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Evaluation of Spring Load Restriction Removal Protocols

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Aurora Project 2022-07

Final Report
February 2024

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16. Abstract

Deciding when to remove spring load restrictions (SLRs) on roadways is complicated given the variable time window during and after thawing when excess moisture remains in the base and subgrade layers, causing the overall roadway structure to remain weak. The main objective of this project was to develop an economical and easy-to-use protocol for timing SLR removal.

To develop the model, the research team utilized falling weight deflectometer (FWD) data from three test cells at the Minnesota Department of Transportation's (MnDOT's) MnROAD research facility. FWD data from nine other sites were used to validate the model, with three sites in North Dakota, three in New Hampshire, two in New York, and one in Maine. Numerous statistical analyses were performed on the FWD data sets, and model/protocol development considered factors such as base layer and subgrade type, effects of moisture, and depth to the groundwater table.

The researchers created a decision tree to help agencies implement the SLR removal guidelines developed in this study. To use the decision tree effectively, it is necessary to know information about the roadway structure, base layer(s), and subgrade soils and the approximate depth to the groundwater table. Using this methodology may help transportation agencies lift their SLRs more quickly than they have in the past.

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EVALUATION OF SPRING LOAD RESTRICTION REMOVAL PROTOCOLS

Final Report
February 2024

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Finally, personnel from other DOTs conducted falling weight deflectometer (FWD) testing and/or gathered other field data used in this project for model validation purposes. These personnel included but were not limited to Robert Eaton and Andrew Hall with the New Hampshire DOT (NHDOT) and Dale Peabody and Steve Colson with the Maine DOT (MaineDOT).

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CHAPTER 1: INTRODUCTION

1.1 Background

Many miles of roads in seasonal frost areas are highly susceptible to damage during the spring thaw period. To minimize that damage, many state and local transportation agencies apply spring load restrictions (SLRs), which limit the allowable load on the road during the critical time interval when the roadway structure is most vulnerable. A previously completed Aurora project (Miller et al. 2020) provided transportation agencies with relatively reliable protocols for predicting when to apply SLRs based on atmospheric weather data.

Deciding when to remove SLRs is complicated given the variable time window during and after thawing when excess moisture remains in the base and subgrade layers, causing the overall roadway structure to remain weak. Over time, as the excess moisture dissipates, the roadway regains its strength and stiffness and the SLR can be removed.

Historically, inspection/observation or time-based methods have been used to decide when to remove SLRs, but those methods have the disadvantage of being highly subjective. Directly measuring the load capacity of a road during the spring thaw recovery typically requires the use of a falling weight deflectometer (FWD), which is expensive and time consuming, requires road closures, and can only address a small segment of the road network. Alternative approaches using embedded moisture sensors also pose challenges in terms of installation and expense and only work for certain soil types. Therefore, the need for a more robust and cost-effective means of deciding when to remove SLRs has been identified.

Miller et al. (2020) validated methods for deciding when to apply SLRs by comparing the predicted SLR start dates with the onset of thawing measured by subsurface temperature sensors. The researchers proposed evaluation of available protocols for SLR removal by comparing predicted SLR end dates with roadway stiffness, as indicated by FWD deflection data. In the project’s original scope, each of five state departments of transportation (DOTs) planned to run a series of FWD or lightweight deflectometer (LWD) tests at their demonstration sites, ideally two times per week during the spring thaw and strength recovery period. Although the North Dakota DOT (NDDOT) provided a set of FWD data, it was not possible for the other participating DOTs to provide the planned FWD or LWD data during either of the study years at their demonstration sites. As a result, validation of SLR removal protocols was limited, and reliable conclusions could not be made.

1.2 Objectives and Scope of Work

NDDOT officials expressed a need to better define and validate methods of determining when roadways can support truck traffic without causing major damage after the spring thaw is complete.

NDDOT has the benefit of a robust array of subsurface temperature depth probes (TDPs) that enable accurate determination of end-of-thaw dates throughout the state. However, NDDOT staff members lacked a reliable protocol or criteria to inform them of how long to wait after thawing was complete before removing their SLRs. Therefore, the main objective of this research was to provide an economical and easy-to-use method for timing SLR removal.

The protocol was anticipated to be able to define the time windows after thawing is complete that are necessary for significant stiffness recovery and thus SLR removal. To achieve the research objective, the following tasks were defined and completed under the scope of work for this project:

1. Select study sites. The research team queried archives of historical data for potential data sets at sites with appropriate instrumentation and adequate frequency of FWD testing during spring thaw and strength recovery periods.

    a. As anticipated, the major source of data for model/protocol development (Task 3) was derived from the Minnesota road research (MnROAD) facility low-volume road (LVR) loop.

    b. Other sites with data appropriate for this study were identified in Maine, New Hampshire, New York, and North Dakota. These sites/data sets were used to validate the recommended SLR removal protocol (Task 5).

2. Assemble data discovered during Task 1 and perform data reduction and manipulation.

    a. Summarize available information about the properties of roadway surface, base, and subgrade soils.

    b. Compute the daily cumulative freezing index (CFI) and cumulative thawing index (CTI) based on air temperatures from the test sites.

    c. Utilize subsurface temperature data to determine the end-of-thaw date for each site/thaw season.

    d. Assemble available data related to moisture. Rainfall data are necessary for the FrezTrax model (to be evaluated as Task 4). For additional model development (Task 3), the research team examined any available data regarding depths to the groundwater table (GWT) and soil moisture content.

    e. Assemble and reduce FWD data and consider various parameters as a means of defining SLR removal dates for each site/season. The research team considered numerous parameters, including temperature-corrected adjusted center deflection (ACD), subgrade modulus, surface modulus, and other FWD deflection basin parameters.

3. Perform statistical analyses on the data assembled in Task 2. These analyses helped to determine the key factor(s) that define time windows required for stiffness recovery (after complete thawing is observed using TDPs). A model and protocol (decision tree) for SLR removal was developed based on these analyses.

4. Because NDDOT had previously shown interest in the FrezTrax model, that model was run and analysis was performed to evaluate whether this model could also reasonably predict SLR removal dates.

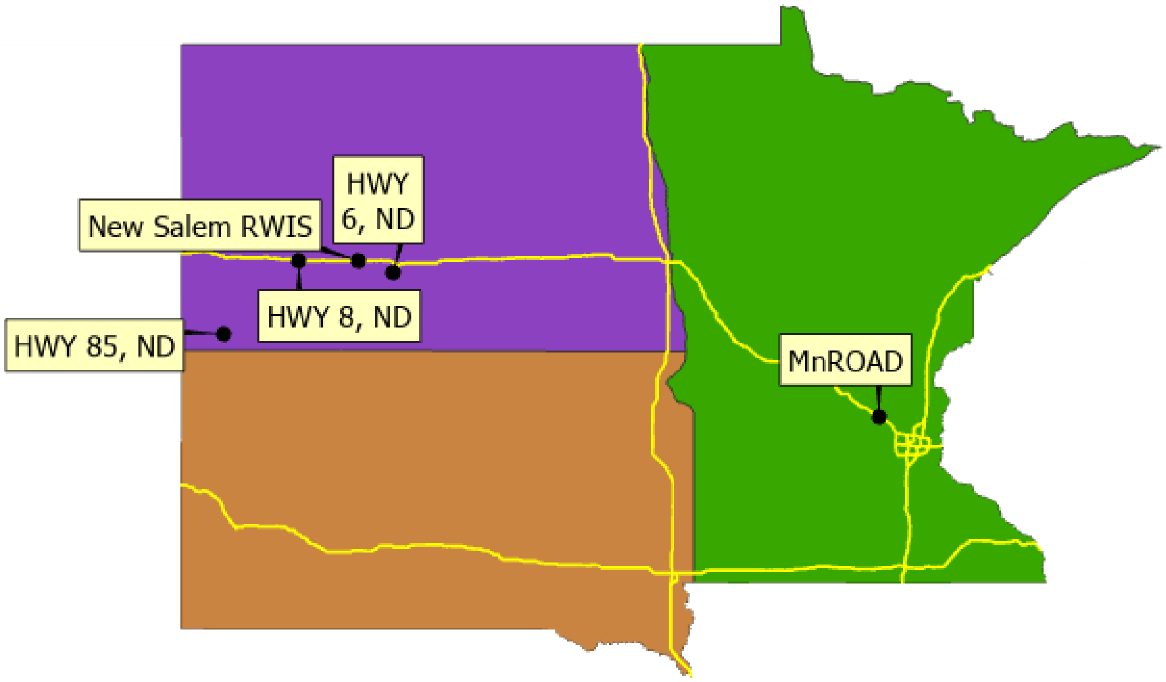
5. The validation data sets obtained in Task 1 were used to confirm validity of the SLR removal protocol developed in Task 3.

6. This final report was prepared summarizing work conducted for this project, conclusions, and recommendations.

CHAPTER 2: STUDY SITES AND AVAILABLE DATA

2.1 Overview and Location of Study Sites

The major source of data for model/protocol development was derived from the Minnesota DOT (MnDOT) MnROAD test facility located in eastern Minnesota, as shown in Figure 1.



RWIS=road weather information system

Figure 1. Location of study sites in Minnesota and North Dakota

For model validation, NDDOT provided FWD data from three sites (Highway 6 [ND 6], Highway 8 [ND 8], and Highway 85 [US 85]), also shown in Figure 1. Additionally, Cornell University, the Maine DOT (MaineDOT), and the New Hampshire DOT (NHDOT) provided FWD data from six sites in the northeast, as shown in Figure 2.

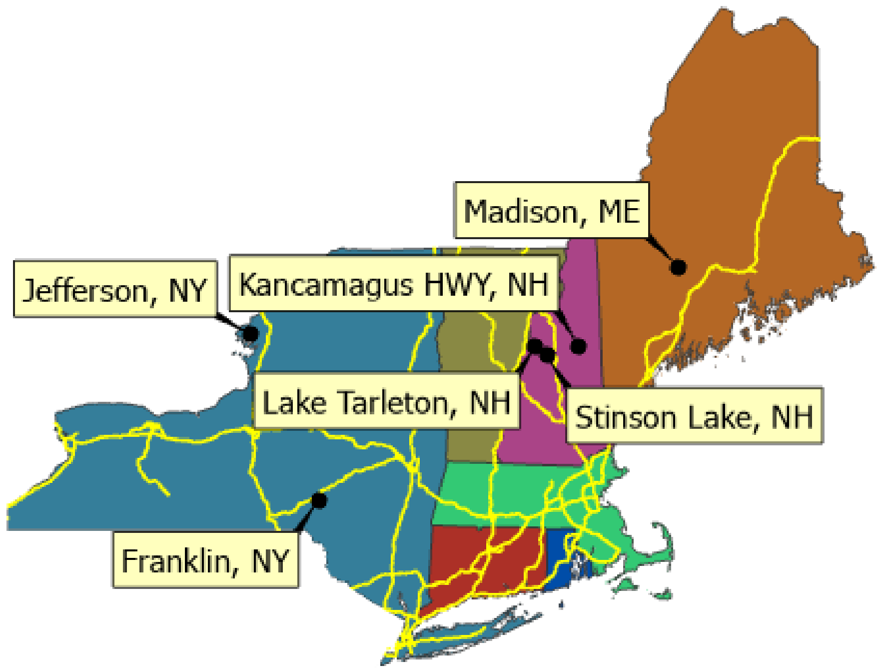
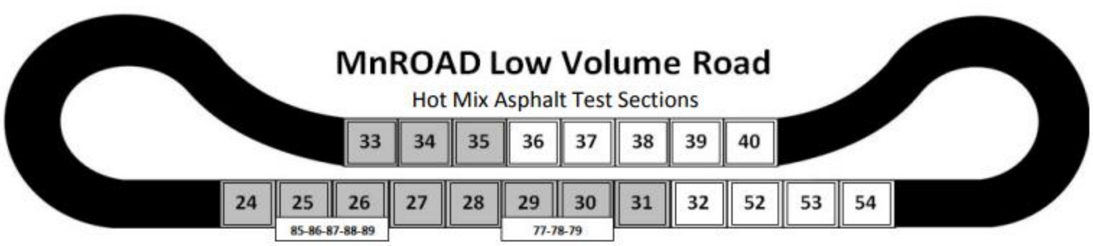


Figure 2. Location of study sites in the northeast

2.2 Sites Selected for Model Development

The major source of data for model/protocol development was derived from three cells (25, 26, and 28) along the LVR loop at the MnROAD test facility (see Figure 3).



https://www.dot.state.mn.us/mnroad/testcells/files/Cell%20Maps%20LVR%20Historical.pdf

Figure 3. MnROAD LVR loop cell designations

MnROAD was constructed from 1990 through 1993 with funding provided by state and federal sources. A partnership between MnDOT and the Minnesota Local Road Research Board then provided the majority of the operations funding for the first 10 years. The LVR loop is a 2.5-mile-long closed loop that runs parallel to I-94 in Otsego, Minnesota, as shown in Figure 4.

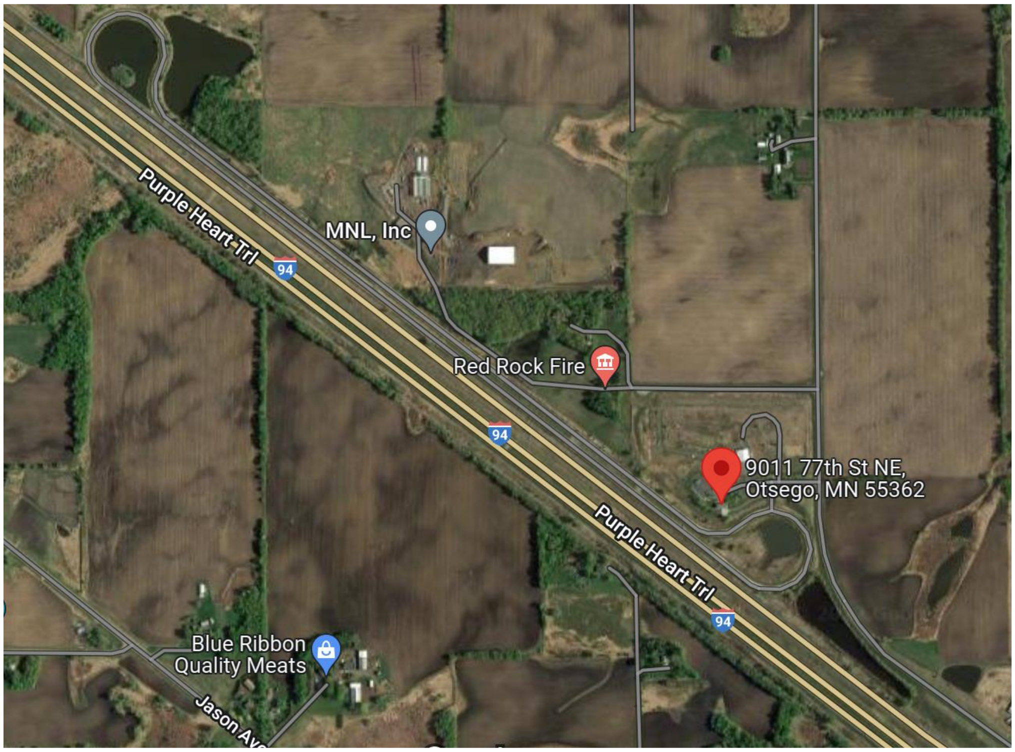


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Figure 4. Location of MnROAD LVR loop

The loop was specifically developed to analyze relatively thin pavements with low traffic volumes. Beginning in 1994, the LVR loop was subject to traffic loads from a five-axle tractor-trailer that drives at 80,000 lb on the inside lane (80K-lane) four days a week, and 102,000 lb on the outside lane (102K-lane) one day a week. Since 2007, only the inside lane has been loaded (https://www.dot.state.mn.us/mnroad/history.html).

A summary of available information about the roadway structure, base and subgrade soils, and data regarding the depth to the GWT are included in Appendix A.

2.3 Sites Selected for Model Validation

Other sites were identified in Maine, New Hampshire, New York, and North Dakota that had appropriate data for use in validating the recommended SLR removal protocol. The following validation data were obtained and analyzed:

- Two years of FWD data from a site in Madison, Maine (clay subgrade). Moisture sensor data were also available at this site.
- One year of FWD data from the Lake Tarleton (LT) and Stinson Lake (SL) sites in New Hampshire (silty sand subgrades). Data regarding the GWT depth were also available at these sites.

- One year of FWD data from the Kancamagus Highway site in New Hampshire (sand subgrade). Data regarding the GWT depth were also available at this site.
- One year of FWD data from the Franklin site in New York State (silty sand subgrade).
- One year of FWD data from the Jefferson County site in New York State (clay subgrade).
- Between one and four years of FWD data from three sites in North Dakota (presumed clay subgrades). These sites were designated as Highway (ND) 6, Highway (ND) 8, and Highway (US) 85.

A summary of available information about the roadway structures, base and subgrade soils, and depths to the GWTs for these validation sites is included in Appendix A.

CHAPTER 3: CLIMATE AND SUBSURFACE TEMPERATURE DATA

3.1 General

To achieve the project objectives, the researchers needed to obtain and reduce various climatic data as well as data regarding subsurface temperature regimes. Specifically, the research team needed to do the following:

- Compute seasonal air temperature parameters, specifically, the seasonal air freezing index (AFI) and the seasonal air thawing index (ATI), as well as onset dates and lengths of the freezing and thawing seasons.
- Compute pavement surface temperature parameters, specifically the daily CFI and CTI.
- Utilize subsurface temperature data to determine the end-of-thaw date for each site/thaw season.

3.2 Seasonal Air Temperature Parameters

For the FrezTrax model, as well as for other correlations with FWD analyses, several parameters were computed from daily average air temperatures. These parameters included the seasonal AFI, the seasonal ATI, freezing and thawing season start dates, and freezing and thawing season lengths. These parameters were computed for MnROAD's LVR site for 1993 through 1999 using the average of the daily maximum and minimum air temperatures obtained from the Modern-Era Retrospective Analysis for Research and Applications (MERRA) data provided at https://infopave.fhwa.dot.gov/MnROAD/DownloadData.

To compute seasonal AFI and ATI values, the first step was to construct a cumulative degree day (CDD) versus time plot. A degree-day is the difference between the daily average temperature and freezing (32°F). To calculate the CDD values, the following equation was used:

$$CDD = \sum_{i=1}^{n}(T_{ave,i} - 32)\Delta t \quad (3\text{-}1)$$

where,

n = number of cumulative Julian days
$T_{ave,i}$ = corresponding Julian day's average temperature in degrees Fahrenheit
Δt = period between consecutive points (taken as 1 day)
32 = the water/ice phase change temperature in degrees Fahrenheit (called the reference temperature in the discussion below)

Note that CDD, AFI, and ATI all have units of °F-days.

As indicated by equation (3-1), the degree days for each day are calculated as the daily average temperature minus 32°F, and then the CDDs are the sum of the daily degree days. Table 1 shows the results of the calculations for the period from January 1 through 18, 1993.

Table 1. Sample calculations for CDD

Date	$T_{ave,i}$ (°F)	Degree Days (°F-days)	CDD (°F-days)
01/01/1993	-16.2	-48.2	-48.2
01/02/1993	10.2	-21.8	-70.0
01/03/1993	15.4	-16.6	-86.6
01/04/1993	-3.5	-35.5	-122.1
01/05/1993	-1.3	-33.3	-155.4
01/06/1993	1.9	-30.1	-185.5
01/07/1993	2.7	-29.3	-214.8
01/08/1993	-0.9	-32.9	-247.7
01/09/1993	-2.6	-34.6	-282.3
01/10/1993	1.9	-30.1	-312.4
01/11/1993	3.4	-28.6	-341.0
01/12/1993	17.8	-14.2	-355.2
01/13/1993	15.8	-16.2	-371.4
01/14/1993	12.4	-19.6	-391.0
01/15/1993	4.3	-27.7	-418.7
01/16/1993	8.8	-23.2	-441.9
01/17/1993	-2.4	-34.4	-476.3
01/18/1993	2.7	-29.3	-505.6

The first and second columns in the table show the date and average daily air temperature, respectively. The third column shows the degree days for the individual days, as computed using equation (3-1), and the fourth column shows the cumulative total of the third column from top to bottom. When each of the CDDs reaches a minimum, the following values in the warmer weather contribute to the seasonal ATI.

Figure 5 shows a plot of the CDDs for the entire period of interest in this work: January 1, 1993, through December 31, 1999.

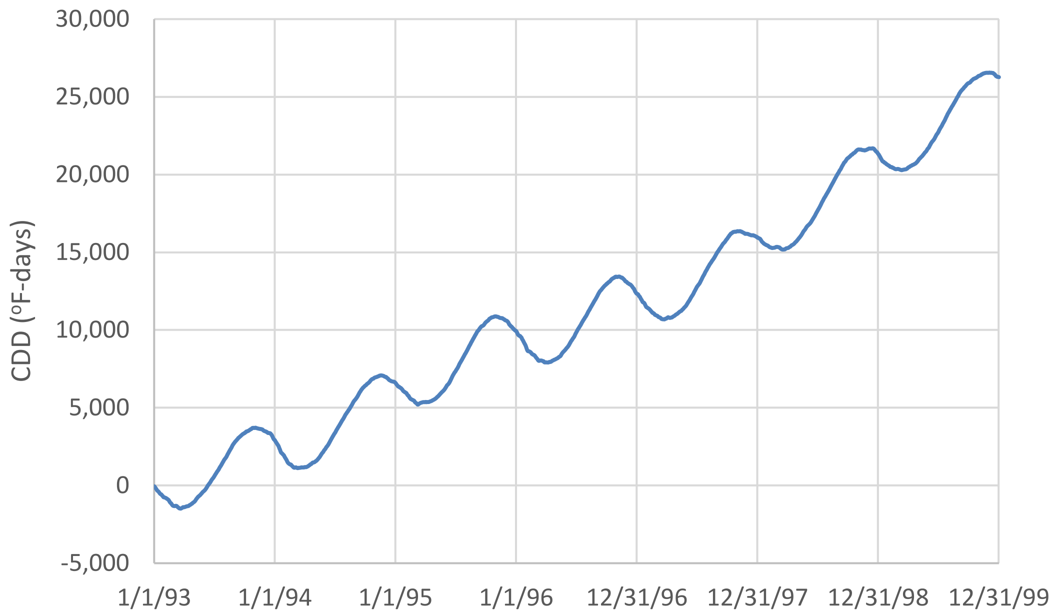


Figure 5. CDD plot for MnROAD LVR site (1993–1999)

Local maxima that occur annually denote the end of the thawing season and the beginning of the freezing season. Similarly, the local minima that occur annually denote the end of the freezing season or the beginning of the thawing season. It should be noted that the air "thawing season" (which contributes to the seasonal ATI) includes the periods of subsurface soil thawing, recovery, and post-recovery.

However, selecting the actual dates that freezing and thawing seasons begin is nearly impossible from this chart. So, generally, a more detailed plot showing the freezing and thawing season for an individual year was constructed, similar to Figure 6.

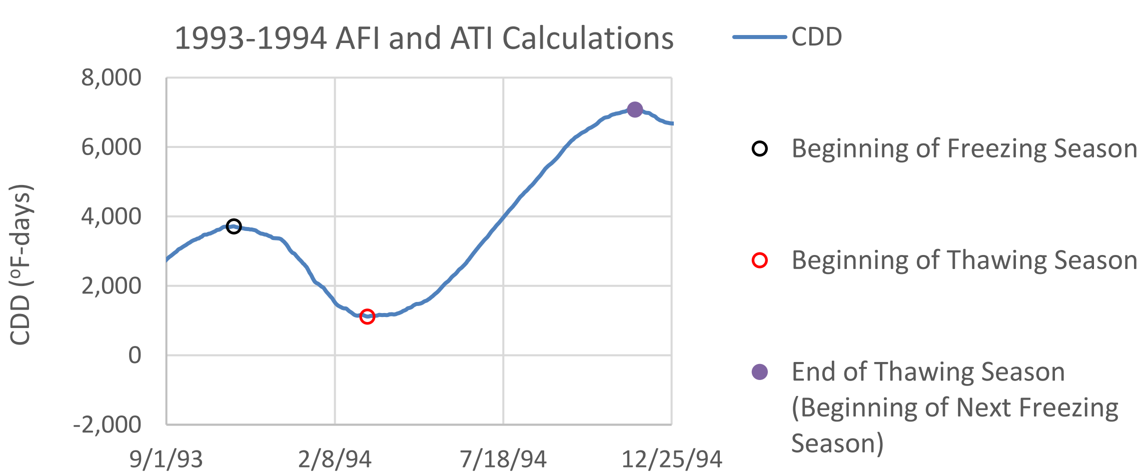


Figure 6. Illustration of AFI and ATI calculations for MnROAD LVR site (1993–1994)

The AFI of any given winter season was determined by taking the difference in the maximum CDD value (beginning of the freezing season) and the minimum CDD value (beginning of the thawing season). Similarly, the ATI was determined by taking the absolute value of the difference between the minimum CDD value (beginning of the thawing season) and the next maximum CDD value (end of the thawing season or beginning of the next freezing season). The minimum and maximum CDD values (along with their corresponding dates) were most accurately determined by using the @MAX and @MIN functions for each year in an Excel spreadsheet. The start date, end date, and length of each freezing and thawing season, as well as the seasonal AFI and ATI values at the MnROAD LVR site, are listed in Table 2.

Table 2. Seasonal air freezing and thawing parameters at the MnROAD LVR site

Season	Freezing Season Start Date	AFI (°F-days)	Freezing Season Length (days)	Thawing Season Start Date	ATI (°F-days)	Thawing Season Length (days)
93				3/22/93	5,204	227
93–94	11/4/93	2,599	127			
94				3/11/94	5,964	254
94–95	11/20/94	1,878	110			
95				3/10/95	5,676	236
95–96	11/1/95	2,968	158			
96				4/7/96	5,527	215
96–97	11/8/96	2,754	137			
97				3/25/97	5,675	229
97–98	11/9/97	1,181	131			
98				3/20/98	6,438	228
98–99	11/3/98	1,332	130			
99				3/13/99	6,275	265

3.3 Pavement Surface Temperature Parameters

The previous section of this report discussed commonly used air temperature parameters, such as the seasonal AFI and ATI. Surface temperatures of asphalt pavements are nearly always warmer than air temperatures, mainly due to the absorption of solar radiation from the sun. Pavement surface degree day indices are often computed using similar methods to those previously described, except that the reference temperature is generally not taken as 32°F.

Mahoney et al. (1986) and MnDOT (2009) were the first to use a reference temperature different from 32°F. Using these, pavement surface thawing starts before air temperatures rise above 32°F in the spring, and pavement surface freezing starts after air freezing begins; therefore, the pavement surface thawing season is longer than the air thawing season. However, pavement surface temperatures are seldom measured, so methods to approximate the temperature differences have been developed.

The US Army Corps of Engineers (Joint Departments of the Army and the Air Force 1988) developed n-factors to relate seasonal AFI and ATI to pavement surface freezing and thawing indices. However, those n-factors apply only to entire seasons, not daily relationships.

Mahoney et al. (1986) developed the first method to relate air and pavement surface CDDs in the early spring by applying a reference temperature of 29°F instead of 32°F. Mahoney et al. (1986) recommend computing CFI and CTI as follows:

$$CFI_n = \sum_{i=1}^{N}(32 - T_{ave.,i}) \quad (3\text{-}2)$$

$$CTI_n = \sum_{i=1}^{N}(T_{ave.,i} - 29) \quad (3\text{-}3)$$

where,

CFI_n = cumulative freezing index for day n (°F-day)
CTI_n = cumulative thawing index for day n (°F-day)
$T_{ave.,i}$ = average daily air temperature (°F)
N = number of cumulative days

Mahoney et al. (1986) stipulate that the CTI cannot be negative and is therefore reset to zero if a thawing period is interrupted by a significant refreezing event.

MnDOT undertook a research effort to improve the approximated pavement surface temperatures in the spring (Van Deusen et al. 1998, Ovik et al. 2000), and their resulting method for posting spring load restrictions (MnDOT 2009, 2014) is now widely used by DOTs in the seasonal frost areas of the United States. MnDOT recommends computing the CFI for a given day as per equation (3-2), but to compute the CTI, they recommend using the equations below with a "floating" reference temperature.

$$CTI_n = \sum_{i=1}^{n}(Daily\ Thawing\ Index - 0.5 \times Daily\ Freezing\ Index) \quad (3\text{-}4)$$

1. $When\ \left\{\frac{T_{max} + T_{min}}{2} - T_{ref}\right\} < 0°\text{F}$

and $CTI_{n-1} \le 0.5 \times \left(32°\text{F} - \frac{T_{max} + T_{min}}{2}\right)$ (Significant thawing has not yet occurred)

So, Daily Thawing Index = 0°F-day and Daily Freezing Index = 0°F-day

2. $When\ \left\{\frac{T_{max} + T_{min}}{2} - T_{ref}\right\} > 0°\text{F}$ (The pavement structure is thawing)

So Daily Thawing Index = $\left\{\frac{T_{max} + T_{min}}{2} - T_{ref}\right\}$ **and Daily Freezing Index = 0°F-day**

3. $When \left\{\frac{T_{max}+T_{min}}{2} - T_{ref}\right\} < 0°F$

and $CTI_{n-1} > 0.5 \times \left(32°F - \frac{T_{max}+T_{min}}{2}\right)$ (The pavement structure is refreezing)

So Daily Thawing Index = 0°F-day and Daily Freezing Index $= \left\{\mathbf{32}°F - \frac{\boldsymbol{T_{max}+T_{min}}}{\mathbf{2}}\right\}$

where,

CTI_{n-1} = Cumulative thawing index for the previous day
T_{max} = Maximum daily air temperature (°F)
T_{min} = Minimum daily air temperature (°F)
T_{ref} = Reference air temperature (°F)

Note that the CTI resets to zero on January 1 and on any day when $CTI_n < 0$.

The use of a reference temperature in equation (3-4) was recommended by MnDOT to compensate for the temperature differential between the air temperature and asphalt temperature. In Minnesota, researchers found that the air temperature required for pavement thawing to begin actually decreases during the early spring, probably due to the increase in the elevation angle of the sun (Van Deusen et al. 1998). Therefore, MnDOT implemented the use of a floating reference temperature to account for increased solar gain. MnDOT recommends using a reference temperature of 32°F between January 1 and January 31. The solar gain is then reflected using a depression of 2.7°F during the first seven days of February and thereafter using a further depression of 0.9°F per week (MnDOT 2009, 2014).

3.4 Pavement Subsurface Temperatures: Frost Out Dates

3.4.1 General Description of Instrumentation

Subsurface temperature data were used to determine the end of thawing or "frost out" date for each study site and year. Temperature sensing at the MnROAD test cells and at most of the validation sites was accomplished using either thermocouples or thermistors. Thermocouples were predominately used at the MnROAD test cells. These thermocouples were manufactured by MnDOT personnel, and a detailed description of their construction and installation is described in MnDOT (2020). According to that document, "thermocouples work for measuring temperature because the joining of two dissimilar metal conductors generates a small voltage, called the Seebeck voltage or thermoelectric effect, which is proportional to the temperature difference between the hot (point of interest) end and a reference junction." A precision of ± 1°C was reported.

Spacing of the subsurface temperature measurement points at MnROAD Cell 26 are shown in Table 3.

Table 3. Spacing of thermocouple measurement points at MnROAD Cell 26 (1994–2000)

Sensor	Depth (in.)
S1*	1.08
S2*	3.48
S3	6.60
S4	11.04
S5	17.04
S6	23.04
S7	35.04
S8	47.04
S9	59.04
S10	95.04

*S1 and S2 were located in the asphalt surface. All other sensors were located in the clay.

This approximate spacing was also typical of the other MnROAD test cells used in this study. Data were recorded at least hourly, and for some cells/seasons, data were recorded every 15 minutes.

At the four validation sites in Maine and New Hampshire, thermistors were the primary means of measuring subsurface temperatures. Thermistors are temperature-sensitive resistors that register large changes in resistance for small changes in temperature, making them useful for measuring small changes in temperature (MnDOT 2020).

In some cases, data from the thermistors were supplemented with data from frost tubes (see Figure 7).

Robert Eaton, New Hampshire DOT

Figure 7. Frost tube with partially frozen zone

A frost tube consists of two concentric plastic pipes installed vertically in the ground with a protective cover and does not provide temperature data, just whether the state of the ground is frozen or unfrozen. The outer pipe acts as a protective casing for the inner pipe, which is removable. The inner pipe is filled with water and dye.

When the dye freezes, its color changes; when it thaws, it returns to its original color. Depths to the top and bottom of the frozen layer are established based on the color change, which is associated with the freezing/thawing of the soil surrounding the outer pipe.

In each of the New Hampshire test sections, a tube was installed to a depth of 7 ft that originally held six independent HOBO pendant temperature data loggers (with integrated thermistors). These were produced by Onset Computer Corporation and had a reported accuracy of ± 0.53°C (± 0.95°F).

In 2007, the data loggers were spaced at depths of approximately 6, 12, 18, 30, 54, and 78 in. beneath the pavement surface. The following year, three additional HOBO sensors were added to each of the sites, then enabling measurements at depths of about 6, 12, 18, 24, 30, 36, 42, 54, and 78 in. Frost tubes were also installed at the New Hampshire test sites.

In October 2012 at the Madison, Maine, test site, a string of thermistors was installed in an approximately 7 ft deep borehole in the roadway. The thermistors (Onset Part # S-TMB-M005) had a reported accuracy of ±0.2°C (±0.36°F). One thermistor was installed in the asphalt surface, one was installed in the middle of the asphalt layer, and the remaining sensors were installed at approximately 6, 12, 18, 24, 30, 36, 48, 60, 72, and 84 in. beneath the pavement surface. All of the temperature sensors at the New Hampshire and Maine validation sites were calibrated in a 32°F ice bath so that freezing temperature offsets could be accounted for in analyses. The sensors (and associated data loggers) recorded and stored hourly temperature readings.

At the two validation sites in New York, only frost tubes were installed. The frost tubes at the New York and New Hampshire validation sites were generally monitored on a weekly to biweekly basis. Figure 8 compares frost and thaw depths determined from thermistors (using linear interpolation between individual sensor locations) and frost and thaw depths determined from the frost tubes at the Lake Tarleton, New Hampshire, site.

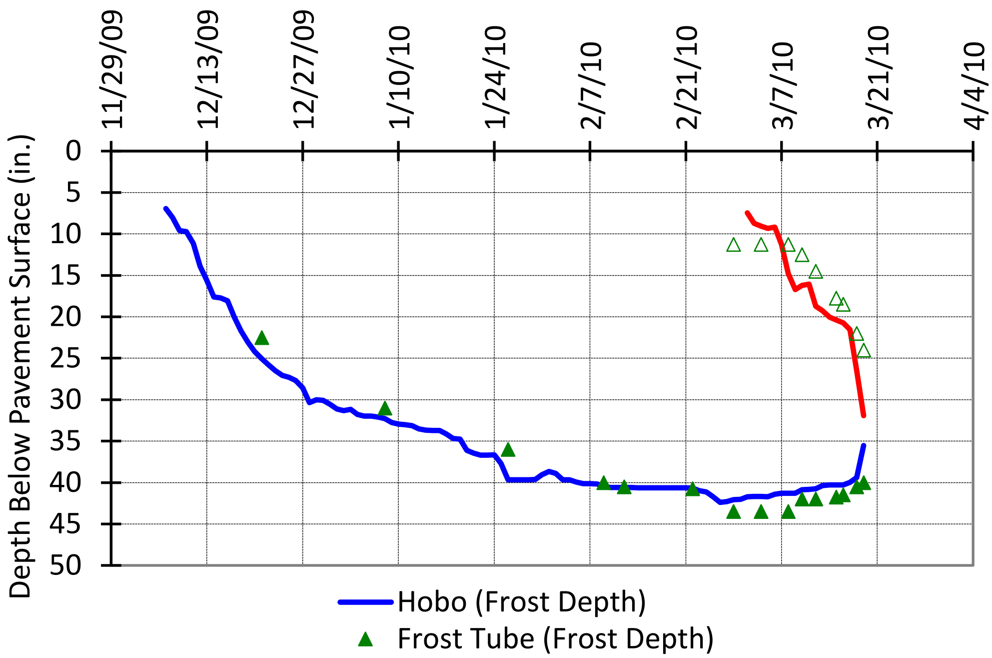


Figure 8. Comparison of frost and thaw depths determined from thermistors and frost tubes at the Lake Tarleton, New Hampshire, site

The results shown in the figure suggest that there is relatively good agreement between the two types of measurements (thermistors and frost tubes).

