A Simplified Model to Predict Frost Penetration for Manitoba Soils

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Abstract

Monitoring the seasonal variation of the properties of pavement materials is an essential practice to protect pavements from early deterioration. In spring season, the top layers of pavement start to thaw while the bottom layers are still frozen. As a result, the moisture remains contained in the top layers and can not be drained. Consequently, pavement layers experience high strains therefore Spring Load Restrictions (SLR) are applied to protect pavement from early deterioration. As thawing continues to advance throughout the spring season, the pavement starts to recover its strength until pavement reaches its full strength at the end of thawing process. Determination of the application and lifting times of SLR is a challenging issue. An early application, or late lifting, of SLR wastes the opportunity to carry more loads. A late application, or early lifting, of SLR causes damage to the pavement structure and accelerates pavement failure.

In winter season, the winter load premium can not be allowed until frost penetration reaches a certain depth. The depth of frost penetration can be either measured in the field. Having a reliable model to predict the depth of frost penetration provides a time and cost effective alternative to field measurements. This paper introduces the analysis conducted to develop a simplified model to predict the frost penetration in Manitoba. This work represents part of an ongoing study which aims to provide better understanding to the seasonal variation of the properties of pavement materials. The climatic and seasonal monitoring data for the Oak Lake test section, which was collected as part of the Long-Term Pavement Performance (LTPP) Program, was utilized for this purpose. The proposed frost penetration model was compared to the Northern Ontario frost penetration model and a good agreement was found between them.

Introduction

Pavements in Canada experience extremely cold temperatures during winter. With the existence of moisture, frost can migrate through the subsurface layers. In spring season, temperature starts to warm up and pavements top layers start to thaw. Spring Load Restriction (SLR) is applied during the thawing process of pavements to protect them from deterioration. An accurate determination of the start and end dates of SLR is a challenging issue for transportation agencies. An accurate determination of the start and end dates of SLR leads to an efficient utilization of the structural capacity of the highway network and protect the pavement structure from excessive damage.

The objective of this project is to study the seasonal variation of pavement materials properties. For this purpose, the Long-Term Pavement Performance (LTPP) climate and seasonal monitoring databases are utilized. This paper introduces the analysis conducted to develop a simplified model to predict the frost penetration in Manitoba.

Background

The strength of pavement materials is affected by the freezing and thawing cycles that pavements experience during the year. In winter, frost starts to migrate through the subsurface layers and the pavement capacity becomes higher than the design value. In spring, the air temperature starts to warm up and thaw starts to penetrate through pavement layers. Due to thawing of top layers while the bottom layers are still frozen, moisture is trapped in the top layers (base layer) and can not be drained. As a result, the pavement structural capacity becomes less than the design value. As thawing continues to advance throughout the spring season, pavement layers start to recover until they reach their full strength again.

The main factor that controls the depth of frost penetration is the variation of air temperature during winter which can be represented by the freezing index. The properties of subgrade soil, such as particles size and moisture content, can also affect the frost penetration. Several formulas and charts have been developed for predicting the depth of frost penetration. The corps of engineers has developed an empirical relationship between the depth of frost penetration and freezing index for well drained base course [1]. The Stefan equation is one of the first known theoretical formulas to calculate frost penetration [2]. The Stefan equation, which is presented below, is derived from the fundamental equations of heat flow and storage.

$$D = \sqrt{\frac{48kF}{L}} \tag{1}$$

Where:

D = Depth of frost penetration (ft)

k = Thermal conductivity (Btu's per ft^2 per degree Fahrenheit per ft per hr)

F = Freezing index (F°. Days)
L = Volumetric heat of latent fusion (Btu's per ft^3)

And,

$$L = 1.434\,\omega\gamma \tag{2}$$

Where:
ω = Moisture content
γ = Dry density (lb per ft^3)

In equation 1, the air freezing index is the variable that has the most influence on the depth of frost penetration. The depth of frost penetration can be estimated with a reasonable accuracy from air freezing index only if the effect of the other variables can be minimized. Argue and Denyes studied the relation between the maximum frost penetration and the freezing index [3]. Different relationships were developed to predict the maximum frost penetration from the freezing index based on the type of surface and whether it is covered with snow or not. Huen et al. used the temperature data collected from road weather information system (RWIS) installed in northern Ontario to predict frost depth [4]. The relationship between cumulative freezing degree days and frost depth was found to be as follows:

$$FD = 5.537\sqrt{TI} \tag{3}$$

Where:
FD = Frost depth (cm)
TI = $\sum (T_{\text{Air, Mean}} + 5.31^{\circ}C)$ (C°. Days)
$T_{Air,\,Mean}$ = Average daily air temperature (C°)

Methodology

The LTPP database was utilized in this research. Air temperature and precipitation are two of the climatic variables that were recorded for the LTPP test sections [5]. As a part of the LTPP Seasonal Monitoring Program (SMP), the depth of frost penetration was monitored for sixty four LTPP sections [6]. The depth of frost penetration was determined by the Electrical Resistivity (ER) method.

