ABSTRACT
In freeze-thaw regions in North America, springtime load restrictions are commonly used as a pavement preservation strategy. During the spring, pavement layers can be in a saturated, weakened state due to partial thaw conditions and trapped water. Precise knowledge of the timing of freeze-thaw events is crucial to a successful load restriction strategy.

Deflection and environmental data collected from eight different low-volume flexible pavement test cells from the Minnesota Road Research Project (Mn/ROAD) was used to assess environmental effects on pavement strength. Relationships between air temperature and measured frost depths were investigated. The deflection data was analyzed in a backcalculation procedure to estimate the stiffness of individual layers. Finally, the rate of strength recovery with respect to base and subgrade type was investigated. In conjunction with this work, Minnesota Department of Transportation (Mn/DOT) is also conducting a statewide study using resistivity probes to monitor frost depth beneath several roads around the state.

The results show that a dramatic decrease in aggregate base stiffness occurs approximately when the thaw has just passed through that layer. This coincides with a short period in which the measured moisture content within the base is relatively high and before the overall surface deflection has reached a maximum.

INTRODUCTION
In freeze-thaw regions of North America, springtime load restrictions are typically used as a strategy to reduce pavement distress caused by loaded trucks. Precise knowledge of the timing of freeze-thaw events is crucial to successful application of a load restriction strategy. The timing and duration of the load restrictions depends on many factors including pavement structure, soil type, and drainage.

Various studies conducted at other locations have found that air and subsurface temperature can be used to identify thawing events. Some of this work has resulted in equations that predict the duration of the thawing period based on the air temperature history for the spring and preceding winter. Work is currently being done in Minnesota to adapt these procedures to Minnesota conditions.

OBJECTIVES
Overall, the objectives of this project are to evaluate current load restriction procedures and suggest improvements. The specific objectives addressed in this paper were to investigate and develop:

• Improve predictive equations for estimating thaw duration;
• Investigate changes in pavement strength relationships during freeze-thaw events; and
• Compare the strength-recovery characteristics of Mn/ROAD aggregate bases to assess the performance of different quality bases.

PROJECT BACKGROUND
This paper is comprised, in part, of the results of seasonal load and environmental testing conducted on the Mn/ROAD low-volume flexible test cells. The low-volume flexible pavement
test facility is a two-lane road and consists of seventeen 150 meter-long cells of which eight are flexible designs. Design hot mix asphalt thickness ranged from 75 to 150 mm (Table 1).

Table 1 - Test sections used in thaw-weakening studies

<table>
<thead>
<tr>
<th>Mn/DOT Resistivity Probe Study</th>
<th>District</th>
<th>Route</th>
<th>Hot Mix Asphalt (mm)</th>
<th>Aggregate Base (mm)</th>
<th>Subgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>2A</td>
<td>71</td>
<td>190</td>
<td>-</td>
<td>Sand</td>
<td></td>
</tr>
<tr>
<td>2A</td>
<td>72</td>
<td>150</td>
<td>140</td>
<td>Silty-clay</td>
<td></td>
</tr>
<tr>
<td>2B</td>
<td>102</td>
<td>140</td>
<td>450</td>
<td>Silt</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>CR 58</td>
<td>240</td>
<td>-</td>
<td>Sandy-clay</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>9</td>
<td>100</td>
<td>305</td>
<td>Clay</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>29</td>
<td>230</td>
<td>-</td>
<td>Sandy-clay</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>104</td>
<td>180</td>
<td>430</td>
<td>Clay</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mn/ROAD Test Cells</th>
<th>District</th>
<th>Cell</th>
<th>Hot Mix Asphalt (mm)</th>
<th>Aggregate Base (mm)</th>
<th>Subgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>24</td>
<td>75</td>
<td>100</td>
<td>Sand</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>25</td>
<td>125</td>
<td>-</td>
<td>Sand</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>26</td>
<td>150</td>
<td>-</td>
<td>Silty-clay</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>27</td>
<td>75</td>
<td>280</td>
<td>“ ”</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>28</td>
<td>75</td>
<td>330</td>
<td>“ ”</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>29</td>
<td>125</td>
<td>250</td>
<td>“ ”</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>125</td>
<td>305</td>
<td>“ ”</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>31</td>
<td>75</td>
<td>405</td>
<td>“ ”</td>
<td></td>
</tr>
</tbody>
</table>

Six of the eight Mn/ROAD asphalt cells are constructed on the native soil that is silty-clay. Cells 24 and 25 are constructed on a sand subgrade. Six of the eight cells are conventional designs with varying thickness of aggregate base and subbase. The base and subbase materials are dense-graded aggregates of varying quality.