3.4.2 Methodology and Frost Out Dates

The thermocouple (TC) data from MnROAD Cells 25, 26, and 28 were downloaded from the following website: https://www.dot.state.mn.us/mnroad/data/environmental-sensors.html. For each cell and study year, two plots were constructed and examined. First, a plot showing temperatures at each TC location from January 1 through mid- to late May each year was constructed (see Figure 9).

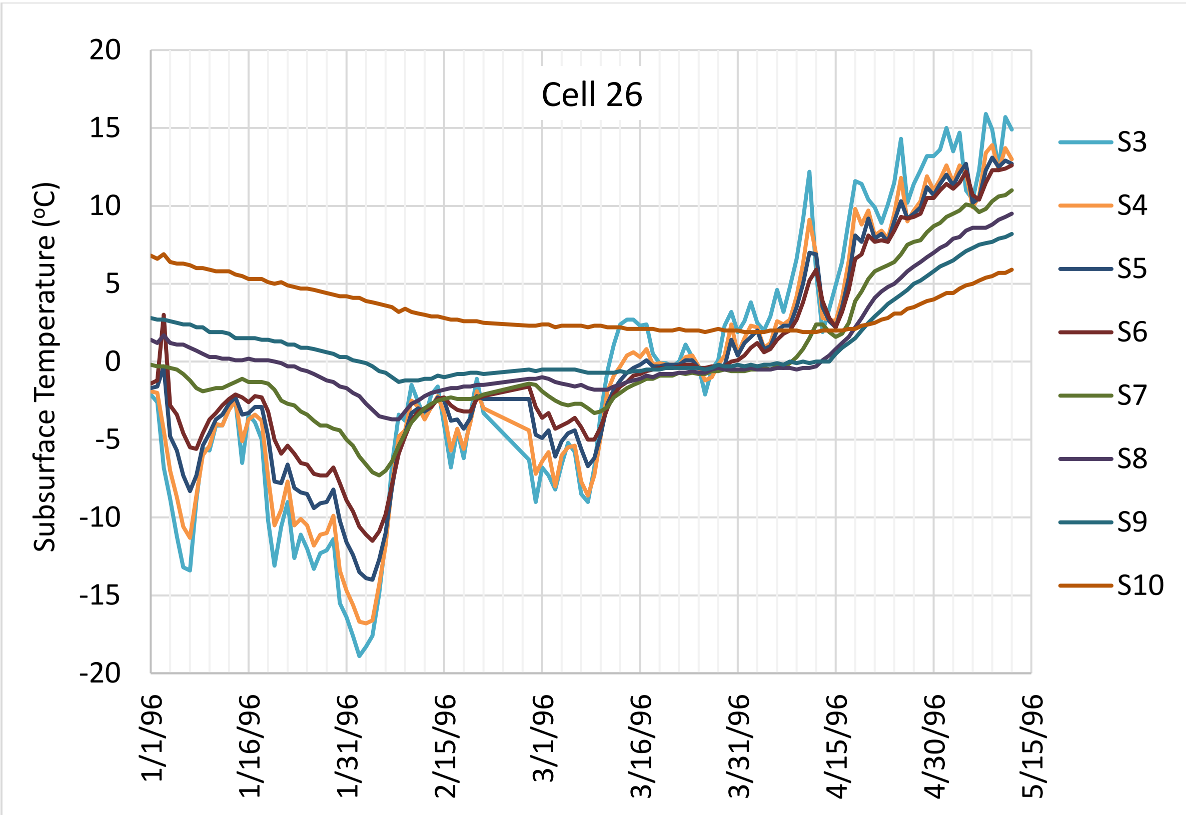


Figure 9. Plot of subsurface temperatures at MnROAD Cell 26 (January 1 through May 15, 1996)

Note that Sensors 1 and 2 were located near the top and mid-depth of the asphalt layer and are not included in this plot. This plot enabled the team to observe general freezing and thawing patterns and to approximately identify the frost out date.

Second, a cropped plot zooming in around the approximate frost out date identified in the first plot was constructed (see Figure 10).

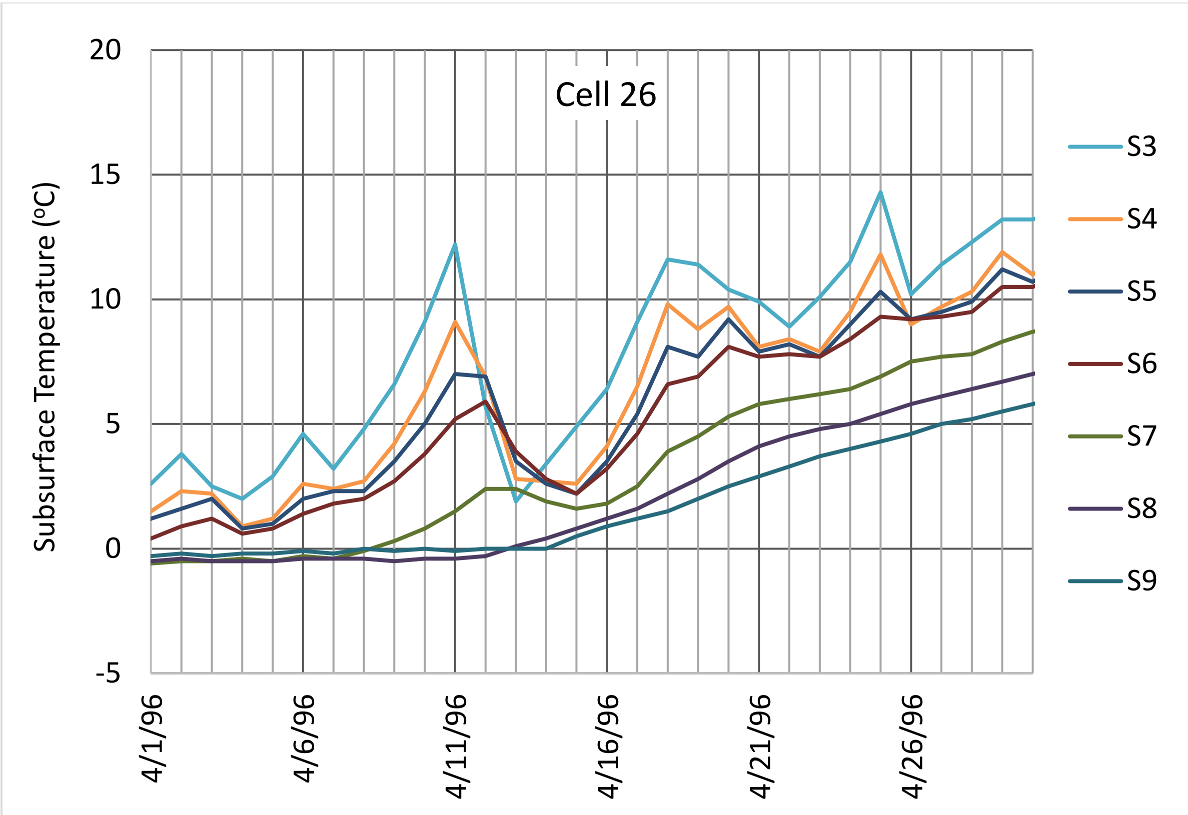


Figure 10. Plot of subsurface temperatures at MnROAD Cell 26 (April 1 through 30, 1996)

In this figure, a frost out date of April 15, 1996, is clearly identified.

The data shown in Figure 9 and Figure 10 were from readings obtained at noon each day. The data were subsequently filtered to display readings at 1 a.m., 6 a.m., 10 a.m., 2 p.m., 6 p.m., and 11 p.m. In the majority of cases, the filtered plots all displayed the same frost out date. In a couple of instances, the frost out date was one day later for readings obtained in the morning versus readings taken from noon onward. For those cases, the later frost out date was tabulated and used for analyses.

The frost out dates for all of the MnROAD study cells used for model development are shown in Table 4.

Table 4. Frost out dates at the MnROAD study cells

Cell No.	1994	1995	1996	1997	1998	1999	2000
25	16-Apr	26-Mar	19-Apr	9-Apr	20-Mar	21-Mar	8-Mar
26	12-Apr	27-Mar	15-Apr	4-Apr	21-Mar	20-Mar	10-Mar
28	9-Apr	27-Mar	18-Apr	4-Apr	21-Mar	19-Mar	

All frost out dates were determined from the available thermocouple data except for the frost out dates for Cells 25 and 26 during 1994. The thermocouple strings had not been installed in those two cells until later in 1994 (after frost out). Therefore, those frost out dates were obtained from resistivity probe data analyzed and reported by Ovik et al. (2000). Also, the thermocouple string was either removed or destroyed when Cell 28 was reconstructed in August 1999, so no frost out date is available there for spring 2000.

The same general procedure was used to determine frost out dates from thermistor data at the validation sites with the exception being the two sites in New York, where only frost tubes were available. At the two New York validation sites, data from the frost tubes were obtained about once or twice per week. As such, an error of perhaps a few days on the estimated frost out dates at those two sites was possible. The frost out dates for the validation sites used in this study are shown in Table 5.

Table 5. Frost out dates at the validation sites

Site	2004	2008	2013	2014	2020	2021	2022	2023
Kancamagus Highway, New Hampshire	–	7-May	–	–	–	–	–	–
Lake Tarleton, New Hampshire	–	9-Apr	–	–	–	–	–	–
Stinson Lake, New Hampshire	–	9-Apr	–	–	–	–	–	–
Franklin, New York	10-Mar	–	–	–	–	–	–	–
Jefferson County, New York	2-Mar	–	–	–	–	–	–	–
Madison, Maine	–	–	6-Mar	8-Apr	–	–	–	–
Bowman, North Dakota	–	–	–	–	22-Feb	17-Mar	29-Mar	11-Apr
New Salem, North Dakota	–	–	–	–	1-Apr	28-Mar	14-Apr	29-Apr

CHAPTER 4: FWD DATA REDUCTION AND INITIAL TRENDS OBSERVED

4.1 Consideration of Possible Parameters for Defining SLR Removal Dates

In prior research projects, the research team has been challenged by a lack of available FWD test data obtained during spring thaw and strength recovery periods. In this study, the team members were faced with the opposite challenge. The database from MnROAD was huge, and it was stored in a single Microsoft Access file. Initially, data from Cell 26 were exported from that Access file into Excel, but that Excel file was also extremely large, so data manipulation was a challenge.

The research team members from Cornell University took the lead on the FWD data manipulation and statistical analysis. Their initial effort involved evaluating several FWD deflection basin parameters, as listed in Table 6.

Table 6. Deflection basin parameters for pavement evaluation

Parameter	Formula
Maximum deflection	D_0 where D_0 is the center deflection at r = 0
Surface curvature index	$SCI = D_0 - D_r$ where D_r is the deflection at r = 12 in.
Base damage index	$BDI = D_{r1} - D_{r2}$ where r_1 = 12 in., r_2 = 24 in.
Base curvature index	$BCI = D_{r1} - D_{r2}$ where r_1 = 24 in., r_2 = 36 in.
Basin area	$Area = \frac{6\text{ in.}}{D_0}[D_0 + 2D_{r1} + 2D_{r2} + D_{r3}]$, where r_1 = 12 in., r_2 = 24 in., r_3 = 36 in. $Area = \frac{150\text{ mm}}{D_0}[D_0 + 2D_{r1} + 2D_{r2} + D_{r3}]$ where r_1 = 300 mm, r_2 = 600 mm, r_3 = 900 mm Note: Dividing by D_0 has normalized the deflections. Sensors must be equally spaced. Area has a maximum value of 36 in. (900 mm) when all four deflections are equal (which could only occur on an extremely stiff pavement) and a minimum value of about 12 in. (300 mm), which would occur on a surface-treated or gravel road.
Radius of curvature	$R = \frac{r^2}{2(D_0 - D_r)}$ where r is either 8 in. (200 mm) or 12 in. (300 mm)

The goal of this analysis was to determine if basin parameters could be used to detect seasonal changes in the response of the pavement, especially during the thaw and the strength recovery period after the thaw is finished.

From their initial analysis, the researchers concluded that none of these parameters could effectively be used to determine the necessary time lag for strength recovery (after thawing is complete) for SLR removal. In some cases, the basin parameters were not able to differentiate the changes in the pavement response; in other cases, the level of stochastic noise from the data made any analyses not applicable.

Further analysis suggested that using surface modulus values computed from Boussinesq equations would be more useful in this regard. This approach is sometimes referred to as "the simplest form of backcalculation." Surface modulus is a stiffness parameter and is reported in units of kPa (or MPa) in SI units or lb/in^2 (or psi) for US customary units.

The equation for surface modulus at the center of the plate is

$$E_0 = \frac{2P(1-\mu^2)}{\pi a d_0} \quad (4\text{-}1)$$

The equation for surface modulus at all sensors is

$$E_r = \frac{P(1-\mu^2)}{\pi r d_r} \quad (4\text{-}2)$$

where,

E_0, E_r = Surface modulus, pounds per square inch or megapascals
P = Applied load, pounds or newtons
μ = Poisson's ratio (usually assumed to be 0.35)
a = Radius of the applied load, inches or millimeters
d_0 = Deflection at the center of the applied load, inches or millimeters
r = Distance from the center of the applied load, inches or millimeters
d_r = Deflection at distance r from the center of the applied load, inches or millimeters

Two main simplifications or assumptions are applied with this method:

- The pavement structure is considered to be a semi-infinite half space composed of only one type of material.
- The stress zone (the primary area of pavement and subgrade materials under stress due to the FWD load) spreads at an approximate 34° angle with depth.

Based on these assumptions, the surface modulus computed using the FWD is a composite of all the layers within the stress zone. For example, the response of a geophone located 36 in. away from the center of the load plate is assumed to be influenced by the subgrade modulus of the combined layers below a depth of 24 in. Likewise, the response of an FWD sensor at 60 in. is influenced almost entirely by the layers below a depth of 36 in. This is how many backcalculation programs work; they assume the outer sensors are only influenced by the deep layers, set the modulus using those layers, and work in toward the center sensor, which is influenced by all the layers.

4.1.1 Procedure Used for Analysis of Surface Modulus Data

The team members from Cornell initially manipulated the huge data set from MnROAD Cell 26 for the years 1994 through 2000 using the following procedure:

1. Look for complete data sets

   Complete data sets include a total of nine drops at three drop heights from a total of 52,173 FWD drops.

2. Load data into Minitab Statistical Software (2023) program and filter out incomplete data.

   This is easy to accomplish in Minitab using the subsetting feature. The total number of data points meeting this criterion for Cell 26 was 45,271. This number was before a final check. After cleaning up some additional data anomalies, the final count was 44,886 FWD drops at 14,962 points.

3. Send data back to Excel and average the data on a daily basis.

   This was done because the math of averaging data (and calculating the various parameters) is easier to do in Excel. The parameters computed were the surface modulus at Sensors 5 and 6 (24 and 36 in., respectively). These parameters were referred to as Ms-24 and Ms-36, respectively. Any other factors could then be easily added and placed into Minitab for review.

4. Send daily average surface modulus data back to Minitab to examine the result and look for trends.

The same general procedure developed to reduce the MnROAD Cell 26 FWD data was used to process the data from MnROAD Cells 25 and 28.

4.2 Observations from MnROAD Cell 26 Data

Daily average surface modulus values were calculated from the FWD tests conducted at Cell 26 between January 1, 1994, and January 1, 2000, given that Cell 26 was reconstructed at some point in the year 2000. The Cornell group looked at the surface modulus values computed from

Sensor 5 and from Sensor 6 and felt that the trends were more difficult to see for Sensor 5. They concluded that Sensor 5 was probably a little too close to the load plate to not be influenced by the surface layers and the plate response. As such, they recommended that the surface modulus values from Sensor 6, Ms-36, be used for the analysis.

A scatter plot of the daily average Ms-36 values from Cell 26 is shown in Figure 11 for all FWD tests with full data sets between January 1994 and December 1999.

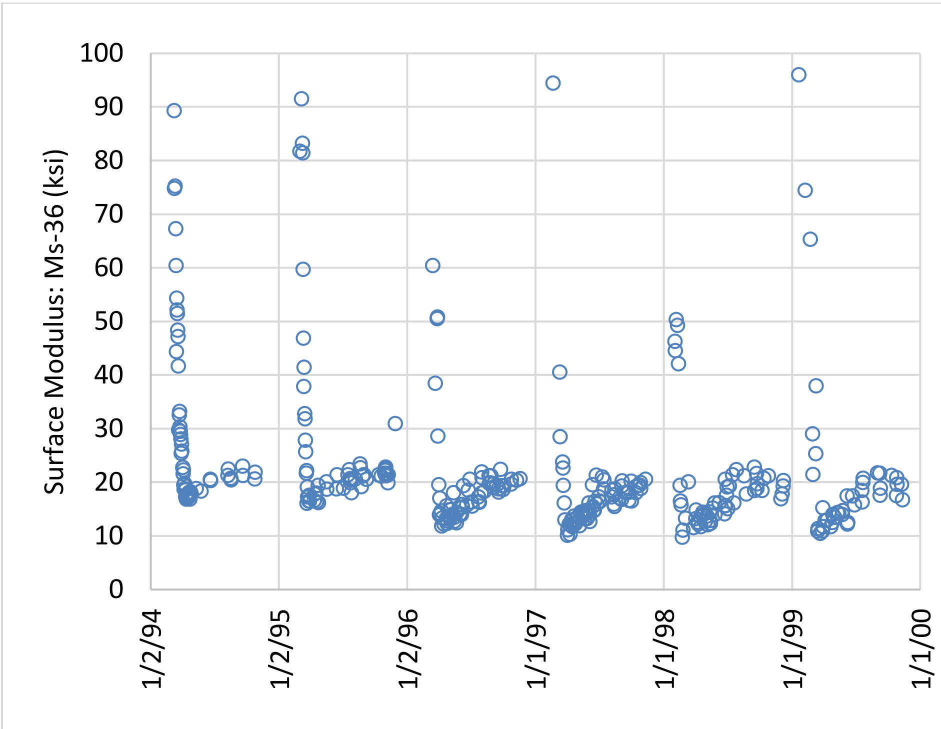


Figure 11. Daily average surface modulus (Ms-36) values from Cell 26 (1994–1999)

When plotting the full data set (Figure 11), the frozen modulus masks the real difference between the days. However, when limiting the y-axis and plotting each thaw-weakening and recovery season on its own, the variations around spring thaw are shown more clearly, as can be seen in Figure 12 showing only 1994 data.

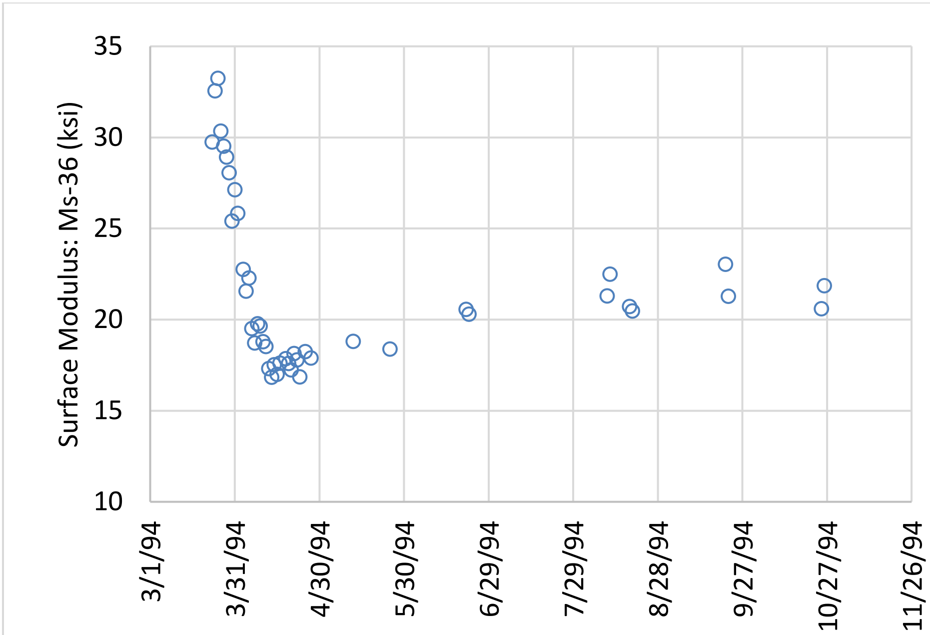


Figure 12. Daily average surface modulus (Ms-36) values from Cell 26 (1994)

The data analyzed for Cell 26 suggested that surface modulus is a useful parameter for monitoring weakening and stiffness recovery during the spring thaw period. Modulus values were quite high during the frozen periods and exhibited a steep decline during the thawing periods. The trend of a sharp drop followed by a slower recovery was fairly consistent, as shown by the data in Figure 11 and Figure 12.

Two observations were made from Figure 11 and Table 7.

Table 7. Minimum Ms-36 values for Cell 26 (1994–1999)

Season	Minimum Ms-36 Value (ksi)	Frost Out Date	Delta* (Days)
1994	16.8	4/12/94	+1
1995	16.5	3/27/95	+1
1996	11.9	4/15/96	-6
1997	10.1	4/4/97	-2
1998	11.6	3/21/98	+6
1999	10.5	3/20/99	+3

Delta = number of days between frost out date and date that minimum Ms-36 value occurred
- means minimum value occurred before frost out date
+ means minimum value occurred after frost out date

First, as shown in Table 7, minimum modulus values during any given year tend to occur just slightly before or slightly after frost out (the date when the subsoil has just completely thawed, as indicated by thermocouple and/or resistivity probe data). Second, the research team observed that the minimum Ms-36 values seemed much higher in 1994 and 1995 than they were during the years 1996 through 1999 (see Figure 11 and Table 7).

Depth to groundwater was checked, and the GWT varied between 11.6 and 12.6 ft deep during the three readings obtained in spring of 1994 and 1995. During the spring seasons between 1996 and 1999, the average water table depth was about 6 ft. That average was based on only one reading in each spring of 1996 and 1997, but five readings during spring 1998 and seven readings during spring 1999. (The following chapter of this report describes the statistical analysis conducted by the Cornell group to determine whether GWT depth is a significant factor affecting the strength recovery response.)

4.3 Observations from MnROAD Cell 25 Data

The Cornell group conducted the same data reduction process described in Section 4.2 to analyze the FWD data obtained from Cells 25 and 28. Cell 25 was a full-depth granular cross section beneath 5.9 in. of asphalt pavement. The cell had a relatively shallow GWT, which ranged from about 2 to 4 ft below the top of the pavement during the study period. Sample scatter plots from two of the study years are shown in Figure 13.

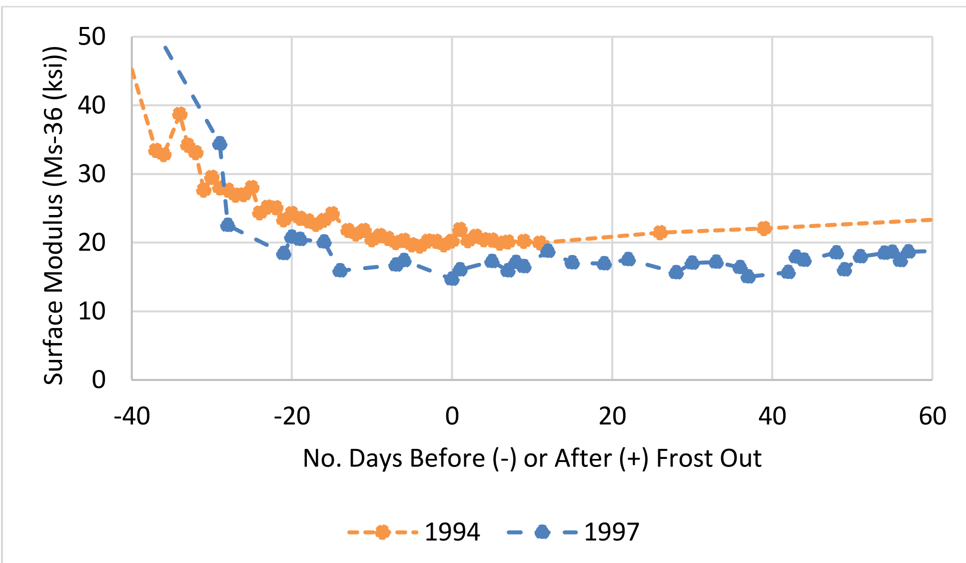


Figure 13. Surface modulus values (Ms-36) from Cell 25 during 1994 and 1997

The surface modulus values in Figure 13 are daily average values computed from deflections at the sensor located at a 36 in. offset from the FWD load plate (Ms-36). The 1994 data suggested that modulus values decreased during the thawing process and reached a minimum right around the day that thaw ended (frost out), with some modest increase in stiffness following the frost out date (day zero). However, the modulus trends for all other years resembled that of 1997. Modulus values reached a minimum around the frost out date (similar to 1994), but no significant recovery was observed beyond the frost out date. Therefore, data from Cell 25 suggested that, for roadways constructed with very free-draining base and subgrade soils, a significant recovery period does not appear after frost out.

4.4 Observations from MnROAD Cell 28 Data

MnROAD Cell 28 consisted of 3.2 in. of asphalt, on top of 13 in. of Class 5 base material, and then a clay subgrade. Cell 28 had a relatively deep GWT, which generally ranged from about 8 to 10 ft below the top of the pavement during the study period. A scatter plot of the daily average surface modulus values during 1995 is shown in Figure 14.

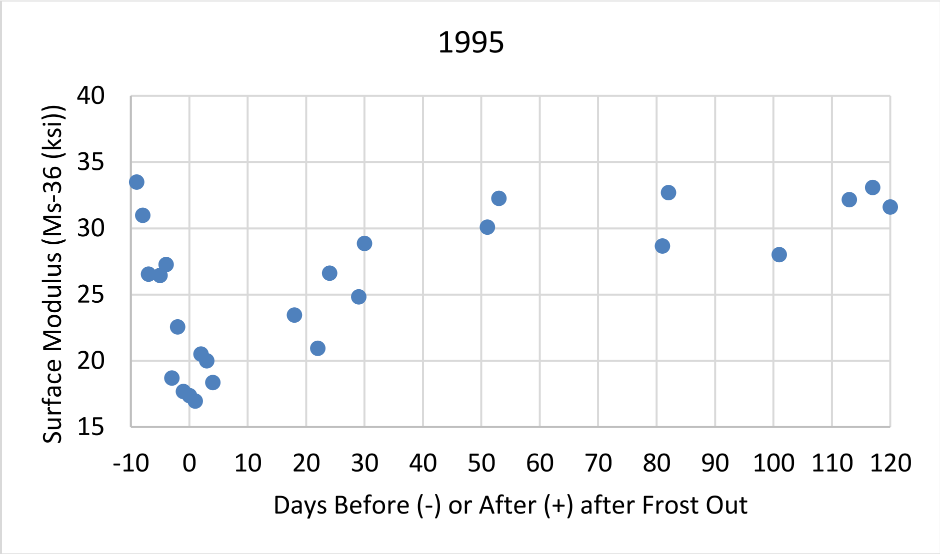


Figure 14. Surface modulus values (Ms-36) from Cell 28 during 1995

Although the vertical axis was cropped from 15 to 40 ksi in order to observe the trends after frost out, the modulus values were quite high during the frozen period and exhibited a steep decline during thawing. After frost out, an initial fairly steep recovery curve appeared, followed by a much more gradual increase or even a leveling out of modulus values. This trend suggested that a bilinear recovery model might be appropriate for fine-grained subgrades. This is discussed in more detail in the following chapter of this report.

CHAPTER 5: STATISTICAL ANALYSIS OF FWD DATA AND MODEL DEVELOPMENT

5.1 MnROAD Cell 26: Effect of GWT Depth

As noted in Section 4.2 of this report, the minimum surface modulus (Ms-36) values in MnROAD Cell 26 appeared much higher in 1994 and 1995 than during the years 1996 through 1999 (see Figure 11 and Table 7). Data showed that the GWT was fairly deep (between 11.6 and 12.6 ft) during spring of 1994 and 1995 and fairly shallow (about 6 ft deep) during the spring seasons between 1996 and 1999. The Cornell group performed the following statistical analyses to determine whether GWT depth is a significant factor affecting the strength recovery response.

The data from Cell 26 were averaged for each testing day, and the average data were filtered to look at the data for the 150 days after thaw was complete. A regression analysis was performed on the data looking at each year separately just to confirm the thought that the higher water table would be a possible variable. As Figure 15 shows, the trend is clearly different between the high and low water table years.

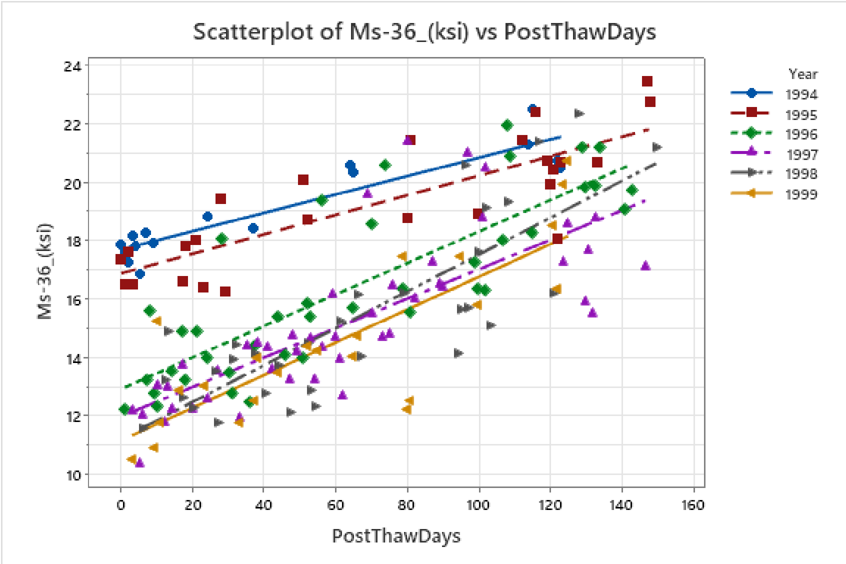


Figure 15. Cell 26 Ms-36 0–150 days post frost 1994–1999 with yearly regression lines

The data for 1994 and 1995 were then combined, as were the data for all years between 1996 and 1999, and then a full regression was done looking at the number of days after thaw as a continuous variable and the GWT as a categorical variable. Table 8 shows the regression equations, and Figure 16 shows the resulting regression lines.

Table 8. Regression equations for shallow and deep GWTs

Shallow	Ms-36_(ksi)	=	12.409 + 0.04740*Days After Frost Out
Deep	Ms-36_(ksi)	=	16.307 + 0.04740*Days After Frost Out

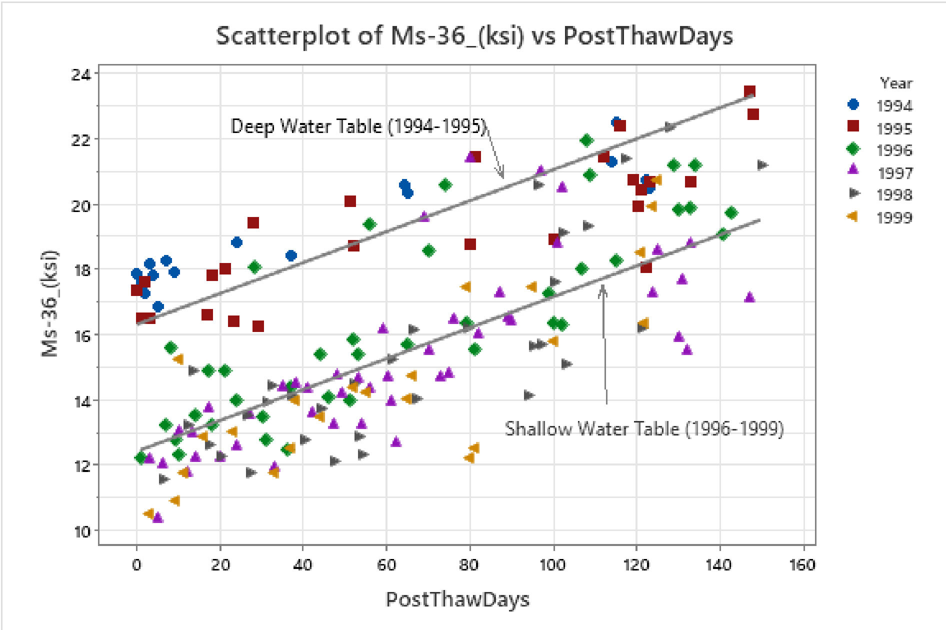


Figure 16. Cell 26 Ms-36 0–150 days post frost 1994–1999 with regression lines based on days after frost out and GWT

The results suggested that modulus values were almost 4 ksi lower for the shallow water table compared to the deeper water table. Note that when using a categorical variable, the slopes of any lines are parallel as opposed to the lines in Figure 15.

Note that the two lines shown in Figure 16 used GWT as a categorical variable. The statistics are shown in Appendix B. GWT was statistically significant with a probability of being significant over 99.9% (1 – p value shown in Appendix B).

The following are a some notes about the equations generated by the statistical software:

- The team also looked at a second-order (parabolic) equation in this analysis given that the data did appear to have a slight curvilinear nature. While statistically significant, the amount of the difference in the actual results was not large. As the team members performed additional analyses, they found that a bilinear model may be more appropriate.

- While the R^2 values were not very high (70.2%), the more critical issue was the statistical significance of the equation. In every case, the coefficients were very strongly significant.

- In Figure 15, the difference in the slope of the lines between the shallow and deep water table was clear. When using a categorical variable in a regression analysis, on the other hand, the slope of the continuous variable line was the same (Figure 16). In the final model, it is recommended that the analyses be done separately for GWT to get a fit that better approximates the data seen. The results of such a model on Ms-36 are presented in Appendix C.

- The MnROAD data had a lot of noise. While this could be due to a variety of reasons, the key takeaway was that it may be necessary to truncate some of the data with a large residual in the final model. This can only be done once and should be done consistently to be valid (Neter et al. 1996).

In summary, although the data from Cell 26 (clay subgrade, no engineered base) probably represent a worst-case scenario regarding thaw weakening and recovery, the data are useful in illustrating the negative effect of a shallow GWT. For more common roadway construction with free-draining bases, where the GWT is within about 6 ft below the top of the pavement, the modulus values may likely start lower, and recovery may take longer after the spring thaw compared to sections of roadway where the GWT is deeper.

5.2 MnROAD Cell 28: Clay Subgrade with Free-Draining Base and Deep GWT

Statistical analysis was performed on the data from MnROAD Cell 28 (clay subgrade with engineered base) that had been assembled in Task 2. These analyses helped to determine the key factor(s) that define the time windows required for stiffness recovery (after complete thawing is observed using TDPs). As noted previously, the 1995 data from Cell 28 suggested that, after frost out, the surface modulus recovery curve appeared to have an initial fairly steep slope, followed by a much more gradual increase or even a leveling out of modulus values (see Figure 14). This trend suggested that a bilinear recovery model might be appropriate.

