Evaluation of Existing Spring Load Restriction Models Based on Experimental Field Data

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ABSTRACT

A large number of road structures are subjected to seasonal freezing and thawing in Canada. Low volume (secondary) roads in frost-prone regions are susceptible to loss of structural capacity during thaw season. During freezing season, ice lenses form in the subgrade soil. Melting of these ice lenses during thawing season is deemed to be the main cause of losing structural capacity. There are several suggested empirical methods in the literature for predicting the onset and duration of thawing condition in the subgrade soil. Generally, transportation agencies use the outcome of these prediction models to apply limitations on maximum allowable loads of trucks passing on the vulnerable roads which is known as Spring Load Restriction (SLR) or Spring Road Ban (SRB).

As part of an ongoing research on the Integrated Road Research Facility (IRRF)'s test road constructed in August 2012 which is a new access road to Edmonton Waste Management Center (EWMC), the temperature data were recorded over the winter of 2013 using thermometers installed across the depth of the pavement structure in order to monitor the temperature variation through different layers (Hot Mix Asphalt (HMA), Granular Base Course (GBC) and subgrade.)

This research is a comparative study between 4 different methods to evaluate their credibility in determining the imposition date of SLR using the recorded field temperature data. It was found that all models were able to accurately predict the onset of thawing through the pavement.

KEYWORDS: Spring Load Restrictions, Freeze Depth, Thaw Depth, Experimental Field Data

INTRODUCTION

Pavement structures are normally comprised of asphalt, unbound granular base and subgrade layers. Due to the presence of moisture in pavement layers, pavement performance is affected by seasonal temperature variation. When the moisture in subgrade layer starts to freeze from top to bottom, it increases the freezing depth and leads to formation of ice lenses and visible frost-heave on the surface of the asphalt layer. During late winter-early spring, with increase in the ambient air temperature, thawing starts to gradually occur in the system within the upper layers while the lower layers are still frozen. This phenomenon leads to accumulation of water close to the saturation level in the upper layer which eventually results in loss of bearing capacity of the affected layers. During this critical period, if therod is open to traffic, severe deformations will be imposed on the pavement structure by traffic loading. Since the subgrade layer is mostly composed of fine-grained soils, the permeability of this layer is very low. Thus, loss in the pavement strength becomes more crucial when thawing process penetrates through the subgrade layers. Normally, it takes weeks or even months for the excess water to drain out of the system which means that the performance of the pavement is affected during this period particularly if the silt or clay in the subgrade layer is moisture susceptible (Baïz et al. 2008, Hannele and Doré 2009, MnDOT 2014).

Low volume roads, also known as secondary roads, play an important role in the economy by providing access to local industries. These roads are subject to high intensity traffic loading yet with low frequency meaning that they undergo less than 1,000 vehicles per day (Baïz et al. 2008). In cold climate regions where freeze-thaw phenomenon is prevalent, low volume roads are prone to traffic-loading-induced damage during the thaw season. In contrast with the primary service roads, it is not recommended to design secondary roads using high quality frost-resistant construction material from financial standpoint. On the other hand, reclamation and rehabilitation of the existing roads with less thaw-weakening susceptibility may not be financially feasible. Thus, in order to reduce structural damage of roadways, many transportation agencies enforce Spring Load Restrictions (SLR) when the pavement structure is susceptible to thaw-season damages (Baïz et al. 2008, Yu et al. 2008, and Miller et al. 2015).

Applying SLR prevents structural damage to low volume roads. However, it exerts financial constraints on trucking industries by preventing them from loading the trucks to maximum capacity or forcing truck drivers to take detour to reach their destination which results in more fuel consumption and increase in the number of passes to haul loads. Therefore, it is a matter of importance to outline the exact time frames of SLR to prevent thaw season damages and minimize the economic constraints upon trucking industries (Miller et al. 2015). This paper attempts to evaluate current methods for predicting the time for implementing SLR and its removal from the road by using field temperature data recorded during winter of 2013 and spring of 2014.