Oak Lake test section is one of the LTPP test sections in Manitoba. The pavement structure of the test section consists of 100 mm of asphalt concrete over 450 mm of base course. The climate and seasonal monitoring data for this section was utilized to study the relationship between the depth of frost penetration and climate data. Due the insufficient number of data points for Oak Lake test section, the climate and seasonal monitoring data for another two LTPP test sections in Saskatchewan and Minnesota, with similar pavement structure and environmental conditions, were utilized.

Two relationships were evaluated in this study. The first relationship is between the maximum depth of frost penetration, as a dependent variable, and freezing index and rain precipitation, as independent variables. The second relationship is between the depth of frost penetration and the cumulative freezing degree-days. The following sections describe the analysis conducted for the two relationships.

Freezing Index and Cumulative Precipitation Model

The average daily air temperature was recorded for the Oak Lake test section (831801) starting from 1993 to 2003. The average daily air temperature database has several missing records. These missing records were replaced by the average daily air temperature obtained for the closest weather stations to the test section. In the LTPP database, the depth of frost penetration is available only for four years. Table 1 shows the maximum frost penetration, the freezing indices, and the cumulative rain precipitation during the previous summer (from March 1st to end of October) for Oak Lake section.

For Oak Lake test section, the frost penetration was measured for 4 years only. The correlation coefficient between the cumulative rain precipitation during summer and the maximum frost penetration for the next winter is 0.74. The good correlation encourages to do further study when more data points are available. The seasonal monitoring data for Saskatchewan test section 906405 and Minnesota test section 276251 (Bemidji Bypass), which have similar pavement structure and environmental condition to Oak Lake section, were added to Manitoba data set. Table 2 shows the maximum frost penetration, the freezing indices, and the cumulative rain precipitation during the previous summer for Saskatchewan 906405 and Minnesota 276251 test sections.

TABLE 1: Maximum Frost Penetration for Oak Lake Test Section

Year	Max. frost penetration (m)	Air Freezing Index (C°. Days)	Cumulative rain precipitation (mm)
1993-1994	1.16	1842	363.6
1994-1995	1.47	1571	336
1996-1997	1.47	2149.4	372.3
2000-2001	1.975	1878.6	415.3

TABLE 2: Maximum Frost Penetration for SK 906405 and MN 276251 Test Sections

	Year	Max. frost penetration (m)	Air Freezing Index (C°. Days)	Cumulative precipitation (mm)
MN 276251	1993-1994	2.25	1584.2	632.9
	1994-1995	2.25	1156.3	642
	1996-1997	2.25	1662.4	486.7
	1999-2000	1.895	866.8	782.3
	2000-2001	2.105	1468.1	620.2
SK 906405	1993-1994	2.05	1879.1	435.7
	1994-1995	1.96	1643.7	357.2
	1996-1997	2.05	2275.9	347.1

A linear regression analysis was conducted to develop a relationship between the maximum frost depth, as a dependent variable, and air freezing index and cumulative rain precipitation, as independent variables. This relationship is given by the following equation:

$$D_{\max} = 2.5\sqrt{FI} + 0.186P \tag{4}$$

Where:

D_{max} = Maximum frost penetration depth (cm)
FI = Air freezing index (C°. Days)
P = Cumulative rain precipitation during the previous summer season from March 1st to end of October (mm)

The coefficient of determination for the proposed model in equation 4 is 0.88. Figure 1 shows the maximum frost penetration calculated from equation 3 and the maximum frost penetration from LTPP database.