The cells were constructed in late summer 1993. Deflection and environmental sensor testing has been conducted for four complete seasonal cycles. A weather station is located at the site. During the winter and early spring months, frost depth was monitored using soil resistivity probes (RP). A complete discussion of these sensors and the installation procedures used at Mn/ROAD are available (Atkins 1979; Schrader et al. 1994).

The climatic variation in Minnesota can be extreme. A historical analysis of air temperatures and freezing index (FI) for the past 30 years was performed using data from selected weather stations around the state. Based on the analysis, the mean yearly air temperature can vary from 3.5°C in the north to 7°C in the south. For the past 30-year period, the average yearly FI ranged from 1600°C-days in the north to 900°C-days in the south. Extreme winters have produced a FI as high as 2100°C-days in the north. FI values for the Mn/ROAD site have ranged from 900 to 1300°C-days over the past four seasons.
Extensive laboratory and field-testing of the Mn/ROAD materials has been done and is summarized elsewhere (Newcomb et al. 1995). The native subgrade soil is a low-to-medium plasticity silty-clay (USCS CL). The imported sand subgrade is classified as a poor to medium-graded sand (USCS SP-SM). The fines content in the aggregate bases range from over 10 percent for the Class-3 material to less than 6 percent for the Class 4, 5, and 6 material. The Class-6 base material is 100 percent crushed granite.

Tests done by the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) on the subgrade and two of the aggregate base materials (Class 3 and 6) addressed the frost susceptibility and effects of environmental variables on the resilient modulus (Bigl et al. 1996; Berg et al. 1996). Based on the CRREL results, the frost susceptibility of the subgrade material at the site is medium to very high. Resilient modulus tests on the Class-3 material indicated that it is extremely sensitive to moisture and freezing while the Class-6 is rated as medium.

A number of soil resistivity probes (RP) sensors have been installed in flexible pavements around the state to measure frost depth and thaw. A description of these sections is given in Table 1. This data is a valuable addition as it provides a broader base and added verification of Mn/ROAD cell observations.

RESEARCH APPROACH
Air temperature records from Mn/ROAD and satellite sites was compiled and analyzed using the following Equation 1.

\[
D = 0.018(FI) + 25
\]

(1)

Where FI = Freezing Index
\( D = \) Thaw Duration

The RP data from Mn/ROAD and the satellite sites was analyzed to determine the dates on which the thaw for each season began and ended. The difference between these dates defines the observed thaw duration (\( D \)) for comparison with the predicted thaw duration.

Pavement layer moduli for cells 25 and 27 through 30 were estimated using linear elastic backcalculation analysis. The backcalculation program EVERCALC 5.11 (WSDOT 1995) was used in this analysis. This program has been found to provide good results with respect to predicted pavement response and reasonableness of predicted moduli (Van Deusen 1995). The pavement structures were modeled as three-layer systems resting on a semi-infinite, fixed-modulus foundation. Experience has shown that this approach provides a more reasonable prediction of material stiffness (Van Deusen et al. 1995).

In order to fulfill the stated objectives the following analyses were done:
- Analyze RP frost profile data from Mn/ROAD and Mn/DOT sites to determine maximum frost penetration and duration of thaw period, based on the local (FI) for each cell calculate the predicted duration (\( D \)) from Equation 1.
- Compare observed durations (from RPs) to predicted durations using Equation 1.
• Analyze backcalculated parameters over time and with respect to thaw begin/end dates.
• Determine approximate date of the minimum base and subgrade stiffness as well as rate of recovery.

ANALYSIS RESULTS
A graph of the predicted and observed thaw durations (D) vs. the freezing index (FI) is shown in Figure 1. It appears that Equation 1 overpredicts the actual duration compared to Mn/ROAD data. Data from the Mn/DOT satellite sites appears to compare well with the Mn/ROAD data.

![Figure 1 - Observed and predicted thaw durations vs. Freezing Index](image)

Equation 1:

\[ D = 0.018\text{FI} + 25 \]

Improvements were made to better predict the thaw duration. In order to include the effects of frost depth, the actual measured frost penetration was incorporated into the regression analysis. The analysis resulted in the following equation:

\[ D = 0.01\text{FI} + 19.1\text{P} - 12090 \left(\frac{\text{P}}{\text{FI}}\right) \]  

Where \( P \) = frost depth in meters (M)  
\( \text{FI} \) = Freezing Index

Regression analysis gave an \( R^2 \) value of 0.50 from Equation 2, which still predicted the actual durations better than Equation 1 as seen in Figure 2. Note the term Standard Error of Estimate (SEE) was noted in this figure.