SLR METHODS REVIEWED IN THIS PAPER

Mahoney et al. (1986) proposed a set of empirical equations to obtain Freezing Index (FI) and Thawing Index (TI). This method uses a fixed temperature point, 29 degrees Fahrenheit, as the reference temperature to calculate TI. The equations are as below:

$$FI = \sum(32 - \bar{T}) \qquad (1)$$

where:

$$\bar{T} = \frac{1}{2}(T_{max} + T_{min})$$

T_{max} = Maximum daily air temperature (^{o}F)

T_{min} = Minimum daily air temperature (^{0}F)

The freezing period is deemed to start when daily temperature becomes less than or equal to 32 °F for several days.

$$CTI = \sum(\bar{T} - 29) \qquad (2)$$

If the air temperature decreases past the reference point, the calculated TI value should be reset to zero meaning that the thawing index value cannot be negative. For thick pavements which are typically comprised of over 2 inch thick asphalt and 6 inch base layers, respectively, the “should-level” to impose the spring load limitations is when TI reaches 25°F and the “must-level” is when TI reaches 50°F.

Based on the regression analysis, they developed two models for the duration of having SLR in effect. The first equation is:

$$\text{Duration (days)} = 25 + 0.01\ (\text{FI}) \tag{3}$$

The prediction obtained from Eq. (3) is more accurate when the FI is within the range of 400 and 2000 °F-days. In another approach, the TI was used as benchmark to estimate the duration of SLR by developing Eq. (4). They reported a better coefficient of correlation for this method in comparison to Eq. (3).

$$\text{TI} = 0.3\ (\text{FI}) \tag{4}$$

Minnesota Department of Transportation (Mn DOT 2014) proposed a method in which the cumulative thawing index (CTI) is calculated for posting SLR. In this method, the threshold point for the CTI to apply SLR is 25 °F-days.

$$CTI_n = \sum_{i=1}^{n}(Daily\ TI - 0.5 \times Daily\ FI) \tag{5}$$

- When $\left(\frac{T_{max}+T_{min}}{2} - T_{reference}\right) < 0°\text{F}$ and $CTI_{n-1} \leq 0.5 \times \left(32°\text{F} - \frac{T_{max}+T_{min}}{2}\right)$ then, daily TI and daily FI should be both assigned 0 °F-day.
- When $\left(\frac{T_{max}+T_{min}}{2} - T_{reference}\right) > 0°\text{F}$ then, daily TI=$\left(\frac{T_{max}+T_{min}}{2} - T_{reference}\right)$ and daily FI = 0 °F-day.
- When $\left(\frac{T_{max}+T_{min}}{2} - T_{reference}\right) < 0°\text{F}$ and $CTI_{n-1} > 0.5 \times \left(32°\text{F} - \frac{T_{max}+T_{min}}{2}\right)$ then, daily TI = 0 °F-day and daily FI = $\left(32°\text{F} - \frac{T_{max}+T_{min}}{2}\right)$

where,

CTI_n = cumulative thawing index calculated over ‘n’ days (°F-days),

CTI_{n-1} = Cumulative thawing index for the previous day

$T_{reference}$ = Reference air temperature (°F)

CTI resets to zero on January 1.

According to Mn DOT’s (2014) recommendation the reference temperature is a changing temperature which aims to account for the increasing solar gain on the pavement surface during spring thaw season. This temperature sets to 32 °F for January after which it decreases by 2.7 °F during the first week of February and then by 0.9 °F weekly until the end of thawing season.

Mn DOT recommends that the end date of SLR in different frost zones should be determined by measuring different factors such as daily ambient air temperature, frost depth and other involving parameters; however, SLR should not last more than eight weeks after the date of application unless inclement weather condition exists.

Manitoba Department of Infrastructure and Transportation conducted weekly Falling Weight Deflectometer (FWD) testing at four pavement test sites during 2009 SLR period. The researchers used the deflection measurements along with temperature and/or moisture data across the depth of the pavement structures to develop a recommendation for imposing SLR (Bradley et al. 2012). In this method, the SLR should be applied when CTI reaches 15 °C-days and the cumulative thawing index was calculated by using the following equation:

$$CTI = \sum Daily\ TI = \sum \left(T_{reference} + \frac{T_{max}+T_{min}}{2}\right) \tag{6}$$

where,

$T_{reference}$ = 1.7°C starting March 1, increasing daily by 0.06°C until May 31 and resetting to zero afterwards.

Note that if $\frac{T_{max}+T_{min}}{2} < 0°C$ then daily TI will change to $T_{reference} + \frac{T_{max}+T_{min}}{4}$ to compensate for the period during which the ambient air temperature oscillates below the freezing point of water. If CTI <0, it should be reset to zero.

