze days (a) annually and for (b) October, (c) November, (d) December, (e) January, (f) February, (g) March, (h) April, and (i) May. Freeze dates are determined from the number of days with a maximum temperature below 32 °F (0 °C).
Long-term climate trends in Minnesota monthly total precipitation were determined with the statewide and climate divisional output from the Minnesota DNR climate trends tool. Figure 4.7 indicates statewide higher precipitation of > 0.25-0.5 inch for the decades after 1980 vs. the decades before 1980 during the transition months in the fall (September-November) and spring (March-May) and in December. Significant interannual variation of wet and dry years occurred in more recent decades for the transition months of October-November with a suggested peak in the precipitation increase from 2001-2010 for the first half of the freeze-thaw cycle season (October-December). For other winter months or late spring, decadal variability is similar before vs. after the 1981-1990 decade. The trends in the nine climate divisions concur with statewide trends, especially for the largest amplification of precipitation in the southern and eastern climate divisions in the transition months of November and March (Figure not shown for brevity).

Figure 4.7 Minnesota statewide long-term decadal distributions of monthly total precipitation for (a) September, (b) October, (c) November, (d) December, (e) January, (f) February, (g) March, (h) April, and (i) May. In each panel, climate trend is denoted by comparing the 20th century long-term mean (1901-1980) and the most recent 40-year period (1981-2020). Error bars represent one-standard deviation of the interannual variability for each decade.
Subregional variations to the climate division trends are represented with the difference of total monthly precipitation between 1981-2020 and 1901-1980 using the IEM auto plot feature in Figure 4.8. The North Central, Northeast, East Central, and Central climate divisions indicate the largest precipitation increase (0.5-1.0 inches) during the fall and early winter (September-December). This maximum departure from the 20th century mean shifts to the southern third of the state with the transition month (March) and return to warm-season rainfall (April-May). Large sub-regions of the Southern third of the state and in the extreme northern sections of the north climate division are somewhat drier over the last 40 years, and these are reflective of the variability of cold-season snow fall during January and February for the south and late spring snow fall in the north.

Figure 4.8 IEM spatial distribution of Minnesota COOP monthly total precipitation difference of the most recent 40-year mean (1981-2020) to the long-term 20th century climate mean (1901-1980) for (a) September, (b) October, (c) November, (d) December, (e) January, (f) February, (g) March, (h) April, and (i) May. Climate division overlay adapted from NOAA CPC U.S. state maps of climate divisions.

4.2.7 Statewide Trend of Minnesota Monthly Soil Temperature

MERRA-2 output from monthly files identified decadal trends in monthly mean air, surface, and soil temperatures with depths from 1981-1990, 1991-2000, 2001-2010, and 2011-2020 for the months of November-May using the NASA Giovanni plotting application (Section 4.2.2). Trends in temperature
across the four decades are indicated in Figure 4.9 for the transition months of November (Figure 4.9a) and March (Figure 4.9b). Between the four decades, substantially warmer air and surface temperatures in 2001-2010 delayed the onset and seasonal progression of the frost zone into the deeper layers of the soil for the northern half of the state. Slightly cooler surface temperatures from the 2001-2010 period occurred in the most recent decade, but these conditions were several degrees above the mean surface temperatures from the 1980s and 1990s. Less decadal variation in surface and soil temperatures occurred in the spring transition month, in which frost depth is several feet into the soil. The later onset of freeze conditions during 2001-2010 also indicates a late thawing for northern portions of the state during March. These subtleties in the variation of freezing temperatures with depth also highlight more frequent warm and cold events during the winter leading to extended frozen soil conditions later into the spring season. These proxy assessments to freeze-thaw events could be further evaluated against F/T cycles determined from MnROAD weather and pavement data in the following sections.
Figure 4.9 Evaluation of MERRA-2 reanalysis monthly mean air temperature, surface temperature and mean soil temperature in the top four levels comparing decades 1981-1990, 1991-2000, 2001-2010, and 2011-2020 for (a) November and (b) March. Climate division overlay adapted from the NOAA Climate Prediction Center U.S. state maps of climate divisions.
**4.3 FREEZE-THAW ASSESSMENT USING MNROAD DATA**

The number of F/T events at the typical air temperature sensor level as well as at each of the pavement layers was determined by using the available historical data from the MnROAD test facility. The number of F/T cycles was evaluated on a monthly and yearly basis. For the quantification of F/T cycles at the air temperature sensor level, the temperature data from the MnROAD weather station was utilized. The MnROAD weather station data was accessed through the LTPP-InfoPave system (MnDOT, 2020e).
weather station data is available from October 27, 1990, to February 09, 2020. For assessing F/T cycles at each of the pavement layers, temperature and moisture sensor data from different test sections in the MnROAD test facility were utilized. The MnDOT provided the MnROAD embedded sensor data. The engineering reasonableness, availability, and accuracy of the MnROAD sensor data were evaluated to identify the suitable cell(s) for F/T assessment.

4.3.1 Freeze-Thaw Cycles at the Air Temperature Sensor Level

To quantify the number of F/T cycles from air temperature, freezing and thawing temperatures of 0 °C (32 °F) were used. This is reasonable since no freezing point depression was expected at the air temperature sensor level. It was also anticipated that the minimum freezing and thawing duration of 1 hour was required to complete an F/T cycle. The consideration of 1-hour freezing and thawing requirements was conservative since the air temperatures are available at hourly intervals between October 27, 1990, and July 07, 1993. In the weather station dataset, only 4.5% of temperature data was missing. Most of the missing data were for 1991 (i.e., December), 1992 (i.e., January, March to June, and October), and 1993 (i.e., March to July, October, and November). Therefore, the years 1990 to 1993 were excluded from the F/T assessment. In addition to 1 hour of minimum freezing and thawing duration, the number of F/T cycles at the air temperature sensor level was also calculated, assuming a minimum of 19 hours freezing and 5 hours thawing duration following the guideline from the TAP. These minimum freezing and thawing duration requirements are adopted by the MnDOT Seasonal Load Limits Program in quantifying the freezing and thawing depths. Thus, two different conditions were applied for the assessment of F/T cycles at the air temperature level. The conditions are as follows:

- **Condition 1**: Freezing temperature = 0 °C and thawing temperature = 0 °C; Minimum freezing duration = 1 hour and minimum thawing duration = 1 hour
- **Condition 2**: Freezing temperature = 0 °C and thawing temperature = 0 °C; Minimum freezing duration = 19 hour and minimum thawing duration = 5 hour

Figure 4.10 shows the yearly number of F/T cycles from winter 1994-95 to 2018-19. As shown in Figure 4.10(a), the yearly number of F/T cycles varied in the range of 45 to 85, when a minimum freezing and thawing duration of 1 hour was assumed (Condition 1). The yearly number of F/T cycles drastically decreased for the consideration of a minimum freezing duration of 19 hours and a thawing duration of 5 hours (Condition 2). For this longer requirement of freezing and thawing durations, the yearly F/T cycles at the air temperature sensor level were between 9 and 25 (Figure 4.10b). In addition, the temporal distribution of the F/T cycles was random. No specific trend in the number of F/T cycles was identified for the analysis period.

The average number of monthly F/T cycles at the air temperature sensor level was also calculated based on two different sets of freezing and thawing durations for the analysis period (i.e., winter 1994-95 to 2018-19). As indicated in Figure 4.11a, for a minimum 1-hour freezing and thawing duration, the number of F/T cycles was the highest during November and March, whereas the lowest for September and May. The average monthly number of F/T cycles decreased remarkably for the requirements of more extended freezing and thawing durations (Figure 4.11b). No F/T cycles were calculated for September and May. The
The lowest number of F/T cycles was found for October, whereas no specific variation on the monthly F/T cycles was observed for November to March.

**Figure 4.10** The number of yearly freeze-thaw cycles between winter 1994-95 and 2018-19 considering 0 °C freezing and thawing temperature and (a) a minimum 1 hour of freezing and thawing durations, and (b) a minimum of 19 hours of freezing and 5 hours of thawing duration.

**Figure 4.11** The average number of monthly freeze-thaw cycles between winter 1994-95 and 2018-19 considering 0 °C freezing and thawing temperature and (a) a minimum 1 hour of freezing and thawing durations, and (b) a minimum of 19 hours of freezing and 5 hours of thawing duration.

The number of monthly F/T cycles was calculated for the analysis period based on the aforementioned two conditions and are presented in Figures 4.12 and 4.13, respectively. As indicated in Figure 4.12, the
maximum number of F/T cycles occurred during November and March. A significant number of F/T cycles were also determined for December and April. The lowest F/T events were observed during September and May. An increase in freezing and thawing duration decreased the number of F/T cycles significantly (Figure 4.13). For instance, no F/T event occurred during the months of September and May, when a minimum freezing duration of 19 hours and thawing duration of 5 hours was applied. For this prolonged freezing and thawing requirement, the highest F/T cycles were determined for November and February. However, between the months of November and March, the number of F/T cycles varied within the narrow range of 77 to 91. The numbers of F/T cycles for October and April were 4 and 23, respectively.