The results of the backcalculation analysis were used to construct seasonal stiffness change curves as shown in Figure 3. The change over time in base (BS) and subgrade (SG) moduli for cell 30 are shown for four consecutive seasons. Similar curves were obtained for the other
cells. Figure 4 shows an expanded view for 1994. The begin/end dates of the thaw are also shown. In all cells, the minimum base modulus occurs sometime during mid-thaw. The only exception is cell 25. Very little springtime weakening was noted for the cells 24-25, which were constructed on a sand subgrade.

Figure 2 – Comparison of observed and predicted thaw durations using new equation (2)

![Figure 2](image-url)

Figure 3 – Seasonal variation in backcalculated moduli – Cell 30 Mn/ROAD

![Figure 3](image-url)
The rate of strength recovery in the backcalculated moduli was investigated and several consistent trends were observed. In general, for the past four spring seasons the bases layer modulus increases at the end-of-thaw relative to the minimum at mid-thaw has been variable and ranged from 15 to over 100 percent. Results are shown in Figure 5. Two weeks past the thawing, the recovered strength levels are at least 50 percent (with some years seeing recoveries well over 200 percent). Incorporation of field test sites from areas with various soil types and drainage properties are desired for broadening the scope of the study. The two cells with aggregate bases having low fines (Class 5 and 6) have overall higher moduli during the spring thaw relative to the base materials with high fines (Class 3 and 4). This results in an apparently higher recovery rate for the Class 3 and 4 base materials (Figure 5).

CONCLUSIONS AND RECOMMENDATIONS
Based on the results presented in this paper it is reasonable to conclude the following:

- The predicted thaw durations from equation 1 appear to be conservative. Based on data sites from Mn/ROAD and around the state, a new equation for thaw duration was developed Equation 2. The standard error of estimate for this equation/model is ±8 days.
- With the exception of the sand subgrade in cells 24-25, the minimum base stiffness period appears to occur sometime during the middle of the thaw period. It is recommended that other sites be investigated to confirm these observations.
- The base layer modulus increase at the end-of-thaw relative to the minimum at mid-thaw has ranged from 15 to over 100 percent. At two weeks past the initial thaw, the recovered strength levels are at least 50 percent with some years seeing recoveries over 200 percent.
The two Mn/ROAD cells with aggregate bases which have low fines (Class 5 and 6) have overall higher moduli during the spring thaw relative to aggregate bases that have higher fines (Class 3 and 4). This implies an apparently higher recovery rate for the Class 3 and 4 base materials.

Eight-week load restriction duration will still be used, as in the past, with an emphasis on early placement. Historically the posting period has averaged 7.9 – 8.6 weeks depending on the zone.

The start of the load restriction period will be determined for each zone using measured and forecasted daily temperatures (obtained from the National Weather Service). The criteria used to determine when load restrictions will be placed will be: a thawing index greater than 25 F degree-days and predicted increases in the thawing index based on the 3-day forecast. This insures a 3-day notice to the public that the posting period is coming.

Figure 5 – Comparison of recovery rates for different Mn/ROAD aggregate base materials, 1994 - 1997

IMPLEMENTATION
Based on the results presented in this paper Mn/DOT is going to:

- Introduce the Process – Notification of the proposed freeze-thaw restriction process will be made to both public and private organizations describing the criteria for determining the road posting dates. This will be done in January 1999.

- Communication of Data – The internet will be used to receive and post air temperatures, frost depths, and measured deflections for a number of locations in Minnesota as the spring thaw approaches. Mn/ROAD Web page address (http:\mnroad.dot.state.mn.us).
• Notification – A recorded telephone message will provide 24-hour access to the status of the road restriction dates. This will provide a 3-day notice of future posting for each zone in the state. The Mn/ROAD web page will also provide this information.

ACKNOWLEDGEMENTS
This work was funded by the Minnesota Local Road Research Board and their support is gratefully acknowledged. Sincere appreciation is extended to John Siekmeier and Dave Van Deusen who are currently working on improving this management tool, along with the personnel who collected the data and assisted with the analysis in this paper. This includes Mn/DOT District personnel and Mn/ROAD researchers John Zollars, Greg Johnson, Ruth Roberson, Greg Larson.

REFERENCES


