New Approach for Surface *n* Factors

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Abstract: Air and surface freezing and thawing indexes and prediction of ground temperatures from air temperatures were investigated. A new method for applying *n* factors on a daily basis to capture localized temperature extremes is presented and compared to conventional seasonal *n*-factor analysis. Measured air temperatures from five locations and measured air and surface temperatures from one location were used. Freezing and thawing indexes were determined using daily and monthly average temperatures, different time frames, and seasonal and daily applications of *n* factors. Air and surface freezing indexes (I_{af} and I_{sf}) varied more than air and surface thawing indexes (I_{at} and I_{st}). Significant variations were observed in air and surface indexes due to the length of the time period used (1, 10, and 30 years) and frequency of temperature data used (daily and monthly). The surface indexes from seasonal *n* factors (using daily average temperatures) and daily *n* factors were similar (within 4%) and higher than the indexes from seasonal *n* factors (using monthly average temperatures). The average surface temperatures were within 2°C, whereas the maximum and minimum surface temperatures were significantly different (up to 26°C) between the seasonal and daily *n* factors. Maximum variations between consecutive daily maximum and minimum temperatures were significantly higher using daily *n* factors (up to 52°C) than seasonal *n* factors (less than 1°C). Surface indexes from seasonal (using daily average temperatures) and daily *n* factors can be used interchangeably. Daily *n* factors are recommended to obtain representative surface and near-

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surface temperature variations, diurnal extremes, representative timing for temperature change events, and localized freezing or thawing indexes during changeover months.

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Introduction

Air and surface freezing and thawing indexes are composite parameters that provide a measure of magnitude and duration of below-freezing and above-freezing temperatures of air and ground surfaces. The indexes are determined as the area bound by the temperature-time curve and the 0 °C baseline with area below 0 °C used for freezing and area above 0 °C used for thawing (Departments of the Army and the Air Force 1987). Freezing and thawing surface n factors [Eq. (1)] are empirical parameters that are affected by climatic and ground surface conditions

$$n_{t/f}=\frac{I_{\mathrm{st}/f}}{I_{\mathrm{at}/f}} \tag{1}$$

where $n_{t/f}$=thawing or freezing factor, as appropriate, and $I_{\mathrm{at}/f}$ and $I_{\mathrm{st}/f}$=air and surface indexes for freeze or thaw, as appropriate. A summary of common ranges of n factors is provided in Andersland and Ladanyi (1994) for estimating ground surface temperatures from measured air temperatures for a variety of ground surface conditions. The n factors provide a convenient means to indirectly estimate ground surface temperature functions (i.e., mean temperature and amplitude), which are otherwise highly complicated to estimate [e.g., Pikul (1991)]. Near-surface (below ground) temperature distributions depend on surface temperature functions [Oak Ridge National Laboratory (ORNL) 1981].

Freezing and thawing indexes are used to estimate a variety of design parameters for surface and near-surface structures such as roadways, building foundations, utility systems, and pipelines. Examples include required depth of foundations (Andersland and Ladanyi 1994), thickness of frost penetration layers in pavement structures (Oiseth and Refsdal 2006), and timing for load restriction limits on roadways (Yesiller et al. 1996). Freezing and thawing indexes and n factors are used to determine frost depth with analytical methods [e.g., modified Berggren equation (Aldrich and Paynter 1953)], chart solutions [e.g., Canadian Geotechnical Society (1985); DeGaetano and Wilks (2002)], or numerical analysis (e.g., finite element analysis or commercial civil engineering software).

Uncertainty is present in the quantification of freezing and thawing indexes due to the length of the time period used and frequency of temperature data used. Freezing and thawing indexes for design purposes are determined using temperatures for the most recent 30-year period of record. The average temperatures for the coldest three seasons and the warmest three seasons are used for determining design freezing and thawing indexes, respectively. When data are not available for 30 years, the single coldest and warmest seasons for the most recent 10-year period of record are used in the analysis (Departments of the Army and the Air Force 1987; Andersland and Ladanyi 1994). Monthly and daily average temperatures have been used for determining freezing and thawing indexes (Boyd 1976; Andersland and Ladanyi 1994). A problem exists in that even though the monthly and daily calculations result in different indexes for a given location, selection of the approach (average monthly versus average daily temperature) is not always specified for design calculations.