To develop that model, all of the daily average surface modulus data obtained in Cell 28 from 1994 through 1999 were combined. An initial regression was completed and then, as previously noted and given that there was a lot of noise in the MnROAD data, data with a large residual were removed.

After removing the high residual data, final linear regressions were performed, initially on data from frost out (day zero) through 15 days after frost out. This created a fitted line for 0 to 15 days. To make sure the data matched to a common intersection, the data for days 16 to 60 were transposed to account for the results from the 0 to 15 day model. The number of days was set to the number of days after day 15 (DaysAfterFrost-15). The surface modulus was reset to the surface modulus minus the fitted value at day 15 from the 0 to 15 day model. (This offset value was 24.5 ksi.) The regression on the transposed data was then driven through the origin.

After the regression was complete, the data were then transposed back (+15 days on the x-axis and +24.5 ksi on the y-axis) to the final results. The fitted lines from those results are shown in Figure 17, along with the data that were used. More details are discussed in Appendix D.

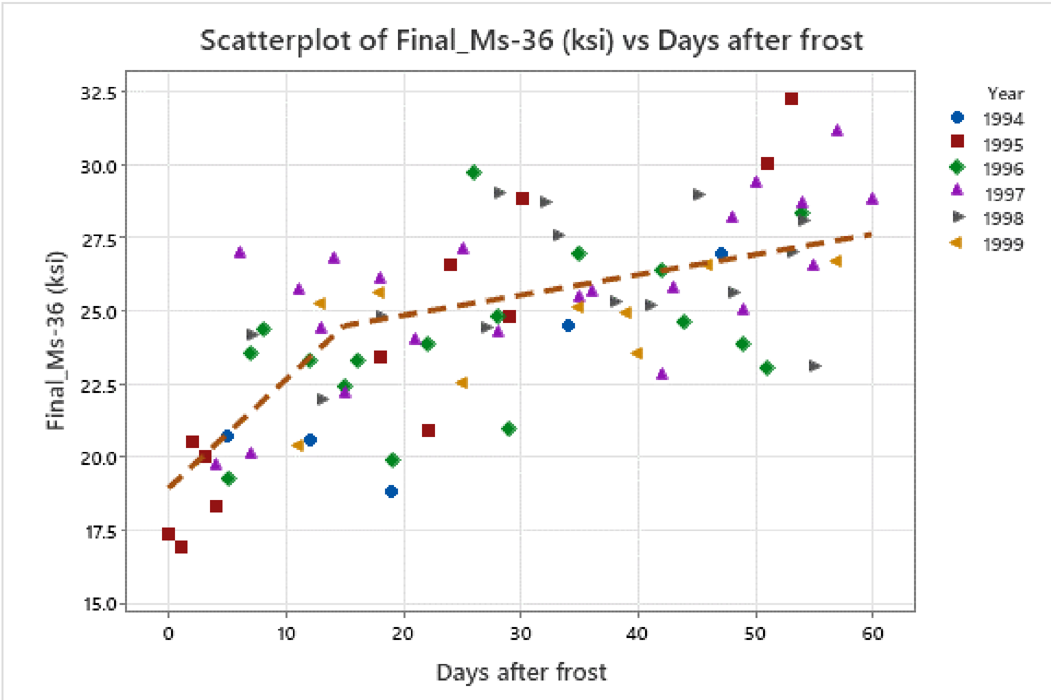


Figure 17. Cell 28 Ms-36 (ksi) 0–60 days post frost 1994–1999 with high residual data removed and dashed line showing fitted bilinear regression line

The regression coefficients determined for the lines of the bilinear model are presented in Table 9.

Table 9. Regression equations for bilinear trends in Ms-36 values

Regression Equation 0–15 Days After Frost Out	Ms-36 (ksi)_0-15_LR	=	1218.92 + 0.37 * days after frost out
Regression Equation 16–60 Days After Frost Out	Ms-36 (ksi)_16-60_LR	=	24.47 + 0.070 * (days after frost out – 15)

All of the statistics were strongly significant, as discussed in Appendix D.

The trends shown in Figure 17 suggested that recovery for cohesive subgrades with relatively deep water tables increases quickly within the first 15 days after frost out. Beyond that, increases occurred much more slowly. For MnROAD Cell 28, the regression lines suggested that modulus values increased from 18.9 to 24.5 ksi (or about 5.5 ksi) during the first 15 days but then only increased by about 3 ksi during the subsequent 45 days. As such, it makes sense to keep the SLR in place for 15 to perhaps 20 days after frost out, but relatively little is gained by leaving the SLR in place much beyond that.

As discussed in the previous section of this chapter, analysis of the Cell 26 data showed the negative effect of a shallow GWT. Therefore, for cohesive subgrades where the GWT is within about 6 ft below the top of the pavement, modulus values may likely start lower, and recovery may take longer after frost out. For such situations, it would be prudent to leave the SLR in place for a longer period of time and/or to reroute heavy traffic away from those sections of roadway.

5.3 Normalization of Data for Comparison with Validation Sites: Percent Recovery

Data from MnROAD Cell 28, presented in the previous section of this chapter, suggested that a bilinear recovery might be appropriate for cohesive subgrades with relatively deep water tables. A bilinear regression was presented in terms of surface modulus at 36 in. (Ms-36), which showed that modulus values increased quickly within the first 15 days after frost out. Beyond that, additional increases in modulus values occurred much more slowly.

To compare trends observed at MnROAD with data from sites in other parts of the country (where surface modulus values might be quite different), the research team decided to normalize data by computing the percentage of recovery relative to a baseline value of surface modulus as follows:

$$\%\ Recovery = \frac{Ms36_i}{Ms36_{Baseline}} \times\ 100\% \qquad (5\text{-}1)$$

where,

$Ms36_i$ = Daily average surface modulus value on any day, *i*
$Ms36_{Baseline}$ = Average baseline surface modulus value for a given site

It is recommended that baseline surface modulus values should generally be computed from FWD tests conducted during the fall or during a time after the spring thaw when the surface modulus curve has essentially flattened out. During mid-summer and other times of the year with very hot temperatures, the asphalt layer gets softer and deflections increase (even though the base and subgrade may be stiff). Given that some influence on the surface modulus exists at 36 in. due to the asphalt layers, the temperature effect can change computed surface modulus values and provide an erroneous value for the baseline. This would result in a lower baseline value and cause the percent recovery to be overestimated in the spring. Also, heavy precipitation events during the late summer and fall may temporarily soften the base and subgrade, again producing an unreasonably low value for the baseline and causing the percent recovery to be overestimated in the spring.

5.3.1 Percent Recovery: Cohesive Subgrades with Engineered Base and Relatively Deep GWT

To convert the Ms-36 values for MnROAD Cell 28 to percent recovery, the research team used a baseline value of Ms-36 = 30 ksi. That value was obtained from FWD tests conducted at Cell 28 during late May and June (years 1994 through 1999). The resulting scatterplot of percent recovery for Cell 28 during the years 1994 through 1999 is presented in Figure 18, and the regression equations for the bilinear fit are shown in Table 10.

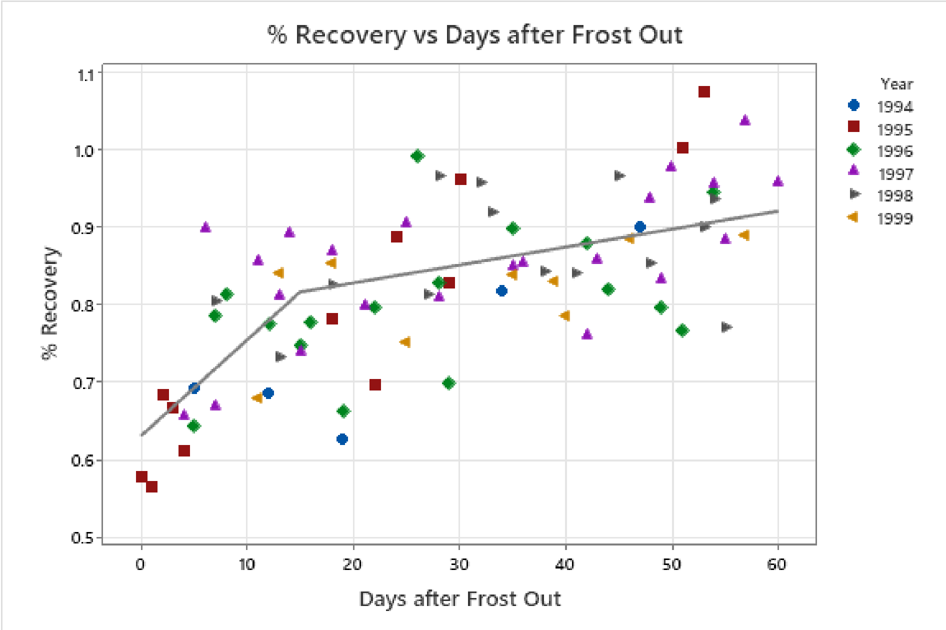


Figure 18. Scatterplot of percent recovery for MnROAD Cell 28 during 1994–1999

Table 10. Regression equations for bilinear model based on percent recovery

Regression Equation 0–15 Days After Frost Out	% Recovery_0-15	=	0.631 +0.0123 * (days after frost out)
Regression Equation 16–60 Days After Frost Out	% Recovery_16-60	=	0.816 +0.00233 * (days after frost out – 15)

To generate the bilinear line, the data were subdivided into 0 to 15 days and 16+ days after frost out. A regression was first performed on the 0 to 15 days after frost out data, and a regression line was generated. From this line, the anticipated value at 15 days after frost out was calculated.

This anticipated value was then used as zero for the 16+ days after frost out data. A new regression line was driven through this anticipated value for the 16+ days after frost out data. All of the data were recombined, forming the bilinear line shown Figure 18.

The overall error and R^2 (coefficient of determination) were generated from the bilinear regression line and the actual data. For Cell 28, the R^2 = 0.476 and the standard error = 0.0789.

Interpreting R^2 and the standard error was done similarly to any liner regression. R^2 shows the strength of the analysis, and the standard error shows the expected error. In this particular case, R^2 was reasonable considering the large variation in the data. The results showed a need for either a curvilinear or bilinear analysis. The bilinear model tends to be an easier one to understand and illustrates the rapid recovery of the pavement strength in the first couple of weeks after thaw is complete. The standard error showed the expected error in the percent recovery was near 7.9%. Note this is the error of the modulus and not the statistical strength. The statistical strength as measured by probability of an error was less than 5%.

In addition to R^2 and standard error, each of the regression coefficients were reviewed to be sure they were statistically significant. This was done on each regression separately. Every one of the coefficients and constants were statistically significant with less than 5% probability of an error in the value.

The bilinear break point occurred somewhere from 12 to 20 days after frost out. The research team discussed this quite a bit and determined that 15 days after frost out was a reasonable compromise between the data and the needs of a highway agency. A review of the possible break point using the range of 12 to 20 days after frost out, as shown in Figure 19, was completed to verify this conclusion. The figure shows the bilinear lines generated using different break point days.

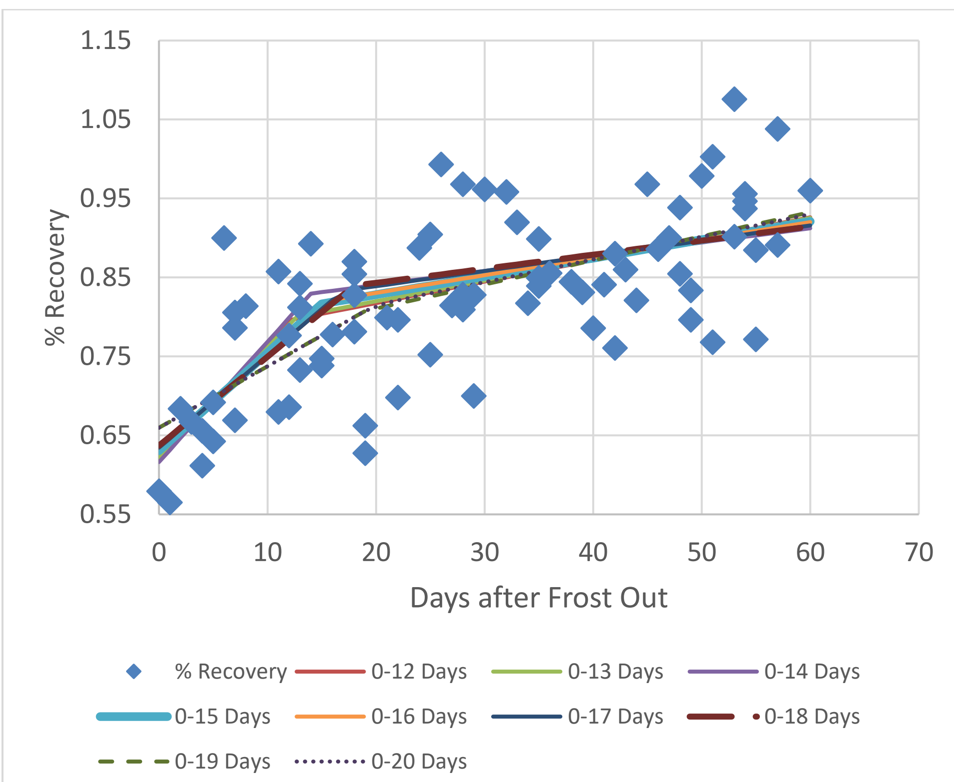


Figure 19. Bilinear regression lines with breakpoint varied from 12–20 days

The statistical differences were minimal, with the R^2 only ranging from 0.489 to 0.458 and the standard error ranging from 0.054 to 0.055. At 12 days after frost out, the statistical power of the initial steep slope line was not large enough with only 16 points available to determine the line. At 19 and 20 days, the data were overly influenced by data at 19 days after frost out.

The bottom line is that almost any break point between 12 and 20 days on the bilinear regression (on percent recovery) would be similar statistically with an R^2 near 0.476 and a standard error near 0.054. As such, the research team concluded that for cohesive subgrades with relatively deep water tables, it makes sense to keep the SLR in place for 15 (to perhaps 20) days after frost out, but that relatively little is gained by leaving the SLR in place much beyond that.

5.3.2 Investigation of Bilinear Model for Silty Sand Subgrades

In Chapter 4 of this report, it was noted that data from MnROAD Cell 25 suggested that, for roadways constructed with a free-draining base and subgrade soils, a significant recovery period does not appear after frost out. On the other hand, surface modulus values for roadways constructed on clay subgrades (Cell 26 and Cell 28) showed very different trends. Ms-36 values were quite high during the frozen period and exhibited a steep decline during thawing. After frost out, an initial fairly steep recovery curve appeared, followed by a much more gradual increase or even a leveling out of modulus values. This trend suggested that a bilinear recovery model might be appropriate for fine-grained, cohesive subgrades. Although a wealth of FWD data were available for the MnROAD facility, all cells were constructed on either sandy subgrades or on fine-grained, cohesive subgrades (see soils data included in Appendix A).

The research team wondered whether an intermediate response might exist for roadways constructed on silt and/or silty sand subgrades. Since there were no silty subgrades at the MnROAD facility, the research team investigated this possibility using FWD data from some of the validation sites. Three sites were identified in New Hampshire and New York that consisted of roadways on silt and/or silty sand subgrades with free-draining base layers: Franklin in New York and Lake Tarleton and Stinson Lake in New Hampshire. Additional information regarding these sites is included in Appendix A.

The research team performed analyses to determine whether statistically significant trendlines could be developed for silty subgrades, similar to the bilinear curve shown in Figure 18 for clay subgrades. A scatterplot of percent recovery for the three silty sand subgrade sites is presented in Figure 20, which is followed by the regression equations for the bilinear fit to those data in Table 11.

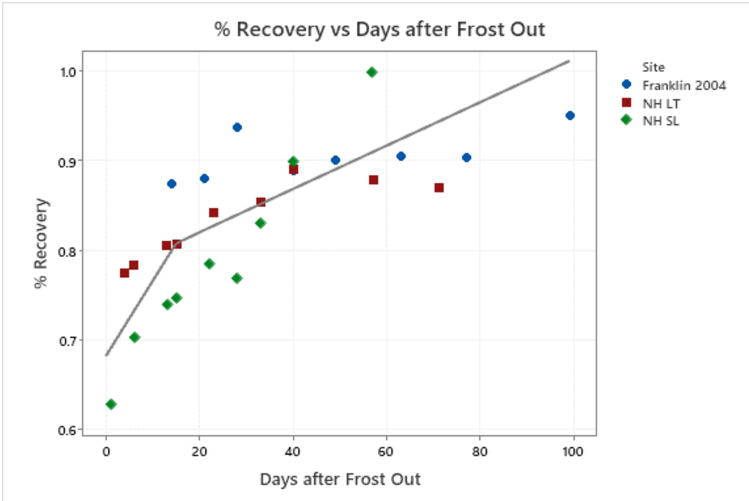


Figure 20. Scatterplot of percent recovery for three sites with silty sand subgrades

Table 11. Regression equations for three sites with silty sand subgrades

Regression Equation 0–15 Days After Frost Out	% Recovery_0-15	=	0.682 + 0.00837 * (days after frost out)
Regression Equation 16–60 Days After Frost Out	% Recovery_16-60	=	0.808 +0.002418 * (days after frost out – 15)

As before, the R^2 and standard error were interpreted like in a linear regression. The R^2 was 0.794, and the standard error was 0.00673 (~0.67%). The statistics for each regression are given in Appendix E.

Looking at Figure 20, clear differences exist for the three sites, but overall they show the quick recovery of the surface modulus in the first 15 days after frost out. The site with the lowest water table (Franklin, New York), showed the flattest recovery and started at the highest percentage. This was not surprising and indicated the rapid recovery (and lessening of the thaw weakening) when the GWT was deep.

Note that a separate regression on each site or use of the site as a categorical variable was also reviewed. The site was not significant in the regression results, so a single combined model was used for the final analysis.

Overall, the data from the three sites with silty sand subgrades, while having a low standard error, were not as robust. A close inspection on each of the coefficients was performed (see Appendix E). The probability of an error on the initial slope for the 0 to 15 days after frost out data was 6.3%, which is not a strong statistical correlation. The data were all combined partially due to this lower statistical confidence.

The research team compared the bilinear curve developed from the MnROAD Cell 28 data (clay subgrade) with the bilinear curve developed from the three silty sand subgrade sites and found very little difference between those curves, as shown in Figure 21.

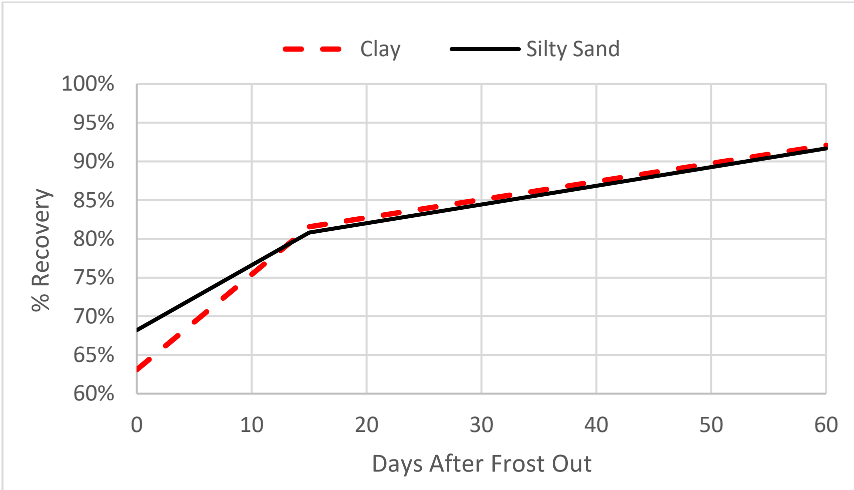


Figure 21. Percent recovery trends for clay versus silty sand subgrades

Based on that observation, as well as the fact that the statistical parameters were not as strong for the regressions performed on data from the silty sand sites, the team decided to use the bilinear model developed from Cell 28 for all roadways with subgrades containing more than 15% fines, as long as they were constructed with a free-draining base layer. However, for roadways with no free-draining base layer and/or for clay subgrades with a shallow GWT, worst-case conditions should be anticipated. Such conditions existed for MnROAD Cell 26 during the years from 1996 through 1999 for instance.

5.3.3 Percent Recovery: Full-Depth Cohesive Cross Section with Shallow GWT

The significant effect that a shallow GWT has on modulus values was discussed in previous chapters of this report. Using the daily average Ms-36 values from Cell 26 for the years 1996 through 1999 (see Figure 11) and a baseline value of 19.41 ksi for percent recovery calculations, the team developed a bilinear curve for worst-case conditions. The baseline value was obtained from FWD tests (N=667) conducted in Cell 26 during the month of October between 1996 and 1999 (when the GWT was shallow). A scatterplot of the data (with high residual data removed) is presented in Figure 22, which is followed by the regression equations for the bilinear fit to those data in Table 12.

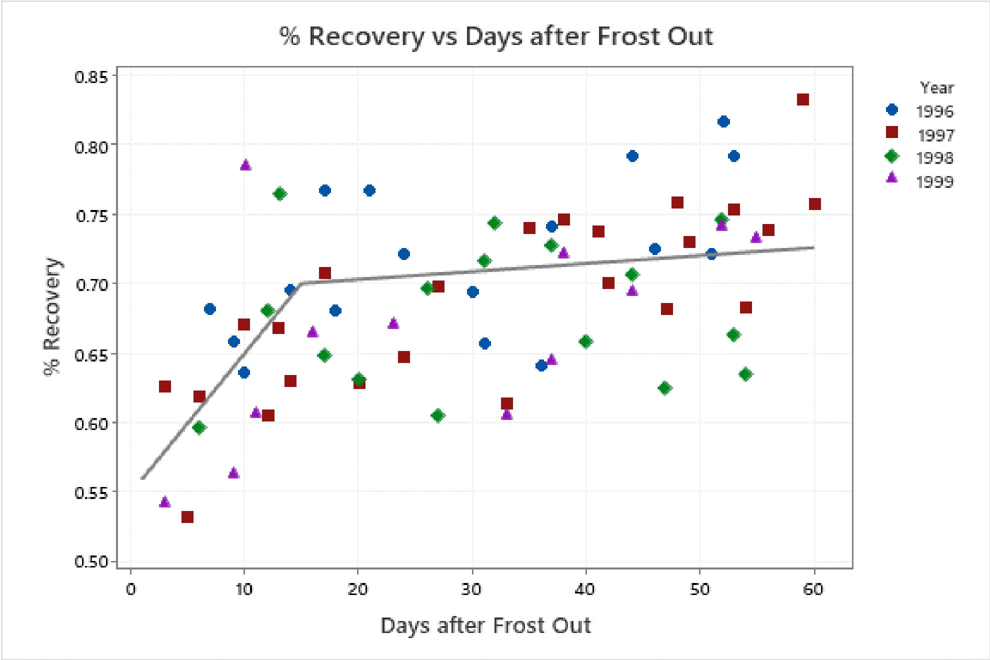


Figure 22. Scatterplot of percent recovery for MnROAD Cell 26 during the years from 1996–1999

Table 12. Regression equations for bilinear curve for MnROAD Cell 26 data (1996–1999)

Regression Equation 0–15 Days After Frost Out	% Recovery_0-15	=	0.5486 + 0.01008 * (days after frost out)
Regression Equation 16–60 Days After Frost Out	% Recovery_16-60	=	0.700+ 0.000575 * (days after frost out – 15)

The R^2 was 0.558, and the standard error was 0.00610. The equation was not as robust with more scattering, but the results showed the bilinear nature of the surface modulus recovery even in this worst-case scenario. Overall, the statistical analyses showed a rapid recovery after thawing is complete, with most of the recovery in the first 15 days after frost out (plus or minus).

A plot showing the bilinear model recommended for roadways constructed on subgrades with more than 15% fines and free-draining base layers is shown in Figure 23, along with the bilinear curve developed from the MnROAD Cell 26 data for worst-case conditions (fine-grained subgrades and no free-draining base layer, as well as a shallow GWT).

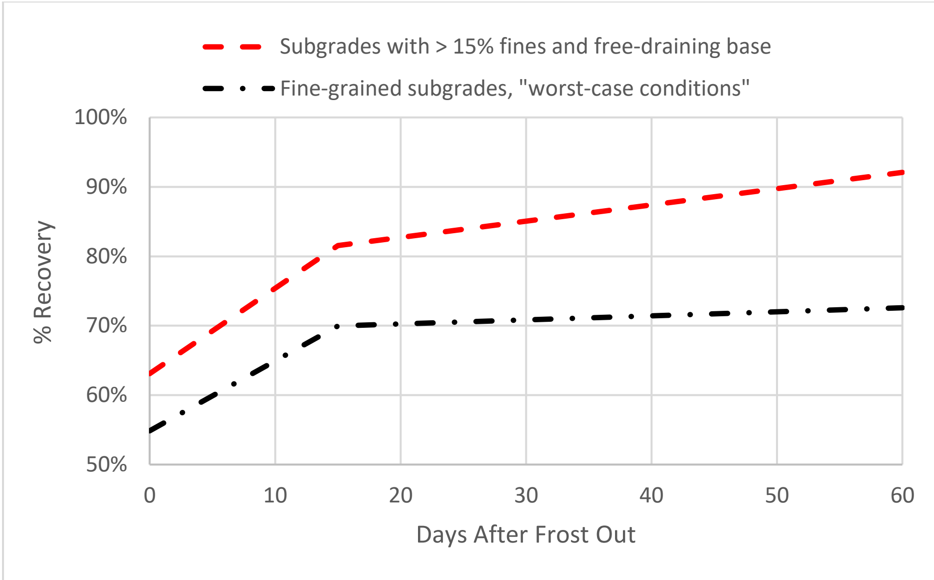


Figure 23. Recommended model for roadways constructed on subgrades with more than 15% fines and free-draining base layers and recommended model for worst-case conditions

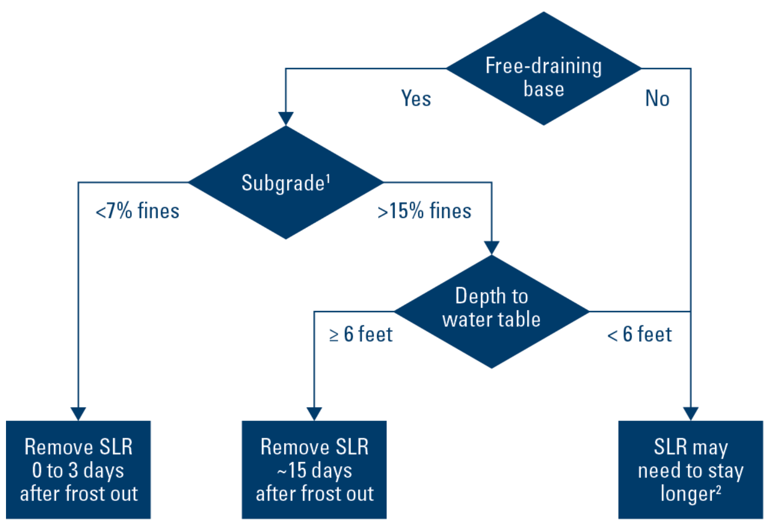
CHAPTER 6: RECOMMENDED SLR REMOVAL PROTOCOL AND BENEFITS OF APPROPRIATE SLR TIMING

The statistical analysis discussed in Chapter 5 suggests that, for roadways constructed with free-draining base layers on subgrades with more than 15% fines, the SLR could be removed at about 15 days after frost out as long as the GWT is deeper than 6 ft below the top of the pavement. These criteria were primarily based on analysis of data from MnROAD Cell 28, which had a Class 5 base layer. The specification for that Class 5 base material was 3% to 10% passing the #200 sieve, and the field sample contained 7.6% fines (passing the #200 sieve). Although material more than about 5% to 7% fines would not generally be considered ideal for a base layer, the MnDOT Class 5 base layer provides enough drainage to be considered free-draining (relative to the higher fines content subgrade).

For sections of roadway with shallower water tables and/or no free-draining base layer, worst-case conditions should be anticipated. For such conditions, it would be prudent to leave the SLR in place for a longer period of time and/or to reroute heavy traffic away from those sections of roadway.

Based on the data from MnROAD Cell 25 that were presented in Chapter 4, minimal (if any) recovery was observed beyond the frost out date for roadways constructed with very free-draining base and subgrade soils. Therefore, for such roadways the SLR could reasonably be removed when the frost has gone out or a few days afterward.

Validation of these recommendations is discussed in Chapter 8 of this report, and a decision tree for SLR removal is presented in Figure 24.



[1] Subgrades between 7% and 15% fines need to be reviewed on an individual basis
[2] Individual site needs to be reviewed for the timing of SLR removal

Figure 24. Decision tree for SLR removal

To illustrate the benefits of appropriate SLR posting, a sensitivity study was performed using the American Association of State Highway and Transportation Officials (AASHTO) 1993 design guidelines that the team members from Cornell had developed into an AASHTO93 design spreadsheet. For initial baseline assumptions, a 6 in. thick asphalt concrete (AC) layer and 6 in. good-quality base gravel layer were used, along with an 8-ton weight limit for SLR posting. The following observations were made:

- Subgrade type seems to have the most effect on both design life and extension of design life due to posting. Computed design life (with no SLR posting) for a clay, silt, or sand subgrade was approximately 10 years, 23 years, or 40 years, respectively. Applying the SLR during the thaw period only increased the design life by 35%, 40%, or 45% for the sand, silt, or clay subgrade, respectively. For fine-grained soils, keeping the SLR in place for an additional 15 days after frost out resulted in an additional increase in service life of 12% and 14% for the silt and clay subgrades, respectively.

- Focusing on clay subgrades only (as presumed at most of the North Dakota FWD test sites), the research team looked at the effects of thinner AC layers and/or poorer quality base materials. As expected, both of these factors decreased the predicted pavement life. The SLR posting for these less desirable conditions and/or materials became slightly more important.

- For a 6 in. poorer quality base layer that has more than 10% fines (poorer quality material, or part of old gravel base that has had fines pumped up into it over the years), posting during thaw only increased the service life by 48% (as opposed to 45% for the baseline assumptions). By keeping the SLR in place for an additional 15 days after frost out, an additional increase in service life of 15% was predicted (as opposed to 14% for the baseline assumptions).

- For a 6 in. good-quality base layer, but a 4 in. thick AC layer, posting during thaw only increased the service life by 49% (as opposed to 45% for the baseline assumptions). By keeping the SLR in place for an additional 15 days after frost out, an additional increase in service life of 16% was predicted (as opposed to 14% for the baseline assumptions).

The computations described above provide a rough idea of how appropriate SLR posting can increase the life of typical low-volume roadways. These findings are in keeping with the analysis conducted by Ovik et al. (2000). They concluded that the critical time for placing SLRs is when the pavement first thaws and the stiffness of the base layer is low.

Ovik et al. (2000) claim that, due to the rapid decrease in strength at the beginning of the thaw, “the damage caused by delaying the start of SLR is 1% of the annual damage per day of delay. Therefore, 10 days of delay each spring results in a 10% loss in the life of the roadway. This is an estimate for a well-maintained roadway in good condition. Roadways not meeting this criterion could be destroyed much faster.” They further suggested that, since conditions are far worse at the beginning of the spring thaw than at the end, it is far more effective to place restrictions early than to delay their removal.

Again, this recommendation is in keeping with the results of this study, which showed that (for roadways constructed with free-draining base or subbase layers on subgrades with more than 15% fines), most of the recovery has occurred by about 15 days after thawing is complete, with only minimal recovery occurring beyond that point.

CHAPTER 7: FWD DATA FROM VALIDATION SITES

7.1 Coarse-Grained, Free-Draining Base and Subgrade Soils

For validation of the protocol developed based on MnROAD Cell 25, the research team obtained validation data from a test site in New Hampshire on NH 112 (Kancamagus Highway site K-1), which also had a free-draining base and subgrade soils. Several miles of the Kancamagus Highway that had deteriorated due to frost action were rehabilitated during the 2005 construction season. As part of a research project funded through the Recycled Materials Research Center, three field test sections were established on the Kancamagus Highway in June 2005.

The test sections were located adjacent to one another and consisted of conventional reconstruction, full-depth reclamation (FDR) with cement stabilization, and FDR without cement stabilization. Those three test sections were designated as K-1, K-2, and K-3, respectively. Extensive instrumentation was installed for long-term monitoring of groundwater and temperature regimes. Details regarding that research project are discussed in Miller et al. (2007, 2010, 2011).

In the fall of 2006, these three test sections were folded into a larger research project sponsored by NHDOT and the United States Department of Agriculture (USDA) Forest Service. For that project, FWD testing was conducted at the three Kancamagus Highway test sections (as well as at several other roadway sites in New Hampshire) to investigate variations in pavement stiffness that result from seasonal changes in temperature and moisture content. Details regarding that research project are discussed in Eaton et al. (2009). The general structure of Kancamagus Highway site K-1 is shown in Figure 25.

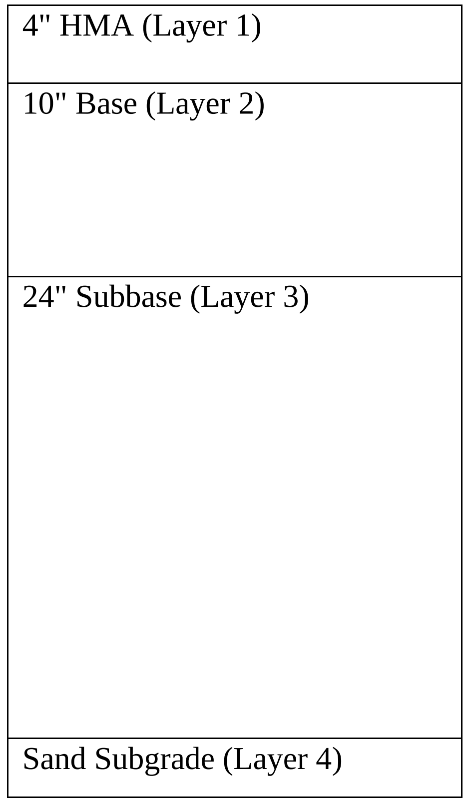


Figure 25. Structure of Kancamagus Highway K-1 site

Reconstruction of this site consisted of excavating about 3 ft of existing asphalt, base, and subgrade soil and then replacing that material with virgin aggregate from a local borrow pit as follows: 14 in. of sand followed by 10 in. of gravel (total 24 in. of subbase) and then 10 in. of crushed gravel base. The test section was paved with hot-mix asphalt (HMA) consisting of a 2 in. binder layer placed in late July 2005 and a 2 in. wearing course placed in October 2005. Results from grain size analysis on samples obtained from the Kancamagus Highway K-1 site are included in Appendix A.

Modulus values of the various pavement layers were backcalculated from FWD data to evaluate variations in pavement stiffness. The roadway cross section was typically divided into five layers of varying thicknesses. The boundaries of the upper four material layers assumed for backcalculations (for the unfrozen state) are shown in Figure 25. Layer 5, not shown in Figure 25, was assumed to be a stiff layer. The top of Layer 5 generally coincided with the water table, which varied to some extent, so the thickness of Layer 4 also varied.

When frost was present, the frozen ground was modeled as one or more discrete layers, and the depth to the top and/or bottom of the second, third, and fourth layers was altered slightly to better accommodate the frozen layer. Additional details regarding modeling and backcalculations are described in Miller et al. (2011). Modulus values obtained from backcalculations at the Kancamagus Highway K-1 site are shown in Figure 26.