4.3.2 Freeze-Thaw Cycles at Different Pavement Layers

4.3.2.1 Cell Selection for Analysis

Eleven different sensor data (i.e., EC – Decagon Conductivity, ET – Decagon Thermistor, EW – Decagon Moisture, TC – Thermocouple, TH – Sensirion Thermistor, VW – Vibrating Wire, XH – Thermistor, XL – Soil Pressure Thermistor, XM – Thermistor, XT – Vibrating Wire Thermistor, and XV – Vibrating Wire Thermistor) for 92 cells in MnROAD test facility was accessed through the MnROAD Oracle database. An overall data summary was created for all the cells indicating the sensor ID, depth of sensors, data availability period, and data frequency. From the overall data summary, TC – Thermocouple, EW – Decagon Moisture, and ET – Decagon Thermistor sensor data were selected for F/T analysis. The TC – Thermocouple and ET – Decagon Thermistor sensors record the pavement temperature at different depths. The spatial and temporal distribution of pavement moisture was provided through the EW – Decagon Moisture sensor data. These sensor data were carefully chosen considering a more extended data availability period, location in pavement layers, and higher embedment depths. The availability of TC – Thermocouple data varied from cell to cell between 1993 and 2019. The EW – Decagon Moisture and ET – Decagon Thermistor data are available from 2008 to 2015. It was found that almost all the cells (87 out of 92) house TC – Thermocouple sensors, whereas EW – Decagon Moisture and ET – Decagon Thermistor sensors were installed in 28 cells. Therefore, to further facilitate the cell(s) selection for F/T analysis, the availability of the EW – Decagon Moisture sensor data was investigated for each of the cells. Based on the moisture data availability, the following benchmarks/criteria were established to identify the cells for further analysis:

- Criterion 1: Cells with at least one EW – Decagon Moisture sensor in each of the pavement layers with data available for a minimum of two consecutive years
- Criterion 2: Cells satisfying Criterion 1 must have more than 80% of the survey period's data at all depths
- Criterion 3: Cells satisfying Criteria-1 and 2 have volumetric moisture contents less than 60% for at least 80% of the survey period
- Criterion 4: Cells satisfying all the criteria for EW – Decagon Moisture sensors must satisfy Criteria-1, 2, and 3 for TC – Thermocouples and the 80% of the survey period remained between -40 °C and +40 °C

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Figure 4.12 Average monthly number of freeze-thaw cycles at the air-temperature sensor level. Note: The minimum freezing and thawing duration of 1 hour was assumed, along with freezing and thawing temperatures of 0 °C.
Figure 4.13 Average monthly number of freeze-thaw cycles at air-temperature sensor level for the minimum freezing and thawing duration of 19 hours and 5 hours, respectively. Note: The freezing and thawing temperature of 0 °C was assumed.
Based on the EW – Decagon Moisture sensor data availability and the benchmarks as set forth above, Cells 20, 35, and 78 were selected for further consideration. It was found that cell 78 has the TC – Thermocouple data available for 2007 to 2015, whereas Cell 35 housed TC – Thermocouples for shallower depths (< 2 ft). Therefore, Cell 20 was identified as the ideal cell for F/T assessment. Cell 20 was initially constructed in July 1993 in the Mainline Test Road with 7.9 inches hot mix asphalt (HMA) layer, overlying on 23 inches Class 5 base layer and subgrade (Figure 4.14a). Cell 20 was initially constructed for full-depth reclamation (FDR), recycled unbound (RU), and low-temperature cracking studies. The Cell was reconstructed in October 2008, and the reconstructed Cell 20 arrangement has been shown in Figure 4.14b. The reconstructed Cell 20 was configured with 5 inches HMA layer, over 12 inches Class 5 aggregates, 12 inches Class 3 aggregates, 7 inches granular select, and subgrade sequentially. The EW – Decagon Moisture and ET – Decagon Thermistor sensors were installed in the reconfigured Cell 20. It was also found that Cells 19, 21, and 22 had similar configuration and sensor arrangement as of Cell 20. Therefore, Cells 19, 21, and 22 were also considered in supporting/validating the analysis. All these cells were reconstructed again in September 2016. Thus, the F/T assessment was limited to 2015, contingent on EW – Decagon Moisture and ET – Decagon Thermistor sensor data availability.

![Figure 4.14](image)

**Figure 4.14 Configuration of Cells 19, 20, 21, and 22: (a) between July 1993 and May 2008, and (b) between October 2008 and September 2016.**

Table 4.1 shows the EW – Decagon Moisture and ET – Decagon Thermistor sensor arrangement in Cell 20. These data were recorded in 15 minutes intervals. The availability of the sensor data between 2008 and 2015 is indicated in the supplementary materials. In addition, sensor moisture data was often reported in raw format. Material-specific calibration factors were used to convert the raw sensor data. Before constructing the cells, the base, subbase, and subgrade materials were characterized in the laboratory and reported in Teshale et al. (2019). The moisture sensor calibration coefficients, along with the maximum dry density (MDD) and optimum moisture contents (OMC), are summarized in Table 4.2. The
calculated volumetric moisture contents (VMC) were converted to gravimetric moisture contents (MC) by dividing the VMC by the MMD of the materials according to the depths.

Table 4.1 EW – Decagon Moisture and ET – Decagon Thermistor sensor arrangement in Cell 20

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<th>S104</th>
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<td>Subgrade</td>
</tr>
<tr>
<td>Materials</td>
<td>CLS5</td>
<td>CLS5</td>
<td>CLS3</td>
<td>CLS3</td>
<td>SG</td>
<td>Clay</td>
<td>Clay</td>
<td>Clay</td>
</tr>
</tbody>
</table>

Note: CLS3 = Class 3 aggregates, CLS5 = Class 5 aggregates, SG = Select granular

Table 4.2 Material properties and the moisture sensor (5TE) calibration coefficients. Adopted from Teshale et al. (2019)

<table>
<thead>
<tr>
<th>Material</th>
<th>Proctor Parameters</th>
<th>Moisture sensor (5TE) Calibration Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MDD (g/cm³)</td>
<td>OMC (%)</td>
</tr>
<tr>
<td>CLS3</td>
<td>2.05</td>
<td>9.4</td>
</tr>
<tr>
<td>CLS5</td>
<td>2.108</td>
<td>7.4</td>
</tr>
<tr>
<td>SG</td>
<td>2.111</td>
<td>7.8</td>
</tr>
<tr>
<td>Clay</td>
<td>1.875</td>
<td>13.1</td>
</tr>
</tbody>
</table>

Note: MDD = Maximum dry density, OMC = Optimum moisture content

4.3.2.2 Spatial and temporal Distribution of Subsurface Moisture and Temperature

The ET – Decagon Thermistor and EW – Decagon Moisture sensor data were used to investigate the spatial and temporal distribution of subsurface temperature and moisture conditions. Figure 4.16 shows the temperature and moisture distributions in Cell 20 up to the depths 36 inches (i.e., 7, 15, 23, and 36 inches) between September 2008 and January 2010. These depths were selected since, at depths beyond 36 inches, most of the moisture and temperature data were unavailable. In addition, sensors worked efficiently in the first two years of installation with the lowest amounts of missing data. A similar observation was made for all the cells housing both the temperature and moisture sensors. However, the least amounts of data were missing for Cell 20 and hence was selected for analysis. As shown in Figure 4.16, with an increase in pavement depth, diurnal temperature variations decreased. The highest variations in temperature were observed at shallower pavement depths. The subsurface temperature was minimum between December and January, whereas the highest temperatures were measured for July and August. Conversely, the lowest moisture contents were calculated for the top pavement layers. With an increase in pavement depths, the subsurface moisture content tended to increase. The highest moisture contents were measured in the subgrade at a depth of 36 inches. The seasonal variations of subgrade moisture were also higher, which may have happened due to the fluctuation of the groundwater table. In addition, a peak in subsurface moisture content was observed in late March and April at shallower pavement layers.
Figure 4.15 Subsurface distribution of temperature at the depths of (a) 7 inches, (b) 15 inches, (c) 17 inches, (d) 23 inches, and (e) 36 inches, and gravimetric moisture content at the depths of (a) 7 inches, (b) 15 inches, (c) 17 inches, (d) 23 inches, and (e) 36 inches in Cell 20. Note: Gray lines indicate the actual temperature at 15-minute intervals, whereas the red line indicates 7-day average temperatures.
Moreover, it was noticed that during the freezing events, the subsurface moisture contents of the pavement layers decreased significantly. As the pore water freezes into ice lenses, it gets segregated from the soil and/or pavement materials. As a result, the dielectric constant also decreases, which is used as the basis of moisture measurement by the sensors installed in the MnROAD test facility. For instance, the dielectric constants of air, water, and ice are 1, 80, and 3, respectively. Therefore, with a decrease in temperature, more water gets frozen and segregated, and consequently, the liquid moisture content kept decreasing with a decrease in the dielectric constant of soil. However, regardless of freezing temperature, some of the pore water remains unfrozen, termed the residual moisture content in previous literature (Kozlowski, 2009; Mahedi et al., 2020; Nagare et al., 2011, 2012; Zheng et al., 2020).