The *n* factors are applied on a seasonal basis to air temperature data to obtain idealized annual sinusoidal surface temperature fluctuations. Localized temperature extremes are effectively disregarded in the seasonal application of *n* factors. A recently developed definition for *n* factor (termed daily *n* factor) is presented and analyzed in this paper. In this approach, the *n* factors are applied on a daily basis to capture localized temperature variations. Comparisons were made between the surface freezing and thawing indexes determined using the existing seasonal *n*-factor approach and the newly proposed daily *n*-factor approach. Ground surface and near-surface temperature variations determined using the two approaches were also compared.

Daily *n* Factors

Daily *n* factors are applied to daily maximum and minimum air temperatures to estimate daily maximum and minimum ground surface temperatures. Air temperatures are assumed to follow sinusoidal variation. The maximum and minimum daily air temperatures ($T_{\max}$ and $T_{\min}$) are adjusted such that:

- The total energy (herein defined with units of degree-days) applied to the surface by a bimodal linear model is equal to that applied from a sinusoidal temperature variation.
- The total energy applied to the surface by the linear model is properly modified by appropriate freezing or thawing factors.

Daily *n*-factor analysis varies from conventional *n*-factor analysis in that calculations are made for daily temperature cycles (instead of annual cycles) and the sinusoidal function is converted to an equivalent bimodal linear function. A schematic of the conversion of sinusoidal function to a bimodal function for 1.5 days is presented in Fig. 1. The daily maximum, $T_{\max}$, and minimum, $T_{\min}$, air temperatures are used to determine the limiting values for the bimodal linear model, as presented below (Hanson et al. 2005).

For thaw- or freeze-only mode: $T_{\max}T_{\min}>0$

$$T'_{\max}=n_{t/f}\left[\frac{T_{\max}(\pi+4)+T_{\min}(\pi-4)}{2\pi}\right] \tag{2}$$

$$T'_{\min}=n_{t/f}\left[\frac{T_{\max}(\pi-4)+T_{\min}(\pi+4)}{2\pi}\right] \tag{3}$$

where $T'_{\max/\min}$=adjusted maximum/minimum ground temperatures and $n_{t/f}$ =thaw/freeze surface *n* factor, as appropriate.

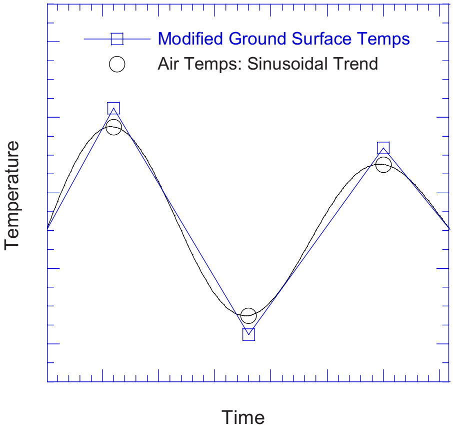


Fig. 1. Schematic of sinusoidal and linear bimodal models

For thaw and freeze modes: $T_{\max}T_{\min}<0$ (for crossover days)

$$T'_{\max}=2(n_tA_1+\sqrt{-n_tA_1n_fA_2}) \tag{4}$$

$$T'_{\min}=2(n_fA_2+\sqrt{-n_tA_1n_fA_2}) \tag{5}$$

where A_1 and A_2=areas bound by the temperature curve above and below freezing

$$A_1=\frac{[T_{\max}-T_{\min}]}{2\pi}\sqrt{1-\left[\frac{T_{\max}+T_{\min}}{T_{\max}-T_{\min}}\right]^2}+\frac{[T_{\max}+T_{\min}]}{4\pi}\left[\pi-2\sin^{-1}\left(\frac{T_{\max}+T_{\min}}{T_{\min}-T_{\max}}\right)\right] \tag{6}$$

$$A_2=\frac{[T_{\max}+T_{\min}]}{2}-A_1 \tag{7}$$

An example of the daily application of n factor is presented in Fig. 2. The figure represents a maximum/minimum daily temperature data string from Detroit (11 consecutive days in December 2004), including days with (1) below freezing; (2) above freezing; and (3) both below- and above-freezing (crossover data for a given day) temperatures. For this analysis, n_t was 1.5 and n_f was 0.9. In general, the daily application of n factor results in estimated surface temperatures extending beyond air temperatures (increases in daily maximum temperatures and decreases in daily minimum temperatures). Increases in daily maximum and decreases in daily minimum temperatures (for above-freezing conditions) occur due to the combined effects of n_t values being greater than 1.0 and the distinction in peak temperature required to provide equivalent areas under bimodal curves as compared to sinusoidal curves. Similarly for subfreezing temperatures, the daily