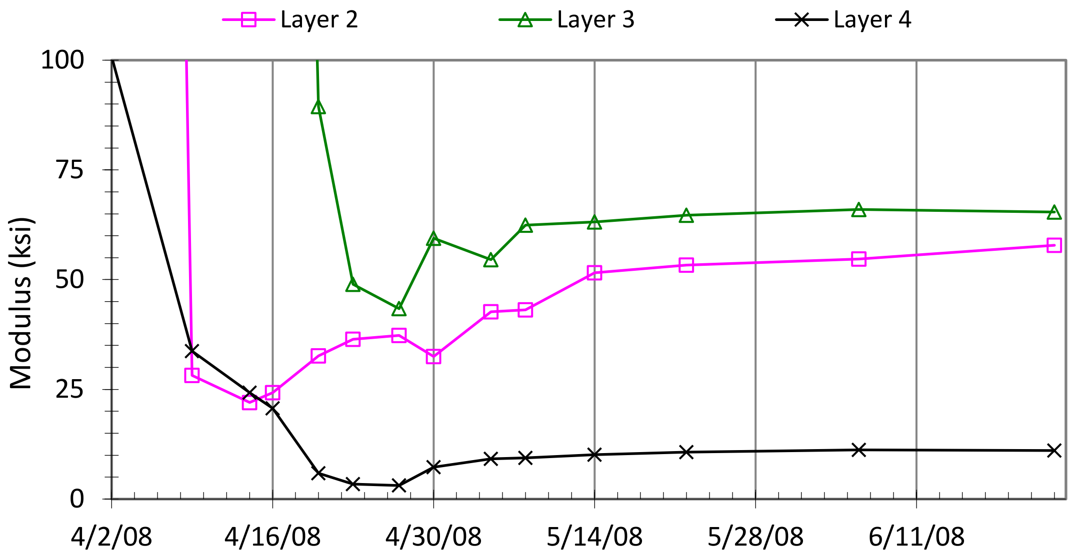


Figure 26. Backcalculated modulus values at Kancamagus Highway site

Layers 2, 3, and 4 all remained frozen during FWD testing on March 24, 2008, and backcalculated modulus values for those layers were quite high. The thaw front initially surpassed the first subsurface temperature sensor (located at 13 in. below the top of pavement) on April 8, 2008. On that date, the interpolated thaw depth was right at the bottom of Layer 2 (14 in. deep). The April 9, 2008, FWD test indicated that the modulus value for Layer 2 was dramatically reduced, as shown in Figure 26. This was likely because the underlying layer was still frozen, hindering excess moisture dissipation from Layer 2. The base (Layer 2) modulus values reached a minimum on April 14, 2008, and gradually increased as thaw progressed through the underlying layers, allowing for more moisture drainage.

Between March 24 and April 9, 2008, Layer 3 (subbase, or upper subgrade) was still completely frozen, and modulus values in that layer remained quite high. Some minor bottom-up thawing had occurred in the deeper subgrade during that period (frost depth receded from about 73 to 71 in.), and some modest decrease in the subgrade (Layer 4) modulus was observed.

Thaw progressed from the top of the subbase/upper subgrade (Layer 3) downward beginning on April 9, 2008, and Layer 3 was completely thawed on April 18, 2008. At that time, frost still existed in the subgrade between depths of about 43 and 69 in. The modulus value in the subbase/upper subgrade (Layer 3) reached a minimum on the April 27, 2008, FWD test date, when frost tubes indicated that the subgrade was still frozen between depths of about 52 and 62 in.

The frost out date was May 7, 2008, for this site/season. However, minimum modulus values were observed before the frost out date in all four layers, and a significant amount of recovery had already occurred in all layers by the frost out date. Given that surface modulus computations were used to analyze the enormous data set available from the MnROAD facility (in lieu of more complicated and time-consuming backcalculations), a comparison between surface modulus and backcalculated modulus values for Layers 3 and 4 is shown in Figure 27.

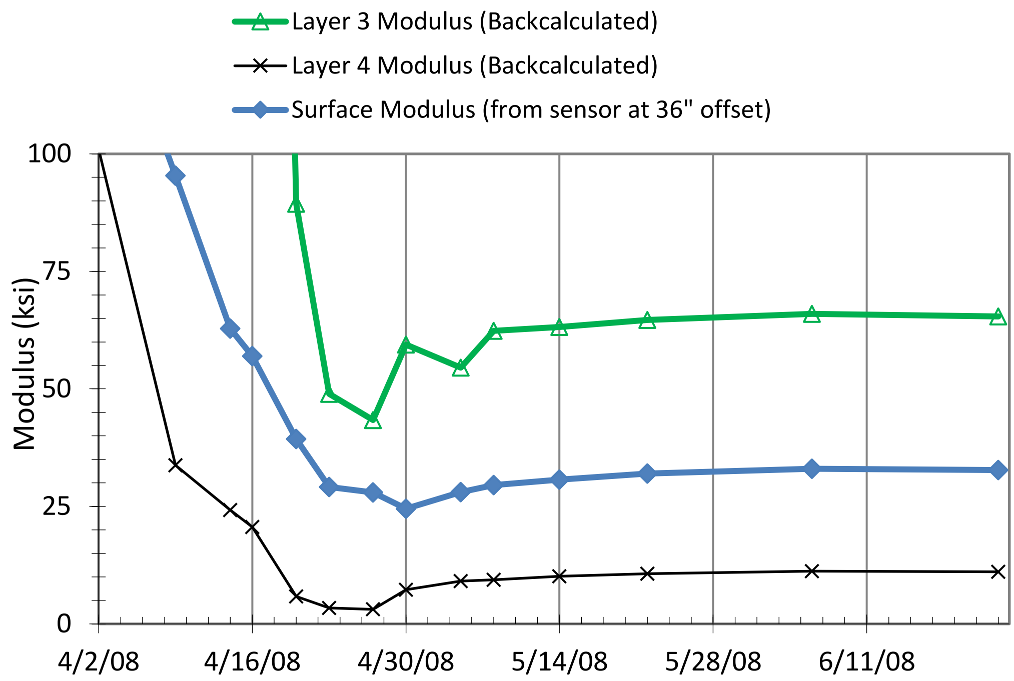


Figure 27. Comparison of backcalculated modulus values with surface modulus values at Kancamagus Highway site

As noted in Section 4.1 of this report, surface modulus values computed from FWD data reflect a composite of all the layers within the stress zone; as such, the sensors located farther away from the load plate are more strongly influenced by the layers deeper below the asphalt surface. A geophone located 36 in. away from the center of the load plate is assumed to be representative of the subgrade modulus of the combined layers at a depth of 24 in. or more. Given the soil profile at this site (shown in Figure 25), it makes sense that the surface modulus values computed from the sensor located at a 36 in. offset fall between the backcalculated modulus curves for Layers 3 and 4.

The following conclusions were made based on the analysis of data from the Kancamagus Highway K-1 site in New Hampshire:

- Placing the SLR as soon as thaw starts penetrating the roadway base layer(s) is important, especially during the critical period when underlying frozen layers exist and prevent drainage of excess moisture from the base layer(s).

- For roadways with very free-draining base, subbase, and subgrade soils, the critical thaw-weakened period occurs just before frost out, but recovery happens as soon as the soil profile thaws. After the entire soil profile thawed, only minimal additional modulus increases were observed, and they occurred gradually. Therefore, the SLR should remain in place at least until frost is out but could likely be removed a few days afterward without causing any significant damage.

7.2 Subgrades with More Than 15% Fines

To validate the model developed for roadways constructed with engineered base layers on subgrades with more than 15% fines, FWD data were initially analyzed from three sites with silty sand subgrades (Lake Tarleton, New Hampshire; Stinson Lake, New Hampshire; and Franklin, New York) and from two sites with clay subgrades (Madison, Maine, and Jefferson County, New York). The percent recovery was computed as described in Section 5.3.3 of this report and was plotted against the number of days after frost out (see Figure 28 and Figure 29). The roadway cross sections and available soil and groundwater information for these sites is included in Appendix A.

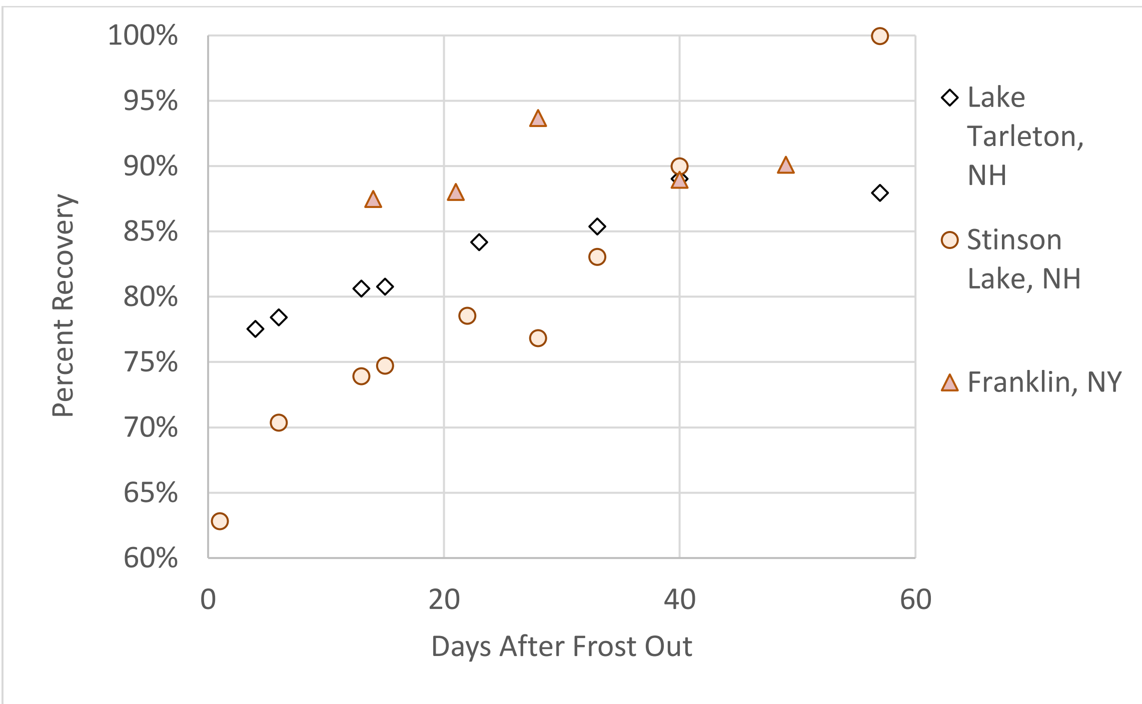


Figure 28. Validation data from three silty sand subgrade sites

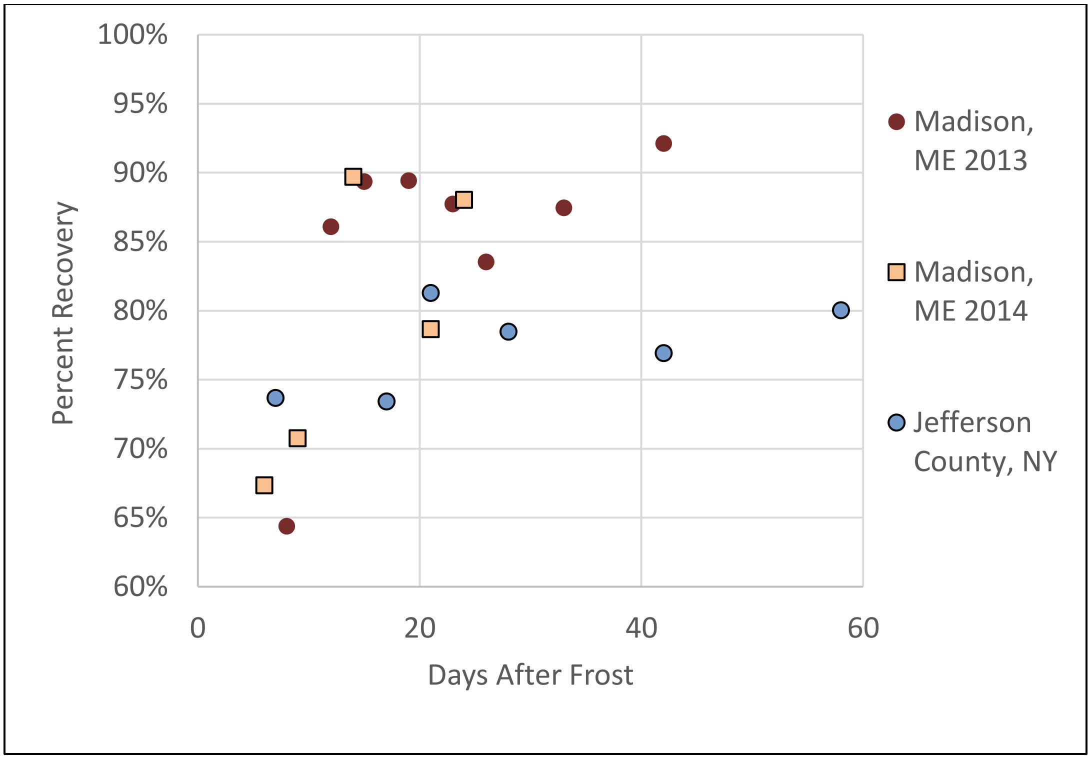


Figure 29. Validation data from two clay subgrade sites

Additionally, FWD data from three sites in North Dakota were provided by NDDOT personnel. The sites were designated as Highway 85 (US 85 in Bowman), Highway 6 (ND 6 near Mandan, slightly southwest of Bismarck), and Highway 8 (ND 8 east of Dickinson). The roadway cross sections and available soils and groundwater information for these sites is included in Appendix A.

Abundant soils data were provided from the Highway (US) 85 Bowman site, some soils information was provided for Highway (ND) 6, and no soils information was available for the Highway (ND) 8 site. The Highway (US) 85 Bowman and Highway (ND) 6 sites have clay subgrades, and, based on experience in the region, NDDOT personnel expect that the subgrade at the Highway (ND) 8 site is also most likely a clay.

To determine frost out dates, subsurface temperatures for Highway (US) 85 were obtained from the TDPs installed at the Bowman, North Dakota, RWIS station. The Highway (ND) 6 and Highway (ND) 8 FWD test sites did not have RWIS stations. Based on discussions with Travis Lutman (NDDOT), the suggestion was to obtain subsurface temperatures for the Highway (ND) 6 and 8 sites from the TDPs installed at the New Salem, North Dakota, RWIS station (see Figure 1). Ms-36 values computed from FWD tests conducted during 2020, 2021, 2022, and 2023 at the three North Dakota validation sites are shown in Figure 30, Figure 31, and Figure 32.

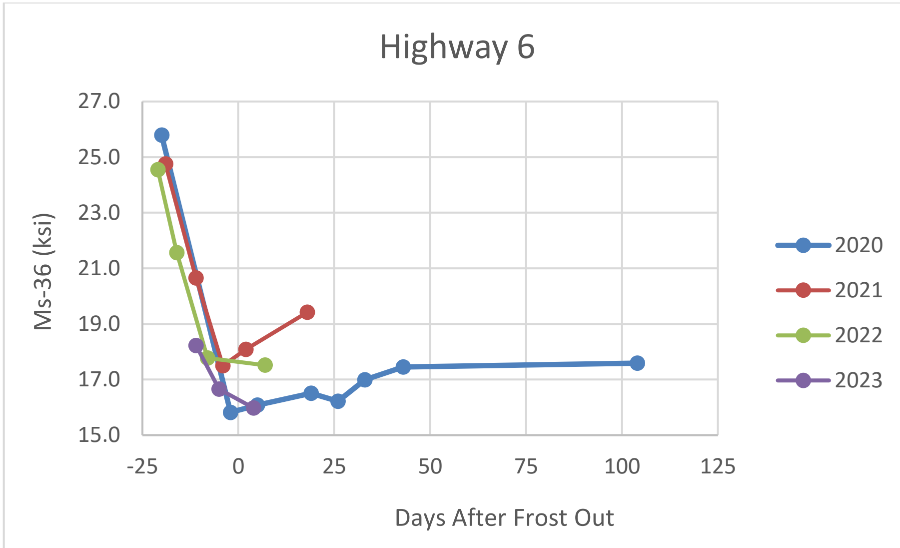


Figure 30. Plot of Ms-36 versus days after frost out at Highway (ND) 6

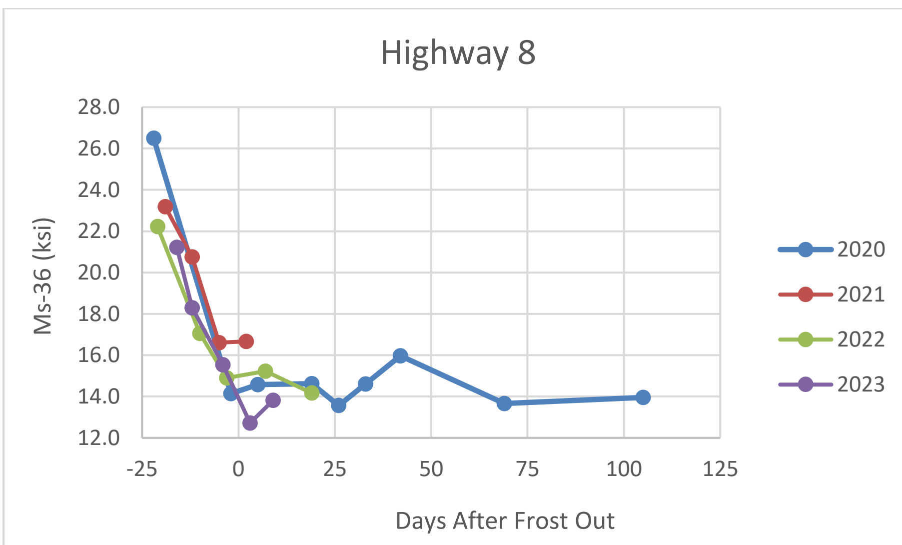


Figure 31. Plot of Ms-36 versus days after frost out at Highway (ND) 8

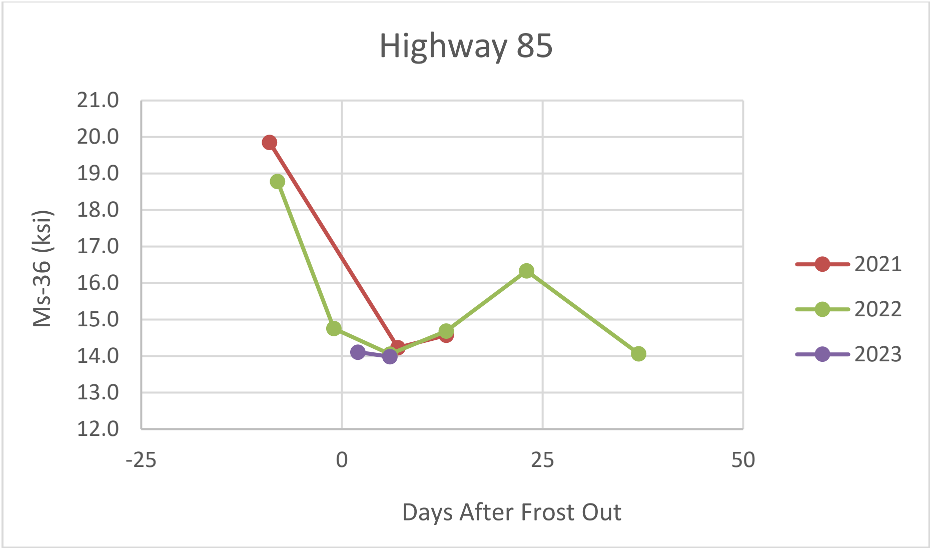


Figure 32. Plot of Ms-36 versus days after frost out at Highway (US) 85

Several observations were noted from these three figures. First, the trends in Ms-36 values during the few weeks before frost out were remarkably consistent at the Highway (ND) 6 and the Highway (ND) 8 sites and were similar to the trends used to build the SLR models described in Chapter 5 of this report.

In all years except for 2023, minimum Ms-36 values were generally observed within a few days before frost out. In 2023, testing was more limited, but minimum Ms-36 values appeared to occur a few days after frost out. This is something the researchers also observed at the other testing sites. At Highway (US) 85, testing was also more limited, and minimum Ms-36 values appeared to occur almost a week after frost out. Overall, these trends were all reasonable considering the trends observed at the MnROAD test cells and at other validation sites.

The research team also noted various data points that may have been affected by very high asphalt surface temperatures. For example, at Highway (US) 85, the 2022 data showed the expected thaw weakening and recovery behavior, except for the last data point on day 37 (May 5, 2022). On that date, the average asphalt surface temperature was 89°F. That relatively hot temperature likely caused that asphalt layer to soften, increasing measured deflections and thus decreasing computed Ms-36 values.

Baseline tests were conducted at the North Dakota sites in the fall of 2019. An Ms-36 value of 14 ksi was computed from the baseline FWD data obtained at the Highway (US) 85 site (on September 4, 2019). Clearly, that baseline value was unreasonably low, and it was also likely affected by the very hot asphalt surface temperature that day (about 100°F).

The research team also observed that the 2021 Ms-36 values at both Highway (ND) 6 and Highway (ND) 8 appeared unusually high compared to other years. The research team wondered whether differences in moisture may have caused that anomaly. Unfortunately, information about the depth to the GWT was not available for either of those sites. The precipitation data shown in Figure 33, however, may help to explain some of the North Dakota FWD data trends at Highway (ND) 6 and Highway (ND) 8.

Ms-36 values were relatively low in 2020, likely due to a lot of rain during the preceding (2019) summer and fall (May to October). There was probably a lot of excess moisture in the soil during late fall 2019, which froze during winter and thawed during spring 2020, softening the subgrade during that SLR season. Conversely, there was a relative lack of rain during the summer and fall of 2020. With less moisture from precipitation available to freeze during late fall 2020 and winter 2021, there would be less excess moisture during the spring 2021 thaw period. That would cause the subgrade to be stiffer and computed Ms-36 values to be higher during the 2021 SLR season.

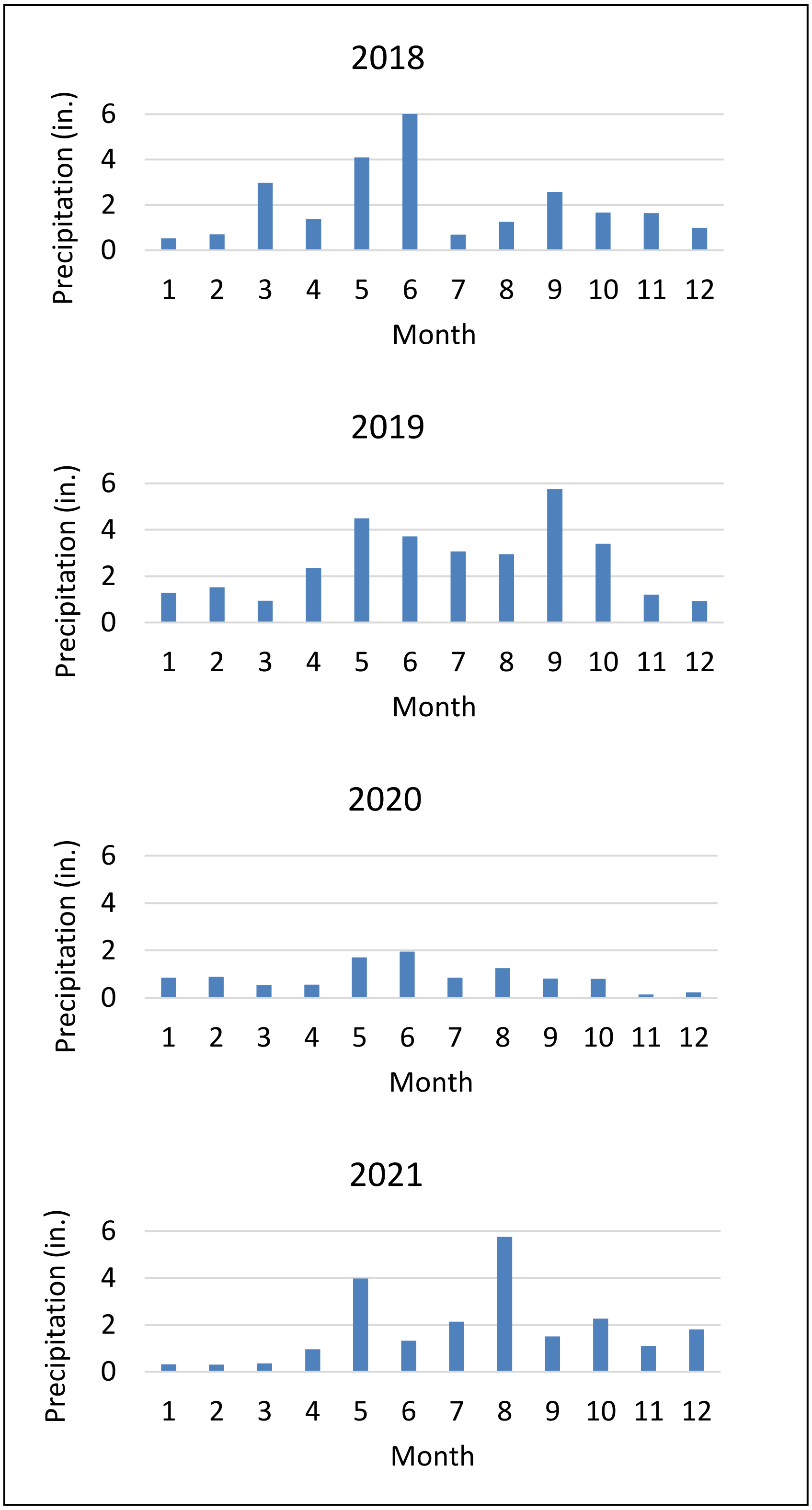


Figure 33. Mean monthly precipitation at New Salem, North Dakota, 2018–2021

CHAPTER 8: VALIDATION OF RECOMMENDED SLR REMOVAL PROTOCOL

8.1 Roadways Constructed with Very Free-Draining Base, Subbase, and Subgrade Soils

Data from MnROAD Cell 25 were used to develop the protocol for this scenario. Cell 25 was a full-depth granular cross section beneath 5.9 in. of asphalt pavement. It had a relatively shallow GWT, which ranged from about 2 to 4 ft below the top of the pavement during the study period.

Time series plots of surface modulus values (Ms-36) during 1994 and 1997 in Cell 25 were presented in Figure 13. The 1994 data suggested that modulus values decreased during the thawing process and reached a minimum right around the day that thaw ended (frost out), with some modest increase in stiffness following the frost out date (day zero). However, for all other years, modulus values reached a minimum around the frost out date (similar to 1994), but no significant recovery was observed beyond the frost out date.

The research team followed up by examining validation data from a test site in New Hampshire (the Kancamagus Highway K-1 site), which also had free-draining base and subgrade soils. A description of that site, the data collected, and an analysis is included in Section 7.1 of this report. Data from that site indicated that modulus values in thawed layers reached minimum values prior to the frost out date, when frozen underlying layer(s) were present, hindering excess moisture dissipation from the thawed layer(s). Stiffness recovery began near the end of the thawing period because the thaw front penetrated fairly deep, allowing for some drainage of the upper subgrade and base. After thawing was complete, additional recovery was only modest and occurred very rapidly. As such, the research team concluded that the SLR should remain in place at least until frost out but that restrictions could reasonably be removed a few days afterward.

8.2 Roadways Constructed with Free-Draining Base Layers on Subgrades with More than 15% Fines

Validation data for this scenario were obtained and analyzed from the following:

- One year of data from the Lake Tarleton (LT) and Stinson Lake (SL) sites in New Hampshire (silty sand subgrades)
- One year of data from the Franklin site in New York (silty sand subgrade)
- One year of data from the Jefferson County site in New York (clay subgrade)
- Two years of data from a site in Madison, Maine (clay subgrade)
- Between one and four years of data from three sites in North Dakota (presumed clay subgrades)

8.2.1 Validation Process

To validate the recommended model/protocol, the researchers used a technique from statistical quality control. The concept of this method is to compare the new (validation) data versus the bilinear model. Rather than using a straight statistical approach, the new data are compared to the bilinear model and error bands are built around that model.

Figure 18 shows the final model as developed for percent recovery with the regression equations for the model listed in Table 10. The overall error and R^2 (coefficient of determination) were generated from the bilinear regression line and the actual data. For Cell 28, the $R^2 = 0.476$ and the standard error = 0.0789.

The standard error can be used to build error bands around the model's bilinear regression line. Figure 34 shows the final model with plus and minus 3 standard error lines on each side (labeled + for plus, - for minus, and s for standard error).

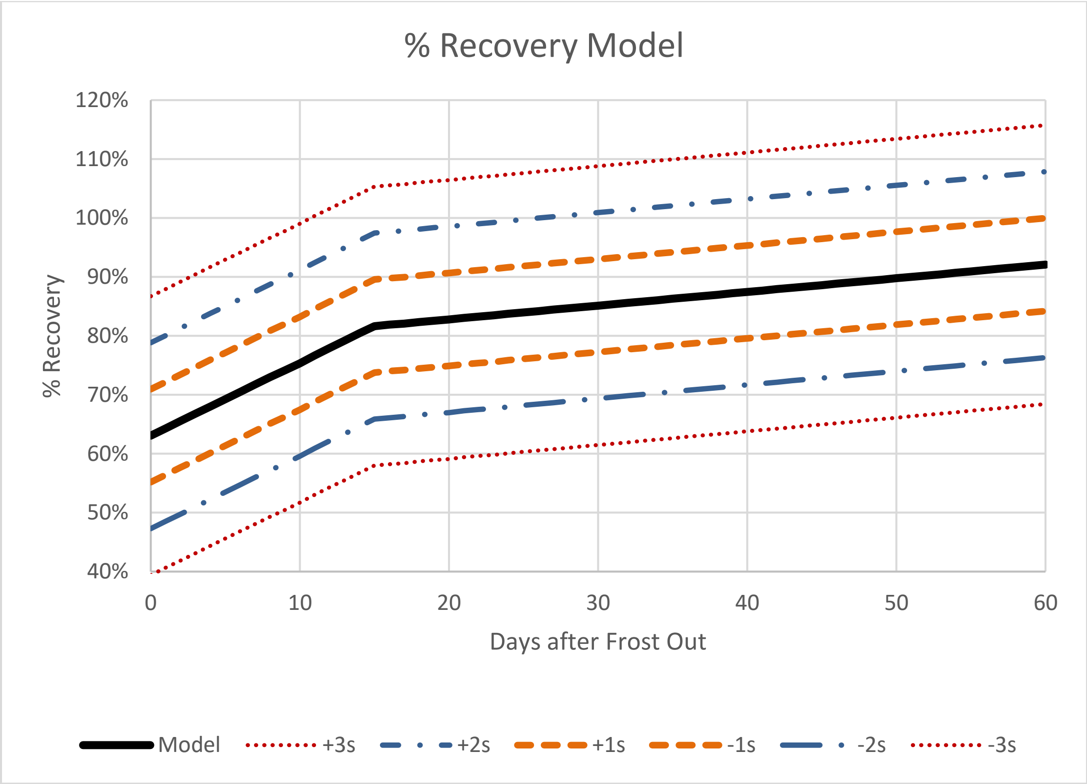


Figure 34. Final model with ±3 standard error bands with no data

Figure 35 shows the data used to build the model, with the error bars shown.

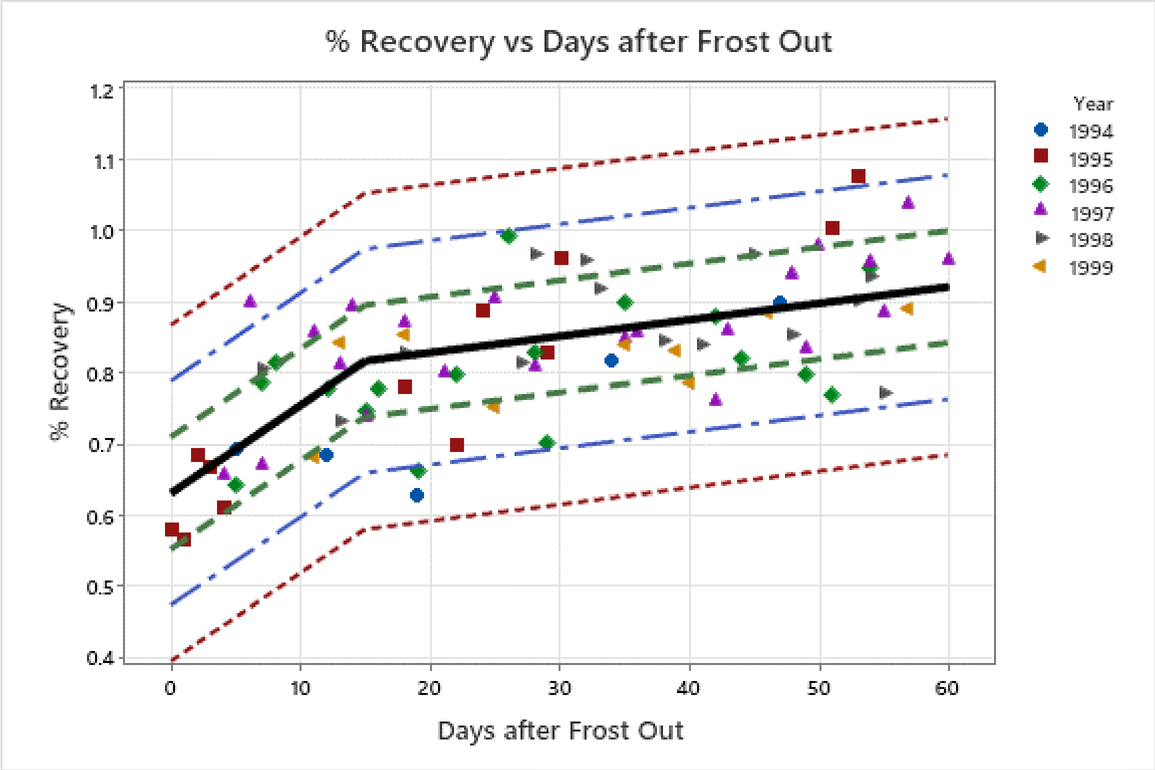
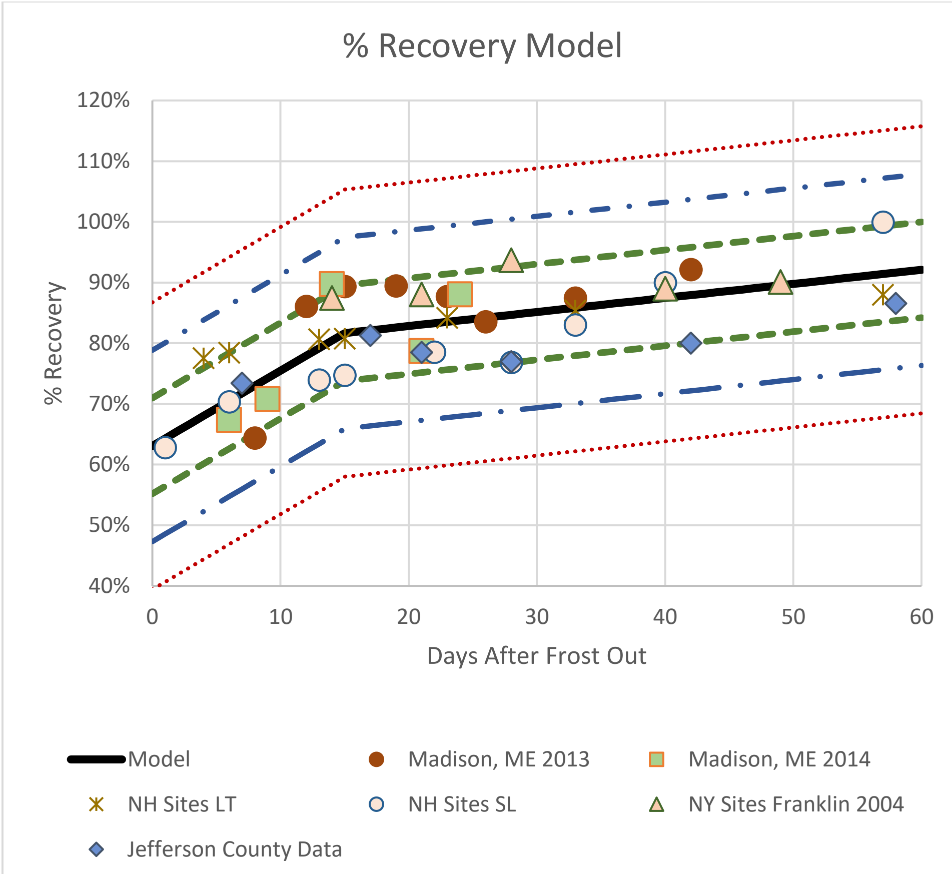


Figure 35. Final model with ±3 standard error bands showing data used to build model

To perform a validation test, new data were plotted on the final model with ±3 standard error bands. Then, the data were reviewed to see if they met basic quality control tests. The tests for out of control are as follows according to the National Council of Examiners for Engineering and Surveying (NCEES 2022):

- A single point falls outside the three standard error control limits.
- Two out of three successive points fall on the same side of and more than two standard errors from the model line.
- Four out of five successive points fall on the same side of and more than one standard deviation from the model line.
- Eight successive points fall above or below the model line.