In this method, SLR should be terminated when CTI reaches 350 °C-days or after its durations exceeds eight weeks, whichever occurs sooner.

Baïz et al. (2008) obtained field data in Northern Ontario, Canada from instrumentation of a low-volume pavement section on Highway 569. They found a strong correlation between the magnitude of frost depth in the pavement and environmental parameters monitored by road weather information systems. The reference temperature was calculated based on the recorded air and pavement surface temperature data followed by the calculation of FI and TI based on Eq. (7) and Eq. (8):

$$\begin{cases} FI_0 = -T_0 \\ FI_{i+1} = FI_i - T_{i+1} \\ FI_i < 0 \Rightarrow FI_i \equiv 0 \end{cases} \tag{7}$$

where,

i = number of days after the day indexed as day

FI_0 = freezing index value on the first day when air temperature falls below 0°C for the first time

FI_i = freezing index on day i (°C-days)

$$\begin{cases} TI_0 = -T_{ref} \\ TI_{i+1} = T_{i+1} - TI_i \\ TI_i < 0 \Rightarrow TI_i \equiv 0 \end{cases} \tag{8}$$

where,

TI_0 = thawing index value the first day when air temperature falls below 0°C for the first time

TI_i = thawing index value on day (°C-days)

In order to obtain the frost depth (FD) and thaw depth (TD), they suggested a a linear model in which FD and TD are functions of the square roots of both TI and FI (Eq. (9) and Eq. (10)). Two different sets of regression coefficients are assigned to the models for the freezing season and for the start of thawing period when TI continually rises above 0 °C:

$$0 \leq i \leq i_0 \Rightarrow FD_i = a+b\sqrt{FI_i}+c\sqrt{FD_i}\ ,\ TD_i = d+e\sqrt{FI_i}+f\sqrt{TI_i} \tag{9}$$

$$i \geq i_0 \Rightarrow FD_i = g+h\sqrt{FI_i}+j\sqrt{FD_i}\ ,\ TD_i = k+l\sqrt{FI_i}+m\sqrt{TI_i}$$

where,

i_0 = day after which TI consistently rises above 0°C

a,b,c,d,e,f,g,h,j,k,l,m = regression coefficients.

SCOPE OF THE WORK

In order to validate the above discussed methods for determining SLR-on and SLR-off dates, the temperature data was recorded from November 2013 to May 2014 at the University of Alberta's Integrated Road Research Facility (IRRF) in Edmonton, Alberta, Canada. The IRRF is a new test road facility connecting Edmonton Waste Management Centre (EWMC) to Antony Henday Drive (HWY 16). The pavement is comprised of a 250-mm hot mixed asphalt (HMA) placed over a 450-mm granular base course (GBC). The subgrade is natural soil, composed of clayey sand (SC). Three thermometers were installed in the GBC layer at depths 40 cm, 50 cm and 60 cm from the surface. Two other thermometers were placed at depths 170 cm and 250 cm within the subgrade layer. One thermistor within the HMA layer was placed at depth 2.5 cm from the surface. The cross section and the location of the embedded sensors are presented in Figure 1.

The data from thermometers were collected using a Datalogger CR-1000 which was connected to an on-site computer. The information was then remotely transmitted to the university from the on-site computer. The Climatic data was collected from the EWMC's closest weather station located at about 700 m from the IRRF test road.

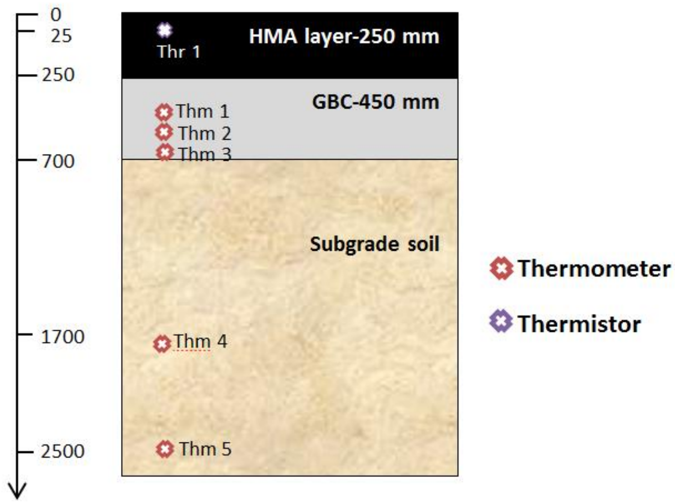


Figure 1- The cross sections and as-built depth of thermometers

The temperatures recorded by thermometer sensors were used to obtain the actual thaw and freeze depth through the pavement depth. The asphalt temperature data recorded by the thermistor were used to find the actual reference temperature of the asphalt layer at the site used in the suggested method by Baïz et al (2008).