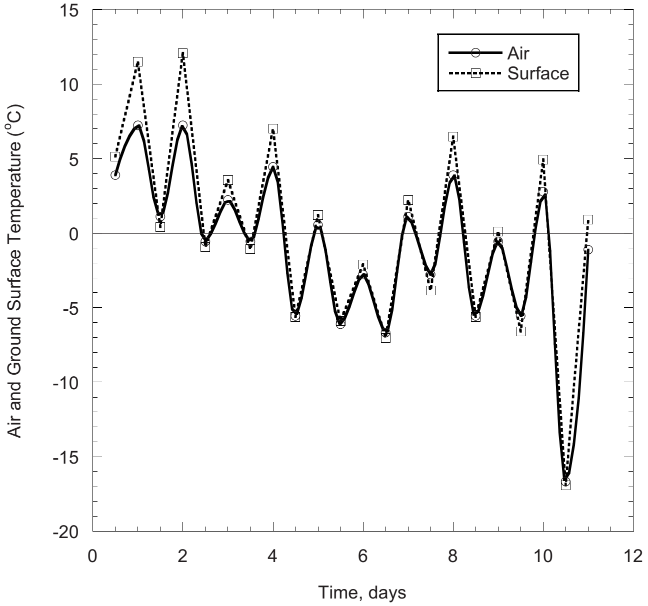


Fig. 2. Example of daily application of n factor (n_f=0.9, n_t=1.5)

application of n factor may result in increases in daily maximum and decreases in daily minimum temperatures due to the effects of the bimodal linear model, even though n_f values are typically less than 1.0 (Fig. 2).

Analyses

Air temperature data were obtained for five locations in the United States, three representing regions with both freezing and thawing temperatures (Detroit; Fairbanks, Alaska; and Minneapolis) and two additional sites (one wet, one warm) that were included for broader application of the n factors used in the study (Eugene, Ore., and Tucson, Ariz.). The climate statistics for the sites are presented in Table 1. Data were obtained for the 30-year period between 1975 and 2004.

Initially, air freezing and thawing indexes (I_{af} and I_{at}) were determined using both average monthly and average daily temperatures independently. The analyses were conducted for three distinct periods of investigation: using the three coldest and three warmest seasons from the 30-year records (1975–2004); using the single coldest and warmest seasons for the past 10 years of the data set (1995–2004); and using data for the 1-year period between July 1, 2003 and June 30, 2004. Then, surface freezing and thawing indexes and associated surface temperature variations were determined using air temperature data for the three periods of investigation and n factors in accordance with both seasonal and daily

Table 1. Climate Statistics at the Sites

City	Average daily high temperature (°C)	Average daily low temperature (°C)	Average daily temperature (°C)	Annual normal precipitation (mm/year)	Annual normal snowfall (mm/year)
Detroit	14.8	4.7	9.8	870.9	1,009.6
Eugene	17.5	5.4	11.5	1,221.9	90.0
Fairbanks	3.5	−7.3	−1.9	270.9	1,646.6
Minneapolis	12.8	2.5	7.6	774.1	1,360.8
Tucson	28.5	13.0	20.8	301.3	21.5
Fargo	11.1	1.0	6.0	538.2	1,168.4

Note: Data from National Climatic Data Center (NCDC) (2006) for a 30-year period of 1975–2004.

applications. Both average monthly and average daily air temperatures were used independently in determining surface freezing and thawing indexes for the seasonal application of n factors. Daily maximum and minimum air temperatures [from Eqs. (2)–(7)] were used to determine surface freezing and thawing indexes for the daily application of n factors. Common civil engineering materials were selected to represent surface conditions. A value of 0.9 for n_f and 1.5 for n_t were used which represented gravel soil surfaces or asphalt and concrete pavement surfaces (Andersland and Ladanyi 1994).

Comparisons were made for the air and surface freezing and thawing indexes between the use of average monthly and average daily air temperature data and also the use of various periods of investigation. Surface indexes and surface temperature variations were also compared for daily and seasonal applications of the n factors. For comparisons, baseline values were established using indexes that were determined using the conventional application of n factors (daily average temperatures, 30-year data, and seasonal application). In addition, maximum temperature differentials between consecutive daily maximum and minimum temperatures (termed half-daily temperature differentials) were determined. Comparisons were not conducted for freezing indexes at Eugene and Tucson as these two sites do not experience significant freezing temperatures.