Six data sets from Maine, New Hampshire, and New York were initially used to check the validity of the SLR model. Figure 36 shows all six plotted on the SLR model, including the error bands.



LT = Lake Tarleton, SL = Stinson Lake

Figure 36. Validation data from northeast sites (Maine, New Hampshire, and New York) plotted versus model, with error bands shown

To illustrate how this was done, a small data set from Lyme, Jefferson County, New York (Jefferson County Data), is shown in Figure 37.

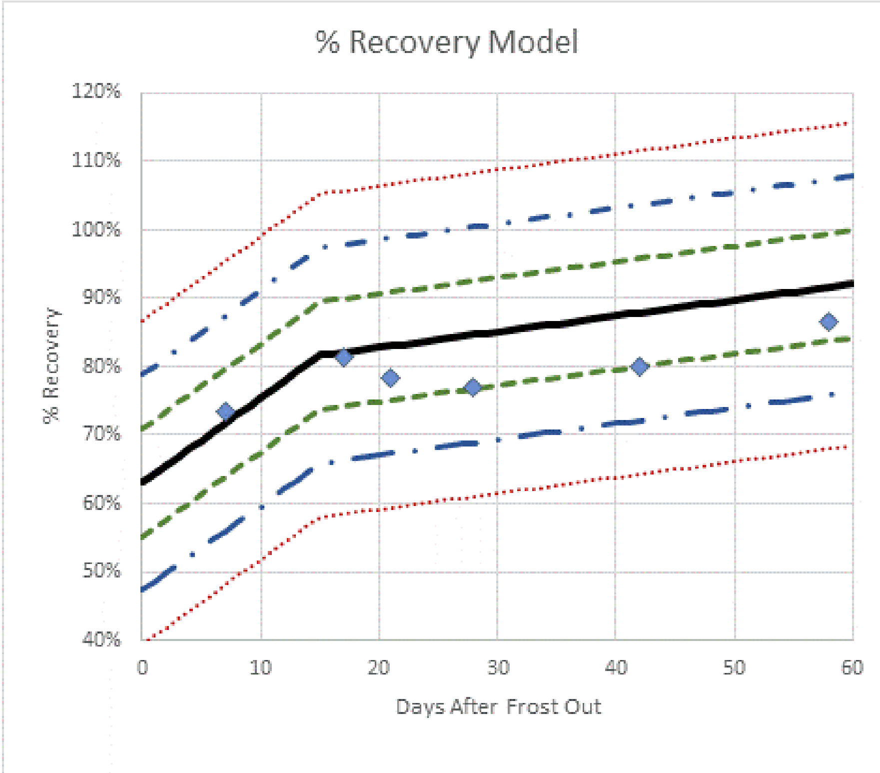


Figure 37. Final model with ±3 standard error bands with Lyme, Jefferson County, New York, data

For each of the first three control tests, the results showed that the model was valid. The fourth control test could not be checked since there were only six data points. This was the case at many of the validation sites because there were often fewer than eight data points. Table 13 shows the results of the control review.

Table 13. Control test summary for Jefferson County, New York, data

Control Test	Jefferson County, New York	Result
A single point falls outside ±3s	Pass	No points outside ±3s
Two of three successive points fall on the same side of and > 2s from the model	Pass	No points outside ±2s
Four of five successive points fall on the same side of and > 1s from the model	Pass	4 of 5 < model, but all within 1s from model
Eight successive points fall above or below the model line	NA	Only 5 data points

The individual plots and control test analyses for the other five validation data sets from sites in the northeast (Maine, New Hampshire, and New York) and for two validation data sets from North Dakota are shown in Figures 38 through 44 and Tables 14 through 20.

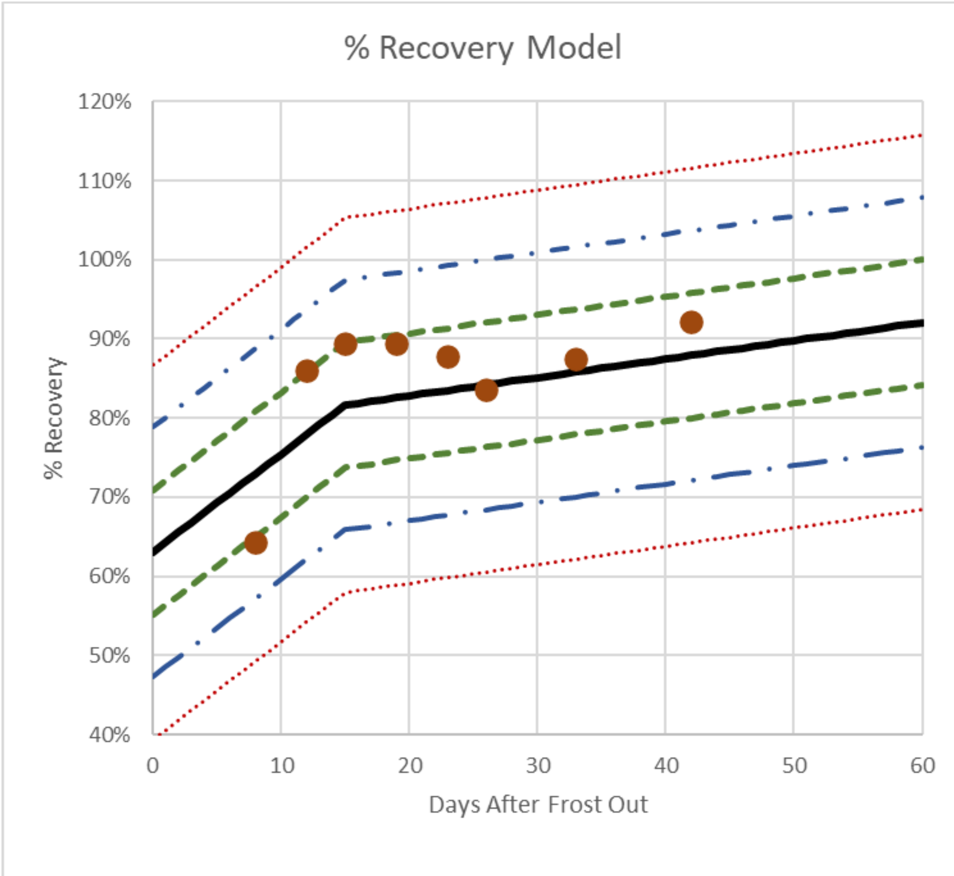


Figure 38. Final model with ±3 standard error bands with 2013 Madison, Maine, data

Table 14. Control test summary for 2013 Madison, Maine, data

Control Test	2013 Madison, Maine	Result
A single point falls outside ±3s	Pass	No points outside ±3s
Two of three successive points fall on the same side of and > 2s from the model	Pass	No points outside ±2s
Four of five successive points fall on the same side of and > 1s from the model	Pass	4 of 5 > model, but only 2 fall outside +1s from the model
Eight successive points fall above or below the model line	Pass	2 points below model line from the 9 overall points

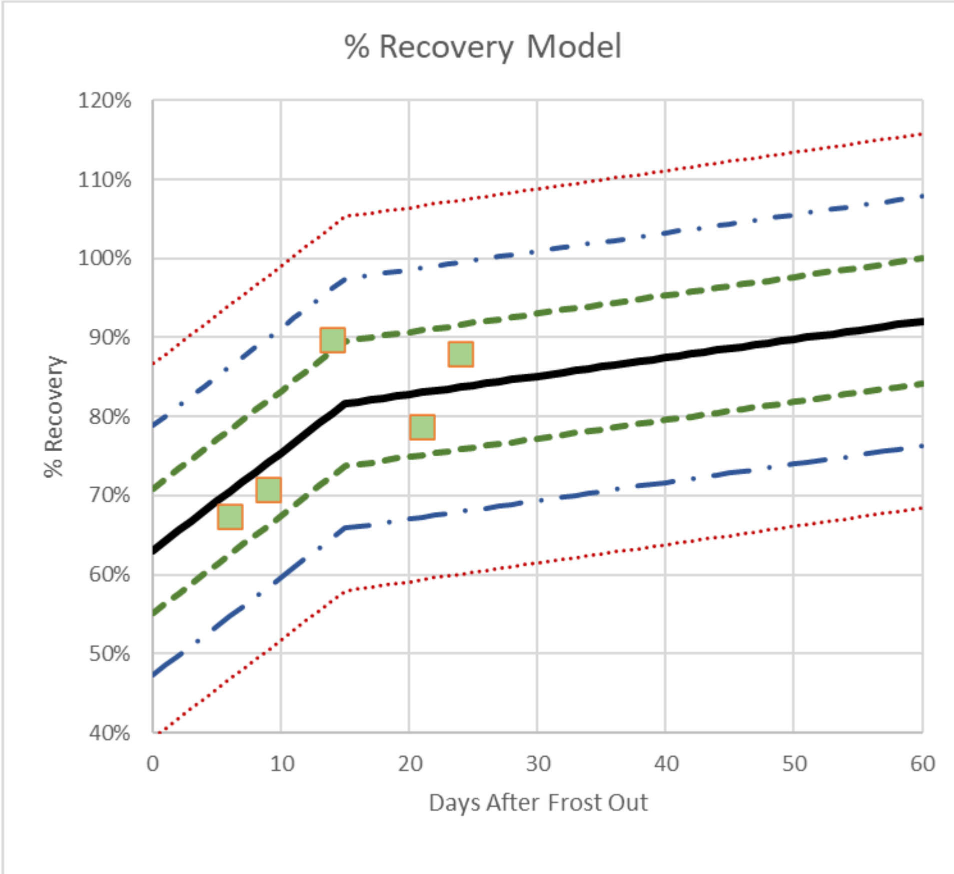


Figure 39. Final model with ±3 standard error bands with 2014 Madison, Maine, data

Table 15. Control test summary for 2014 Madison, Maine, data

Control Test	2014 Madison, Maine	Result
A single point falls outside ±3s	Pass	No points outside ±3s
Two of three successive points fall on the same side of and > 2s from the model	Pass	No points outside ±2s
Four of five successive points fall on the same side of and > 1s from the model	Pass	At no time do 4 of 5 points fall to one side of the model
Eight successive points fall above or below the model line	NA	Only 5 data points

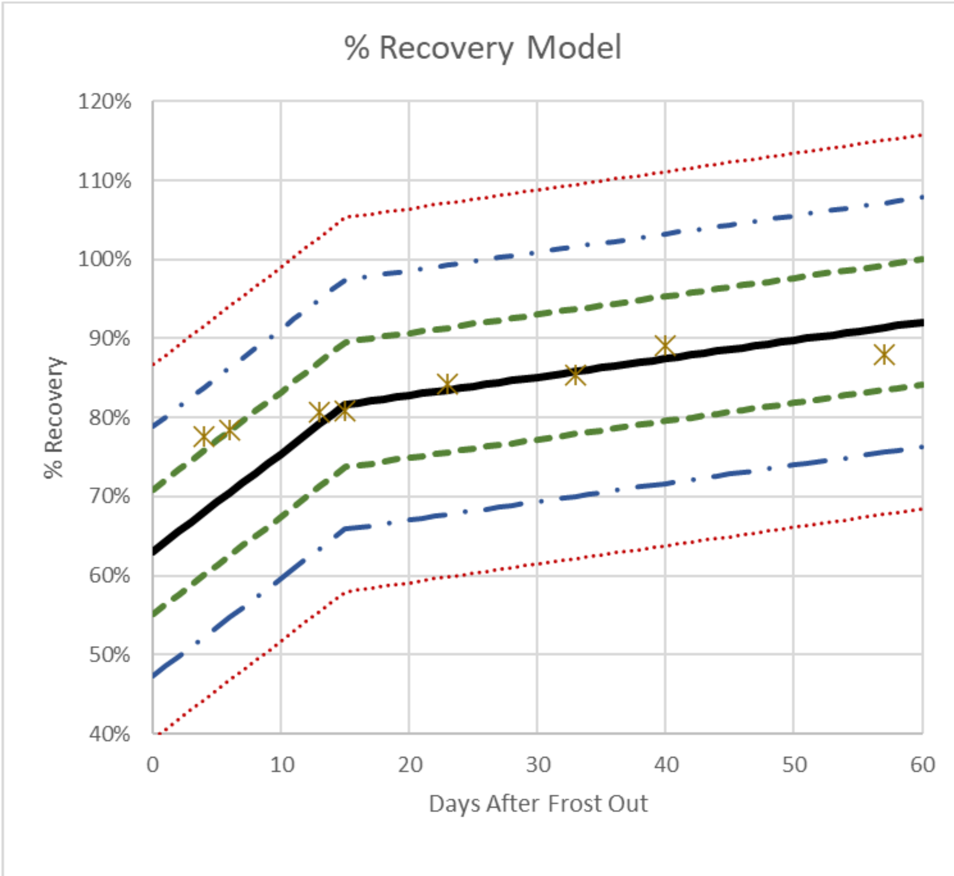


Figure 40. Final model with ±3 standard error bands with Lake Tarleton, New Hampshire, data

Table 16. Control test summary for Lake Tarleton, New Hampshire, data

Control Test	Lake Tarleton, New Hampshire	Result
A single point falls outside ±3s	Pass	No points outside ±3s
Two of three successive points fall on the same side of and > 2s from the model	Pass	No points outside ±2s
Four of five successive points fall on the same side of and > 1s from the model	Pass	At most, 3 of 5 points fall to one side of the model and only 1 point is outside the +1s line
Eight successive points fall above or below the model line	Pass	At most, 3 of 5 points fall to one side of the model

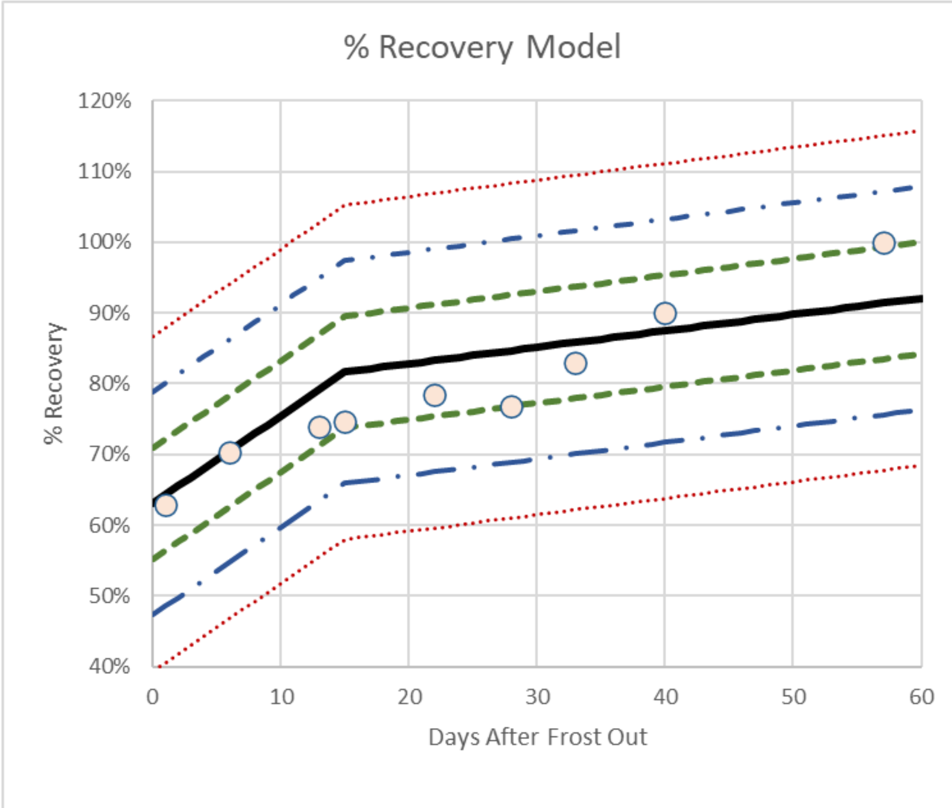


Figure 41. Final model with ±3 standard error bands with Stinson Lake, New Hampshire, data

Table 17. Control test summary for Stinson Lake, New Hampshire, data

Control Test	Stinson Lake, New Hampshire	Result
A single point falls outside ±3s	Pass	No points outside ±3s
Two of three successive points fall on the same side of and > 2s from the model	Pass	No points outside ±2s
Four of five successive points fall on the same side of and > 1s from the model	Pass	Even including the point on the line at day 6, only one of the series of 7 points falls >1s from the model
Eight successive points fall above or below the model line	Pass	Even including the point on the line at day 6*, only 7 points fall to one side of the model line

*The point on day 6 is technically below the line at 70.3% recovery, while the model is at 70.5% on day 6.

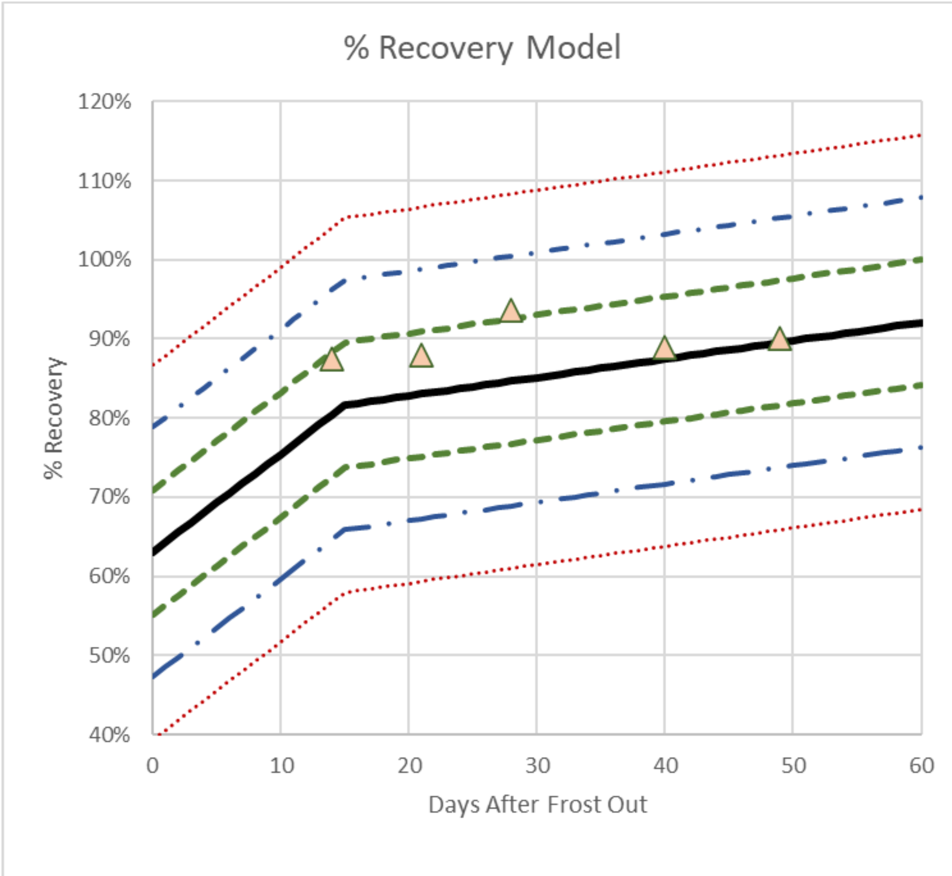


Figure 42. Final model with ±3 standard error bands with 2004 Franklin, New York, data

Table 18. Control test summary for 2004 Franklin, New York, data

Control Test	2004 Franklin, New York	Result
A single point falls outside ±3s	Pass	No points outside ±3s
Two of three successive points fall on the same side of and > 2s from the model	Pass	No points outside ±2s
Four of five successive points fall on the same side of and > 1s from the model	Pass	4 of 5 points are above the model line, but only 1 falls more than 1s from the model
Eight successive points fall above or below the model line	NA	Only 5 data points

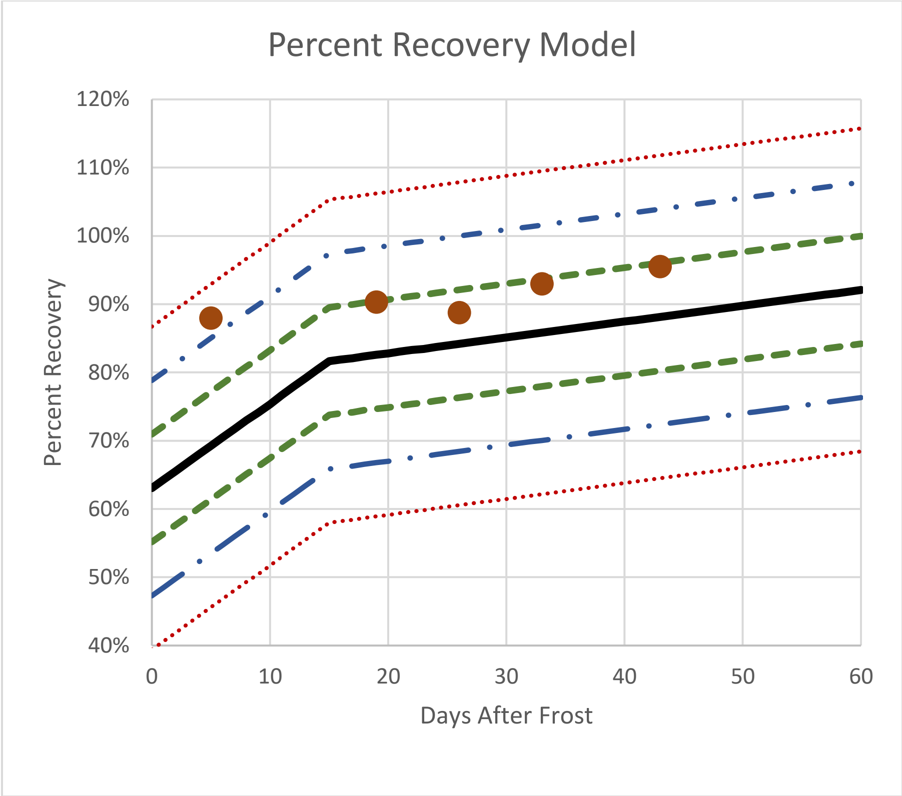


Figure 43. Final model with ±3 standard error bands with 2020 North Dakota Highway 6 data

Table 19. Control test summary for 2020 North Dakota Highway 6 data

Control Test	2020 ND 6 Data	Result
A single point falls outside ±3s	Pass	No points outside ±3s
Two of three successive points fall on the same side of and > 2s from the model	Pass	Only 1 point outside ±2s
Four of five successive points fall on the same side of and > 1s from the model	Pass	All 5 points on the positive side of the model, but only 1 over 1s from model
Eight successive points fall above or below the model line	NA	Only 5 data points

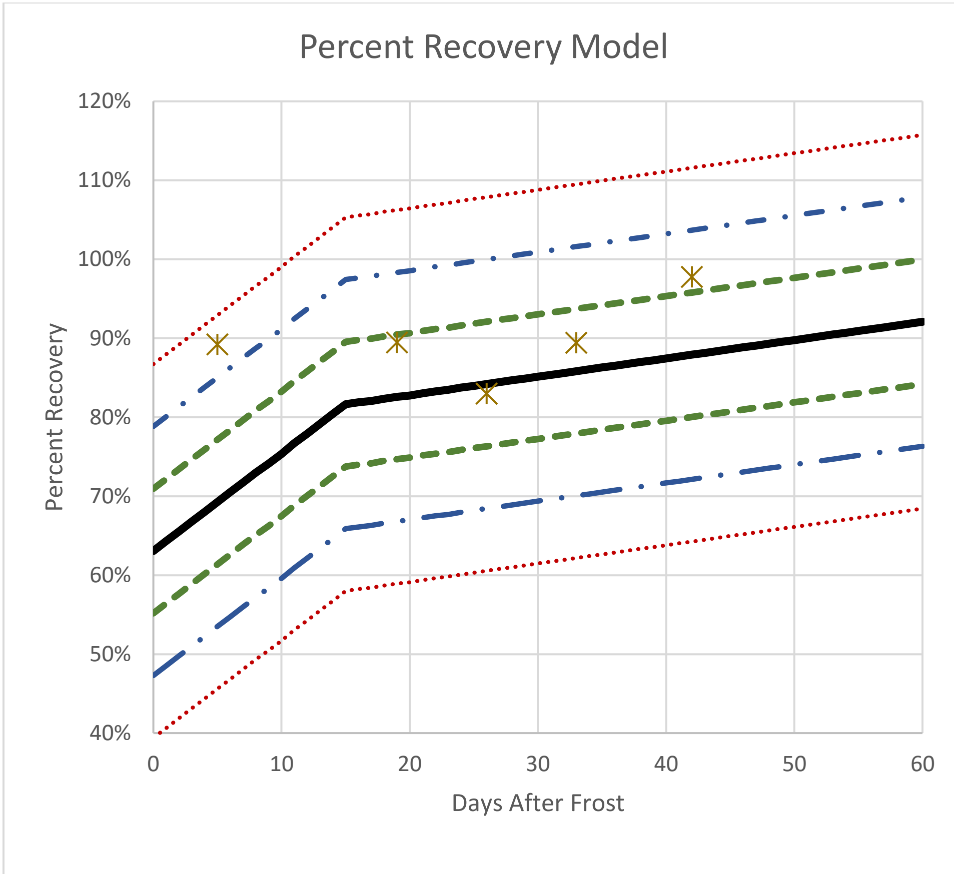


Figure 44. Final model with ±3 standard error bands with 2020 North Dakota Highway 8 data

Table 20. Control test summary for 2020 North Dakota Highway 8 data

Control Test	2020 ND 8 Data	Result
A single point falls outside ±3s	Pass	No points outside ±3s
Two of three successive points fall on the same side of and > 2s from the model	Pass	Only 1 point outside ±2s
Four of five successive points fall on the same side of and > 1s from the model	Pass	4 of 5 > model, but only 2 fall outside +1s from the model
Eight successive points fall above or below the model line	NA	Only 5 data points

These results show the model does a good job of estimating the recovery at various sites. Almost all of the validation data points fell within +/- 1 standard error, and most of the data points that fell outside of the 1 standard error bar were extremely close to that limit.

Note that only two validation data sets from North Dakota are presented in this section of the report. For Highway (ND) 6 and Highway (ND) 8, only the 2020 data sets had a sufficient number of data points after the frost out dates. All other years had fewer than three data points that fell after the frost out dates, so three of the four control test checks could not be performed.

As discussed in Section 7.2 of this report, the baseline Ms-36 value at the Bowman, North Dakota, site was deemed to be unreasonably low and was likely affected by the hot asphalt surface temperature (about 100°F) on the September 4, 2019, test date. As such, that baseline could not be used to compute reliable percent recovery values and the control test checks could not be performed on the data from that site.

CHAPTER 9: EVALUATION OF OTHER POTENTIAL TOOLS TO ASSIST IN SLR REMOVAL DECISIONS

9.1 Evaluation of the FrezTrax Model

In a previous Aurora project (Miller et al. 2020), FROST Associates was asked to evaluate the FrezTrax model as a possible tool for SLR timing decisions. Although no documentation regarding the FrezTrax model and software interface could be found in a search of peer-reviewed literature, NDDOT provided FROST Associates with an excerpt from an in-house report describing that tool/protocol.

The freezing and thawing index calculations included in the FrezTrax model were originally developed by Mahoney et al. (1986), and a description of those calculations are included in Section 3.2 of this report. The FrezTrax model appears to modify and further build on the work by Mahoney et al. (1986) by considering moisture effects.

Climatological fall precipitation amounts (August 1 through November 30) were correlated to the pre-established climatological moisture zones and used (along with seasonal AFI values) in defining the critical CTI benchmark values recommended for SLR application and removal. Additional details are provided in Miller et al. (2020).

According to the FrezTrax protocol, the SLR should be removed when the cumulative thaw index, or CTI (computed according to Mahoney et al. 1986), reaches a critical value expressed as a percentage of the maximum seasonal AFI established for the immediate past winter. The critical percentages are shown in Table 21.

Table 21. FrezTrax SLR removal criteria

August–November Precipitation (in.)	SLR Removal CTI (% of Seasonal AFI)
4.75	25
6.25	30
7.00	35
7.75	40

The FrezTrax protocol specifies that values of less than 25% or more than 40% of seasonal AFI are not permitted. Once the CTI at a given location reaches its critical percentage of the maximum seasonal AFI, restrictions can be removed.

The FrezTrax model was run to determine SLR removal dates for each year between 1994 and 1999 at the MnROAD LVR site, and then a time window was computed for each of those years as the number of days between the frost out date and the FrezTrax SLR removal date. Although the FrezTrax model yields the same SLR removal date in any given year regardless of pavement structure or subgrade type, the results of this study suggest that significant differences exist in recovery times for coarse-grained versus fine-grained subgrades. Therefore, data from MnROAD Cell 25 (coarse-grained subgrade) are presented in Table 22, and data from MnROAD Cell 28 (fine-grained subgrade) are presented in Table 23.

Table 22. FrezTrax time window for SLR removal based on frost out dates at Cell 25

Winter-Spring Season	Fall Precipitation (in.)	Seasonal AFI (°F-days)	FrezTrax SLR Removal Date	Cell 25 Frost Out Date	Time Window* (days)
1993–94	10.9	2599	21-May	16-Apr	35
1994–95	15.9	1878	13-May	26-Mar	48
1995–96	12.3	2968	5-Jun	19-Apr	47
1996–97	11.1	2754	30-May	9-Apr	51
1997–98	8.4	1181	22-Apr	20-Mar	33
1998–99	7.1	1332	21-Apr	21-Mar	31

* Number of days between frost out date and FrezTrax SLR removal date

Table 23. FrezTrax time window for SLR removal based on frost out dates at Cell 28

Winter-Spring Season	Fall Precipitation (in.)	Seasonal AFI (°F-days)	FrezTrax SLR Removal Date	Cell 28 Frost Out Date	Time Window* (days)
1993–94	10.9	2599	21-May	9-Apr	42
1994–95	15.9	1878	13-May	27-Mar	47
1995–96	12.3	2968	5-Jun	18-Apr	48
1996–97	11.1	2754	30-May	4-Apr	56
1997–98	8.4	1181	22-Apr	21-Mar	32
1998–99	7.1	1332	21-Apr	19-Mar	33

* Number of days between frost out date and FrezTrax SLR removal date

The time window between the frost out date in Cell 25 and the FrezTrax SLR removal date (Table 22) ranged from 31 to 51 days, with an average value of 41 days. Clearly, for roadways constructed with very free-draining base, subbase, and subgrade soils, the FrezTrax model is far too conservative given that data suggest that SLRs could reasonably be removed a few days after frost out for those roadways.

Based on frost out dates observed in Cell 28 (Table 23), the time window between the frost out date and the FrezTrax SLR removal date ranged from 32 to 56 days, with an average value of 43 days. Those time windows are clearly more conservative than the 15 day +/- window suggested by the surface modulus trends observed in Cell 28, as discussed in the previous chapter of this report.

Considering that the SLR should be applied at the beginning of the thawing process rather than at the end of thawing (i.e., the frost out date), the duration of the SLR using the FrezTrax model to determine SLR removal dates would be excessive.

In a previous Aurora project (Miller et al. 2020), the research team recommended that SLR application dates be selected according to the MnDOT protocol (MnDOT 2009, 2014). SLR application dates according to that protocol are shown in Table 24 for the six study years. Also included in the table are SLR removal dates and durations according to the FrezTrax model and the SLR removal dates and durations according to SLR removal at 15 days after frost out, as recommended in this study.

Table 24. Comparison of SLR duration for fine-grained subgrades: FrezTrax model versus removal at 15 days after frost out (as recommended in this study)

Winter-Spring Season	SLR Application Date (MnDOT Protocol)	SLR Removal Date (FrezTrax Model)	SLR Duration: FrezTrax Removal Date (days)	SLR Removal Date (Frost Out + 15 Days)	SLR Duration: Recommended in This Study (days)
1993–94	5-Mar	21-May	77	24-Apr	50
1994–95	12-Mar	13-May	62	11-Apr	30
1995–96	13-Mar	5-Jun	84	3-May	51
1996–97	21-Mar	30-May	70	19-Apr	29
1997–98	18-Feb	22-Apr	63	5-Apr	46
1998–99	28-Feb	21-Apr	52	3-Apr	34

For the FrezTrax model, the total SLR duration ranged from 52 to 84 days, with an average duration of 68 days. Using the criterion of SLR removal at 15 days after frost out, the SLR duration ranged from 30 to 51 days, with an average of 40 days.

In a previous Aurora project by Miller et al. (2020), analyses suggested that, in general, the FrezTrax model was somewhat nonconservative with regard to SLR application given that the CTI threshold dates for application of the SLR tended to fall too late (i.e., after thawing had already progressed past the 12 in. deep subsurface temperature sensor). On the other hand, analyses conducted during this current Aurora project suggest that the FrezTrax model is overly conservative with regard to SLR removal. In other words, the FrezTrax model would suggest placing SLRs too late and leaving SLRs in place longer than necessary. Both of these scenarios are in opposition to prior research conducted by others, as well as to the trends suggested by the analyses conducted during this current Aurora project.

In a previous MnDOT project report, Ovik et al. (2000) concluded that the critical time for placing SLRs is when the pavement first thaws and the stiffness of the base layer is low. They claimed that "due to the rapid decrease in strength at the beginning of the thaw, each day of delay in implementing restrictions is equivalent to 28 additional days of reduced loads at the end of the restricted period." They further suggested that since conditions are far worse at the beginning of the spring thaw than at the end, it is far more effective to place restrictions early than to delay their removal.

With regard to SLR removal, this team's current analysis of data from MnROAD Cell 28 suggests that for cohesive subgrades with free-draining base layers, significant modulus recovery occurs on the initial (steep) portion of a bilinear recovery curve. But beyond the inflection point on that bilinear recovery curve (about 15 days), the extra delay in removing the SLR does not result in significant increases in surface modulus values. With these considerations in mind, the research team does not believe that the FrezTrax model is an effective tool for use in making SLR timing decisions.