In this study, four methods outlined in the previous section are used to calculate CTI for the winter of 2013 and the spring thaw season of 2014 based on the air temperature data recorded from the weather station. Consequently, it would be determined when the SLR should be applied according to each method's recommendations. The results were verified by the actual physical condition of the test road obtained from the temperature data.

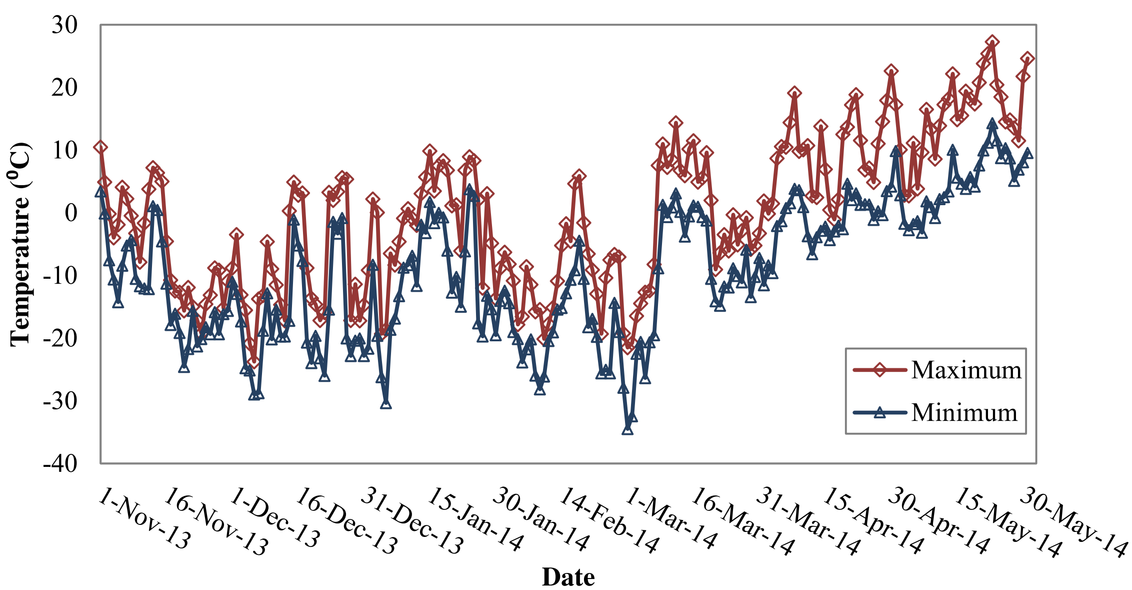


Figure 2- Daily minimum and maximum air temperature time history (winter 2013-summer 2014)