Field-measured air and ground surface data between 1995 and 2004 in Fargo (J. W. Enz, personal communication, 2006) were used to compare seasonal and daily applications of n factors. Calculations were made for two distinct periods of investigation: using the single coldest and warmest seasons for the 10-year data set and using data for the 1-year period between July 1, 2003 and June 30, 2004. The ground surface data at the site were obtained at 1-cm depth, consistent with the definition for "ground surface temperature" provided in Andersland and Ladanyi (1994). The measured ground surface temperatures were compared with the ground surface temperatures estimated using air temperatures and seasonal and daily applications of n factors. An n_t of 1.0 was used to represent the grass ground cover and two n_f values of 0.5 (grass cover) and 0.3 (snow-covered plants) were used to represent the range of potential ground conditions in winter months.

In addition, a finite element method was used to perform 1D conductive heat transfer analysis for the site (using ABAQUS standard version 6.3). Thermal properties provided in Smerdon et al. (2003) were used for the site. The far-field boundary at great depth was set to 7.6°C (obtained as the average of measured temperatures at the deepest sensor at the site). This analysis was conducted using seasonal (with daily air temperatures) and daily application of n factors for the 1-year period between July 1, 2003 and June 30, 2004 with an n_f of 0.3 and an n_t of 1.0. Measured and predicted temperature envelopes with depth were compared to investigate spatial trends. Measured and predicted temperature-time responses at the ground surface and at 10-cm depth were used to investigate temporal trends including quality of predictions and onset of freezing and thawing phenomena during change-over seasons. In particular, calendar dates were compared for the onset of the first 7 and 10 consecutive days of freezing and thawing as well as for the first occurrence of 5 and 10°C-day freezing and thawing indexes.

Results

Results are presented for (1) variation in air and surface indexes as a function of length of time period and frequency of temperature data; (2) variation in surface indexes as a function of method of n-factor application (daily versus seasonal); and (3) comparison of spatial and temporal trends in surface temperatures as a function of method of n-factor application.

Air freezing and thawing indexes were determined for 30-, 10-, and 1-year durations using both monthly and daily average temperatures (Table 2). The air indexes determined using daily temperatures were higher than the indexes determined using monthly temperatures. The variations between the monthly and daily data were 2–32% and 0–7% for I_{af} and I_{at}, respectively. The monthly data for crossover months were modified using the Boyd method (Boyd 1976). This typically resulted in a general increase in the calculated air indexes; yet the variations between the modified monthly and daily data were 2–38% and 0–4% for I_{af} and I_{at}, respectively. Therefore, monthly average temperatures were used directly for the entire study.

Greater variation was observed between the indexes determined using different periods of investigation (Table 2). The 30-year period of investigation included the most extreme climate conditions and thus, in general, resulted in the largest I_{af} and I_{at}. Variations for daily average temperatures were

- Air freezing indexes for the 30-year data were 12–49% higher (absolute value) than the 1-year data and 2–18% higher (absolute value) than the 10-year data.
- Air thawing indexes for the 30-year data were 1–6% higher than the indexes obtained for the 1-year data and were within 3% of the 10-year data.

The surface freezing and thawing indexes determined using the seasonal and daily applications of n factors are presented in Table 3. The surface indexes were termed $I_{\mathrm{sf}/t\text{-SM}}$ for seasonal application using average monthly air temperature data, $I_{\mathrm{sf}/t\text{-SD}}$ for seasonal application using average daily air temperature data, and $I_{\mathrm{sf}/t\text{-DD}}$ for daily application using maximum and minimum daily air temperature data. The $I_{\mathrm{sf}/t\text{-SD/SM}}$ (Table 3) have similar variations with respect to the use of

Table 2. Air Freezing and Thawing Indexes

City	Index (°C day)	2003–2004 (1 year) M^a	2003–2004 (1 year) D^b	1995–2004 (10 years) M^a	1995–2004 (10 years) D^b	1975–2004 (30 years) M^a	1975–2004 (30 years) D^b
Detroit	I_{af}	−272.0	−378.6	−392.5	−581.3	−583.2	−706.4
	I_{at}	4,011.7	4,126.0	4,357.4	4,513.8	4,238.2	4,393.8
Eugene	I_{af}	0.0	−13.8	0.0	−42.8	−2.7	−95.8
	I_{at}	4,447.3	4,458.5	4,433.1	4,439.5	4,513.2	4,518.8
Fairbanks	I_{af}	−2,862.3	−3,018.7	−3,270.6	−3,352.3	−3,321.9	−3,412.1
	I_{at}	2,053.9	2,215.6	2,302.7	2,369.6	2,255.2	2,335.1
Minneapolis	I_{af}	−651.7	−780.3	−1,047.5	−1,166.9	−1,129.0	−1,285.9
	I_{at}	3,645.0	3,784.0	3,852.7	3,989.4	3,857.0	3,994.0
Tucson	I_{af}	0.0	−3.4	0.0	−3.6	0.0	−5.0
	I_{at}	7,819.4	7,821.8	7,846.2	7,854.8	7,911.6	7,919.1

[a] Using monthly average air temperatures.
[b] Using daily average air temperatures.

daily versus monthly average temperatures and different time frames as those listed above (Table 2). For surface indexes determined using daily *n* factor, the variations were 11–46% between 1- and 30-year data and were 2–17% between 10- and 30-year data for $I_{\text{sf-DD}}$. The variations were 1–6% between 1- and 30-year data and were within 3% between 10- and 30-year data for $I_{\text{st-DD}}$ (Table 3).