4.3.2.3 Material-Specific Freezing Points and Freeze-Thaw Cycles at Different Pavement Layers

The occurrence of freezing and thawing in subsurface conditions is greatly reliant on the freezing point of the materials. The pore water freezes at a temperature lower than the 32 °F (0 °C) depending on the types of materials, matric suction, moisture content, presence of the solute (i.e., cation and anions from the soil and deicing salts), and pore diameter (Kozlowski, 2009). Therefore, the freezing temperature varies from material to material and even could be different for the same material. In this study, material-specific freezing temperatures of pavement materials were determined by using the moisture-temperature relationship. Focusing on this goal, the in-situ cooling curves of Class 3, Class 5, select granular (SG), and subgrade soil were generated using the ET – Decagon Thermistor and EW – Decagon Moisture sensor data. Figure 4.17 shows the cooling curve for Class 5 materials in Cell 20 at the depths of 7 and 15 inches. As seen from Figure 4.16, with a decrease in temperature, the moisture content of Class 5 materials decreased because of ice formation. The reduction in moisture content was initiated at around 0 °C. At very low temperatures, the moisture content of Class 5 materials became stable and did not change further with a decrease in temperature. This moisture content could be considered as the residual moisture content of Class 5 materials. The freezing point of Class 5 materials was determined by identifying the intersection of a tangent to the cooling curve and residual moisture content. The freezing point determined through this method represents the minimum freezing temperature, ensuring that the material was completely frozen.
A similar approach was adopted to determine the freezing point for all three materials (i.e., Class 5, Class 3, select granular, and clay). Cooling curves were generated using the sensor data from Cells 19, 20, 21, and 22. All the cooling curves are presented in Appendix A. Table 4.3 provides the freezing temperatures of the materials determined at various pavement depths. As indicated in Table 4.3, the freezing temperatures for a material determined from the in-situ cooling curves at different depths were very close to each other. The average freezing temperature for the base materials (i.e., Class 5, Class 3, and select granular) was -1 °C, whereas it was -1.5 °C for clay subgrade. These material-specific average freezing temperatures were used in quantifying the number of F/T cycles at different pavement layers. Similar assessment for the topmost pavement layer (i.e., HMA and PCC) was not possible since none of the cells have moisture sensors installed at the top layer. Therefore, a freezing temperature of -0.5 °C was assumed, following the procedure described in Zhang et al. (2018).

Table 4.3 Freezing temperatures of Class 5, Class 3, select granular (SG), and clay subgrade

<table>
<thead>
<tr>
<th>Materials</th>
<th>Sensor Sequence</th>
<th>Depth (in)</th>
<th>Minimum Freezing Temperature (°C)</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cell 19</td>
<td>Cell 20</td>
</tr>
<tr>
<td>CLS5</td>
<td>101</td>
<td>7</td>
<td>-1</td>
<td>-1.1</td>
</tr>
<tr>
<td></td>
<td>102</td>
<td>15</td>
<td>-1.1</td>
<td>-1</td>
</tr>
<tr>
<td>CLS3</td>
<td>103</td>
<td>17</td>
<td>-</td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td>104</td>
<td>23</td>
<td>-</td>
<td>-1</td>
</tr>
<tr>
<td>SG</td>
<td>105</td>
<td>30</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Clay</td>
<td>106</td>
<td>36</td>
<td>-</td>
<td>-1.5</td>
</tr>
</tbody>
</table>

Note: CLS5 = Class 5 aggregates, CLS3 = Class 3 aggregates, SG = Select granular, - indicates inadequate data or data quality. *Omitted from analysis.
For quantifying the number of F/T cycles at different pavement layers, TC – Thermocouple data from Cell 20 was utilized. The TC – Thermocouple data is available from 1994 to 2015, allowing the F/T assessment for a more extended period of time. The initial thermocouple tree installed in Cell 20 was discontinued in 2007. A new set of thermocouples was housed in the reconstructed Cell 20 during 2008. Between 1994 and 1997, temperatures were recorded in 1-hour intervals, whereas the data frequency was 15 minutes starting from 1998. A missing data analysis was performed to ensure the data quality and reasonableness. Except for the depths of 1.5, 5, and 30 inches, all the thermocouple data was available for Cell 20. The location of reinstalled thermocouples was changed from the initial thermocouple tree, thus resulting in distinct offset values. In addition, the depths of reinstalled thermocouples varied significantly. Therefore, to ensure the quantification of F/T cycles at constant pavement depths, specific thermocouples were selected by closely matching the installation depths. Table 4.4 lists the thermocouples in Cell 20 selected for F/T assessment. Slight variations in installed thermocouple depths were observed. For uniformity, the average depths of two closely installed thermocouples were used for analysis.

**Table 4.4 Selected sensors in Cell 20 for the quantification of the freeze-thaw cycles**

<table>
<thead>
<tr>
<th>Cell 20: Selected Sensor Sequence</th>
<th>Offset (ft)</th>
<th>Depth (in)</th>
<th>Average Depth (in)</th>
<th>Pavement Layer</th>
<th>Data Availability Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>104</td>
<td>-5.6</td>
<td>3.5</td>
<td>HMA</td>
<td>2008-2015</td>
<td></td>
</tr>
<tr>
<td>05</td>
<td>-9.76</td>
<td>11.64</td>
<td>11.32</td>
<td>CLS3</td>
<td>1993-2006</td>
</tr>
<tr>
<td>108</td>
<td>-5.6</td>
<td>11</td>
<td>CLS5</td>
<td>2008-2015</td>
<td></td>
</tr>
<tr>
<td>07</td>
<td>-9.76</td>
<td>23.64</td>
<td>23.82</td>
<td>CLS3</td>
<td>1993-2006</td>
</tr>
<tr>
<td>111</td>
<td>-5.6</td>
<td>24</td>
<td>CLS3</td>
<td>2008-2015</td>
<td></td>
</tr>
<tr>
<td>08</td>
<td>-9.76</td>
<td>35.64</td>
<td>35.82</td>
<td>CLS3</td>
<td>1993-2006</td>
</tr>
<tr>
<td>113</td>
<td>-5.6</td>
<td>36</td>
<td>CLS3</td>
<td>2008-2015</td>
<td></td>
</tr>
<tr>
<td>09</td>
<td>-9.76</td>
<td>47.64</td>
<td>47.82</td>
<td>Clay</td>
<td>1993-2006</td>
</tr>
<tr>
<td>114</td>
<td>-5.6</td>
<td>48</td>
<td>Clay</td>
<td>2008-2015</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>-9.76</td>
<td>59.64</td>
<td>59.82</td>
<td>Clay</td>
<td>1993-2006</td>
</tr>
<tr>
<td>115</td>
<td>-5.6</td>
<td>60</td>
<td>Clay</td>
<td>2008-2015</td>
<td></td>
</tr>
</tbody>
</table>

Note: HMA = Hot-mix asphalt, CLS5 = Class 5 aggregates, CLS3 = Class 3 aggregates, and SG = Select granular

Figure 4.17 shows the average monthly number of F/T cycles at different pavement layers between the winter of 1995-96 and 2014-15. Winter of 1994-95 was omitted since the temperature data during November 1994 was not available. For calculating the number of F/T cycles, material-specific freezing points, as indicated in Table 4.3, were used. A melting temperature of 0 °C was assumed to ensure complete thawing. It was also anticipated that the minimum freezing and thawing duration of 1 hour was required to complete an F/T cycle. As depicted in Figure 4.17, a higher number of F/T cycles were determined at shallower pavement depths. With an increase in depth, the number of F/T cycles decreased considerably. Maximum F/T events occurred during March, followed by the number of F/T cycles in February and December. The average numbers of F/T cycles were similar for November and January. At deeper depths (> 12 inches), the highest number of F/T cycles was observed for March.
Figure 4.17 Average monthly F/T cycles between 1995-96 and 2014-15 at the depths of (a) 3.37 in, (b) 11.32 in, (c) 23.82 in, (d) 35.82 in, (e) 47.82 in, and (f) 59.82 in considering material-specific freezing and thawing temperature with 1 hour of freezing and thawing durations.

The yearly number of F/T cycles at different pavement layers is shown in Figure 4.18. It was observed that, between winter 1995-96 and 2014-15, the yearly F/T cycles tended to decrease at a depth of 3.37 in. As summarized in Table 4.5, analysis of variance (ANOVA) with a confidence level of 95% indicated that the decrease in yearly F/T cycles at 3.37 inches is statistically significant (high coefficient of determination, high F-value, Significance F < 0.05). In addition, a higher number of F/T cycles were determined at shallower pavement depths. With an increase in depth, the number of F/T cycles decreased considerably. At deeper pavement layers, the number of F/T cycles did not change significantly (Table 4.5) throughout the analysis period. Thus, it was concluded that the yearly number of F/T cycles decreased at shallower pavement layers, whereas at deeper depths, the number of F/T cycles remained unchanged.
Figure 4.18 The number of yearly F/T cycles at the depths of (a) 3.37 in, (b) 11.32 in, (c) 23.82 in, (d) 35.82 in, (e) 47.82 in, and (f) 59.82 in in considering material-specific freezing and thawing temperature with 1 hour of freezing and thawing durations.

Table 4.5 ANOVA for the number of yearly F/T cycles based on material-specific freezing temperatures

<table>
<thead>
<tr>
<th>ANOVA</th>
<th>Depths Below the Pavement Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.37 in</td>
</tr>
<tr>
<td>Coefficient of Determination ($R^2$)</td>
<td>0.46</td>
</tr>
<tr>
<td>t-Stat</td>
<td>-3.72</td>
</tr>
<tr>
<td>F-Value</td>
<td>13.8</td>
</tr>
<tr>
<td>Significance F</td>
<td>0.0018</td>
</tr>
</tbody>
</table>
To further elaborate on the observed trend in the yearly number of F/T cycles, the monthly number of F/T cycles was evaluated at a depth of 3.37 inches. As observed in Figure 4.19, the number of F/T decreased during November and March, whereas remained random for the rest of the winter months. The decreases in F/T cycles at 3.37 inches during November and March are statistically significant (Table A1 at appendix A). Thus, it could be said that at shallower pavement depths, the number of F/T cycles decreased during early and late winter. However, at deeper depths and other winter months, the changes in F/T events were not significant.