9.2 Evaluation of Moisture Sensors

Some researchers have correlated moisture content with FWD measurements and suggested that monitoring excess moisture content dissipation may serve as a good indicator of when the soil recovers stiffness after the spring thaw-weakened period, and thus when the SLR might safely be removed. Given that NDDOT officials indicated an interest in possibly installing moisture sensors at some of the state's RWIS sites, the research team assembled data from sites where moisture sensors were installed and where FWD testing was conducted during and after the spring thaw periods. This section outlines trends that were observed at the site in Madison, Maine, and Cell 28 at the MnROAD research facility.

A sample set of data from the moisture sensor located 9 in. below the top of the clay subgrade at the Madison, Maine, site is shown in Figure 45.

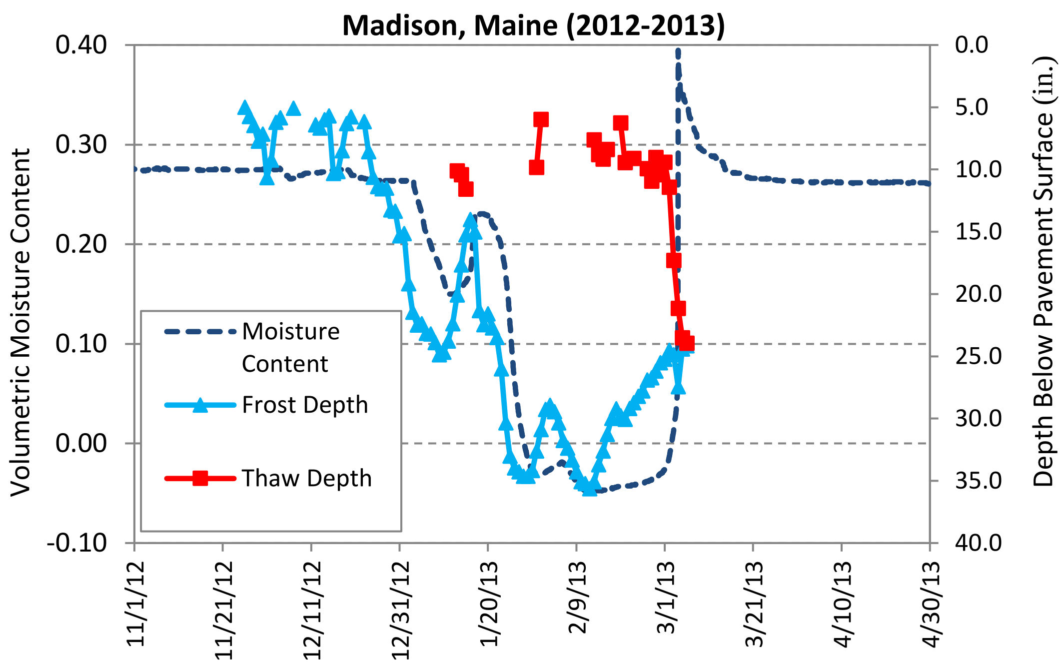


Figure 45. Frost and thaw depths and volumetric moisture content at Madison, Maine (2012–2013)

Most moisture sensors (including the ones used at the Madison site) estimate moisture content based on dielectric constant. When the water in the soil void spaces freezes (becomes solid), the dielectric constant (and thus the reported value of moisture content) drops very low, as can be seen on the plot. When the soil thaws and the water again becomes liquid, the moisture content dramatically increases (due to the excess moisture that was drawn up, forming ice lenses as the soil froze). Then, as the excess moisture drains out over time, the moisture content decreases and eventually stabilizes.

Figure 46 presents frost-thaw depths (including secondary freezing) and surface modulus (Ms-36) values at the Madison, Maine, site during winter–spring 2013, and Figure 47 presents the moisture content during that same season.

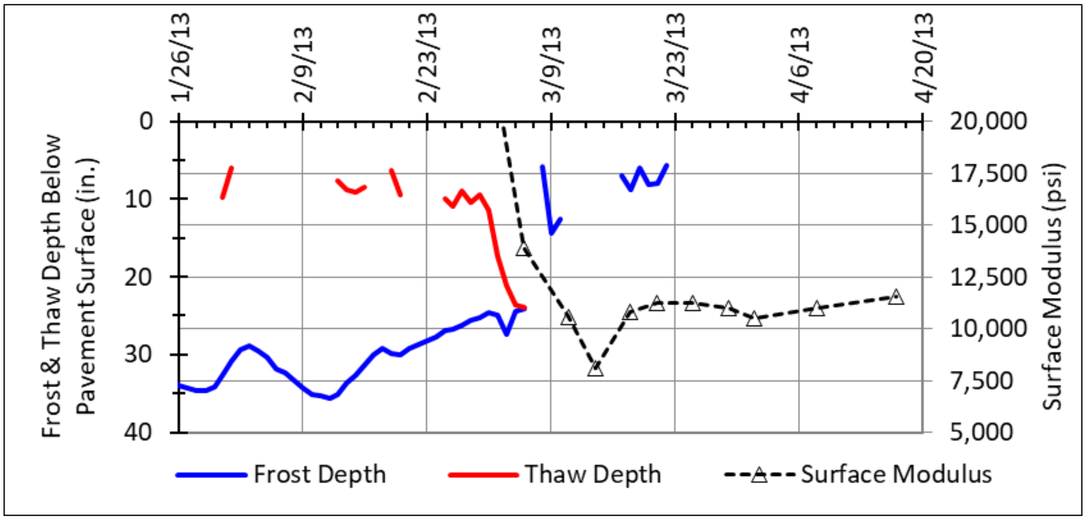


Figure 46. Frost and thaw depths (including secondary freezing) and surface modulus values at Madison, Maine (2013)

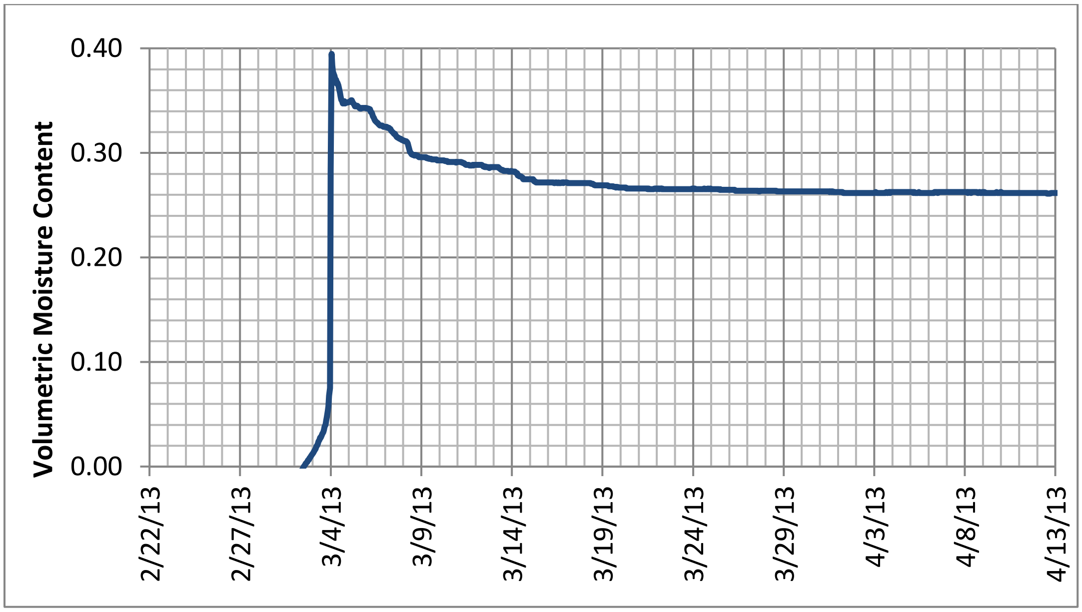


Figure 47. Volumetric moisture content at Madison, Maine (2013)

Figure 48 presents frost-thaw depths and surface modulus (Ms-36) values at the Madison, Maine, site during winter–spring 2014, and Figure 49 presents the moisture content during that same season.

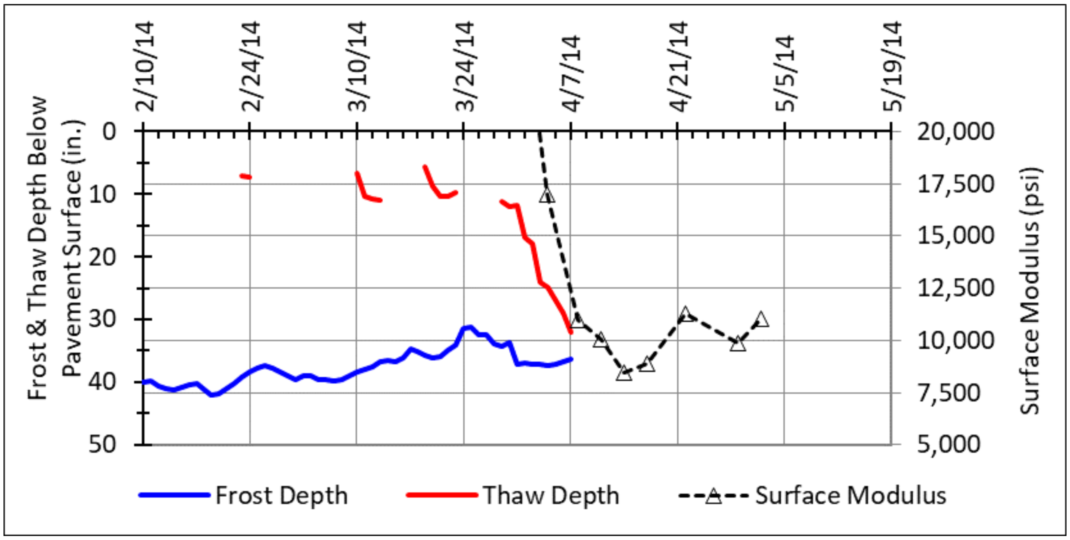


Figure 48. Frost and thaw depths and surface modulus values at Madison, Maine (2014)

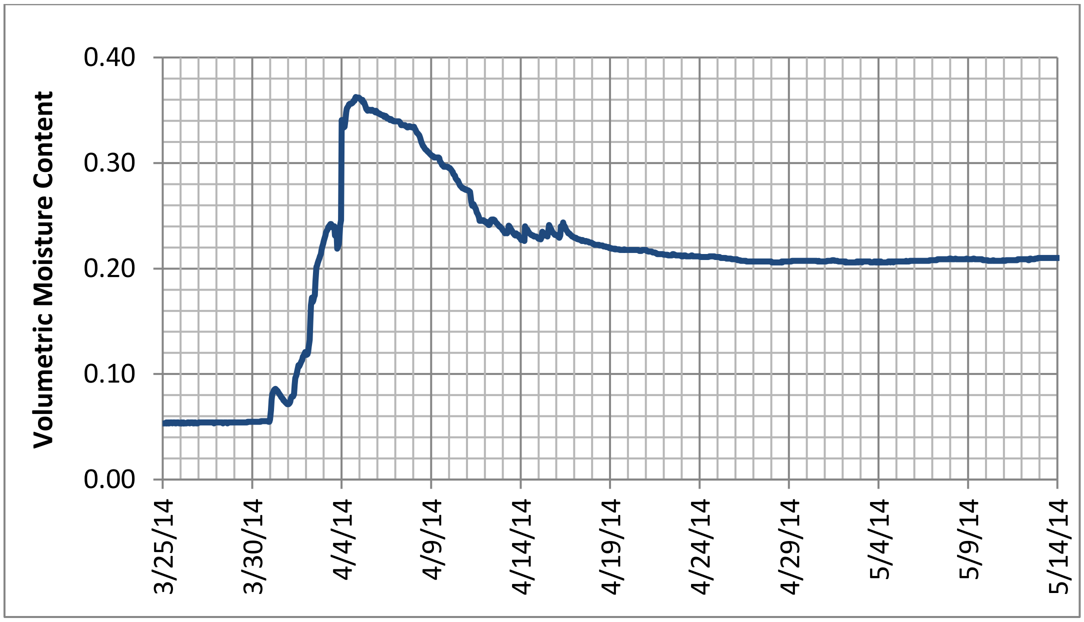


Figure 49. Volumetric moisture content at Madison, Maine (2014)

The following observations were noted from the 2013 plots:

- End of thaw was on March 6, 2013.

- Surface modulus values continued to decrease from March 6 through March 14 (when the minimum value was reached) and then increased significantly between March 14 and 21, when they began to level out. However, modulus values were still not back to the baseline value (12,556 psi, measured in fall 2012) and continued to show very gradual increases beyond March 21.

- Moisture content spiked on March 4 and then dissipated rapidly from about 0.40 to 0.30 between March 4 and March 9. Moisture then dissipated much more slowly and leveled out around March 21 to a value of about 0.27.

The following observations were noted from the 2014 plots:

- End of thaw was on April 8, 2014.

- Surface modulus values decreased from April 1 (first test date) through April 14. Fairly significant recovery occurred between April 14 and April 22, and then modulus values began to level out (albeit with a bit of scatter). Modulus values still did not reach the baseline value (12,556 psi), but May 2 was the last test date that season.

- Moisture content spiked to 0.36 on April 4 and then dissipated rapidly to 0.24 by April 12. Moisture then dissipated much more slowly and began to level out around April 24 at a moisture content of about 0.21.

Figure 50 presents surface modulus (Ms-36) values at MnROAD Cell 28 during spring 2007, and Figure 51 presents the moisture content data obtained during that same season.

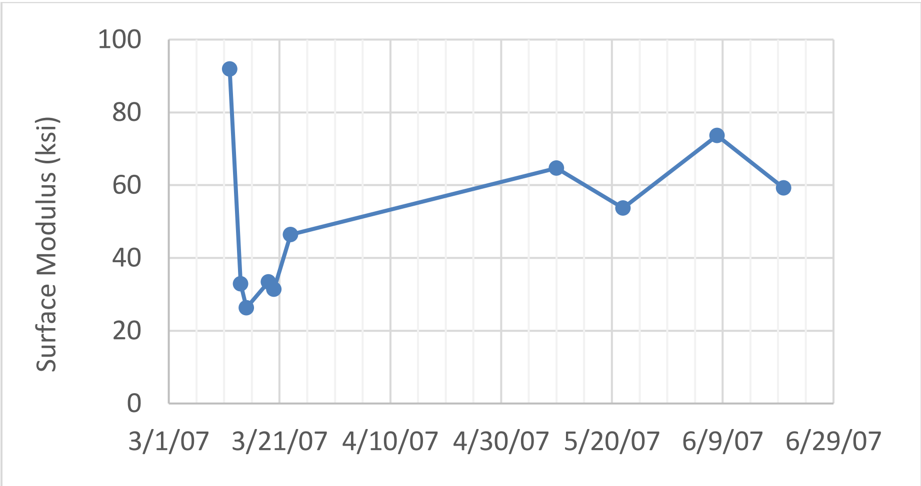


Figure 50. Surface modulus values at MnROAD Cell 28 (2007)

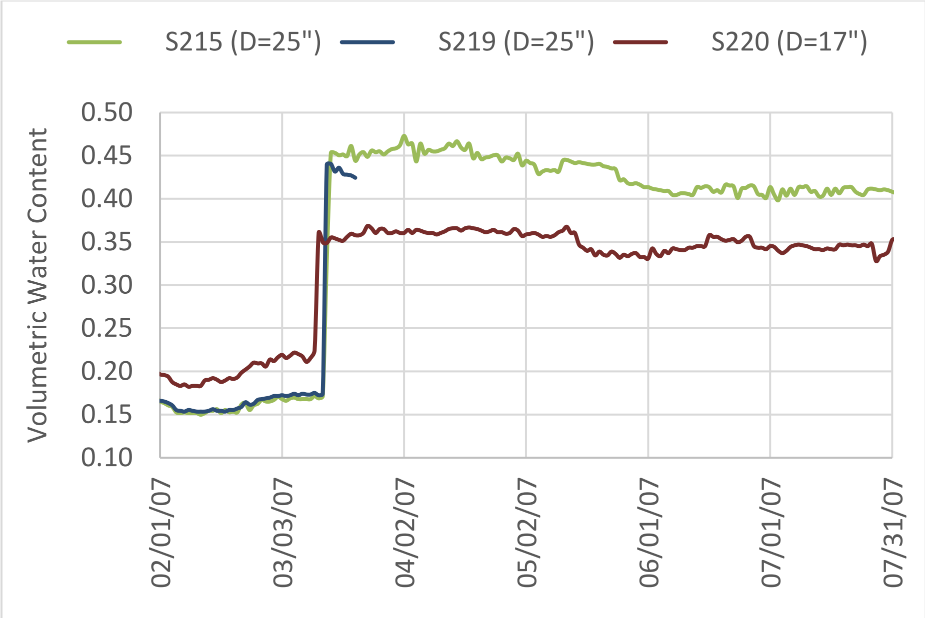


Figure 51. Volumetric moisture content at MnROAD Cell 28 (2007)

The end of thaw was estimated to be March 14, 2007. (The thermocouple string in Cell 28 was removed or destroyed during cell reconstruction, so the frost out date was estimated from a thermocouple string in Cell 29.)

The following observations were noted from the 2007 MnROAD data:

- Surface modulus values reached a minimum on March 15. Fairly significant recovery was observed in several FWD tests conducted during the next week. Unfortunately, no FWD tests were performed for the seven weeks between March 23 and May 10, so the shape of the recovery curve between those dates could not be accurately determined. Surface modulus values appeared to be stabilizing just above 60 ksi after May 10, albeit with a fair degree of scatter.

- Moisture content in Sensor 220 increased from about 0.22 to 0.36 around March 12. That sensor was at a depth of 17 in. below the top of the pavement (7 in. below the top of the clay subgrade), so it is likely that the thaw depth had reached that point a couple of days before frost out. At that sensor location, moisture content fluctuated slightly above and below 0.35 from March 12 through the end of July.

- Moisture content in Sensor 215 spiked from 0.17 to 0.45 between March 13 and 15, respectively (right around the frost out date of March 14). Excess moisture dissipated gradually between March 15 and June 8, when it subsequently stabilized at around 0.40 to 0.41. Sensor 215 was at a depth of 25 in. below the top of the pavement (15 in. below the top of the clay subgrade), so it was not surprising that moisture content increased more dramatically around frost out and dissipated much more slowly compared to values measured by Sensor 220. The more muted response in Sensor 220 may be due to the fact that Sensor 220 was farther from the GWT and so not as much excess moisture was pulled up into that vicinity during freezing (and thus less excess water was available to lose post thaw). The difference in response might also be due to the fact that Sensor 220 was close to the free-draining base layer, so any excess moisture near that sensor could drain more easily and quickly than it could deeper in the clay subgrade.

- Sensor 219 stopped recording data after mid-March; however, those data were included because they illustrate some consistency in trends at different locations along the roadway. Sensors 215 and 219 were at the same depth but were located about 200 ft apart (both at +/- 3.25 ft off centerline). Sensors 215 and 219 recorded almost identical readings during the frozen period, and moisture content values in both sensors spiked to similar values right around the frost out date.

In summary, based on data collected from both the Madison, Maine, site and the MnROAD Cell 28 site, the research team believes that moisture sensors show promise as a tool for monitoring stiffness recovery in clay subgrades following the spring thaw. In most cases, the sensors showed dramatic increases in volumetric moisture content right around the end of the thaw period (or the time when the thaw front reaches the moisture sensor, which may be before frost out if the moisture sensor is located above a still-frozen portion of the subgrade). The one exception was where moisture sensors were placed close to a free-draining base layer, in which case the increases in moisture content may have been muted due to drainage through the base layer.

At the Madison, Maine, site, the excess moisture dissipated quite rapidly during the first week +/- after frost out and then dissipated at a much slower rate for about a week before reaching a fairly stable value. This was in contrast to data from Sensor 215 at MnROAD Cell 28, which took about 2.5 months to return to a stable value. Again, this difference may have been due, in part, to the distance between the sensor and the drainage (base) layer. At the Madison, Maine, site, the moisture sensor was located 9 in. below the base layer, whereas Sensor 215 was located 15 in. below the base layer in Cell 28 (so drainage likely occurred more slowly due to the longer drainage distance).

Although a direct relationship between moisture dissipation and modulus increase could not be quantified based on the data presented herein, a trend was evident. For both study years at the Madison, Maine, site, the trends in volumetric moisture content reflected the bilinear recovery model proposed herein for soils with greater than 15% fines. Significant decreases in surface modulus values and corresponding increases in moisture content were observed as the soil initially transitioned from the frozen to the thawed state. Then, within the first couple of weeks +/- after frost out, excess moisture dramatically decreased, and surface modulus values showed substantial increases. By the date at which moisture content readings stabilized, surface modulus values appeared to level out or show only slight/gradual additional increases.

CHAPTER 10: CONCLUSIONS AND RECOMMENDATIONS

10.1 Summary of Major Findings

The main objective of this research project was to develop an economical and easy-to-use protocol for timing SLR removal. This project was funded primarily by NDDOT, which has the benefit of a robust array of subsurface TDPs throughout its state. Since those TDPs enable accurate determination of frost out dates, the researchers anticipated that the protocol would define time windows after thawing is complete, which are necessary for significant stiffness recovery and thus SLR removal.

To achieve the research objective, the research team utilized a wealth of FWD data from three test cells at the MnROAD research facility. Chapter 2 of this report describes the MnROAD cells used for model development, as well as nine sites that were used for model validation (three in New Hampshire, three in North Dakota, two in New York, and one in Maine). A summary of available information about the roadway structures, bases, and subgrade soils, as well as data regarding depth to the GWT for these sites is included in Appendix A.

During model development (Chapter 5), the researchers found two factors that had the most significant influence on the recovery time necessary for SLR removal:

- Subgrade type
- Depth of the water table

In terms of subgrade type, the research team found that coarse-grained subgrades with less than about 5% to 7% fines recover much more quickly than subgrades with greater than 15% fines. This was not surprising, since clean, coarse-grained soils drain much more rapidly than soils with higher fines contents.

Based on the data from MnROAD Cell 25 presented in Chapter 4, minimal (if any) recovery is observed beyond the frost out date for roadways constructed with very free-draining base and subgrade soils. Therefore, for such roadways the data suggested that the SLR could reasonably be removed when the frost has gone out or a few days afterward.

Validation data from the Kancamagus Highway (NH 112) site K-1 in New Hampshire did, however, suggest that even for free-draining base and subgrade soils, it is important to place the SLR as soon as thaw starts penetrating the roadway base layer(s) and to keep the SLR in place during the critical period when underlying frozen layers exist and prohibit drainage of excess moisture from the base layer(s). These data are discussed in Section 7.1 of this report.

Sensitivity studies conducted according to AASHTO 1993 design guidelines suggested that maintaining the SLR from the start through the end of the thawing period can increase the design life of roadways constructed with free-draining base and subgrade soils by about 10%.

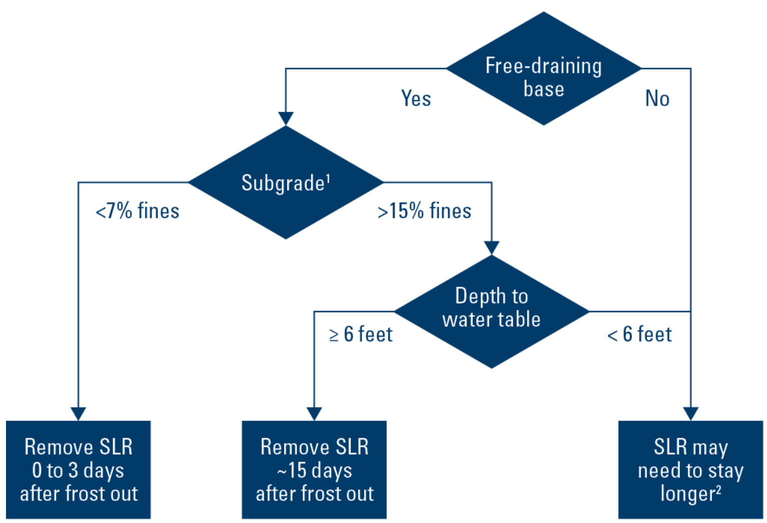
For subgrades containing a higher percentage of fines (15% or more), the statistical analysis discussed in Chapter 5 suggested that the SLR could be removed around 15 days after frost out, as long as the roadways were constructed with free-draining base layers and the GWT was deeper than about 6 ft below the top of the pavement.

For sections of roadway with shallower water tables and/or no free-draining base layer, worst-case conditions should be anticipated. For such conditions, it would be prudent to leave the SLR in place for a longer period and/or to reroute heavy traffic away from those sections of roadway.

Sensitivity studies conducted according to AASHTO 1993 design guidelines also suggested that maintaining the SLR from the start through the end of the thawing period can increase the design life of roadways constructed on fine-grained subgrades by approximately 40% to 49%, depending on other factors such as the thickness of the AC layer and the thickness and quality of the base layer. Keeping the SLR in place for an additional 15 days after frost out results in an additional increase in service life of 12% to 16%, again depending on details of the AC and base layers.

10.2 Suggested Implementation of Research Findings

The decision tree shown in Figure 52 is suggested as a means of implementing the recommended SLR removal protocol. Knowledge about the roadway structure, base layer(s), and subgrade soils is necessary to effectively use the decision tree.



[1] Subgrades between 7% and 15% fines need to be reviewed on an individual basis
[2] Individual site needs to be reviewed for the timing of SLR removal

Figure 52. Decision tree for SLR removal timing

The first consideration is whether a free-draining base layer exists. A granular material with up to 10% fines (passing the #200 sieve) is considered to be a free-draining base layer. This criterion was initially based on analysis of data from MnROAD Cell 28, which had a Class 5 base layer. The MnDOT specification for Class 5 base material is 3% to 10% passing the #200 sieve, and the Cell 28 field sample contained 7.6% fines. Although material more than about 5% to 7% fines would not generally be considered ideal for a base layer, the Cell 28 Class 5 base layer provided enough drainage to be considered free-draining (relative to the higher fines content subgrade). This criterion was further validated based on data from the Lake Tarleton and Stinson Lake sites in New Hampshire and the Jefferson and Franklin sites in New York, which had base layers containing between 8% and 10 % fines. All four of those validation sites passed the control checks described in Section 8.2 of this report.

If the road has no free-draining base layer (and/or if other conditions prevent drainage of the base layer), then that particular site needs to be reviewed, and extra precautions may need to be taken regarding the SLR. For example, allowable loads may need to be further reduced and/or the SLR may need to be left in place for a longer period of time. Alternatively, a transportation agency may decide to limit SLR durations and accept that such roadways may face additional maintenance costs and a shorter design life.

If the roadway is constructed with a base that can drain freely, then the subgrade type becomes the primary consideration. For subgrades with relatively clean gravels and sands (less than 7% fines), the SLR could reasonably be removed within 0 to 3 days after the frost goes out. For subgrades with clays, silts, and silty (or clayey) sands (soils with more than about 15% fines), the depth to the GWT becomes important. If the GWT is determined to be relatively deep (6 ft or more), then the SLR should remain in place for 15 days beyond the frost out date, but little is gained by leaving it in place much longer. For subgrades with more than 15% fines and shallow water tables (less than about 6 ft deep), the site needs to be reviewed, and extra precautions may need to be taken regarding the SLR, as noted above. This is especially true for roads with clay subgrades and shallow water tables, where worst-case conditions such as those observed at MnROAD Cell 26 may exist.

10.3 Limitations

It should be noted that no sites were available for this study with subgrades containing between 7% and 15% fines. For such cases, the research team feels that it would be prudent to err on the side of caution and leave the SLR in place for about 15 days after frost out.

It should also be noted that the criteria for subgrades with more than 15% fines were based on analysis of MnROAD Cell 28 data. Maximum frost depths were determined for Cell 28 and ranged between about 48 and 60 in. for four of the five study years between 1994 and 1999. For the 1997–1998 winter, the maximum frost depth in Cell 28 was about 36 in. It is possible that SLR durations at sites with frost depths much greater than those observed at MnROAD Cell 28 might be excessive due to longer time spans between the start and end of the thaw period. It might also be possible that some rebound in modulus occurs at these sites before the ultimate frost out date due to drainage horizontally out of the roadway side slopes as well as vertically through the thawed portion of the subgrade. In either case, the recommended delay of 15 days between frost out and SLR removal might need to be modified.

Both of the limitations discussed in this section present opportunities for future research. The protocol recommended herein might need to be modified slightly for subgrades with fines contents between 7% and 15% and/or for sites where frost penetrates deeper than about 4 to 5 ft.

10.4 Additional Research Findings and Recommendations for Future Research

As discussed in Chapter 9, two additional tools were evaluated to see whether they could help inform SLR removal decisions. The FrezTrax model was evaluated, as described in Section 9.1. In a previous Aurora project by Miller et al. (2020), analyses suggested that the FrezTrax model is somewhat nonconservative regarding SLR application given that the CTI threshold dates for application of the SLR tended to fall too late (i.e., after thawing had already progressed past the 12 in. deep subsurface temperature sensor). On the other hand, analyses conducted during this current Aurora project suggest that the FrezTrax model is overly conservative regarding SLR removal. In other words, the FrezTrax model would suggest leaving the SLR in place longer than is necessary.

Both scenarios are in opposition to research conducted by others (Ovik et al. 2000) as well as trends suggested by analysis conducted during this current Aurora project, which suggest that it is far more effective to place restrictions early (i.e., at the start of thaw) than to delay their removal. Therefore, the research team concluded that the FrezTrax model is not an effective tool for use in SLR timing decisions.

Given that NDDOT officials indicated an interest in possibly installing moisture sensors at some of the state’s RWIS sites, the research team assembled data from sites where moisture sensors were installed and where FWD testing was conducted during and after the spring thaw periods. Data were collected from moisture sensors placed in the clay subgrades at both the Madison, Maine, site and the MnROAD Cell 28 site, as discussed in detail in Section 9.2 of this report.

The moisture sensors all showed increases in volumetric moisture content right around the end of the thaw period. Some of that measured response was likely due to the phase change of water from the solid to the liquid state as thawing occurred, and some of the response was likely due to excess moisture that had been drawn up to the freezing front as ice lenses formed during the late fall and winter. At the Madison, Maine, site, the excess moisture tended to dissipate rapidly during the first week +/- after frost out and then dissipated at a much slower rate before reaching a fairly stable value.

Although a direct relationship between moisture dissipation and modulus increase could not be quantified based on the data presented herein, a trend was evident. For both study years at the Madison, Maine, site, surface modulus values showed significant increases by the date at which moisture content readings stabilized; beyond that date, surface modulus values appeared to level out or to show only slight/gradual increases.

At MnROAD Cell 28, FWD testing was not conducted frequently enough to clearly define the recovery curve during the spring when volumetric moisture content data were available.

Nevertheless, the data overall suggested that moisture sensors show promise as a tool for monitoring stiffness recovery in clay subgrades during and after the spring thaw period. The researchers suggest that this potential application also be investigated during future research.