The use of seasonal (with daily average temperatures) and daily *n* factors resulted in similar values for surface indexes: variations of 1–4% between $I_{\text{sf-DD}}$ and $I_{\text{sf-SD}}$ and less than 1% between $I_{\text{st-DD}}$ and $I_{\text{st-SD}}$ (Table 3). Higher variations were observed between seasonal (with monthly average temperatures) and daily *n* factors: variations of 3–53% between $I_{\text{sf-DD}}$ and $I_{\text{sf-SM}}$ and 0–9% between $I_{\text{st-DD}}$ and $I_{\text{st-SM}}$. The highest variations in surface freezing index ($I_{\text{sf-DD}}-I_{\text{sf-SD}}$ and $I_{\text{sf-DD}}-I_{\text{sf-SM}}$) occur between the methods for locations with significant intraseasonal and diurnal variations about freezing. The greatest sensitivity in this regard was observed in Detroit. The variations between methods were lower for surface thawing indexes than freezing indexes. Overall, the surface indexes determined using seasonal *n* factors with daily average temperatures and daily *n* factors are similar and can be used interchangeably for applications where surface indexes are required.

The effects of seasonal and daily applications of *n* factors on surface temperature variations at the sites were also investigated (Table 4). While the differences were less than 2°C among the average temperatures determined using seasonal and daily *n* factors, the maximum and minimum surface temperatures from daily *n* factors were significantly higher and lower than the corresponding temperatures from seasonal *n*-factor analyses. Differences up to 26°C for maximum and up to 20°C for minimum surface temperatures were observed. For seasonal application of *n* factors, the maximum half-daily temperature differentials were less than 0.3°C for the sinusoidal temperature versus time data. Significantly higher half-

Table 3. Surface Freezing and Thawing Indexes

		2003–2004 (1 year)			1995–2004 (10 years)			1975–2004 (30 years)		
City	Index (°C day)	SM[a]	SD[b]	DD[c]	SM[a]	SD[b]	DD[c]	SM[a]	SD[b]	DD[c]
Detroit	I_{sf}	−244.8	−340.7	−354.4	−353.3	−523.2	−540.1	−524.9	−635.8	−651.1
	I_{st}	6,017.5	6,189.0	6,213.1	6,536.1	6,770.7	6,795.0	6,357.3	6,590.7	6,617.8
Eugene	I_{sf}	0.0	−12.4	−16.7	0	−38.5	−50.1	−2.4	−86.2	−97.1
	I_{st}	6,671.0	6,687.8	6,698.8	6,649.7	6,659.3	6,672.6	6,769.8	6,778.2	6,790.8
Fairbanks	I_{sf}	−2,576.1	−2,716.8	−2,731.6	−2,943.5	−3,017.1	−3,030.3	−2,989.7	−3,070.9	−3,084.4
	I_{st}	3,080.8	3,323.4	3,347.8	3,454.1	3,554.4	3,577.7	3,382.8	3,502.7	3,529.4
Minneapolis	I_{sf}	−586.6	−702.2	−715.4	−942.8	−1,050.2	−1,066.7	−1,016.1	−1,157.3	−1,169.2
	I_{st}	5,467.5	5,676.0	5,698.5	5,779.1	5,984.1	6,012.2	5,785.5	5,991.0	6,024.0
Tucson	I_{sf}	0.0	−3.0	−6.3	0	−3.2	−6.3	0.0	−4.5	−7.8
	I_{st}	11,729.1	11,732.7	11,739.6	11,769.3	11,782.2	11,787.8	11,867.4	11,878.7	11,885.1

[a] Seasonal *n* factor using monthly average air temperatures.

[b] Seasonal *n* factor using daily average air temperatures.

[c] Daily *n* factor using daily maximum and minimum air temperatures.