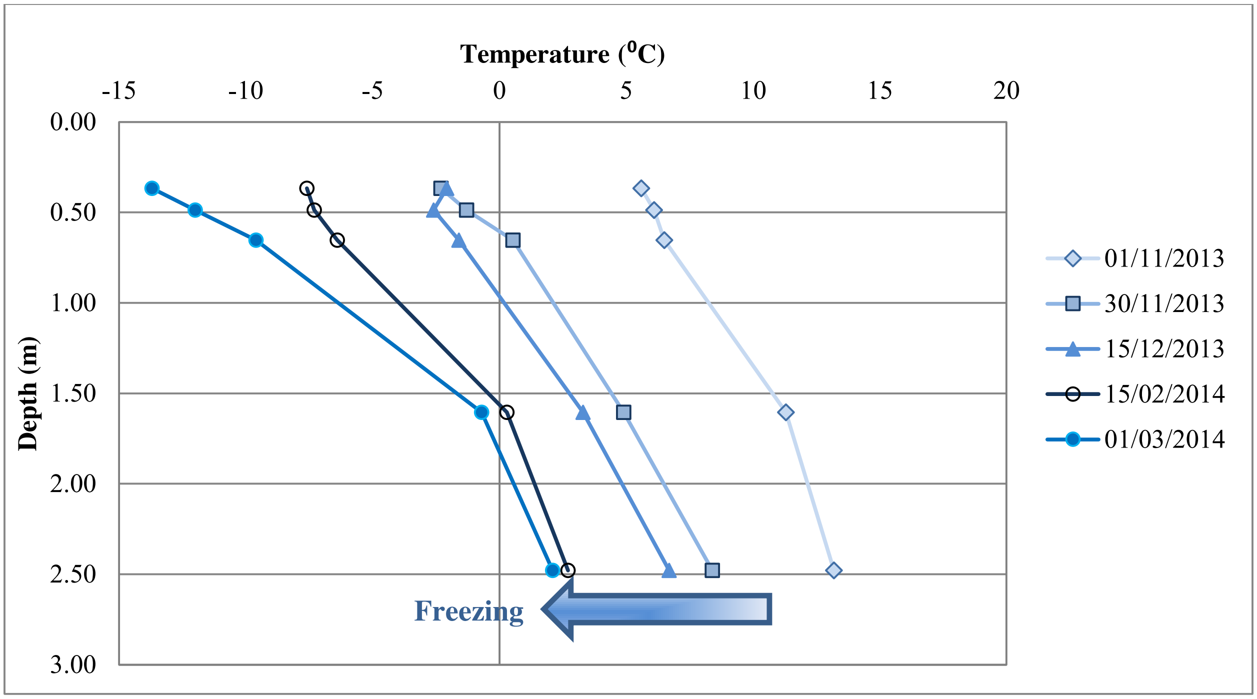
ANALYSIS

Figure 2 depicts the time history of the minimum and maximum daily temperature data recorded from the weather station during the winter 2013 and the summer 2014. The temperature varied between -35 ^{o}C (the minimum temperature that was recorded on March 1, 2014) and +25 ^{o}C (the maximum temperature that occurred on the last day of May 2014). This indicates that the pavement experienced 60 ^{0}C variation in temperature from cold to warm months.

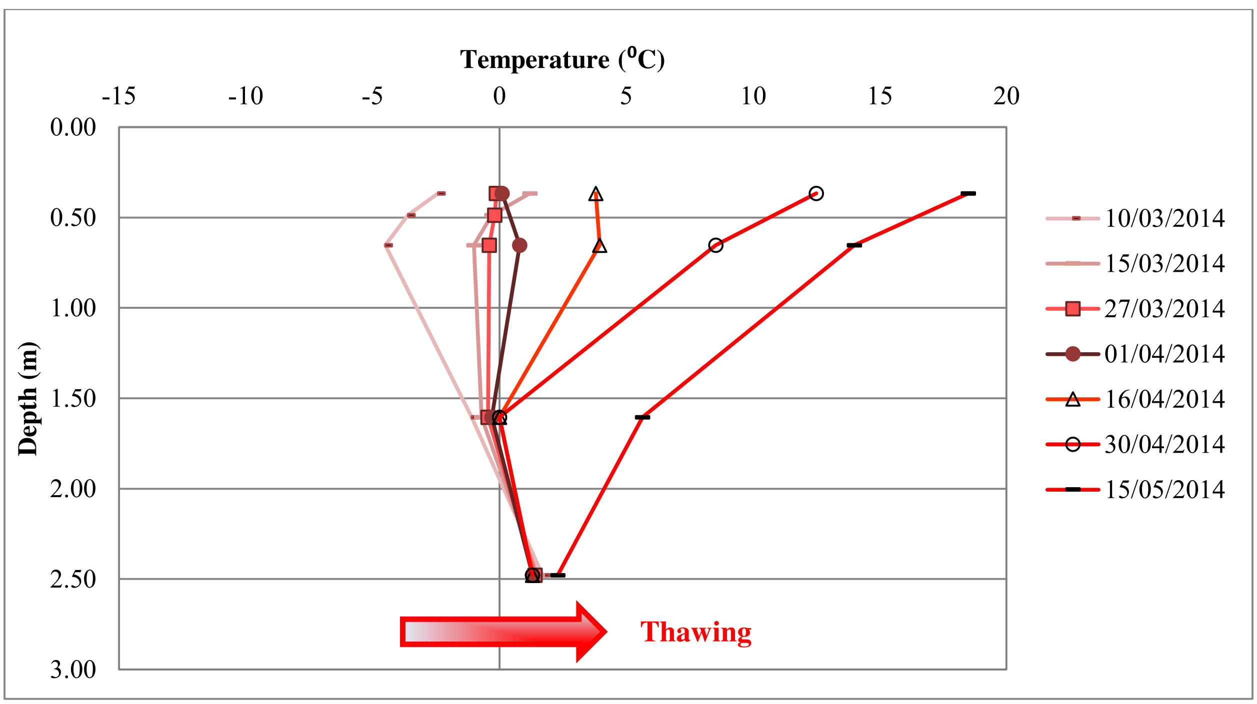
To obtain the time history of freeze and thaw depths through the IRRF's test road, the temperature profiles against depth were drawn in different dates. Figure 3 illustrates how the temperature varied with time across the depth of the test road. The crucial time period starts around March 15 when the ambient air temperature rose above 0^{0}C leading to start of thawing process in the base layer of the pavement. In this condition the frozen water started to melt from top to bottom leading to accumulation of excess water in the base and subgrade layers while the lower layers were still frozen. It should be noted that even though the air temperature decreased again throughout the last week of March, the thawing depth in the pavement oscillated around 50 cm from the surface. Figure 4 shows continuous increase in the freezing depth until March 15, 2014, when, as previously discussed, the air temperature started to increase above 0 ^{0}C. After this date, the freezing depth decreased through a short period of time within two weeks by the end of March, 2014. It is worth mentioning that a significant increase in thaw depth occurred from March 30 to April 1. The decrease in freezing depth occurred simultaneously along with increase in the thawing depth until around April 16, 2014, when thaw depth reached the freezing depth implying that thawing happened thoroughly across the depth of the pavement layers.