Figure 4.19 The number of monthly F/T cycles at the depths of 3.37 in (a) November, (b) December, (c) January, (d) February, (e) March, and (f) April considering material-specific freezing and thawing temperatures with 1 hour of freezing and 1 hour of thawing durations.
4.3.2.4 Fixed Freezing Temperature and Freeze-Thaw Cycles at Different Pavement Layers

The number of F/T cycles at different pavement layers was also calculated by considering the freezing and thawing temperatures of 0 °C. Two different freezing and thawing duration requirements were applied to quantify the F/T events with fixed freezing and thawing temperatures. In condition 1, a minimum freezing and thawing duration of 1 hour was required to complete an F/T cycle. In condition 2, a minimum of 19 hours of freezing and 5 hours of thawing was utilized following the TAP guidelines. Thus, the freeze-thaw conditions applied herein are identical to the conditions employed in quantifying the number of F/T cycles at the air temperature sensor level. Figure 4.20 shows the number of yearly F/T cycles at different pavement layers considering 0 °C freezing and thawing temperatures, along with a minimum of 1 hour of freezing and thawing durations (Condition 1). A higher number of F/T cycles was calculated for each pavement layer than those determined using material-specific freezing temperatures. As confirmed in Figure 4.20, the number of yearly F/T cycles at a shallow depth (i.e., 3.37 in) also decreased for the analysis period. The decrease in annual F/T cycles during the analysis period was statistically significant (Table A2 at appendix A). The yearly number of F/T cycles was random at higher depths and did not follow any specific trend.
The number of monthly F/T cycles at a depth of 3.37 inches satisfying the requirements of Condition-1 is presented in Figure 4.21. Similar to the F/T assessment based on material-specific freezing temperatures, it was observed that the number of F/T cycles at 3.37 inches decreased during early and later winter (i.e., November and March). ANOVA indicated that the decreasing trend of F/T cycles during November and March was statistically significant (Table A3 at appendix A). For other winter months, the number of F/T cycles was random, following no specific patterns.
Figure 4.21 Number of monthly F/T cycles at the depths of 3.37 in (a) November, (b) December, (c) January, (d) February, (e) March, and (f) April considering 0 °C freezing and thawing temperature with 1 hour of freezing and 1 hour of thawing durations

Similarly, the number of yearly F/T cycles for Condition-2 (i.e., 0 °C freezing and thawing temperature, and a minimum of 19 hours freezing and 5 hours thawing duration) was calculated and presented in Figure 4.22. The lowest number of F/T cycles was calculated for Condition-2 because of prolonged freezing and thawing requirements. In addition, it was also observed that the number of yearly F/T cycles was inclined to decrease at a shallow depth (i.e., 3.37 inches). However, the trend was weaker compared to F/T cycles calculated from Condition-1 and material-specific freezing temperatures. At higher depths, the changes in the yearly number of F/T cycles were random and did not follow any specific trend (Table A4 at appendix A).
For Condition-2, the monthly number of F/T cycles at 3.37 inches is provided in Figure 4.23. Similar to the F/T assessment based on Condition-1 and material-specific freezing temperatures, the number of F/T cycles at 3.37 inches decreased during early winter (Table A5 at appendix A). However, the trend was weaker than the F/T cycles calculated by the other two methods because of prolonged freezing and thawing requirements. For other winter months, the number of F/T cycles was random, following no specific patterns.
The quantification of F/T cycles at different pavement layers, following three distinct methods, provided similar results. It was found that the yearly number of F/T cycles tended to decrease at shallow depths during the analysis period. However, smaller variations in the annual number of F/T cycles were observed at higher depths. Further assessment revealed that the decrease in F/T cycles at top pavement layers was demonstrated by reduced F/T cycles in the early and late winter months. The freezing and thawing events at different pavement layers were random for other winter months, following no specific patterns.
4.3.2.5 Validation and Freeze-Thaw Profile

The number of F/T cycles quantified in this study was compared with the F/T counts determined in a similar study conducted by MnDOT (MnDOT, 2006). In the MnDOT (2006) study, the average monthly F/T cycles were determined at 1 inch below the pavement surface between 1994-95 and 2004-05 with a reference temperature of 0 °C. In the current study, the number of F/T cycles was assessed for Cell 20 between 1995-96 and 2014-15. Cell 20 had a varying top layer thickness (5 and 7.9 inches), and the number of F/T cycles was quantified at a depth of 3.37 inches. Material-specific freezing temperature and 0 °C fixed reference temperature with two sets of freezing and thawing durations were used to determine the number of F/T cycles. Figure 4.24 shows the comparison of average monthly F/T counts between these two studies. From both studies, the highest number of F/T cycles was determined in March, following the F/T cycles in February, December, November, January, April, and October. However, the average monthly F/T cycles determined in this study were slightly lower than the MnDOT (2006) study because of a higher analysis depth (1 inch vs. 3.37 inches). Nonetheless, the average monthly F/T cycles determined in this study mirrored the monthly F/T counts reported in MnDOT (2006).

Figure 4.25 shows the yearly F/T profile for Cell 20 based on three different conditions. The number of F/T cycles quantified by using material-specific freezing temperature is depicted in Figure 4.25a. It was observed that at a shallow depth (< 5 inches), the number of F/T cycles decreased during the analysis period. At depths higher than 8 inches, the F/T contours became horizontal, indicating no significant changes in yearly F/T events. At greater depths, freezing and thawing were minimal and did not change noticeably throughout the analysis period. A similar observation was made for the yearly F/T events determined with 0 °C freezing and thawing temperatures with a minimum of 1-hour freeze and thaw duration (Figure 4.25b). However, for more extended freezing and thawing requirements, the yearly F/T cycles decreased significantly (Figure 4.25c). Freezing with a minimum of 19 hours requirement indicates the hard freezing with severe winter temperatures. As illustrated in Figure 4.25c, hard freezing was extended to a depth of 3 ft below the pavement surface. In addition, the hard F/T events were random and did not follow any specific patterns throughout the analysis period.
Figure 4.24 The average number of monthly freeze-thaw cycles for (a) 1994-95 to 2004-05 at 1-inch depth from MnDOT (2006), (b) 1995-96 to 2014-15 at 3.37 inches considering material-specific freezing temperature, and (d) 1995-96 to 2014-15 at 3.37 inches considering 0°C freezing temperature. Note: 1 hour of freezing and thawing durations were applied in all cases.
Figure 4.25 Yearly freeze-thaw profile with depth: (a) material-specific freezing temperature, (b) 0 °C reference temperature with a minimum of 1-hour freezing and thawing duration, and (c) 0 °C reference temperature with a minimum of 19 hours freezing and 5 hours thawing duration

4.4 FREEZE/THAW CYCLE ASSESSMENT FROM HISTORICAL MINNESOTA CLIMATE MEASUREMENTS AND REANALYSIS

F/T cycles were calculated using temperature measurements from long-term COOP daily observations and MERRA-2 reanalysis data for air, surface, and soil layer output. Although this project focuses on determining the F/T events for the Minnesota pavement system, similar quantification of F/T cycles is possible using these air temperature measurements from historical climate data. This analysis of F/T cycles based on long-term air temperature records provides a direct comparison of F/T cycles determined from air temperature measurements at the MnROAD test facility. F/T cycles from historical climate data also inform understanding of the regional representation of Minnesota F/T cycle long-term climate trends.
for the pavement system beyond the single site at MnROAD. The following data sources provide both interpretations of F/T cycle trends during measurement collection at MnROAD (e.g., 1994-2019) and from observations predating the facility construction (e.g., 1901-current).

4.4.1 Freeze/Thaw Cycles from Minnesota COOP Measurements Near MnROAD

COOP measurements were selected from a single long-term climate site within 40 miles to MnROAD with similar microclimate conditions. A few stations (Buffalo and Elk River) were identified within 10 miles of the facility but had significant influence from the surrounding land-use changes in urban expansion on the northwest periphery of the Twin Cities metropolitan area. Other stations (Milaca and St. Cloud) were considered but are located 30-40 miles away from MnROAD, and the F/T cycles from these regions may have a less spatial association to the F/T cycles calculated from the MnDOT instrumentation at the test site. (Buffalo and St. Cloud had similar seasonal variations in F/T cycles, with St. Cloud cycles slightly higher than at Buffalo. This comparison demonstrated that the closest spatial association of F/T cycles to MnROAD would be from a nearby location). Buffalo was chosen to provide this assessment recognizing the limitation in understanding F/T cycles with land-use changes surrounding the site. The COOP Measurements archived at the IEM were downloaded at:

https://www.mesonet.agron.iastate.edu/request/coop/fe.phtml?network=MNCLIMATE.

Daily records of maximum and minimum air temperature were used to calculate the number of freeze-thaw cycles from June 1, 1940, to May 31, 2020, accounting for a complete 80-year period (1941-2020) to study long-term climate trends. Freezing and thawing temperatures were chosen based on two methods as follows:

- **Method 1**: Freezing temperature = 0 °C and thawing temperature = 0 °C
- **Method 2**: Freezing temperature = 0 °C and thawing temperature = determined from the MnDOT provided reference temperatures for calculating the Cumulative Thawing Index (Designated herein as $T_{ref}$). The reference temperatures accounting for decreased thawing temperature from 0 °C according to increased solar radiation beginning on January 1 for each calendar year according to the MnDOT Technical Memorandum No. 14-10-MAT-02

Annual and monthly F/T cycles were analyzed from the Buffalo location both during the MnROAD years of data availability from air temperature measurements (from 1994-1995 up to 2018-2019) and the more extended 80-year period. Additional considerations for changes in the longer climate trends were determined between 40-year periods; (1941-1980) vs. (1981-2020), and between recent decades from 1981-1990, 1991-2000, 2001-2010, and 2011-2020.