Table 4. Surface Temperature Predictions for Various Time Periods and Methods of *n*-Factor Application

		2003–2004 (1 year)			1995–2004 (10 years)			1975–2004 (30 years)		
City	Temp.	SM[a]	SD[b]	DD[c]	SM	SD	DD	SM	SD	DD
Detroit	T_{max}	36.1	37.7	52.5	40.0	42.5	56.1	40.1	42.0	55.3
	T_{min}	−4.6	−5.9	−21.1	−6.2	−8.2	−20.5	−8.1	−9.4	−23.0
	T_{avg}	15.7	15.9	16.0	16.9	17.1	15.2	16.0	16.3	15.0
Eugene	T_{max}	36.2	37.0	63.1	36.3	37.6	63.1	37.3	39.0	63.4
	T_{min}	0.2	−0.6	−9.0	0.2	−1.3	−8.9	−0.2	−2.3	−12.5
	T_{avg}	18.2	18.2	18.3	18.2	18.1	16.7	18.5	18.3	17.2
Fairbanks	T_{max}	25.5	27.4	49.7	28.9	29.7	50.8	28.5	29.4	52.7
	T_{min}	−22.9	−24.2	−41.3	−26.1	−26.8	−42.4	−26.3	−27.1	−39.8
	T_{avg}	1.3	1.6	1.7	1.4	1.5	1.4	1.1	1.2	1.6
Minneapolis	T_{max}	35.0	36.8	57.0	38.6	40.3	54.2	38.9	40.8	59.5
	T_{min}	−8.4	−9.7	−29.4	−12.1	−13.3	−31.3	−12.8	−14.3	−30.6
	T_{avg}	13.3	13.5	13.6	13.3	13.5	12.2	13.0	13.2	12.7
Tucson	T_{max}	62.3	64.2	69.1	63.4	64.8	69.1	63.7	65.4	72.1
	T_{min}	1.0	−0.3	−10.8	1.1	−0.3	−10.8	1.3	−0.4	−8.7
	T_{avg}	32.1	32.0	32.1	32.2	32.3	31.8	32.5	32.5	32.3

[a] Seasonal *n* factor using monthly average air temperatures.

[b] Seasonal *n* factor using daily average air temperatures.

[c] Daily *n* factor using daily maximum and minimum air temperatures.

Table 5. Air and Surface Freezing and Thawing Indexes for Fargo

Index (°C day)	2003–2004 (1 year)				1995–2004 (10 years)			
I_{af}	−1,114.0[a]	−1,232.0[b]	—	—	−1,649.4[a]	−1,741.9[b]	—	—
I_{at}	3,199.5[a]	3,328.2[b]	—	—	3,475.3[a]	3,607.3[b]	—	—
I_{sf} ($n_f=0.5$)	−557.0[c]	−616.0[d]	−624.3[e]	−340.7[f]	−824.7[c]	−870.9[d]	−875.5[e]	−501.3[f]
I_{sf} ($n_f=0.3$)	−334.2[c]	−369.6[d]	−375.0[e]	−340.7[f]	−494.8[c]	−522.6[d]	−525.5[e]	−501.3[f]
I_{st}	3,199.5[c]	3,328.2[d]	3,344.3[e]	3,468.0[f]	3,475.3[c]	3,607.3[d]	3,616.1[e]	4,138.2[f]

[a] Using monthly average air temperatures.

[b] Using daily average air temperatures.

[c] Seasonal *n* factor using monthly average air temperatures.

[d] Seasonal *n* factor using daily average air temperatures.

[e] Daily *n* factor using daily maximum and minimum air temperatures.

[f] Using field-measured ground surface temperatures.

daily temperature differentials (38–52 °C) were obtained for daily application of *n* factors where the diurnal extremes were represented in the temperature versus time data. The number of 0 °C crossover occurrences (temperatures crossing from freezing to thawing or from thawing to freezing using daily maximum and minimum temperatures) was compared for air temperature, seasonal application of *n* factor, and daily application of *n* factor. As an example, in Fairbanks, for the 1-year analysis period between 2003 and 2004, the number of crossover occurrences was 130 for air temperature, two for seasonal application of *n* factor, and 170 for daily application of *n* factor.

Field-measured air and surface temperature data in Fargo were used for comparison of seasonal and daily applications of *n* factors (Table 5). Snow-covered conditions ($n_f=0.3$) provided representative results at the site for the cold season. The $I_{\text{sf}/t\text{-DD}}$ and $I_{\text{sf}/t\text{-SD}}$ were within 2% and they provided surface indexes within 4–13% of the indexes from field-measured data. The variations between $I_{\text{sf}/t\text{-SM}}$ and $I_{\text{sf}/t\text{-FM}}$ (field-measured data) were between 1 and 16%.