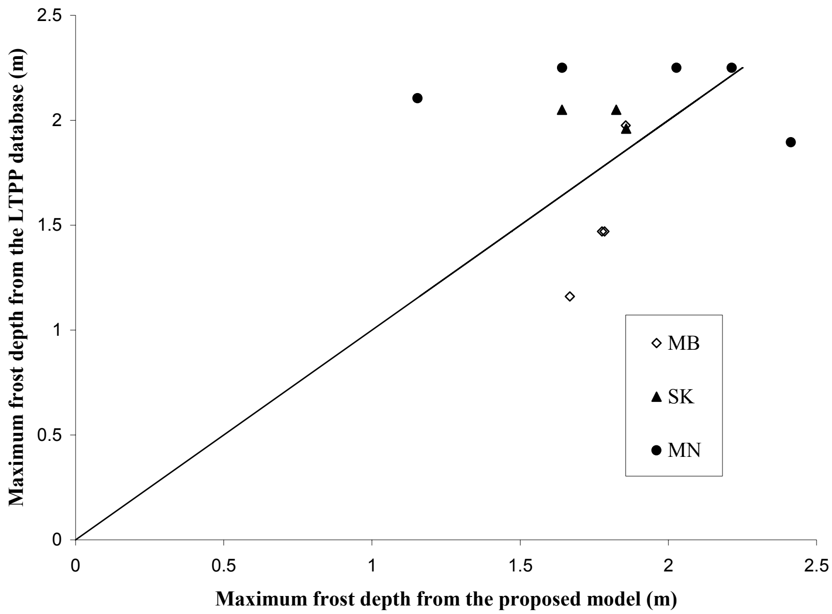

FIGURE 1: Maximum Frost Penetration Depth from the Proposed Model

More measurements for frost penetration in Manitoba are needed for improving the accuracy of this model.

Cumulative Freezing Degree-Days Model

The maximum frost penetration and the air freezing index were replaced by the frost depth and the cumulative air freezing degree-days, respectively, to increase the number of data points. The cumulative freezing degree-days was accumulated starting from the freezing point, which is the maximum of the cumulative air temperature curve in the autumn season. Figure 2 shows the frost depth and the cumulative air freezing degree-days for the three test sections.

From Figure 2, Minnesota test section (27625) showed higher frost depth than Manitoba and Saskatchewan at the same cumulative freezing degree-days. This can be due to the higher rain precipitation in Minnesota test section, where the cumulative rain precipitation (for summer season) for Minnesota test section ranged from 150% to 200% of the cumulative precipitation in Manitoba and Saskatchewan test sections. Therefore, the Minnesota test section was excluded from the analysis.

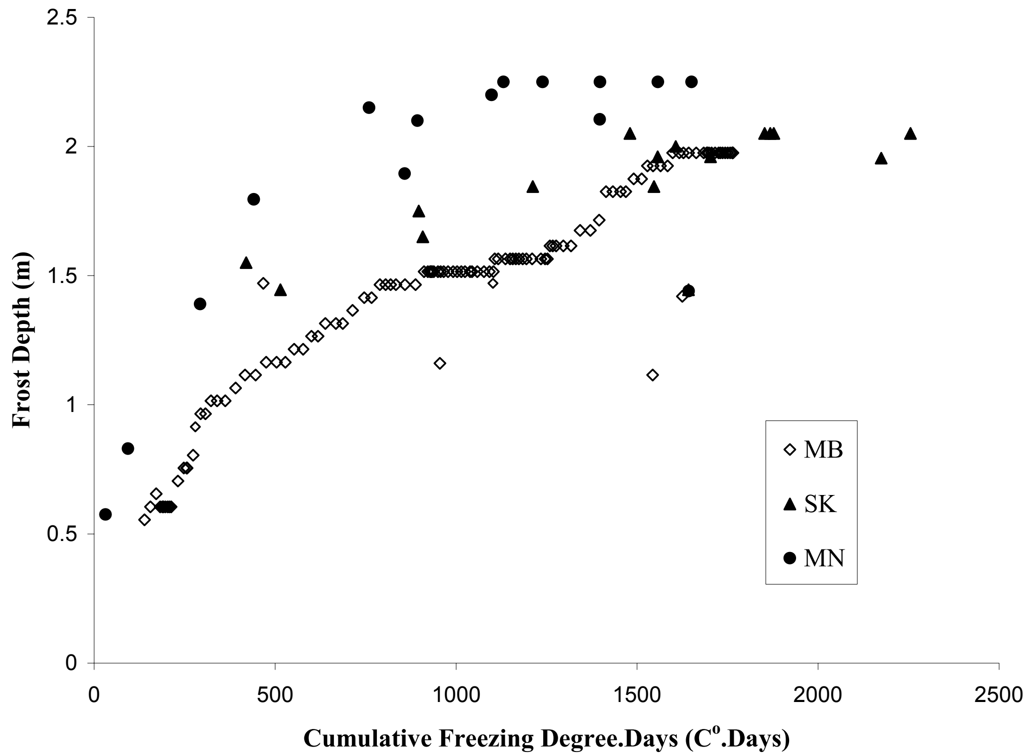

FIGURE 2: Frost Depth and Cumulative Air Freezing Degree-Days for MB, SK, and MN

The best fitting function for the frost depth and the cumulative freezing degree-days data set was found to be a power function with a power of 0.5. The relationship between frost depth and cumulative freezing degree-days can be represented by the following equation:

$$D_F = 4.8\sqrt{F} \tag{5}$$

Where:

D_F = Frost depth (cm)

F = Cumulative freezing degree-days starting from freezing point (C°. Days)

The coefficient of determination for the proposed model in equation 5 is 0.89. Figure 3 shows the predicted and measured frost depth.