Yearly F/T cycles calculated by MnROAD year according to Method 1 (Figure 4.26a) and Method 2 (Figure 4.26b) are similar with a larger number of freeze-thaw cycles using the Method with a thawing temperature based on the MnDOT reference temperatures. In both methods, F/T cycles slightly overestimated the total number of cycles determined from the 1-hour duration of freezing and thawing temperatures at 0 °C specified from the MnROAD weather station data (e.g., Figure 4.10a). These larger F/T cycle estimates are consistent from prior analysis of air temperature F/T cycles determined from
multiple daily resolution temperature thresholds for freezing and thawing compared to hourly
temperature (Baker and Ruschy, 1995). Year-to-year variability of F/T cycle accumulations from the nearby
COOP location indicates about 72% agreement of the relative increase or decrease in F/T cycles from year-
to-year for the 25-year MnROAD dataset.

Figure 4.26  COOP annual freeze-thaw cycles between winter 1994-95 and 2018-19 for 0 °C freezing temperature
and (a) 0 °C thawing temperature or (b) reference thawing temperature determined from the application of the
MnDOT cumulative thaw index.

Monthly F/T cycles calculated from Method 1 and Method 2 are similar; therefore, only Method 2 is shown
to represent the maximum number of freeze-thaw events. Monthly long-term 40-year composites of
mean F/T cycles from both Methods 1 and 2 indicate similar trends of reducing freeze-thaw periods in
late Fall (November) and mid to late Spring (April-May) and increasing cycles in the early winter season
(December-January). Transition cycles using both methods are inconsistent in showing a larger increase
or decrease for the most recent 40-year period. These monthly trends are also representative of the
decrease in late Fall and early spring F/T cycles from the MnROAD weather station (Figure 4.11) and Baker
and Ruschy (1995). An expansion of the monthly F/T cycle decadal variability for the COOP station (Figure
4.27) demonstrates a progressive decline in early spring freeze-thaw events similar to the trends occurring
at MnROAD. However, there is less difference in monthly F/T cycles between decades for the late fall and
early winter with slightly higher cycles in December and January during the 2001-2010 and 2011-2020
decades (Figure 4.28). There is little change in the interannual variability of freeze-thaw events between
each decade. The yearly progression of average monthly F/T cycles using Method 2 is depicted in Figure
B1 in Appendix B and is consistent with overall little or no trend in F/T cycles determined from the
MnROAD station data (Figure 4.12).
Soil temperature reanalysis data at multiple depths provide an analog assessment to freeze-thaw events determined in the MnROAD pavement system. As mentioned in section 4.2, the hourly time-resolution MERRA-2 datasets are extensive and require limitations on size and location to analyze in a downloadable format. Fortunately, NASA provides instructions and access to the time-series data for a single point or
gridded subset of points into for individual model variables each calendar year from the Unidata THREDDS data server NetCDF Subset Service:


This investigation of F/T cycles from historical Minnesota climate data corresponds to the F/T cycles determined at MnROAD. Therefore, this report focuses on evaluating MERRA-2 data at a single point nearest to the MnROAD location. For each year beginning in January 1980 and ending in December 2020, hourly temperature data were downloaded for air temperature sensor level (~6 ft), surface (0-2.4 in), and the six soil layers (2.4-6.0 in, 6.0-14.4 in, 14.4-28.8 in, 28.8-58.8 in, 58.8-117.6 in, and 117.6-516 in) from the NASA Global Modeling and Assimilation (GMAO) Office repository (GMAO, 2015a; 2015b). Yearly data files for each temperature variable were combined into a single spreadsheet for computation of F/T cycles according to the first two criteria for freezing and thawing temperature and duration (Condition 1 and Condition 2) determined for the pavement measurements at MnROAD discussed in section 4.3.

Yearly F/T cycles calculated by MnROAD year according to Condition 1 (Figure 4.29a) and Condition 2 (Figure 4.29b) have similar decreasing trends to the F/T cycles determined from the pavement temperature measurements at MnROAD. Freeze-thaw events are highest directly at the soil-surface interface as in the first pavement layer from MnROAD. The decline in F/T cycles with soil depth is consistent with the observed decrease in F/T cycles in deeper pavement layer measurements from MnROAD. For F/T cycles calculated with Condition 1, MERRA-2 reanalysis overestimates the total number of cycles at MnROAD by about 10-30 F/T cycles each year, whereas the yearly estimated accumulation using Condition 2 is within ±2-3 cycles. MERRA-2 skill prediction in the relative increase or decrease in F/T cycles from year-to-year is about 55% for the 18 years represented in the MnROAD dataset. MERRA-2 monthly F/T cycles for both Condition 1 and Condition 2 for each year also indicate a high bias at the air temperature sensor level and subsurface conditions. For Condition 1, estimated F/T cycles are 5-10 cycles higher than Condition 2, and there are a larger number of years with mismatched prediction in the relative increase or decrease of F/T cycles from year-to-year (Figures B2 and B3 at appendix B). Years in which MERRA-2 predictions match MnROAD data correspond to strong fluctuations in freeze-thaw events related to climate trends. For Condition 2, monthly freeze-thaw cycles are at or < 5 cycles for any given year, as shown in the MnROAD analysis. Deep soil layer cycles are highest during March and show little variability to any climate trend between the 1990s and early 2000s. F/T cycles are approximately constant in or below the second soil layer (6.0-14.4 in) in agreement with previous findings for soil F/T cycles from Minnesota (Baker and Ruschy, 1995) and Indiana (Sinha and Cherkauer, 2008). Lower F/T cycles at shallow soil layers in December, January, and February from about 2008 onward are also consistent with a decline in cycles determined from the MnROAD data.
Figure 4.29 MERRA-2 predicted annual freeze-thaw cycles near MnROAD between winter 1994-95 and 2014-15 considering 0 °C freezing and thawing temperature and (a) a minimum 1 hour of freezing and thawing durations, and (b) a minimum of 19 hours of freezing and 5 hours of thawing duration.

Monthly F/T cycles calculated from Condition 1 (Figure 4.30a) and Condition 2 (Figure 4.30b) for the 1981-2020 MERRA-2 reanalysis period are representative of the seasonal changes to freeze-thaw events from MnROAD (Figure 4.17). As determined for the annual F/T cycle variability by year, MERRA-2 re-analysis using Condition 1 (Figure 4.30a) predicts ten or more F/T cycles per month from air temperature and surface layer data than those determined at MnROAD (Figure 4.17). The difference in monthly F/T cycles between the Air temperature and the temperature at the soil surface is smallest during the start of winter (December-January). However, the differences in F/T cycles increase for the transition fall and spring months (e.g., October-November, and March-April) when soil temperatures are much warmer than the air temperature and snow cover is absent (Baker and Ruschy 1995). The longer duration requirement of freezing and thawing for Condition 2 (Figure 4.30b) significantly reduces the number of cycles to a similar accumulation found at MnROAD, but these estimates also may have larger variability because of the lower number of F/T cycles. F/T cycles are compared between each of the four decades between 1981-2020 to determine the mean monthly differences attributed to changes in Minnesota climate contributing to warmer winters. These decadal differences determined using Condition 1 (Figure 4.31) are more sensitive to variations in climate as compared to Condition 2, for which the mean decadal differences are within ±1 F/T cycles with ±2 standard deviations (Figure not shown for brevity). For Condition 1, the increase in December and January F/T cycles peaked during the 2001-2010 decade, whereas in the most recent decade, the number of F/T cycles declined in the late winter and spring months (February-March). Relative sensitivity of F/T cycle differences to climate trends is attenuated with increasing soil depth. Several factors are represented by these overall differences in F/T cycles determined from MnROAD measurements vs. model analysis. Firstly, MERRA-2 determines soil temperatures for mean layers instead of a single level measurement at MnROAD. Secondly, MERRA-2 provides information only about a representative soil profile for that climatological region, whereas MnROAD data represents a composite layered pavement foundation with subgrade soil characteristics. Thirdly, modeled subsurface
temperatures may or may not be insulated by shallow or deep snowpack, whereas snow is optimally removed from the roadway surface, and the pavement experiences higher freeze-thaw events.

Snow processes in numerical models may also have limited representation of actual snow depth and snowmelt conditions surrounding a roadway. In addition to snow cover reducing strong subsurface daytime heating and nighttime cooling, fresh snowpack reflects greater sunlight, and the phase change of snowmelt slows thawing of the surface (Baker and Ruschy, 1995; Friesen et al. 2021). Unfortunately, there are very few measurements to validate these simulated properties to better assess the correlation of soil F/T cycles from natural surfaces to subgrade F/T cycles for the pavement system. Lastly, there are high uncertainties in the soil type and thermal characteristics in the model and whether those properties are representative of subgrade composition at MnROAD cells. Additional interpretation of F/T cycles over multiple locations with variations in soil composition will inform a better understanding of the shallow soil freeze-thaw events influenced by current climate trends.
4.4.3 Minnesota Statewide Freeze/Thaw Cycles from COOP Measurements

Minnesota COOP measurements were also selected from several long-term climate sites to develop a gridded spatial map of F/T cycle climatology for the 20th century into the most recent decade (e.g., Haley 2011). The IEM features an automated calculation of F/T cycles for each location according to tunable thresholds for freezing and thawing temperatures:

https://www.mesonet.agron.iastate.edu/plotting/auto/?q=121.

F/T cycles were calculated for the spring and fall seasons in each calendar year. F/T cycles were then aggregated to represent an entire seasonal progression (i.e., the summation of the previous year’s fall cycles to the current year’s spring cycles). A total of 99 Minnesota locations were selected for which daily records of maximum and minimum air temperature were available starting at or before June 1, 1940, to begin F/T cycle assessment in the 1940-1941 winter season through the 2019-2020 winter season. (F/T cycles were also calculated from additional locations where measurements were available after June 1,
1940, and several regions were biased by a lower accumulation of F/T cycles from those shorter-duration observations. Additional COOP locations from 10 stations were chosen from bordering states (Iowa, North Dakota, South Dakota, and Wisconsin) to fill the F/T cycle map for most of the state of Minnesota based on the grid interpolation method. A GIS-compatible shapefile with county-level boundaries was downloaded from the United States Department of Agriculture Natural Resource Conservation Service Geospatial Data Gateway: https://datagateway.nrcs.usda.gov/ as downloadable map background for the image processing. Freezing and thawing temperatures for F/T cycle calculations were chosen from the two air temperature methods described in section 4.1. In understanding these F/T cycle maps, it is important to remember that many COOP sites have experienced microclimate modification from land-use changes over the 20th century. Decreasing the number of COOP sites in analysis, F/T cycle spatial resolution would be degraded and not represent a greater number of locations that would benefit from having F/T cycles in a pavement location that is more susceptible to damage from freeze-thaw events.