Air temperature data were used to calculate the CTI using the four methods discussed in this paper. The results of the calculations for CTI values are illustrated in Figure 5. As seen in this figure, all the methods showed the same trend aside from the values which are different from each other depending on each method's approach. By looking meticulously at Figure 5, one can recognize a jump in the CTI values calculated in all four methods starting March 9, 2014, which was caused by a noticeable increase in the ambient air temperature. It should be mentioned that in order to obtain the reference temperature required in Baïz et al. (2008) method, the asphalt temperature data recorded by the thermistor located at 2.5 cm below the pavement surface were plotted against the average daily air temperature during the months of November, 2013 and January, 2014. Using linear regression analysis, the intercept of the equation of the regression line (-0.4851 ^{0}C) was obtained which further defined the reference air temperature. For other methods, their respective recommended reference air temperature was used, accordingly.

Table 1 shows the recommended dates for imposing the SLR as suggested by the four discussed methods. The start dates were determined after ignoring the beginning part of each CTI curve, which was constant, during the cold season until early March, 2014. In other words, the CTI values were taken into consideration only after a sharp jump followed by a steady increase in the respective graphs was observed.



(a)



(b)

Figure 3- Temperature change through depth (a) freezing, (b) thawing (winter 2013-summer 2014)

Referring back to Figure 4 shows that the SLR start dates determined by the four discussed methods matched well with the actual physical conditions throughout the depth of the IRRF's test road when thawing began after March 12, 2014. This fact indicates that the aforementioned methods are reliable in predicting the start date of imposition of SLR.