Surface temperature parameters for Fargo are presented in Table 6. Trends similar to those for the other field sites were observed with low differences in average temperatures (within 2 °C) and high differences in extreme temperatures between daily and seasonal applications of *n* factors. The surface temperatures obtained using seasonal *n* factors significantly underestimated the maximum surface temperatures (differences up to 24 °C) and overestimated the minimum surface temperatures (differences up to 8 °C). The maximum and minimum temperatures from daily *n*-factor analysis were within 10 and 5 °C of the measured temperatures, respectively. In addition, the maximum half-daily temperature differential from daily *n*-factor analysis (37 °C) was more representative of the measured differential (21 °C) than seasonal *n* factors (0.1 °C).

Temperature envelopes obtained using finite element analysis and measured data are presented in Fig. 3. The limiting surface temperatures from the daily *n*-factor analysis agreed well with the measured data. However, the surface amplitude from the seasonal *n*-factor analysis was significantly lower than the amplitude of the measured data. The use of daily *n* factor provided more representative temperature variations than seasonal *n* factor at the ground surface and at shallow depths. The amplitudes of the three envelopes converged at depths be-

Table 6. Surface Temperatures for Fargo ($n_f=0.3$)

	2003–2004 (1 year)			1995–2004 (10 years)		
Method	T_{max}	T_{min}	T_{avg}	T_{max}	T_{min}	T_{avg}
Seasonal *n*-factor monthly average temperature	20.5	−4.8	7.9	22.9	−6.6	8.2
Seasonal *n*-factor daily average temperature	21.5	−5.3	8.1	23.8	−6.9	8.5
Daily *n* factor	37.6	−11.2	8.1	36.9	−10.4	7.9
Field measured	32.8	−11.8	8.5	47.0	−14.9	10.0

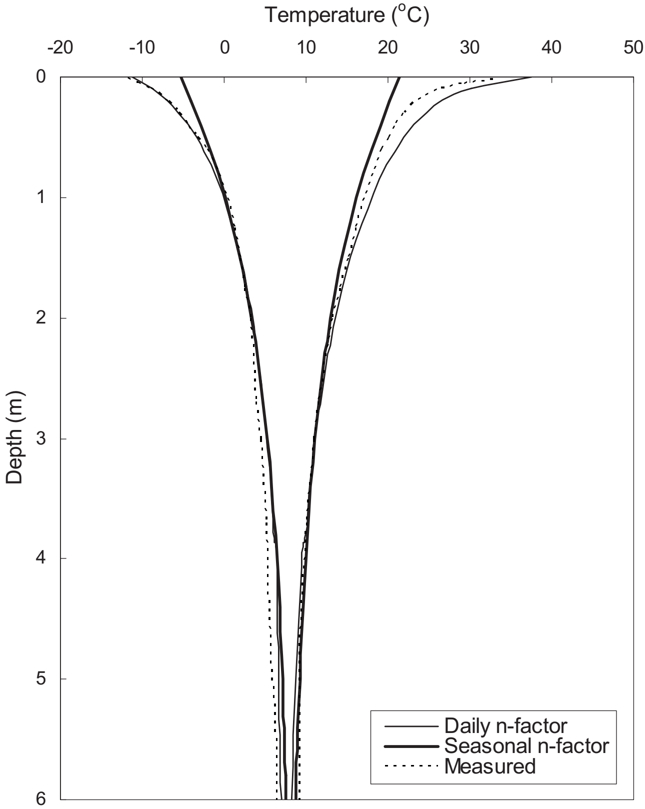
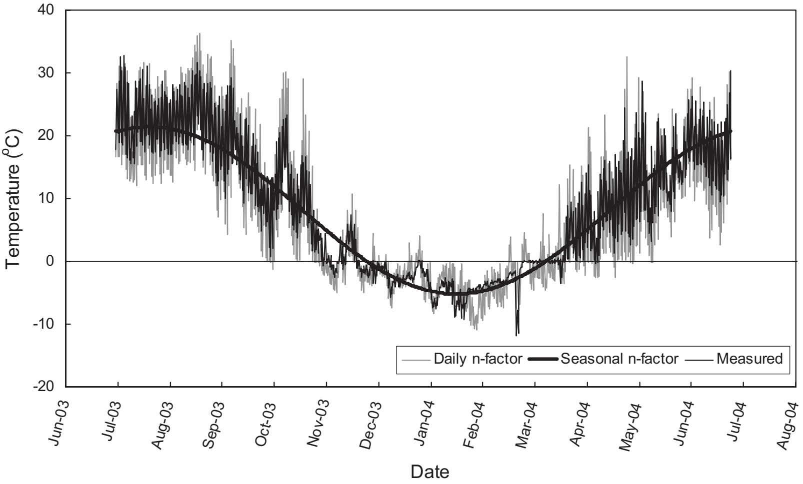