Annual and monthly F/T cycles are determined for two long-term 40-year means (1941-1980 and 1981-2020). Decadal means beginning in 1941-1950 are also evaluated to assess the impact of climate trends on F/T cycles more precisely. Annual and monthly F/T cycles are compared between the most recent 40-year period and the previous 40-year period and for multiple decades within the current 40-year period to establish tests for statistically significant differences to the 95% confidence level. The non-parametric Kruskal-Wallis one-way ANOVA on ranks test-statistic was chosen for analyzing F/T cycle differences between multiple decadal means when the distributions and the residuals both may not be normally distributed (e.g., Sinha and Cherkauer, 2008).

The 1981-2020 composite mean for yearly F/T cycles indicates 10-20 lower cycles in Method 1 (i.e., consistent freezing and thawing temperature thresholds) compared to Method 2, where the thawing temperature threshold decreases in the first half of the year (Figure 4.32). Cycle accumulation is generally lower in metropolitan areas but is also significantly higher in the northcentral, southwest, and southeast portions of the state. A surface elevation map generated from the COOP location elevation was compared to the F/T cycle map to determine any correlation with terrain on F/T cycles. There were only isolated regions in which a high or low elevation was represented by only a difference of 5-10 F/T cycles from surrounding COOP stations. Therefore, these F/T cycle differences are more reflective of the latitudinal and longitudinal variations in air temperature occurring over Minnesota responding to seasonal shifting in warm and cold air-masses contributing to freeze-thaw events. Monthly variations in F/T cycles between the two methods emphasize the highest number of cycles in the transition months of November, February-April, and higher accumulation with Method 2 is consistent with the other analyses presented from the measurement and model reanalysis near MnROAD (Figure 4.33).

Decadal mean annual F/T cycles were also compared between each decade since 1941-1950 in Figure B4 Appendix B. From both 1961-1970 and 1981-1980, there were over 100 F/T cycles in North Central, Northeast, Southwest, and Southeast Minnesota. F/T cycles decreased from 1971-1980, corresponding to a colder, snowier decade compared to the later 1980s and 1990s, which were also warmer. In the first two decades of the new millennium, cycles show statewide decreases consistent with the trend in air temperature and pavement F/T cycles determined from MnROAD.
Figure 4.32  Minnesota statewide 1981-2020 annual mean freeze-thaw cycles determined for 0 °C freezing temperature with (a) 0 °C thawing temperature or with (b) seasonally adjusted reference thawing temperature from COOP station measurements.

Figure 4.33  Minnesota statewide 1981-2020 monthly mean F/T cycles determined from COOP station measurements considering daily records of 0 °C freezing temperature and seasonally adjusted reference thawing temperature for (a) September, (b) October, (c) November, (d) December, (e) January, (f) February, (g) March, (h) April, and (i) May.
The relative difference in F/T cycles between periods of long-term climate before 1980 and the recent 40-year period using both Method 1 and Method 2 indicate very small differences (±5 cycles) across the state for the exception of a portion of the Northeast climate division and these are statistically significant for isolated locations (Figure 4.34). Relative differences in these 40-year mean F/T cycles for individual months (only Method 2 discussed) are ±2 cycles for November, February, March, April, and May, whereas a statewide increase in 1-2 F/T cycles occurred for October, December, and January. However, very few of these locations exhibit statistically significant differences (Figure not shown for brevity).

![Figure 4.34](image)

**Figure 4.34** Composite differences of Minnesota statewide annual average freeze-thaw cycles between 1981-2020 mean from 1941-1980 mean for daily records (a) with 0°C freezing and thawing temperatures and (b) with 0°C freezing temperature and seasonally adjusted reference thawing temperature. “X” marked locations denote 95% confidence in statistically significant differences between mean periods.

Further separation of differences into single decades for the most recent 40-year period (Figure 4.35) pinpoints a peak increase in F/T cycles during 1981-2000 followed by a decrease in cycles from 2001-2020, with the largest decrease occurring in the most recent decade (2011-2020). Regions with the largest cycle decline in the first two decades of the 21st century also correspond to areas with the highest number of cycles from the latter two decades from the 20th century. However, these differences are statistically significant for only about 7-10% of the COOP locations. Monthly mean F/T cycle trends are compared with the difference of 2011-2020 mean to 1981-1990 mean (Figure B5 at appendix B). Small decreases in cycles are noted in the East Central, Central, and Southern portions of the state for October and November. In February, F/T cycles have decreased for the Western, Northwest, and North Central regions of Minnesota. In stark contrast to the overall annual decline in most months is the 2-4 cycle increase for most of the state during April. However, very few (1-5) locations exhibit statistically significant differences each month than yearly accumulated cycle differences. The high interannual variability of F/T cycles pose challenges for determining a clear shift in freeze-thaw events attributed to recent climate trends. The interpolation method may also overemphasize data from the sparse locations near the international border. This gridding method may be improved if additional Southeast Saskatchewan and Southwest Manitoba locations were selected, but daily data from these sites were not available on the IEM network. Despite these limitations with the COOP data, the cycle trends estimated statewide are reflective of the measured F/T cycle decreases from the MnROAD dataset and estimated F/T cycles from the MERRA-2 reanalysis.
Determination of F/T cycles over a uniform grid of model reanalysis (e.g., MERRA-2) may provide additional context to the representative calculation of F/T cycle annual and monthly maps determined from these point COOP locations, but these were not the focus of the Phase I study.

4.4.4 Preliminary Investigation into Missing Data Curing

The aforementioned data analyses are based on observed data sets from diverse sensors and weather databases. However, there are incomplete data sets in nearly all kinds of data types. For Phase I of this project, such incomplete data are excluded for coherent data analysis and statistical investigation. Such straightforward treatment of incomplete data values is the so-called Naïve method. It is efficient and widely used in machine learning or statistical fields for its practical ease. Such Naïve method may result in a substantial loss of information gleaned from expensive observations, tests, and surveys of researchers and engineers since any incomplete instance is totally removed. Also, Naïve data curing may result in biased conclusions in the following statistical inference or machine learning since the deleted (or mistreated) data may hold important contributions to the trends of interest.

Therefore, Phase I of this project conducted a preliminary investigation into missing data curing by focusing on theoretically proven and reliable imputation (i.e., statistical theory to fill in missing values) methods. Figure 4.36 shows an example of F/T counts from October through April in the year 1994 through 2015. Due to various reasons such as human error, measurement device malfunctions, power shutdown, or replacement, some months’ data (e.g., November in the year 1994) or entire year data (e.g., 2006-2008) are missing.

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Figure 4.36 Example of missing data (marked by NA in red) from 1994 through 2015 at a sensor (Cell 20). Numbers are processed monthly total counts of freeze/thaw (F/T) according to the rule [Freeze Temp = 0 °C, Thaw Temp = 0 °C, Freezing Time = 1 hour, Thawing Time = 1 hour]. Depths -0.123 inch corresponds to air measurement above the ground, and underground depths are 3.37, 11.32, 23.82, 35.82, 47.82, and 59.82 inches (up to 23.82 in are shown).

ISU developed general-purpose missing data curing software FHDI (i.e., fractional hot-deck imputation) and shared it on global computational statistical software platform CRAN [https://cran.r-project.org/]. The central power of FHDI is that it does not require a difficult statistical or distributional assumption of the data set, but it only requires the observed data values. That is why the method is coined as “hot-deck” since it seeks to best preserve the joint distribution of the observed data via the so-called expectation maximization method. Detailed theory and methods are available in Im, et al., (2018).
To demonstrate that missing F/T-related data sets can be cured with statistical rigor, this project used the FHDI (R package FHDI: https://cran.r-project.org/web/packages/FHDI/index.html) to cure the example incomplete data set (shown in Figure 4.36).

Figure 4.37 shows the outcome of the FHDI with the incomplete data set of Figure 4.36. As seen from figure 4.37, the cured data set has the same dimension and format as the original incomplete data sets. The subsequent statistical inference and machine learning can occur without any special treatment or post-processing of data. Figure 4.38 compares the yearly mean counts of F/T before and after the missing data curing. Especially during the year 2006-2008, only air temperature data are available; without data curing, the yearly mean of F/T counts are highly biased as expected. After FHDI-based data curing, such biased behavior in yearly mean F/T counts can be resolved.
This preliminary investigation demonstrates the feasibility of the reliable data curing of F/T-related data sets. Reliable data curing may hold a significant positive impact on subsequent statistical inference and machine learning up to multiple fold decrease in prediction errors (see details in Song et al. 2019). During Phase I of this project, due to time constraints and limited availability of large sensor databases, only one cell (Cell 20) in MnROAD has been chosen and cured by FHDI. However, to tackle the extreme case when there are many sites, sensors, and a large volume of incomplete data sets, Yicheng et al. (2020) has developed high-performance computing algorithm-based FHDI (named P-FHDI) with support from National Science Foundation.
CHAPTER 5: SUMMARY AND CONCLUSIONS

The advancement in pavement engineering provides adequate design considerations to mitigate damages induced by traffic loading. The distresses related to traffic loading are no longer a major concern for the design life of the pavements. Yet, the pavements deteriorate, and significant damages are created by climatic factors. Among the climatic factors, freezing and thawing of pavements could play the most crucial role in seasonally frozen areas, such as Minnesota and the midwest portion of the United States. The most destructive freeze-thaw events are related to a number of factors. Freezing and thawing in frost-susceptible soils, along with higher groundwater table, have the most detrimental effects on pavement performance. In addition, the severity of damage is dependent on the number of freeze-thaw cycles. Therefore, correlating the number of freeze-thaw events with pavement deterioration is crucially important for sustainable pavement management. However, the quantification of the number of freeze-thaw cycles is dependent on the freezing temperature of pavement layers, which may not coincide with the phase change temperature of pure water. Freezing point depressions are often apparent depending on depth, pressure, pore diameter, and the presence of salts and/or ions in the pore solution.