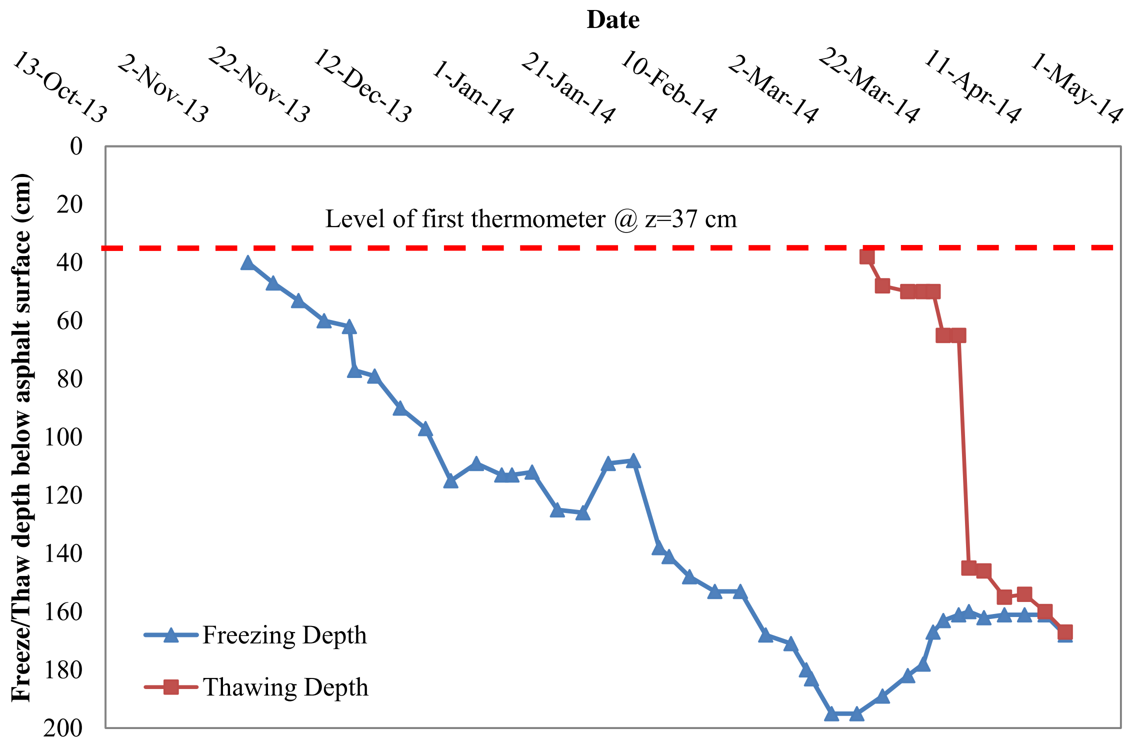


Figure 4- Time history of freeze and thaw depths across depth (winter 2013-summer 2014)

Table 2 illustrates the end date of SLR application calculated using the four methods. Considering the actual thaw depth during thawing season as shown in Figure 3, it is very noticeable that Mahoney's method (Mahoney et al. 1987) underestimates the SLR-on duration since the temperature profile of the IRRF's test road shows that sublayers remained frozen until around April 30, 2014, indicating that the excess water from the melted ice lenses could have not drained out of the system completely. However, Manitoba and MN DOT methods provided a more accurate approximation for the SLR end date (eight weeks after the start date of the SLR) since the temperature profile of the pavement showed that thawing was completed across the depth of the test road by around May 10, 2014. It should be mentioned that the method suggested by Baïz et al. (2008) does not determine a definitive date for the end of SLR imposition.