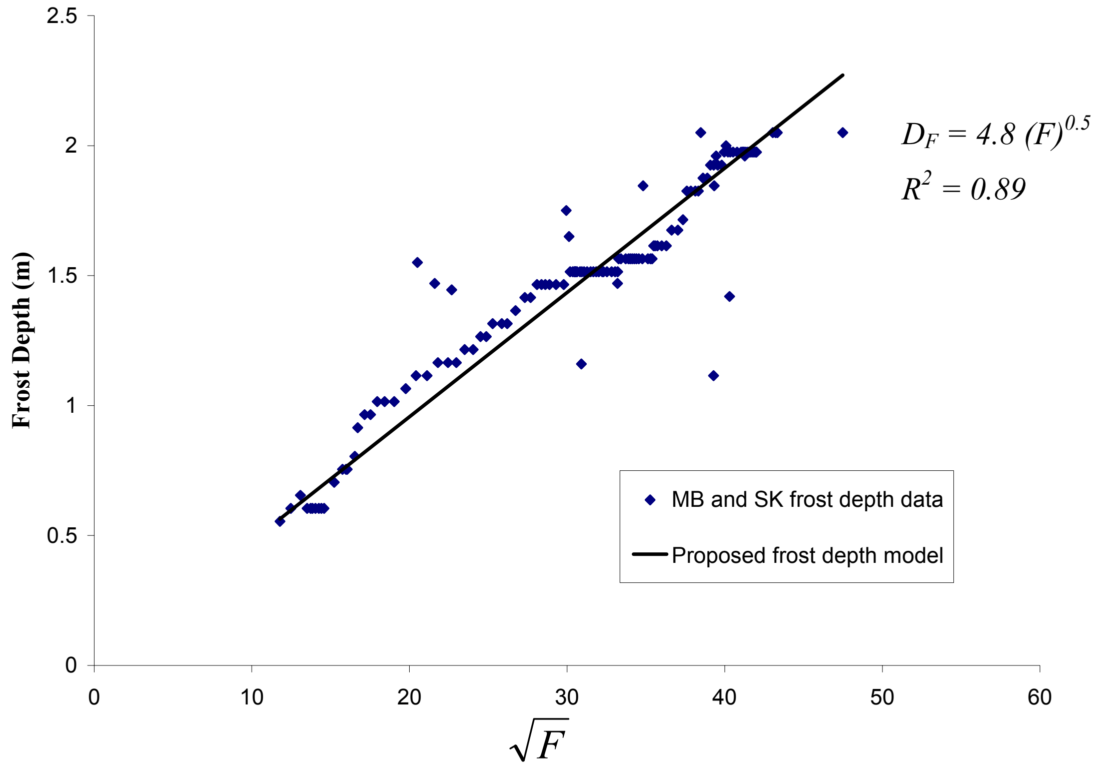

FIGURE 3: Proposed Frost Depth Model for Manitoba

There is a good agreement between this model and the model proposed by Huen et al. [4] for frost penetration in northern Ontario.

Summary and Conclusions

Air temperature, which can be represented by freezing index, is the dominant variable that controls the depth of frost penetration. A relationship with an acceptable accuracy can be developed between the depth of frost penetration and the freezing index by minimizing the effect of the other variables.

Cumulative rain precipitation showed a good correlation to maximum frost penetration in the following winter. The good correlation encourages to do further study for this relationship. The coefficient of determination for the maximum frost depth, freezing index, and cumulative rain precipitation model was 0.88. More data points are required to verify the quality of this model.

The coefficient of determination for the frost depth and cumulative freezing degree-days model was 0.89. A good agreement was found between this model and the model developed by Huem et al. [4] for frost penetration in northern Ontario.

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References

1. U.S. Army corps of Engineers (1958) *"Engineering and Design, Pavement Design for Frost Conditions"*, EM-1110-345-306.

2. Yoder E. J.; and Witczak M. W. (1975) *"Principles of Pavement Design, Second Edition"*, John Wiley & Sons, INC.

3. 1. Argue, G. H.; and Denyes, B. B. (1974) *"Estimating the Depth of Pavement Frost and Thaw Penetrations"*, Transportation Research Record, Volume 497, p 18- 30.

4. Huen, K.; Tighe, S.; Mills, B.; and Perchanok, M. (2006) *"Development of Tolls for Improved Spring Load Restriction Policies in Ontario"*, The Annual conference of the Transportation Association of Canada (TAC), Charlottetown, Prince Edward Island.

5. Mohseni, A. (1998) *"LTPP Seasonal Asphalt Concrete (AC) Pavement Temperature Models"*, Federal Highway Administration, U.S. Department of Transportation, Publication No. FHWA-RD-97-103.

6. Ali, H. A.; and Tayabji, S. D. (1999) *"Determination of Frost Penetration in LTPP Sections, Final Report"*, Federal Highway Administration, U.S. Department of Transportation, Publication No. FHWA-RD-99-088.