The freezing point would also be material-specific and thereby require the use of multiple freezing temperatures. Therefore, this research intended to consider and evaluate several freezing temperatures (e.g., 0 °C (32 °F), -0.5 °C (31.1 °F), -1 °C (30.2 °F), and -1.5 °C (29.3 °F)) in quantifying the number of freeze-thaw cycles through the data analyses by using the historical data from the MnROAD test facility. Based on the findings from this study, recommendations were developed for more reliable quantification of freeze-thaw events. The literature review also revealed that liquid moisture content decreases as the pore water gets frozen and becomes segregated from the soil matrix. However, some of the pore water remained unfrozen regardless of the freezing temperature, which was defined as residual water content. Therefore, the moisture-temperature relationship was used in evaluating the freezing temperatures of pavement materials as a function of depth. The number of freeze-thaw events (i.e., monthly and annually) can be determined at hourly intervals for air temperatures, as well as at each of the pavement layers by using the available sensor data. The selection of the depths was dependent on MnROAD cell selection, configuration, sensor location, data availability, and sensor data accuracy. The number of freeze-thaw events at different pavement layers could be correlated with the number of freeze-thaw cycles at air temperatures to identify the most representative material specific, freezing temperature(s). Besides, substantial increases in the knowledge base over the past few years offer potential opportunities to develop and refine fundamental guidelines for recognizing (planning) and responding to (restrictions) pavement vulnerability to freeze-thaw actions.

5.1 WEATHER DATA RESOURCES AVAILABLE FOR MINNESOTA

Several data resources were reviewed to assess the historical climatological data available for Minnesota and were summarized in Table 5.1. The MnROAD test facility offered the most comprehensive weather data for Minnesota. However, the MnROAD test data was generated from a specific location and may not be representative of the whole state. In addition, the earliest data availability for the MnROAD test facility was from 1993. An assessment with more extended historical data series was thus required to quantify
the decadal change in winter temperature, addressing the changes in freeze-thaw events. Therefore, data resources with a wide distribution of weather stations could help assess the number of freeze-thaw events and their impact on Minnesota pavement systems.

It was found that the Road Weather Information System (RWIS) database could be a comprehensive source for Minnesota climatological data with spatial and temporal variability in data series. The RWIS data could be accessed through the MnDOT VAISALA/SCAN website and the IEM. There were discrepancies in the RWIS data pulled from these two different sources. The IEM RWIS archive started on October 15, 2010, whereas through the MNDOT VAISALA/SCAN RWIS web interface, the data stream was accessible starting from June 2015. The MNDOT RWIS contained more details about road conditions, pavement temperature, and road treatments in freezing conditions. However, there was no simple way to extract large quantities of data (spanning several years from each site) into a single file. Conversely, the IEM provided this capability. There were differences in the temporal resolutions as well. For instance, the MnDOT RWIS outputs were available at 5-second to 1-minute intervals, whereas the IEM RWIS temporal resolution was 15 to 25 minutes. Additionally, data could also be missing from either the IEM or MnDOT VAISALA/SCAN RWIS for one or more pavement layers. The subsurface temperature, along with pavement temperature for at least one depth, could often be omitted in the IEM RWIS database.

The review showed that the MnDOT Seasonal Load Limits program provides detailed information on the pavement, base, and subgrade temperatures and moisture conditions at various depths, along with the freezing index, thawing index, and frost penetration depths. However, other relevant weather data are limited compared to other data resources (i.e., RWIS, NOAA, MERRA, etc.). The NOAA database provides historical information on Minnesota weather conditions. However, soil temperature and frost depth data, which are crucial for quantifying freeze-thaw events, are widely missing. In addition, soil temperatures are reported for unknown soil cover, bare ground, and sod cover, which may not represent pavement layer systems due to diverse thermal characteristics. Yet, NOAA NCEI features long-term climate observations (starting in the late 1890s and ending in 2019) from the Cooperative Observer Network (COOP) stations. The long-term COOP data is also readily available through the IEM and the Minnesota Department of Natural Resources (MN DNR) featured Climate Trends Tool web-applet, which could help assess the decadal trends in Minnesota daytime and nighttime temperatures. The MERRA-1 and MERRA-2 featured by NASA could be a comprehensive source of climatic data for Minnesota. However, MERRA provides simulated past atmospheric and surface environmental conditions by using satellite-driven remote sensing data. Nonetheless, MERRA data could potentially be implemented to assess the impact of environmental factors (e.g., temperature change, soil moisture content, subsurface temperature) on the freeze-thaw events in Minnesota. The FHWA’s LTPP program could be a prominent source for Minnesota climatological data. However, only one GPS section (i.e., the LTPP Section ID 27-6251) is currently active in Minnesota, restricting the availability of necessary data required for freeze-thaw assessment.

In the Phase I study, the MnROAD sensor and weather station data, along with the Minnesota Department of Natural Resources, Iowa Environmental Mesonet, and Modern-Era Retrospective analysis for Research and Applications, Versions 1 and 2 (MERRA-1 and 2) database, were used extensively to evaluate the climate change and quantify the number of freeze-thaw events in Minnesota. In conjunction with the MnROAD data, other data sources such as NOAA, COOP through MN DNR and IEM, and MERRA were
applied to investigate the decadal changes in Minnesota air temperature, total precipitation, pavement subsurface temperature, and thawing days.
### Table 5.1 Summary of Available Data Types for Minnesota in Various Weather Data Resources

<table>
<thead>
<tr>
<th>Climatic and Subsurface Conditions</th>
<th>MnROAD Test Facility</th>
<th>RWIS Data from MnDOT</th>
<th>RWIS Data from IEM</th>
<th>MnDOT Seasonal Load Limits</th>
<th>NOAA</th>
<th>MERRA-1 and MERRA-2 from NASA</th>
<th>MERRA-1 and MERRA-2 from LTPP</th>
<th>VWS from LTPP</th>
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<td>Air Temperature</td>
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</table>

**Note:** RWIS = Road Weather Information System, MnDOT = Minnesota Department of Transportation, IEM = Iowa Environmental Mesonet, NOAA = National Oceanic and Atmospheric Administration, MERRA = Modern-Era Retrospective Analysis, NASA = National Aeronautics and Space Administration, LTPP = Long-Term Pavement Performance, VWS = Virtual Weather Stations. “Green” indicates data availability, “Yellow” indicates data non-availability.
5.2 HISTORICAL MINNESOTA CLIMATE DATA TRENDS

This analysis of the MN COOP data and MERRA-2 reanalysis data provided an initial knowledge of long-term climate conditions in Minnesota (from 1901 to 2020). The related climate impact focusing on seasonal changes in temperature was emphasized for the most recent 40-year period 1981-2020. The key notes form the assessment of historical Minnesota climate data are summarized as follows:

- Minnesota winters represent 1-2 °F warmer daytime temperatures and 2-5 °F warmer nighttime temperatures, reducing the number of below-freezing dates in the most recent 40-year period.
- Minnesota autumn and spring transition months (October-November and March-April) highlight increased 0.5”-1” precipitation occurring before and at the end of the cold season, which may exacerbate moisture penetration in pavement layers and contribute to subgrade heaving.
- Minnesota winters experience a large variation in extreme warm and cold conditions and extreme wet and dry conditions between years and consecutive months each year. These extreme variations in Minnesota winters could instigate pavement deteriorations significantly. A previous study indicated that winters with warmer and wetter conditions with an intermittently deep cold period followed by thaw for the Northeastern U.S. led to pothole formation during 1977-1978 (Hershfield 1979). However, according to Hershfield (1979), these winter conditions did not lead to an increase in F/T cycles.
- Minnesota’s shallow (< 6 inches) soil temperatures respond to climate trends in air temperature and precipitation, leading to a delay in subsurface freezing into November or December.
- Minnesota’s deep soil (> 12 inches) is less sensitive in response to the progression of freezing in January-February and thawing typically occurring in March.

These interpretations are addressed considering the following limitations. COOP measurements are not without changes in microclimate siting, instrumentation reporting, and influence from land-use changes occurring over the latter half of the 20th century. Subsurface freezing and thawing represented in the MERRA-2 reanalysis may not describe freeze-thaw events in the pavement base, subbase, or subgrade soil layers. Moreover, modeled snow reflectivity, snow depth, and snowmelt influence subsurface freeze-thaw events, and these conditions also do not represent a roadway system. Soil moisture reanalysis is challenging to interpret in wet freeze conditions because of the material-specific properties of soil saturation and freezing temperatures. These parameters based on existing measurements are largely unknown for a spatial representation of Minnesota soil characteristics and may not validate the reanalysis predictions.