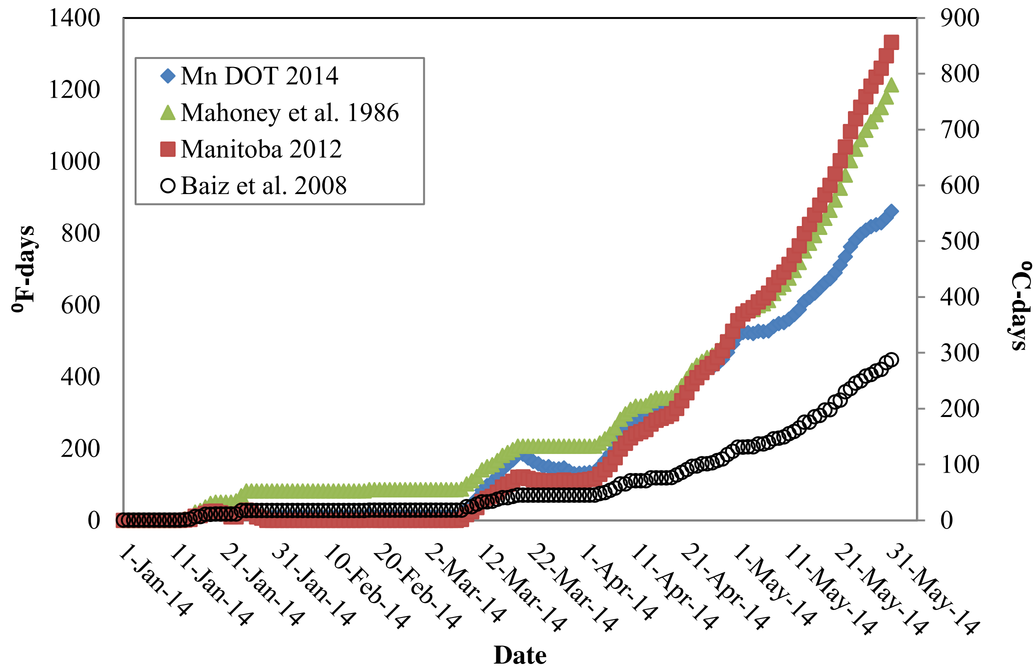


Figure 5- Calculated CTI values from the daily air temperature data

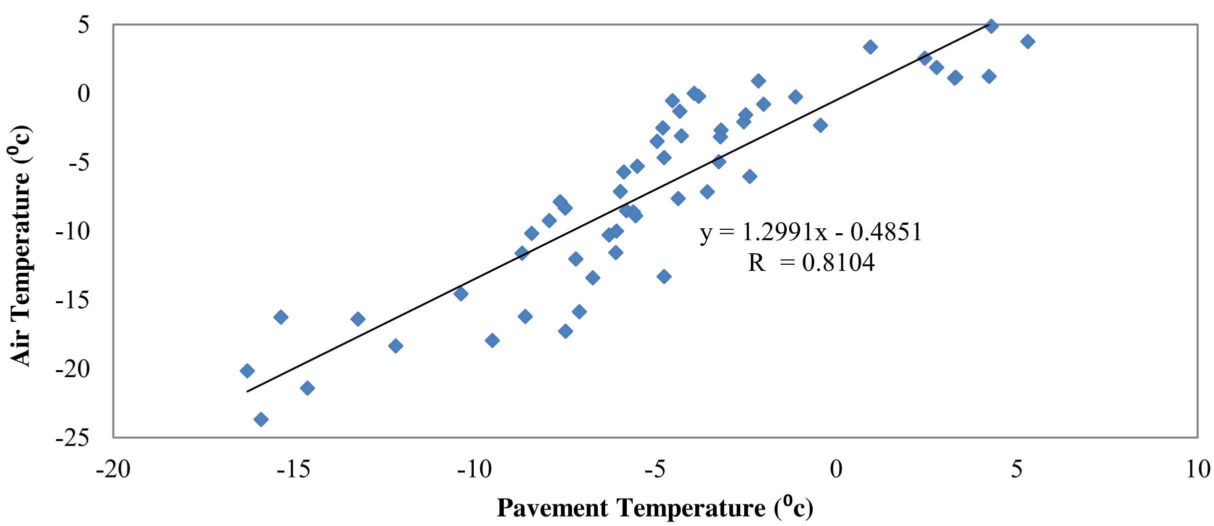


Figure 6- Air temperature vs. pavement temperature at 2.5 cm below surface

Table 1- Start date of SLR application found by different methods

Method	Date to apply SLR
Mahoney et al. (1986)	March 12
Baïz et al. (2008)	March 10
Manitoba (2012)	March 10
Mn DOT (2014)	March 10

Table 2- End date of SLR application found by different methods

Method	Date to remove SLR
Mahoney et al. (1986)	April 21
Baïz et al. (2008)	-
Manitoba (2012)	May 10
Mn DOT (2014)	At the latest: May 10

CONCLUSION

Numerous methods are suggested in the literature to predict the onset and estimate the duration of SLR on secondary roads out of which four methods were reviewed and used in this study to check their credibility in accurate estimation of the SLR-on duration based on the temperature measurements through the IRRF's test road depth in Edmonton. The ambient air temperature data recorded from a weather station near the IRRF test road were used to carry out the calculations of the CTI followed by the recommendations given in each method. The temperature data measured across the depth of the test road by thermistor and thermometers installed in the pavement layers where used in order to obtain the temperature profile through the depth of the pavement and compare each method's results with the real time observation from the test road.

According to the comparison with the test road data, all methods estimated the start of applying SLR around March 10 which was in good agreement with the actual observation from the temperature profiles in which thawing started to happen on March 15 within the top 50 cm from the pavement surface. However, Mahoney's method failed to estimate the removal date of SLR as the pavement sublayers were not fully thawed before April 21. Manitoba and Mn DOT methods could successfully estimate the date to remove SLR application.

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