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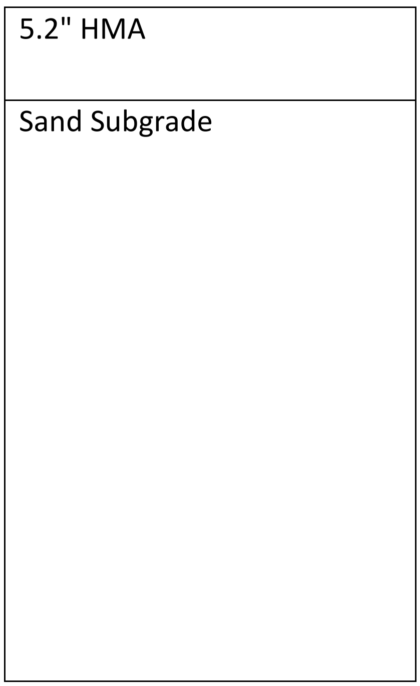
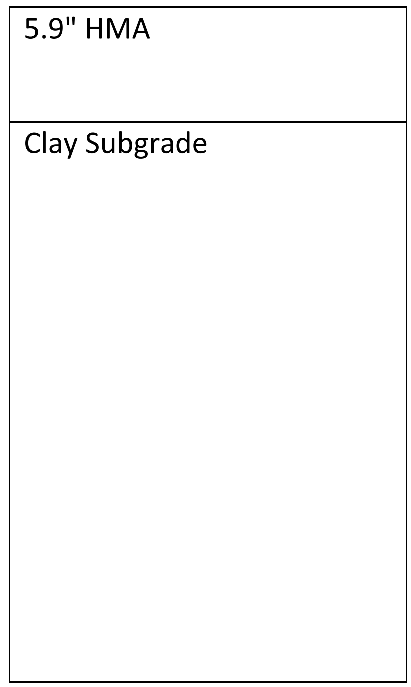
APPENDIX A: STUDY SITE CROSS SECTIONS AND SOILS AND GROUNDWATER INFORMATION

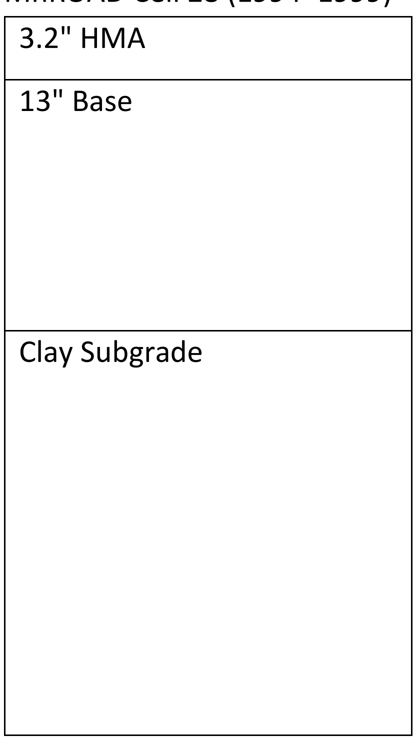
MnROAD Cell 25



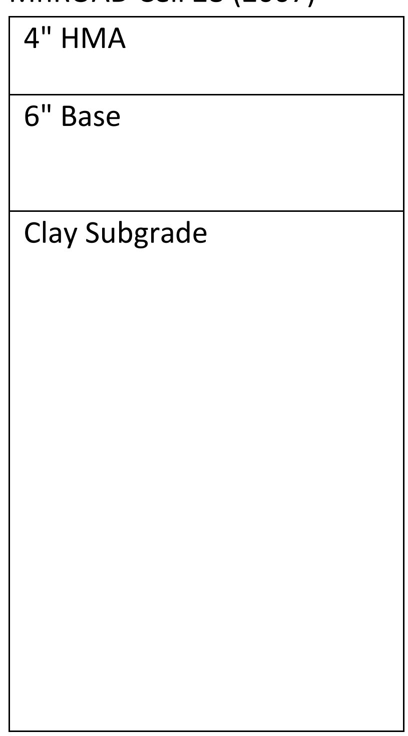
MnROAD Cell 26



MnROAD Cell 28 (1994–1999)



MnROAD Cell 28 (2007)



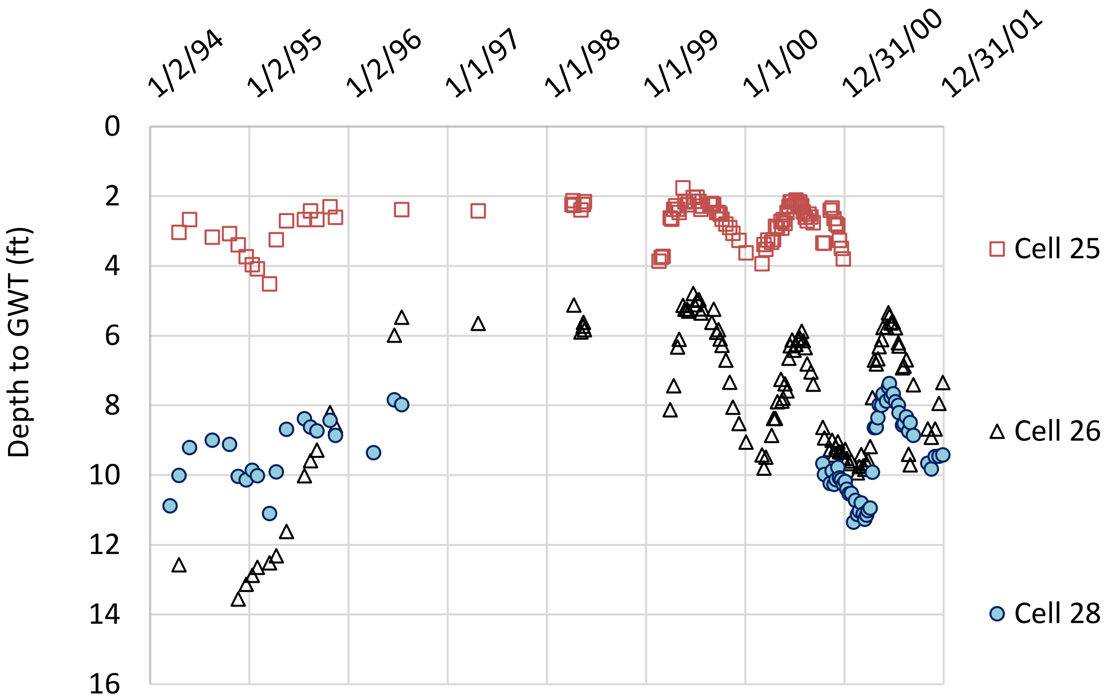
Grain Size Distribution of MnROAD Unbound Base Materials and Subgrade Soils

	Base (Class-5)		Clay	Sand
	Percent Passing			
Sieves Size	Spec.	Field	Field	Field
2"		100	100	100
1"		100	100	100
3/4"		97	99	98
3/8"		81	95	96
4	30–80	70	90	86
10	20–65	59	84	
20		42	78	
40	10–35	24	69	39
60		15	61	
100		10	52	8
200	3–10	7.6	43	4.6

Atterberg Limits Data from MnROAD Clay Subgrade Soil Samples

Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
37	18.5	18.5
26.4	15.5	10.9
31.2	16.9	14.3

Groundwater Table Depths at MnROAD Cells 25, 26, and 28



Madison, Maine

6" HMA
18" Base
Clay Subgrade

Atterberg Limits Data at Madison, Maine, Site

Depth (ft)	Liquid Limit (%)	Plastic Limit (%)
2.00–5.00	37.4	20.2
5.00–7.00	36.9	23.8

Results of Grain Size Analyses and Moisture Content Determinations at Madison, Maine, Site

	% Components (based on USCS Particle Size Criteria)							
Depth (ft)	% C. Gravel	% F. Gravel	% C. Sand	% M. Sand	% F. Sand	% Fines	Water Content (%)	USCS Symbol
0.50–2.00	7	18	10	38	20	6	7	SW-SM
2.00–5.00	0	0	0	5	9	86	24	CL
5.00–7.00	0	0	0	2	5	94	27	CL

Lake Tarleton, New Hampshire

9.6" HMA (6" overlay; 3.3" Old mix)
13" Base
Silty Sand Subgrade

Results of Grain Size Analyses at Lake Tarleton, New Hampshire, Site

	% Components (based on USCS Particle Size Criteria)						
Depth (ft)	% C. Gravel	% F. Gravel	% C. Sand	% M. Sand	% F. Sand	% Fines	USCS Symbol
1–3	15	13	12	26	24	10	SW-SM
3–5	0	4	13	43	31	8	SP-SM
5–7	0	22	13	20	29	15	SM
7–9	0	14	18	23	24	20	SM
9–11	0	22	14	18	25	21	SM

Stinson Lake, New Hampshire

9.6" HMA (8.4" overlay; 1.2" Old mix)
26" Base
Silty Sand Subgrade

Results of Grain Size Analyses at Stinson Lake, New Hampshire, Site

	% Components (based on USCS Particle Size Criteria)						
Depth (ft)	% C. Gravel	% F. Gravel	% C. Sand	% M. Sand	% F. Sand	% Fines	USCS Symbol
.8–2.8	23	13	11	23	23	8	SP-SM
3–5	0	6	5	23	55	11	SP-SM
5–7	0	6	4	15	46	30	SM
7–9	0	14	6	16	40	24	SM
9–9.9	0	4	5	16	46	28	SM

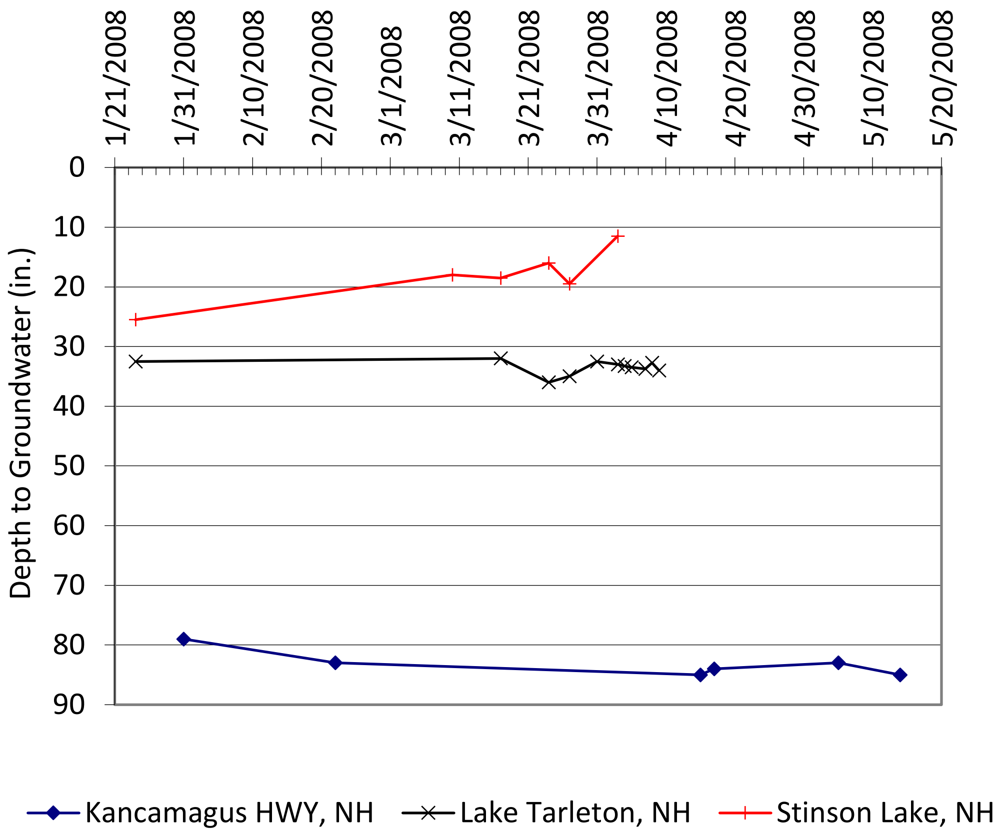
Kancamagus Highway, New Hampshire

4" HMA
10" Base
24" Subbase
Sand Subgrade

Results of Grain Size Analyses at Kancamagus Highway, New Hampshire, Site

	% Components (based on USCS Particle Size Criteria)						
Depth (ft)	% C. Gravel	% F. Gravel	% C. Sand	% M. Sand	% F. Sand	% Fines	USCS Symbol
.55–2.5	20	17	12	29	17	4	SP
2.5–4.5	9	13	10	34	28	6	SP-SM
4.5–6.5	0	16	10	33	36	5	SP
6.5–8.5	17	22	11	28	15	7	SP-SM
8.5–10.5	13	20	18	30	15	5	SW

Groundwater Table Depths at New Hampshire Sites



Bowman (Highway 85), North Dakota

6" HMA
16" Base
Clay Subgrade

Note: The "**Base**" at Highway 85 is described as a blended base by NDDOT personnel, constructed as follows. First, 4 in. of modified Class 3 aggregate is placed on the roadway. That material is then blended with the existing bituminous material and 3 in. of the existing aggregate. The freshly blended material is then laid and compacted over the entire width of the roadway. An additional 6.25 in. of Class 5 aggregate is then added to bring the thickness of the aggregate section to 18 in.

Highway 85: NDDOT Laboratory Soil Tests and Classification of Clay Subgrade

Depth below top of pavement, (ft)		Soil Classification (AASHTO M-145)	Texture Classification	LL	PI	PL	Water Content (%)
From	To						
2.1	3.1	A-7-6 (16)	CLY	49	30	19	26.8
3.1	5.1	A-7-6 (11)	CLY LM	47	29	18	24.6
5.1	7.1	A-7-6 (15)	CLY	49	30	19	28.5
7.1	9.1	A-7-6 (7)	CLY LM	34	18	17	15.4
9.1	11.1	A-7-6 (14)	CLY	43	28	15	17.1

Highway 8, North Dakota

6" HMA
6" Base
Subgrade (TBD)

The “**Base**” at Highway 8 is described by NDDOT personnel as most likely a Class 3 or 5 aggregate base.

The “**Subgrade**” at Highway 8 has not been sampled and tested. However, based on experience in the region, NDDOT personnel expect that the subgrade is most likely a clay.

Highway 6, North Dakota

5" HMA
12" Base
Subgrade (see side note)

The “**Base**” at Highway 6 is described by NDDOT personnel as most likely a Class 3 or 5 aggregate base.

Information on the “**Subgrade**” at Highway 6 was provided in a NDDOT report, “Linear Soil Survey and Design Recommendations Project NH-1-006(006)042 (From Heart River Bridge at Mandan South to Jct Inn),” dated December 30, 1992. In that report, the subgrade was described as “being chiefly lean clay soils, ranging predominantly within the A-4 and A-6 soil groups. In the deeper cut sections, however, clay will be encountered, which is of a much heavier texture and will range in the upper indexes of the A-7-6 soil group. In many of the low areas, the soil possesses characteristics and qualities associated with the A-7-5 and A-7-6 groups.”

Franklin, New York

16.5" HMA (7.5" overlay; 9" Old mix)
12" Base
Silty Sand Subgrade

Results from Sieve Analysis (Subgrade) at Franklin, New York, Site

Sieve Size	% Passing
3/4"	71.7%
1/2"	70.6%
1/4"	69.2%
#4	68.7%
#10	66.7%
#20	63.5%
#40	60.2%
#100	53.7%
#200	46.5%

Results from Atterberg Limits Tests (Subgrade) at Franklin, New York, Site

Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
26	21	5

Jefferson County, New York

7" HMA
15" Base
Clay Subgrade

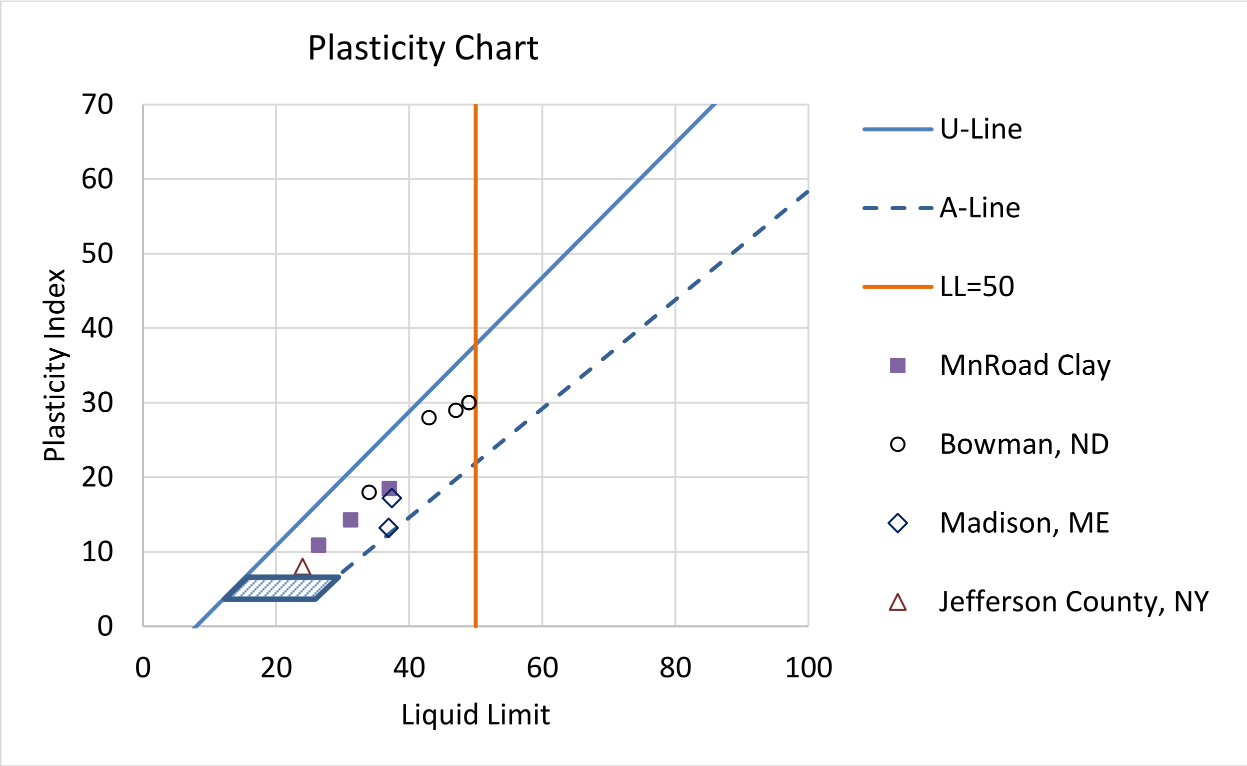
Results from Sieve Analysis (Subgrade) at Jefferson County, New York, Site

Sieve Size	% Passing
3/4"	100.0%
1/2"	100.0%
#4	99.9%
#10	98.4%
#20	97.1%
#40	94.0%
#80	81.3%
#100	78.8%
#200	74.8%

Atterberg Limits Tests (Subgrade) at Jefferson County, New York, Site

Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
24	16	8

Plasticity Characteristics of Clay Subgrades at Test Sites



APPENDIX B: INITIAL STATISTICAL REVIEW OF MNROAD CELL 26 DATA

The equation and graphs for MnROAD Cell 26 were generated using Minitab Statistical Software. The output from Minitab is shown in this appendix. The regression equation is shown as well as the statistics on the coefficients and some key statistical analyses. The key value to review in the coefficients is the P-value. The smaller the P-value, the stronger the statistical significance. The probability of the coefficient being statistically significant is 1 minus the P-value. For the constants PostThawDays and GWT, the probability of significance is very high.

Also shown in this appendix is the analysis of variance (ANOVA). The key takeaway is the large lack of fit for the P-values. Essentially, this highlights the noisiness of the data from the MnROAD site. The unusual observations are included below and could be removed to generate a final model, but this can only be used either on data that are obviously in error or one time as a way to remove data that are likely nonnormal (do not match the model methodology).

Plots of normal probability and residual versus fit are shown below. These were reviewed and show a good random variation but some nonnormal behavior.

POSTFROST 1994–1999 0–150 DAYS
Regression Analysis: Ms-36_(ksi) versus PostThawDays, GWT

Regression Equation

GWT			
Shallow	Ms-36_(ksi)	=	12.409 + 0.04740 PostThawDays
Deep	Ms-36_(ksi)	=	16.307 + 0.04740 PostThawDays

Coefficients

Term	Coefficient	SE Coef	T-Value	P-Value	VIF
Constant	12.409	0.235	52.83	0.000	
PostThawDays	0.0474	0.00291	16.26	0.000	1.00
GWT					
Deep	3.898	0.304	12.84	0.000	1.00

SE Coeff = Standard Error of the Coefficient
T-Value = T-test statistical result
P-value = probability statistic
VIF = variance inflation factor; a value of 1 shows no correlation between variables (independence)

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
1.70872	70.02%	69.68%	69.10%

S = Standard Error of the regression (ksi)

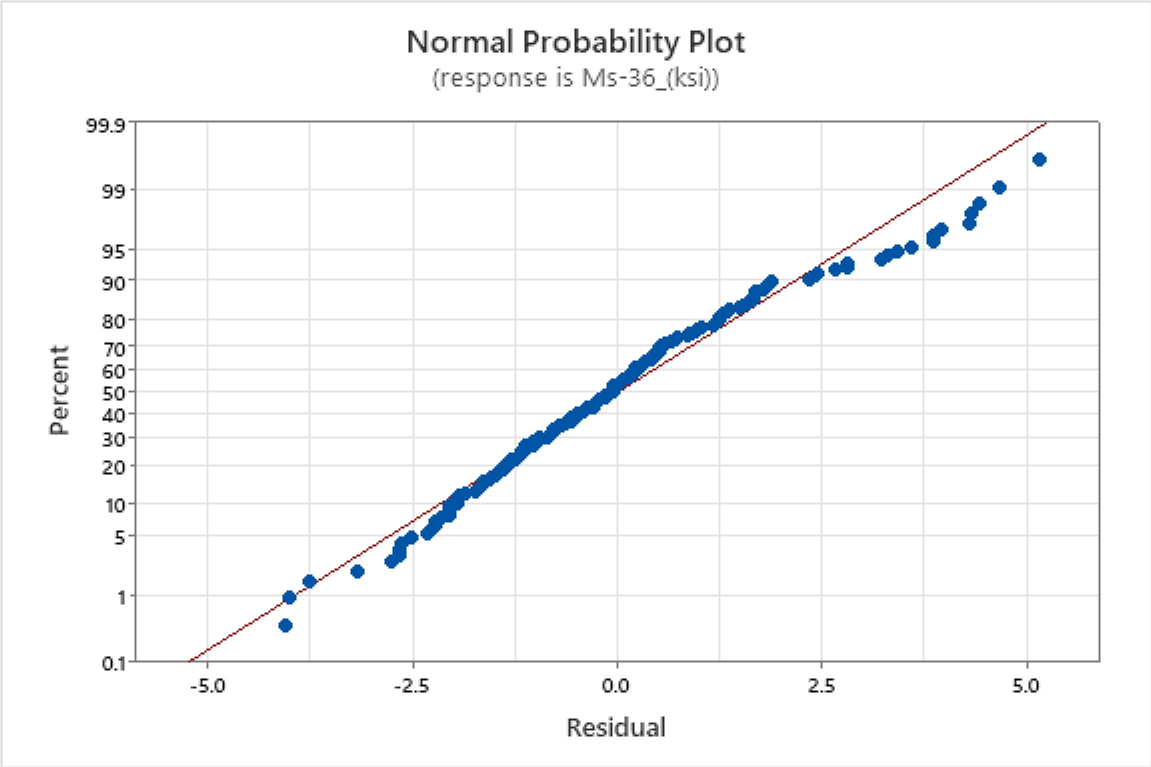
Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	2	1213.6	606.818	207.83	0.000
PostThawDays	1	772.0	771.991	264.41	0.000
GWT	1	481.3	481.333	164.86	0.000
Error	178	519.7	2.920		
Lack-of-Fit	125	371.5	2.972	1.06	0.410
Pure Error	53	148.2	2.797		
Total	180	1733.3			

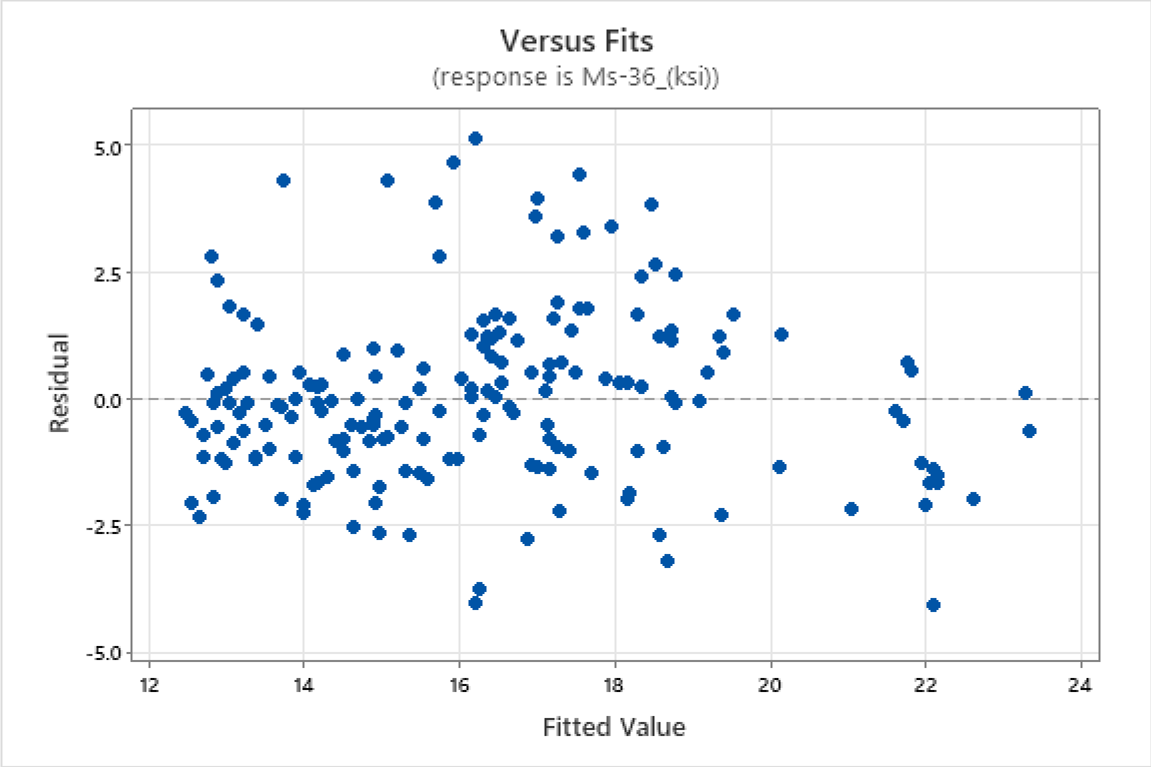
Fits and Diagnostics for Unusual Observations

Obs	Ms-36_(ksi)	Fit	Residual	Std Residual	
37	18.029	22.090	-4.060	-2.42	R
52	18.060	13.736	4.324	2.54	R
62	19.374	15.063	4.310	2.53	R
65	20.592	15.916	4.675	2.75	R
72	21.961	17.528	4.433	2.61	R
107	19.552	15.679	3.873	2.27	R
112	21.364	16.201	5.163	3.03	R
117	20.978	17.007	3.971	2.34	R
149	20.556	16.959	3.597	2.12	R
155	21.375	17.954	3.420	2.02	R
157	22.330	18.476	3.855	2.28	R
174	12.201	16.201	-3.999	-2.35	R
175	12.494	16.248	-3.754	-2.21	R

R Large residual



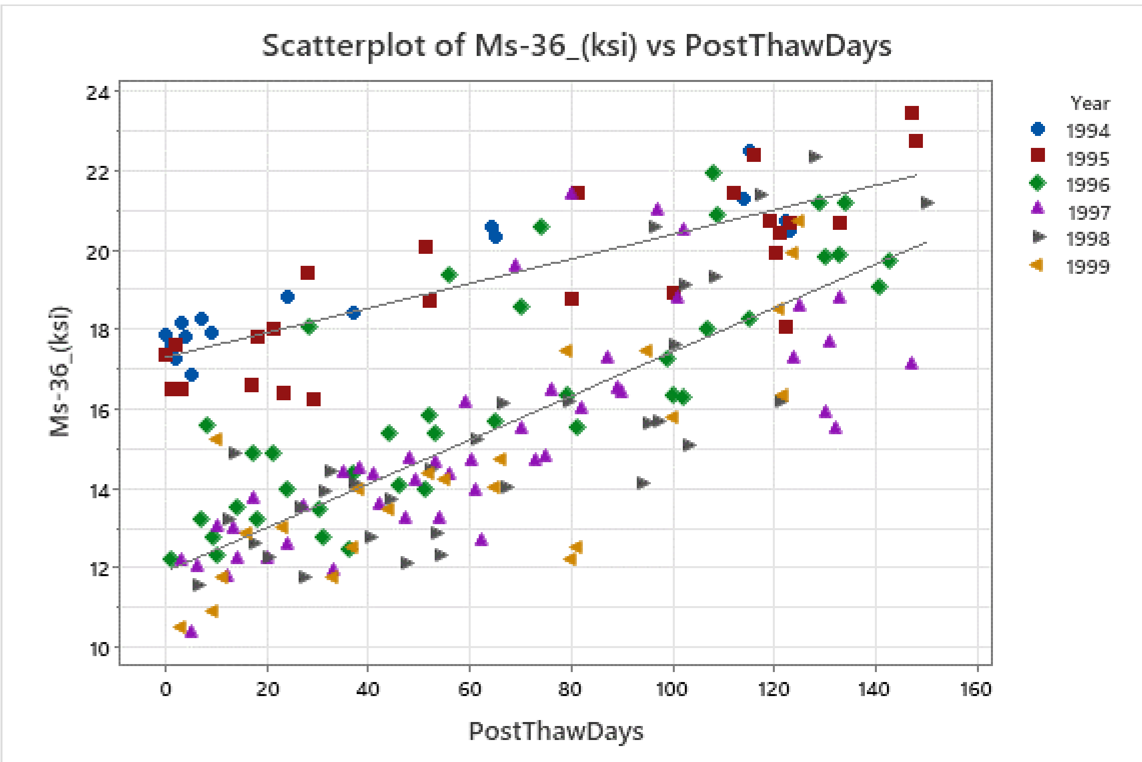
Note: The data in the upper right show some nonstandard residuals.



APPENDIX C: STATISTICS ON MNROAD CELL 26 DATA—EFFECTS OF GROUNDWATER DEPTH

To illustrate the analysis of the GWT, a separate regression was performed on the high (shallow) and low (deep) GWT for MnROAD Cell 26. The results are shown in this appendix. In the headings that follow, H is the high GWT data from the years 1996 through 1999 and L is the low GWT data from the years 1994 and 1995.

The fitted lines shown in the scatterplot below are strongly significant and show that while the recovery of the high water table surface modulus occurs more rapidly, it starts more than 3.5 ksi lower and is still not at the same overall level as the low GWT, even at 150 days after thaw is complete.



Regression Analysis: Ms-36_(ksi)_L versus PostThawDays

Regression on just the low water table data from 1994 and 1995.

Regression Equation

Ms-36_(ksi)_L = 17.296 + 0.03094 PostThawDays

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	17.296	0.255	67.70	0.000	
PostThawDays	0.03094	0.00322	9.62	0.000	1.00

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
1.07049	70.34%	69.58%	67.23%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	105.988	105.988	92.49	0.000
PostThawDays	1	105.988	105.988	92.49	0.000
Error	39	44.692	1.146		
Lack-of-Fit	33	38.936	1.180	1.23	0.433
Pure Error	6	5.756	0.959		
Total	40	150.680			

Fits and Diagnostics for Unusual Observations

Obs	Ms-36_(ksi)_L	Fit	Resid	Std Resid	
37	18.029	21.070	-3.040	-2.93	R

R Large residual

Regression Analysis: Ms-36_(ksi)_H versus PostThawDays

Regression on just the high water table data from 1996 through 1999.

Regression Equation

Ms-36_(ksi)_H = 11.911 + 0.05522 PostThawDays

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	11.911	0.276	43.09	0.000	
PostThawDays	0.05522	0.00366	15.09	0.000	1.00

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
1.76671	62.25%	61.98%	61.15%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	710.3	710.286	227.56	0.000
PostThawDays	1	710.3	710.286	227.56	0.000
Error	138	430.7	3.121		
Lack-of-Fit	91	288.2	3.168	1.04	0.443
Pure Error	47	142.5	3.032		
Total	139	1141.0			

Fits and Diagnostics for Unusual Observations

Obs	Ms-36_(ksi)_H	Fit	Resid	Std Resid	
52	18.060	13.458	4.602	2.62	R
62	19.374	15.004	4.369	2.48	R
65	20.592	15.998	4.593	2.61	R
72	21.961	17.876	4.085	2.33	R
107	19.552	15.722	3.830	2.18	R
112	21.364	16.329	5.035	2.86	R
117	20.978	17.268	3.709	2.11	R
124	15.480	19.201	-3.721	-2.14	R
174	12.201	16.329	-4.128	-2.35	R
175	12.494	16.385	-3.891	-2.21	R

R = Large residual

APPENDIX D: STATISTICS ON MNROAD CELL 28 DATA FOR BILINEAR MODEL

These analyses were done on the data for MnROAD Cell 28 after an initial regression and removal of high residual data. The full data set and analyses are available from the principal investigator upon request.

Regression Analysis: Ms-36 (ksi)_0-15_LR versus Days after frost

Regression Equation

Ms-36 (ksi)_0-15_LR	=	18.919 + 0.372 Days after frost

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	18.919	0.990	19.11	0.000	
Days after frost	0.372	0.105	3.53	0.002	1.00

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.33268	37.20%	34.21%	26.10%

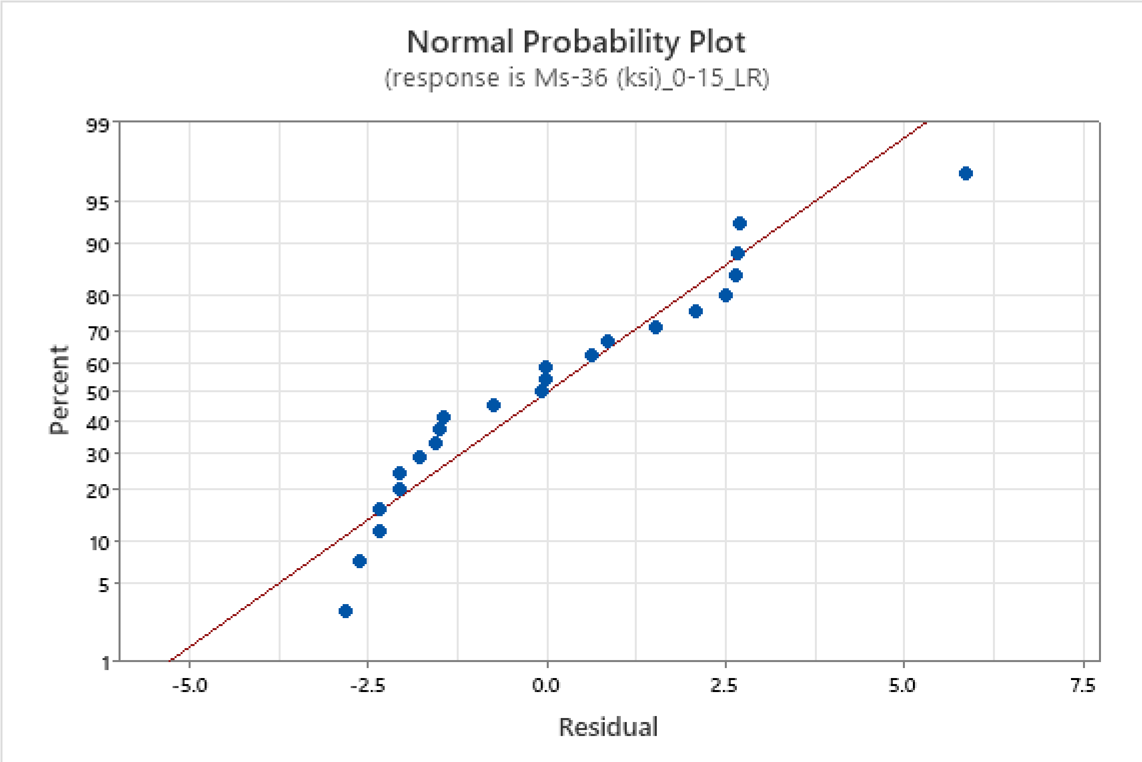
Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	67.68	67.684	12.44	0.002
Days after frost	1	67.68	67.684	12.44	0.002
Error	21	114.27	5.441		
Lack-of-Fit	12	78.79	6.566	1.67	0.225
Pure Error	9	35.48	3.942		
Total	22	181.95			

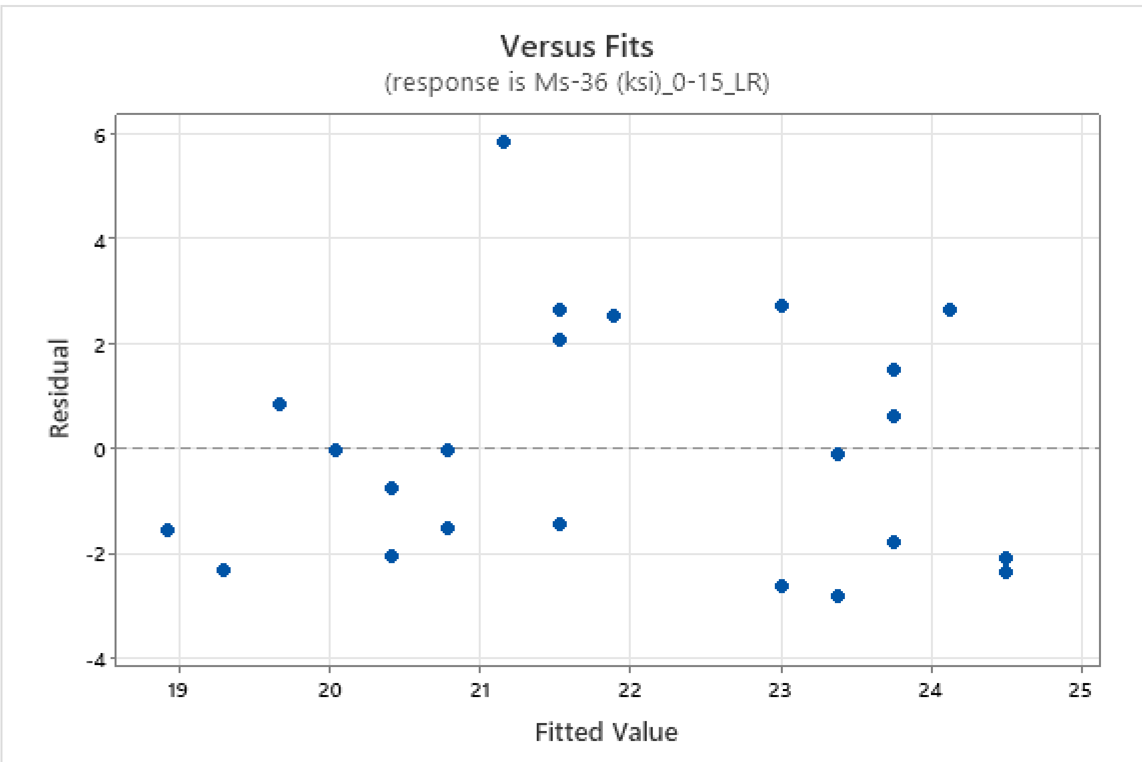
Fits and Diagnostics for Unusual Observations

Obs	Ms-36 (ksi)_0-15_LR	Fit	Resid	Std Resid	
11	27.00	21.15	5.85	2.58	R

R = Large residual
Note: This analysis was done after a removal of the high residual data from a first regression. As such, any additional high residual data should not be removed.



Normal Probability Plot
(response is Ms-36 (ksi)_0-15_LR)
Percent
99
95
90
80
70
60
50
40
30
20
10
5
1
-5.0
-2.5
0.0
2.5
5.0
7.5
Residual



Versus Fits
(response is Ms-36 (ksi)_0-15_LR)
Residual
6
4
2
0
-2
-4
19
20
21
22
23
24
25
Fitted Value

Regression Analysis: Ms-36 (ksi)_16-60_LR-Offset versus DaysAfterFrost-15

This regression was performed on the transposed data after driving the results through the data point of 15 days and a surface modulus of 24.5 ksi. To use the final model, the fitted model was transposed back.