5.3 F/T CYCLE ASSESSMENT FROM MNROAD DATA

Yearly and monthly freeze-thaw cycles at the air temperature sensor level and different pavement layers were quantified using the MnROAD data. The F/T events at the air temperature sensor level were calculated considering 0 °C reference temperature, along with a minimum of 1-hour freezing and thawing duration. The number of F/T cycles was also counted for more extended freezing and thawing conditions, such as a minimum of 19 hours of freezing and 5 hours of thawing duration. The numbers of F/T cycles at
six different pavement layers were determined by employing similar requirements. In addition, the material-specific freezing point was quantified by generating in-situ cooling curves by using moisture and temperature data. The material-specific freezing temperatures were also used in determining the yearly and the monthly number of F/T cycles at different pavement layers. Depending on data availability, the F/T assessment at the air temperature level was performed for winters occurring from 1994-95 to 2018-19, whereas data for winters between 1995-96 and 2014-15 were limited for pavement layers. The key findings of this study are summarized as follows:

- The annual F/T events at the air temperature sensor level were randomly distributed throughout the analysis period. The maximum number of F/T events at the air temperature sensor level occurred during November and March.
- With a decrease in freezing temperature, the number of F/T cycles at different pavement layers decreased. Conversely, the requirement of prolonged freezing and thawing duration reduced the F/T events.
- The yearly number of F/T cycles tended to decrease at shallow pavement depths whereas remained sporadic at deeper pavement layers. The decrease in F/T cycles at shallower depths was statistically significant.
- Further analyses indicated that the decrease in F/T cycles at shallower depths was governed by a reduction in F/T events during the early and late winter months (November and March). However, hard F/T events (frozen for a minimum of 19 hours) only declined for the month of November.
- It is worth mentioning that the MnROAD test facility is located at a single location and may not represent the whole state. A statewide analysis, involving different subsurface conditions, data resources, and a longer analysis period is required to confirm the initial findings of this study.

**5.4 F/T CYCLE ASSESSMENT FROM HISTORICAL MINNESOTA CLIMATE DATA**

The MN COOP data and MERRA-2 reanalysis data provided complementary evidence for the measured changes in F/T cycles from 1995 to 2015 using the MnROAD air and pavement temperatures. The F/T events for daily maximum and minimum air temperature from COOP data were calculated considering 0 °C reference temperature for both freezing and thawing, as well as for a seasonally adjusted thaw temperature. F/T cycles for MERRA-2 reanalysis were determined according to the same first two conditions applied to the MnROAD data. F/T cycles determined from measured and model data resources reveal long-term climate trends on cycles before MnROAD construction.

Minnesota warmer winters have both increased and decreased monthly and annual freeze-thaw cycles based on the following key points:

- COOP and MERRA-2 reanalysis data slightly overestimate air and shallow subsurface F/T cycles compared to the MnROAD determined F/T cycles. These discrepancies are more minor for methods with hourly resolution data and longer freezing and thawing than for once daily temperatures or hourly temperatures with 1-hour duration (e.g., Baker and Ruschy 1995, Hershfield et al. 1974).
• Annual and monthly F/T cycle year-to-year variability from the historical climate data is representative of the 1995-2015 decreasing trend in cycles determined from air and pavement measurements at MnROAD.

• The maximum number of F/T cycles statewide and at MnROAD occur in the transition months of November and March.

• F/T cycles variation across Minnesota is higher during October-November at the start of freezing conditions and April at the beginning of warm-season thawing conditions in the north. The variations in F/T cycles across the state are lowest during the coldest winter months (January and February).

• Minnesota statewide mean annual F/T cycles from 1961-1970 were as high as recent decade cycles corresponding to the climate trends. Cycles were also considerably lower from 1971-1980 during a colder, snowier winter period than for 1981-2000. F/T cycles increased during 1981-2000, particularly over December and January, whereas cycles have decreased during 2001-2020, mainly in the last decade for October, November, February, and March.

• F/T cycle differences between recent decades are generally small statewide (< 5 cycles/year). However, these changes were not statistically significant at the 95% confidence level (Haley, 2011) compared to stronger statistical trends in shallow depth pavement cycles and air temperature cycles from the MnROAD data.

Based on the findings from the Phase I study, the TAP recommended that a Phase 2 study be conducted focusing on the implications of increased precipitation due to climate change and the performance of road foundations using weather stations and extensive instrumentation data available at MnROAD while also developing a vulnerability map for the state road network.
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Song, I., Yang, Y., Im, J., Tong, T., Ceylan, H., & Cho, I. H. (2019). Impacts of fractional hot-deck imputation on learning and prediction of engineering data. *IEEE Transactions on Knowledge and Data Engineering*, 32(12), 2363-2373. https://doi.org/10.1109/TKDE.2019.2922638

Tarefder, R., Faisal, H., & Barlas, G. (2018). Freeze-thaw effects on fatigue life of hot mix asphalt and


APPENDIX A: ANALYSIS OF MNROAD DATA
Table A1. ANOVA for the number of yearly F/T cycles at 3.37 inches based on the material-specific freezing temperatures

<table>
<thead>
<tr>
<th>Coeff. of Determination (R²)</th>
<th>November*</th>
<th>December</th>
<th>January</th>
<th>February</th>
<th>March*</th>
<th>April</th>
</tr>
</thead>
<tbody>
<tr>
<td>t-Stat</td>
<td>-3.01</td>
<td>-1.02</td>
<td>0.49</td>
<td>-0.099</td>
<td>-2.93</td>
<td>-1.91</td>
</tr>
<tr>
<td>F-Value</td>
<td>9.09</td>
<td>1.05</td>
<td>0.24</td>
<td>0.0098</td>
<td>8.6</td>
<td>3.66</td>
</tr>
<tr>
<td>Significance F</td>
<td>0.0082</td>
<td>0.32</td>
<td>0.63</td>
<td>0.92</td>
<td>0.0098</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Note: *Statistically significant

Table A2. ANOVA for the number of monthly F/T cycles based on 0 °C reference temperature and a minimum 1 hour of freezing and thawing duration

<table>
<thead>
<tr>
<th>Coefficient of Determination (R²)</th>
<th>3.37 in*</th>
<th>11.32 in</th>
<th>23.82 in</th>
<th>35.85 in</th>
<th>47.82 in</th>
<th>59.82 in</th>
</tr>
</thead>
<tbody>
<tr>
<td>t-Stat</td>
<td>-3.83</td>
<td>-2.11</td>
<td>-2.76</td>
<td>-1.93</td>
<td>-0.39</td>
<td>0.87</td>
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<tr>
<td>F-Value</td>
<td>14.69</td>
<td>4.46</td>
<td>4.66</td>
<td>3.72</td>
<td>0.15</td>
<td>0.75</td>
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<tr>
<td>Significance F</td>
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<td>0.054</td>
<td>0.07</td>
<td>0.7</td>
<td>0.4</td>
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</table>

Note: *Statistically significant

Table A3. ANOVA for the number of monthly F/T cycles at 3.37 inches based on 0 °C reference temperature and a minimum 1 hour of freezing and thawing duration

<table>
<thead>
<tr>
<th>Coeff. of Determination (R²)</th>
<th>November*</th>
<th>December</th>
<th>January</th>
<th>February</th>
<th>March*</th>
<th>April</th>
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</thead>
<tbody>
<tr>
<td>t-Stat</td>
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<td>F-Value</td>
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<td>0.54</td>
<td>0.001</td>
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<td>Significance F</td>
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Note: *Statistically significant
Table A4. ANOVA for the number of monthly F/T cycles based on 0 °C reference temperature and a minimum of 19 hours of freezing and 5 hours of thawing duration

<table>
<thead>
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<th>ANOVA</th>
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<tr>
<td></td>
<td>3.37 in*</td>
<td>11.32 in</td>
<td>23.82 in</td>
<td>35.85 in</td>
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<td>Significance F</td>
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Note: *Statistically significant

Table A5. ANOVA for the number of monthly F/T cycles at 3.37 inches based on 0 °C reference temperature and a minimum of 19 hours of freezing and 5 hours of thawing duration

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<th>January</th>
<th>February</th>
<th>March</th>
<th>April</th>
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<td>F-Value</td>
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<td>0.103</td>
<td>NA</td>
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Note: *Statistically significant, NA = Not available
Figure A1. Seasonal moisture-temperature relationship for Class 3 aggregates (CLS3) and select granular (SG)
Figure A2. Seasonal moisture-temperature relationship for Class 5 aggregates (CLS5)
APPENDIX B: ANALYSIS OF HISTORICAL CLIMATE DATA
Figure B1. Buffalo COOP freeze-thaw cycles by months (a) September, (b) October, (c) November, (d) December, (e) January, (f) February, (g) March, (h) April, and (i) May between winter 1994-95 and 2018-19 considering daily records of 0 °C freezing temperature and MnDOT reference temperature.
Figure B2. MERRA-2 freeze-thaw cycles by months (a) November, (b) December, (c) January, (d) February, (e) March, and (f) April between winter 1994-95 and 2014-15 considering 0 °C freezing and thawing temperature and a minimum 1 hour of freezing and thawing durations.
Figure B3. MERRA-2 freeze-thaw cycles by months (a) November, (b) December, (c) January, (d) February, (e) March, and (f) April between winter 1994-95 and 2014-15 considering 0 °C freezing and thawing temperature and a minimum 19 hours of freezing and 5 hours of thawing durations
Figure B5. Composite decadal differences of Minnesota statewide monthly average F/T cycles between 2011-2020 mean from 1981-1990 mean for daily records of 0 °C freezing temperature and seasonally adjusted reference temperature in (a) September, (b) October, (c) November, (d) December, (e) January, (f) February, (g) March, (h) April, and (i) May. “X” marked locations denote 95% confidence in statistically significant differences between mean periods.