Regression Equation

Ms-36 (ksi)_16-60_LR-Offset = 0.0695 DaysAfterFrost-15

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
DaysAfterFrost-15	0.0695	0.0126	5.53	0.000	1.00

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.42929	35.76%	34.59%	33.49%

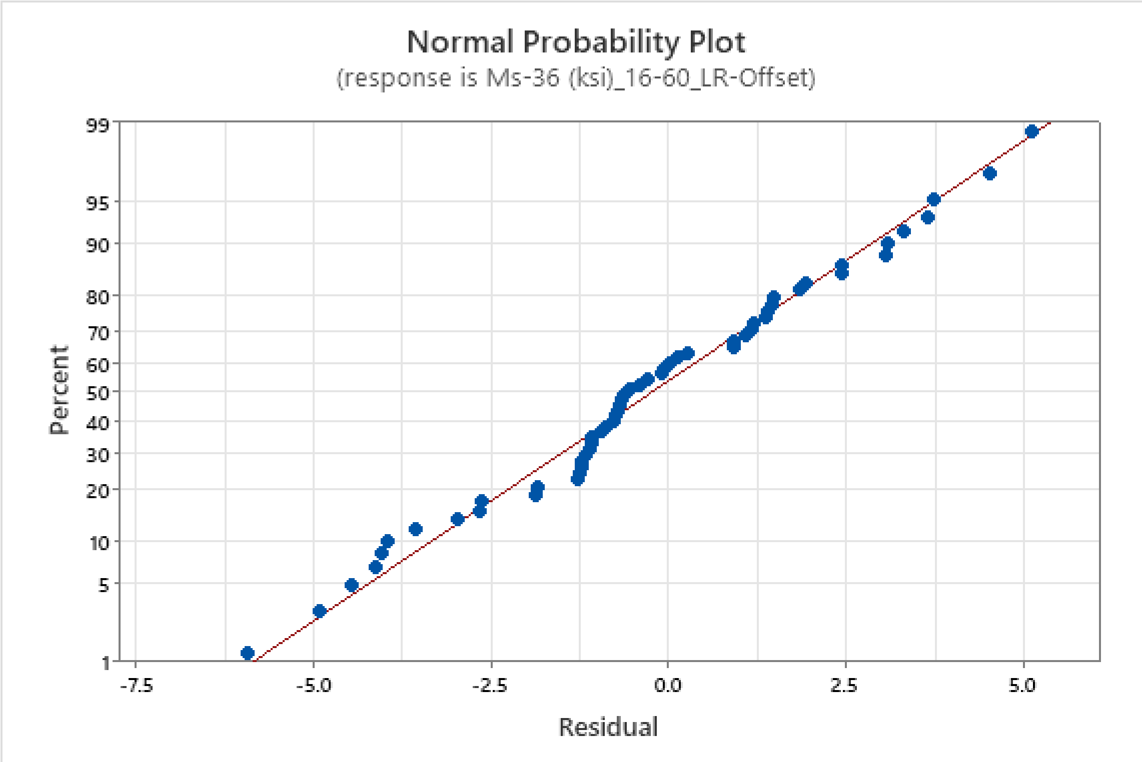
Analysis of Variance

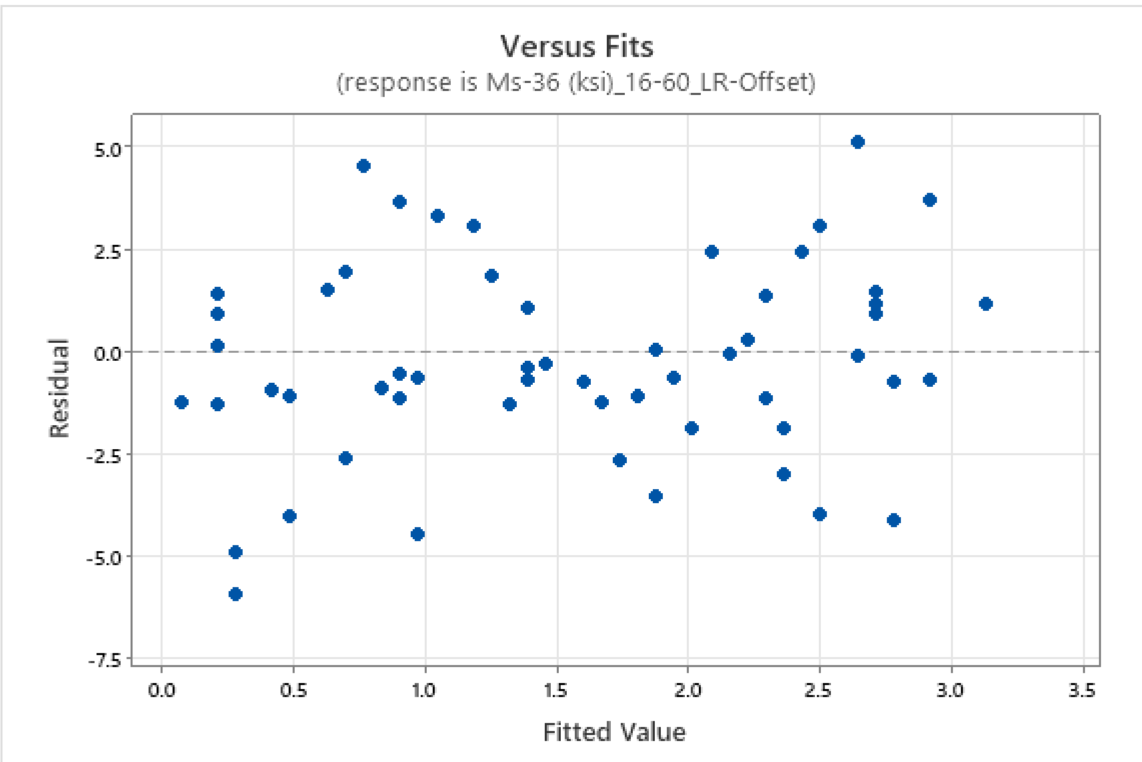
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	180.7	180.652	30.61	0.000
DaysAfterFrost-15	1	180.7	180.652	30.61	0.000
Error	55	324.6	5.901		
Lack-of-Fit	35	218.1	6.231	1.17	0.362
Pure Error	20	106.5	5.326		
Total	56	505.2			

Fits and Diagnostics for Unusual Observations

Obs	Ms-36 (ksi)_16-60_LR-Offset	Fit	Resid	Std Resid		
32	-5.672	0.278	-5.950	-2.45	R	
33	-4.632	0.278	-4.910	-2.02	R	
75	7.770	2.642	5.128	2.15	R	
85	4.296	3.129	1.167	0.49		X

R = Large residual
X = Unusual X
Note: This analysis was done after removal of the high residual data from a first regression. As such, any additional high residual data should not be removed.


Normal Probability Plot
(response is Ms-36 (ksi)_16-60_LR-Offset)
Percent
99
95
90
80
70
60
50
40
30
20
10
5
1
-7.5
-5.0
-2.5
0.0
2.5
5.0
Residual


Versus Fits
(response is Ms-36 (ksi)_16-60_LR-Offset)
Residual
5.0
2.5
0.0
-2.5
-5.0
-7.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Fitted Value

APPENDIX E: STATISTICS ON THREE SITES WITH SILTY SUBGRADES

The four analyses covered in this appendix were conducted using the data sets from Minitab Statistical Software. They are illustrative of the statistical analyses done for this project.

For all four analyses, the results are using low residual data only and are comparing the percent recovery versus a baseline value for each site. After the initial analysis, any high residual data were removed. This was only done once to reduce the chances of data mining. The concept was to remove any data that might unduly influence the final regression.

The first two analyses were for the combined silty subgrade seasonal sites:

- % Recovery versus 0–15 Days after Frost Out
- % Recovery-15thDay versus 16–60 Days after Frost Out (DaysAfter15)

The other two analyses were for MnROAD Cell 26 for the years 1996 through 1999:

- % Recovery versus 0–15 Days after Frost Out
- % Recovery-15thDay versus 16–60 Days after Frost Out (DaysAfter15)

The regression line for the % Recovery-15thDay versus 16–60 Days after Frost Out is the value for each day after subtracting the expected fit from the 0–15 Days after Frost Out value from the %_Recovery and 15 days from the number of days after frost out.

For each site, the first section shows the overall statistical analyses, including the regression equation derived and the statistics on the coefficients. A low P-value shows a strong statistical significance. The model summary shows the standard error (s) and the R^2 values on the data with and without adjustments based on sample size. The analysis of variance (ANVOA) shows the source of the different errors in the model. Again, a low P-value is a sign of strong statistical significance in the various source of errors in the model. Plots of the statistical results follow each ANOVA table.

Also for each site, a normal probability chart is used to visually show if the model is behaving as expected and has mostly normal probability distribution. The residual versus fits plot shows the error of each data point versus the model. The key is a random nature to the plot. This is true for each analysis.

% Recovery versus 0–15 Days after Frost Out – Silty Subgrade Sites

Regression Equation

Perc Recovery Ms-36_1 = 0.6820 + 0.00837 DaysAfterFrostOut

Coefficients

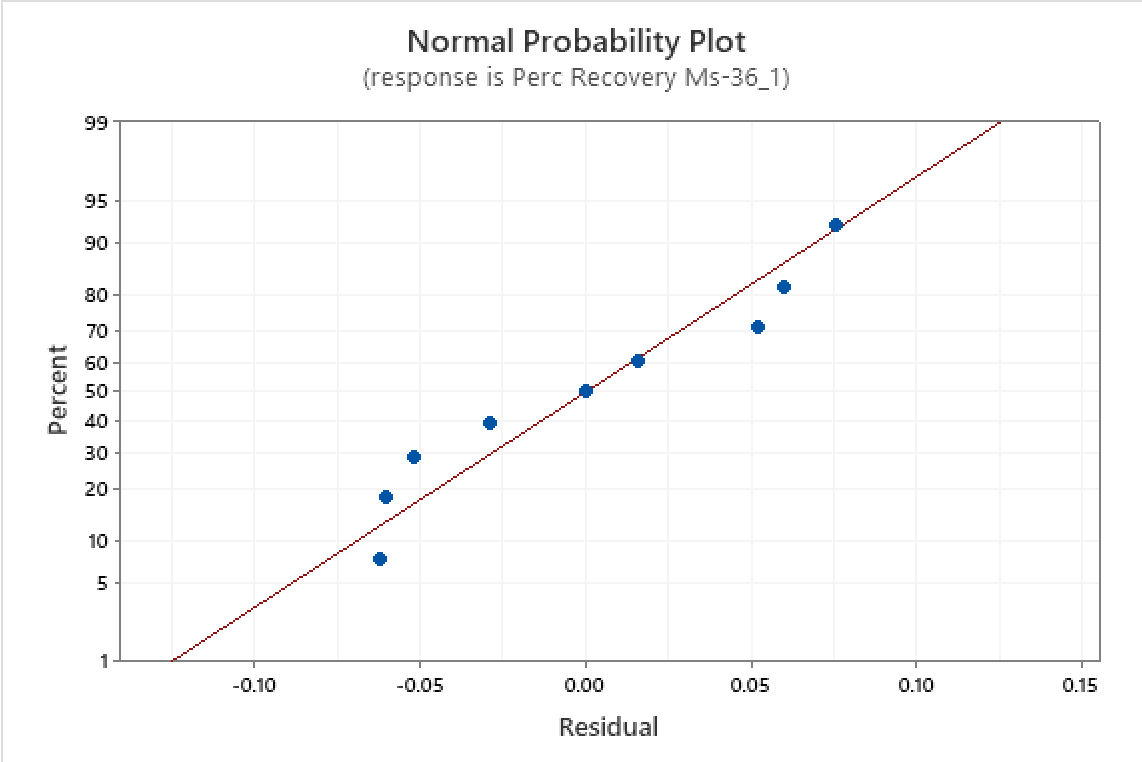
Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.6820	0.0413	16.52	0.000	
DaysAfterFrostOut	0.00837	0.00378	2.21	0.063	1.00

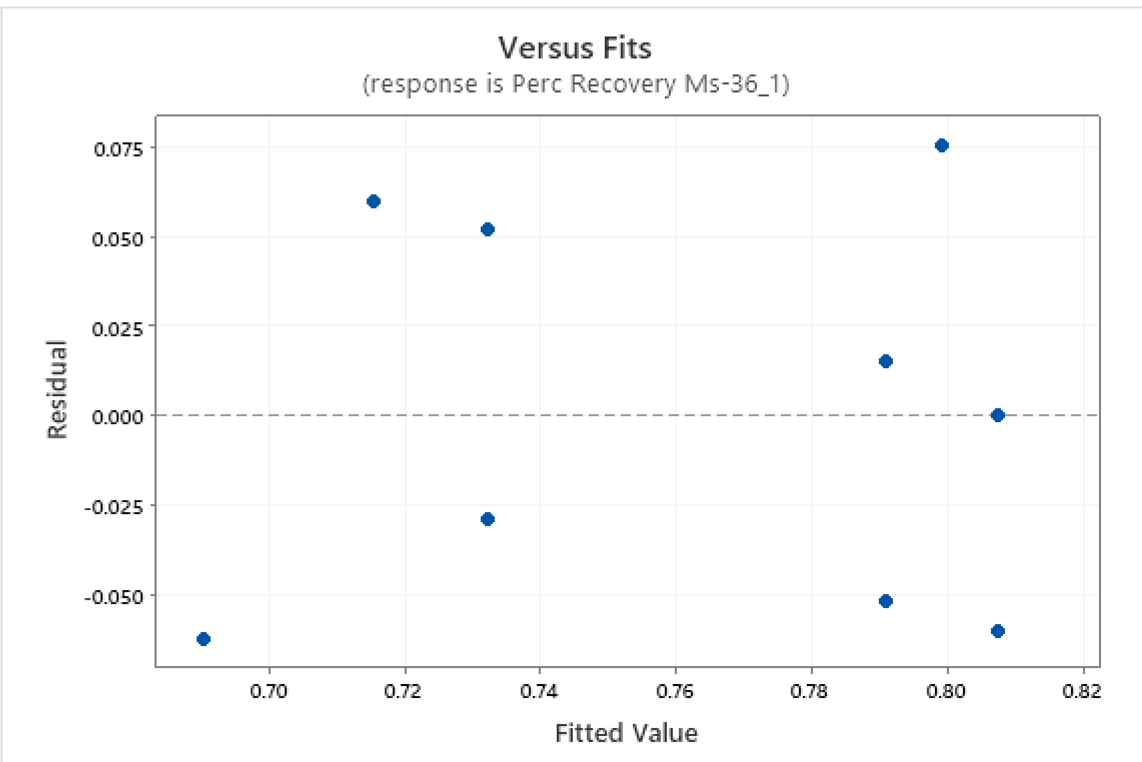
Model Summary

S	R-sq	R-sq(adj)
0.0576064	41.16%	32.76%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	0.01625	0.01625	4.90	0.063
DaysAfterFrostOut	1	0.01625	0.01625	4.90	0.063
Error	7	0.02323	0.00332		
Lack-of-Fit	4	0.01590	0.00397	1.63	0.359
Pure Error	3	0.00733	0.00244		
Total	8	0.03948			


Normal Probability Plot
(response is Perc Recovery Ms-36_1)
Percent
99
95
90
80
70
60
50
40
30
20
10
5
1
-0.10
-0.05
0.00
0.05
0.10
0.15
Residual


Versus Fits
(response is Perc Recovery Ms-36_1)
Residual
0.075
0.050
0.025
0.000
-0.025
-0.050
0.70
0.72
0.74
0.76
0.78
0.80
0.82
Fitted Value

% Recovery = 15th Day versus 16–60 Days after Frost Out – Silty Subgrade Sites

Regression Equation

%Recovery-15thDay = 0.002418 DaysAfter15

Coefficients

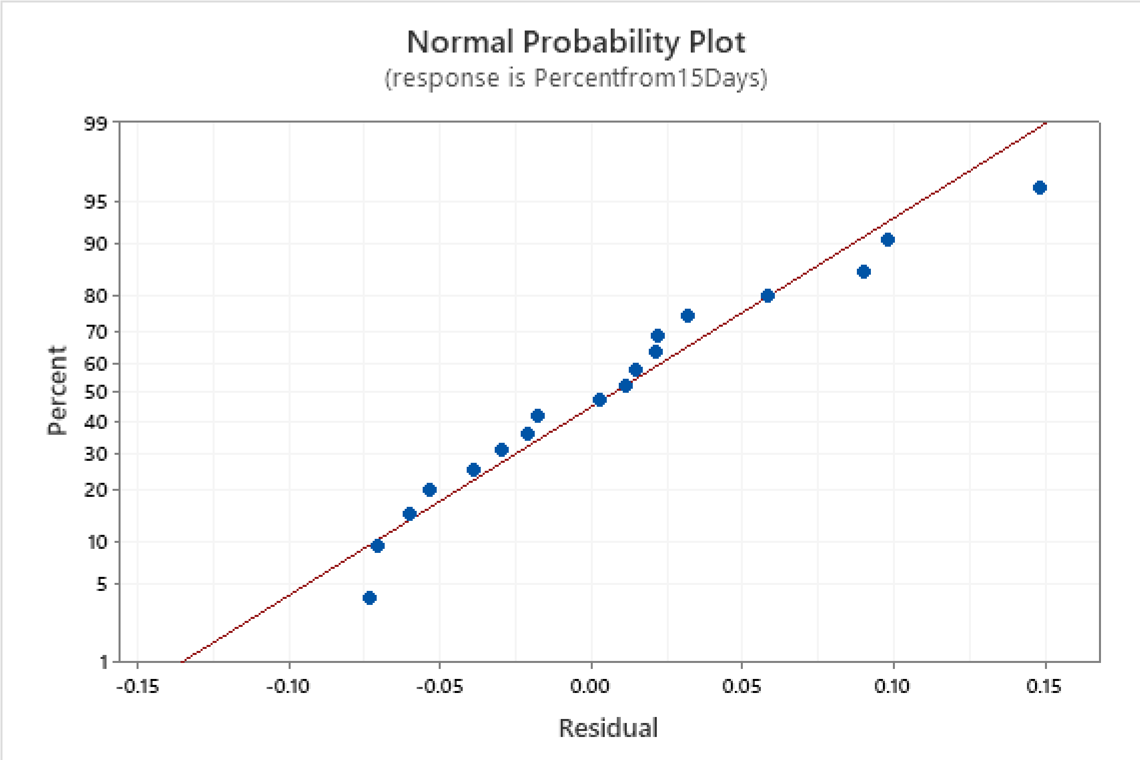
Term	Coef	SE Coef	T-Value	P-Value	VIF
DaysAfter15	0.002418	0.000376	6.42	0.000	1.00

Model Summary

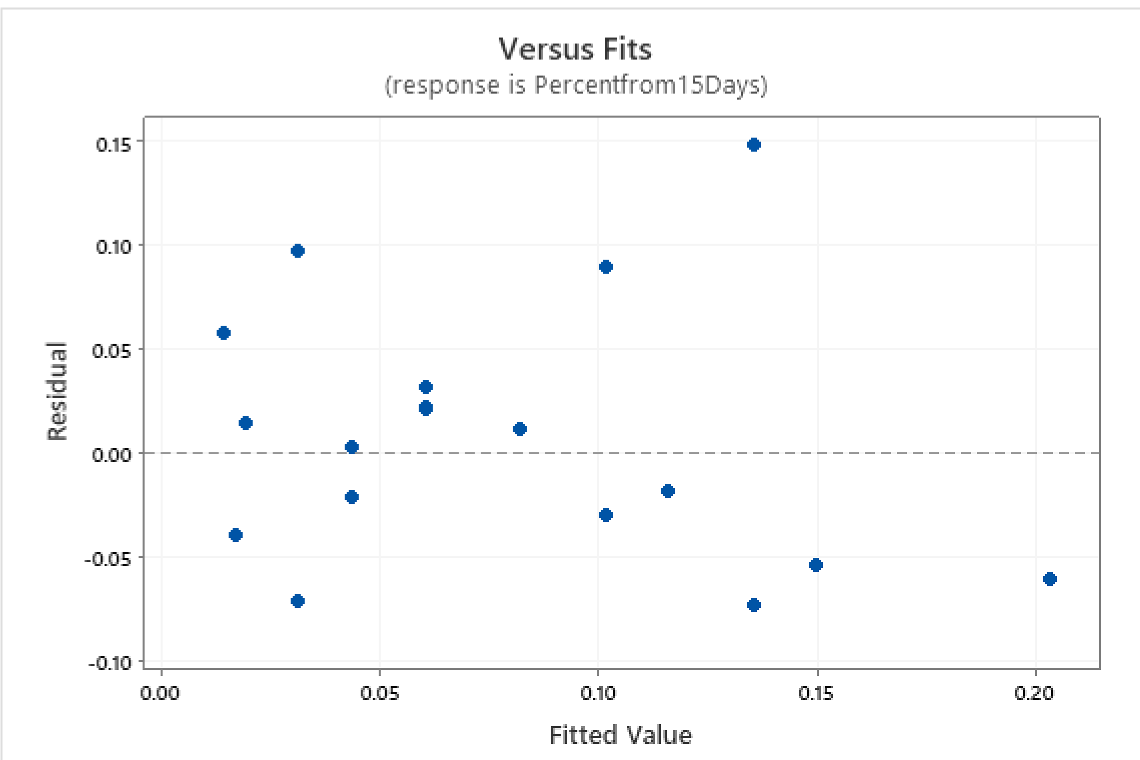
S	R-sq	R-sq(adj)
0.06205	70.82%	69.11%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	0.15886	0.158855	41.26	0.000
DaysAfter15	1	0.15886	0.158855	41.26	0.000
Error	17	0.06545	0.003850		
Lack-of-Fit	11	0.01915	0.001741	0.23	0.984
Pure Error	6	0.04630	0.007717		
Total	18	0.22430			



Normal Probability Plot
(response is Percentfrom15Days)
99
95
90
80
70
60
50
40
30
20
10
5
1
Percent
-0.15
-0.10
-0.05
0.00
0.05
0.10
0.15
Residual



Versus Fits
(response is Percentfrom15Days)
0.15
0.10
0.05
0.00
-0.05
-0.10
Residual
0.00
0.05
0.10
0.15
0.20
Fitted Value

% Recovery versus 0–15 Days after Frost Out – MnROAD Cell 26

Regression Equation

%_Recovery = 0.5486 + 0.01008 DaysAfterFrostOut

Coefficients

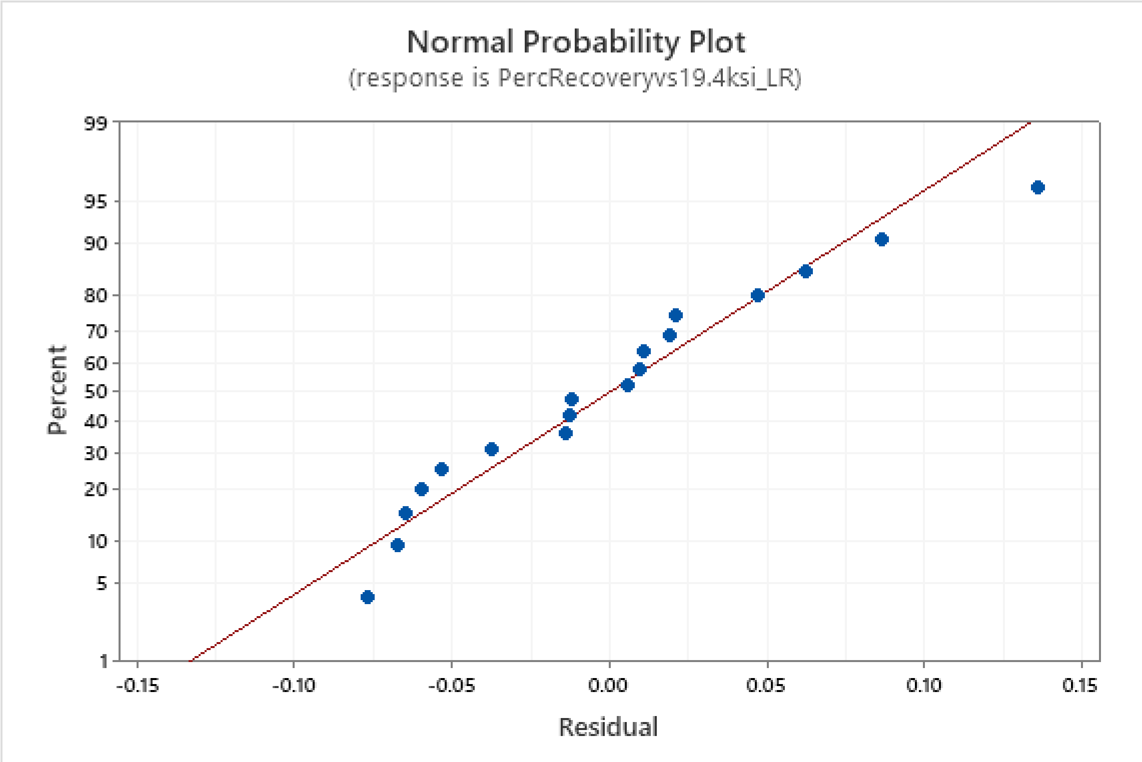
Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.5486	0.0400	13.73	0.000	
DaysAfterFrostOut	0.01008	0.00404	2.50	0.024	1.00

Model Summary

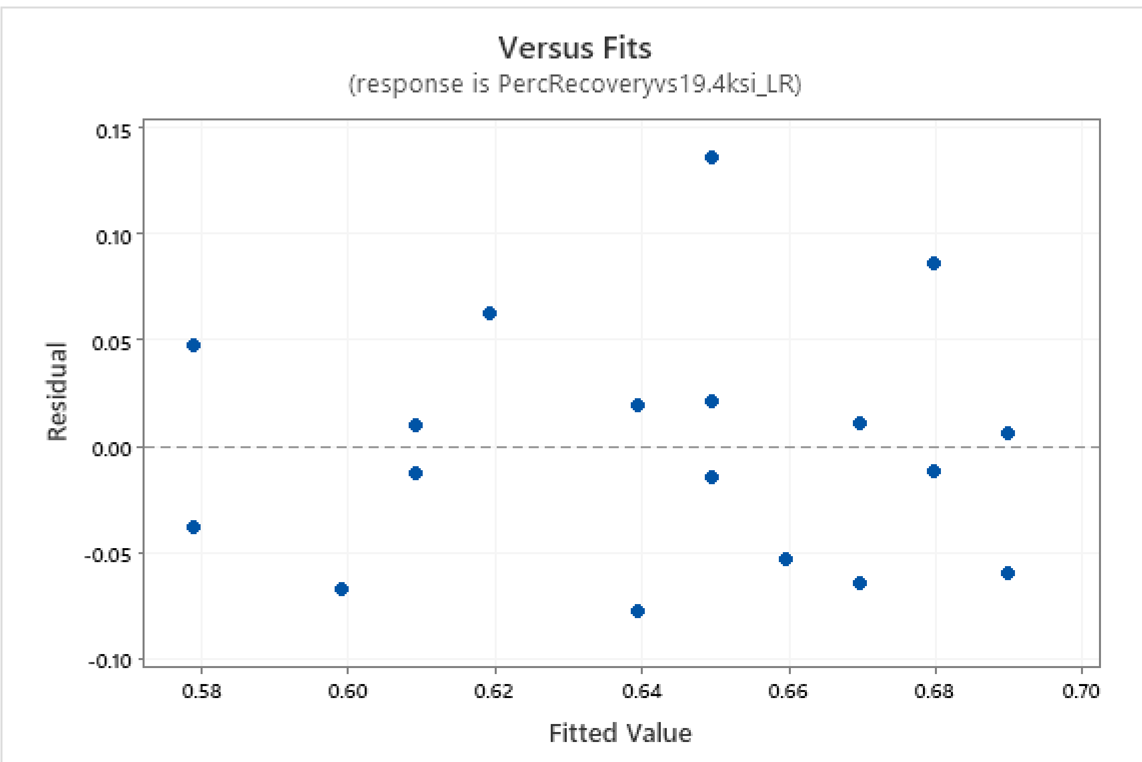
S	R-sq	R-sq(adj)	R-sq(pred)
0.0592553	28.04%	23.55%	11.08%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	0.02190	0.0219	6.24	0.024
DaysAfterFrostOut	1	0.02190	0.0219	6.24	0.024
Error	16	0.0562	0.00351		
Lack-of-Fit	8	0.0255	0.00319	0.83	0.600
Pure Error	8	0.0307	0.00383		
Total	17	0.0781			



Normal Probability Plot
(response is PercRecoveryvs19.4ksi_LR)
Percent
Residual
99
95
90
80
70
60
50
40
30
20
10
5
1
-0.15
-0.10
-0.05
0.00
0.05
0.10
0.15



Versus Fits
(response is PercRecoveryvs19.4ksi_LR)
Residual
Fitted Value
0.15
0.10
0.05
0.00
-0.05
-0.10
0.58
0.60
0.62
0.64
0.66
0.68
0.70

% Recovery = 15th Day versus 16–60 Days after Frost Out – MnROAD Cell 26

Regression Equation

%Recovery-15thDay = 0.000575 DaysAfter15

Coefficients

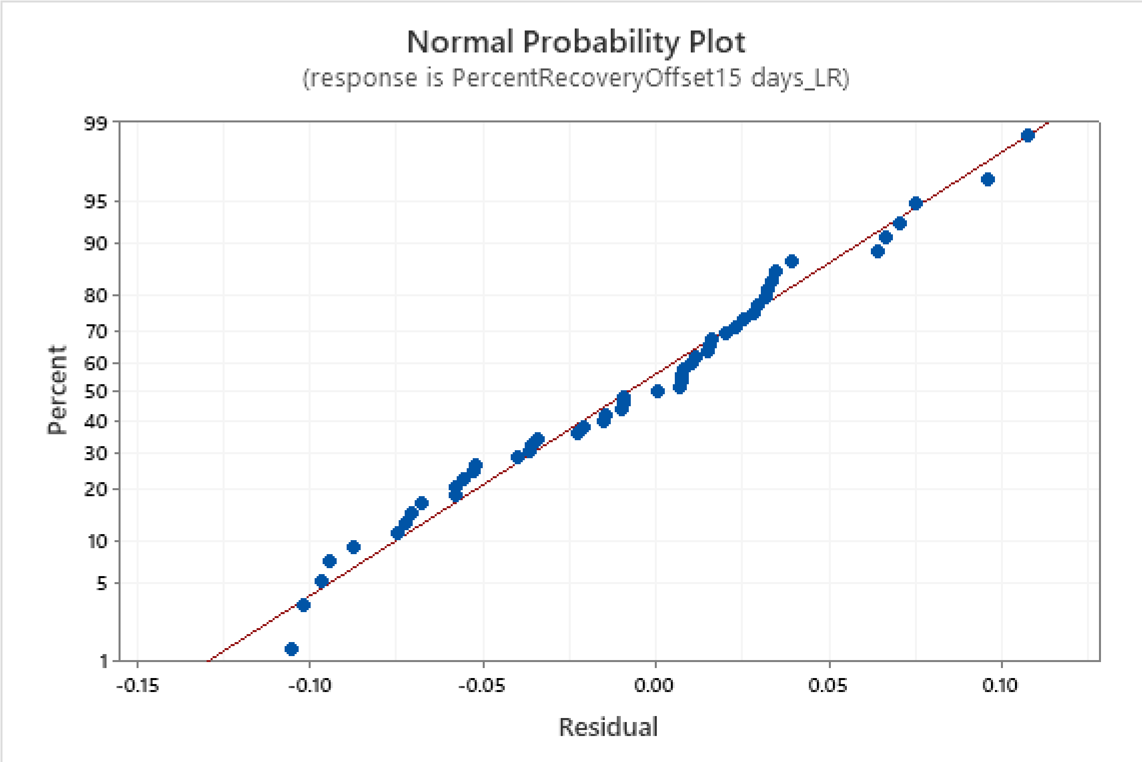
Term	Coef	SE Coef	T-Value	P-Value	VIF
DaysAfter15	0.000575	0.000281	2.05	0.046	1.00

Model Summary

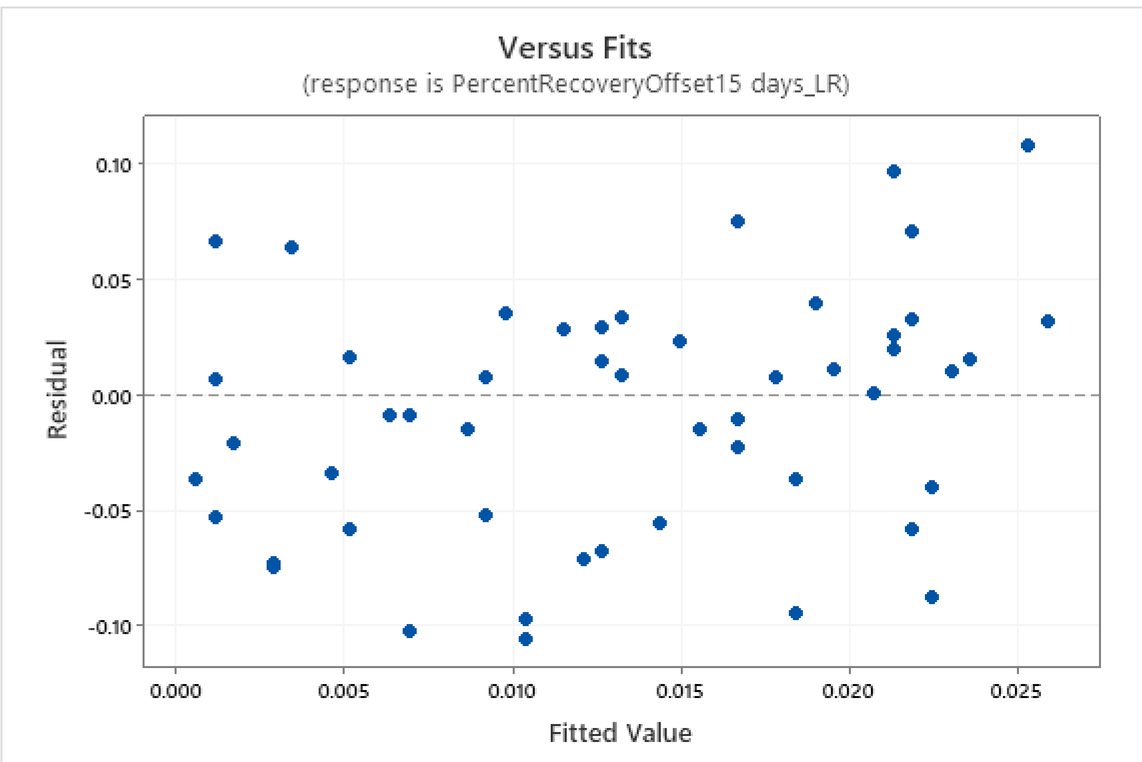
S	R-sq	R-sq(adj)	R-sq(pred)
0.0529860	7.74%	5.89%	3.72%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	0.01177	0.011771	4.19	0.046
DaysAfter15	1	0.01177	0.011771	4.19	0.046
Error	50	0.14038	0.002808		
Lack-of-Fit	32	0.09785	0.003058	1.29	0.286
Pure Error	18	0.04252	0.002362		
Total	51	0.15215			



Normal Probability Plot
(response is PercentRecoveryOffset15 days_LR)
Percent
Residual
99
95
90
80
70
60
50
40
30
20
10
5
1
-0.15
-0.10
-0.05
0.00
0.05
0.10



Versus Fits
(response is PercentRecoveryOffset15 days_LR)
Residual
Fitted Value
0.10
0.05
0.00
-0.05
-0.10
0.000
0.005
0.010
0.015
0.020
0.025

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