Fig. 3. Measured and predicted temperature envelopes with depth for Fargo

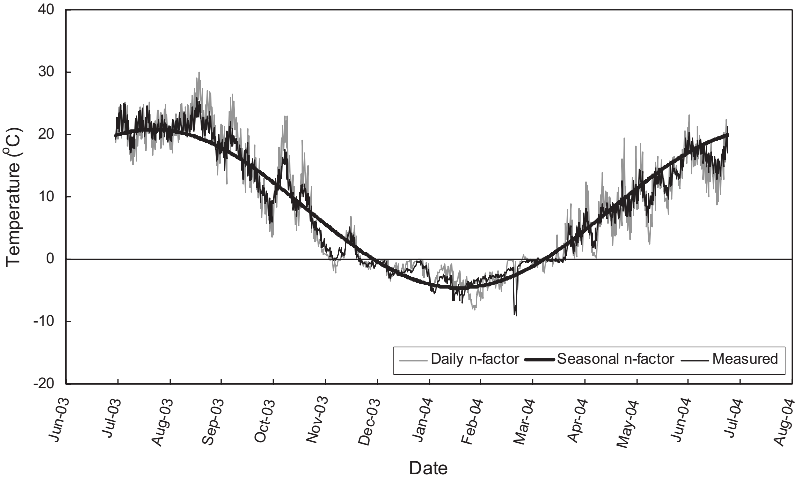
yond approximately 1 m (cold extremes) and 3 m (warm extremes).

Comparisons of temperature versus time data are provided between the seasonal and daily applications of *n* factors and the measured data for Fargo in Fig. 4. For the ground surface, a least-squares error analysis between the measured data and the two *n*-factor approaches indicated that the quality of the temperature predictions with the use of the daily *n* factor was better than the use of seasonal *n* factor (30% less error). Latent heat effects (relatively stable ground surface temperatures near 0 °C) are evident in the measured data during spring thaw.

Further analysis was conducted for freeze/thaw conditions at 10-cm depth in relation to possible pavement applications. For 10-cm depth, the agreement between predicted and measured data was better for use of daily *n* factors than seasonal *n* factors for onset of both freezing and thawing during change-over months. The onsets of predicted first 7 and 10 consecutive days of freezing and thawing were within 1 day of measured data for daily *n* factors. Using seasonal *n* factors, the onset of the predicted first 7 and 10 consecutive days of freezing was 9 days later and the onset of 7 and 10 consecutive days of thawing was 12 days



a) 1-cm-depth



b) 10-cm-depth

Fig. 4. Comparison of measured and predicted temperatures versus time for Fargo

earlier than measured data. The first occurrence of 5 and 10°C-day freezing and thawing indexes occurred within 1–4 days of measured data when daily *n* factors were used. Using seasonal *n* factors, the first occurrences of 5 and 10°C-day freezing indexes were 6–10 days later and the first occurrences of 5 and 10°C-day thawing indexes were 4–7 days earlier than measured data. Late predictions may unnecessarily delay posting of load limits for winter season, whereas early predictions of thawing may extend the duration of thaw periods.

Overall, the temperature versus time relationships obtained using daily *n* factors provide a better representation of measured data than the use of seasonal *n* factors even though some extreme temperatures are accentuated due to the bimodal linear model used in the daily *n*-factor application. The diurnal localized variations in measured data can be represented effectively using daily *n* factors while the seasonal application of *n* factors does not allow for capturing such variations.

Conclusions

Freezing and thawing indexes were determined using daily and monthly average temperatures, different time frames, and the seasonal and daily applications of *n* factors. Freezing indexes have higher variations than thawing indexes. The variations in freezing indexes observed in the study were up to:

- 32% between daily and monthly average air temperatures for I_{af} and I_{sf};
- 49% between 1- and 30-year data for I_{af} and I_{sf}; and
- 53% between methods of application of *n* factors ($I_{sf\text{-}DD}$ and $I_{sf\text{-}SM}$).

For comparison, the maximum variation was only 7% for thawing indexes (air or surface). Freezing indexes are more sensitive to characteristics of raw data and analysis methods than thawing indexes. Therefore, establishing analysis details is critical in determination of freezing indexes both in practical applications and for archival reference materials.

The use of seasonal *n* factor results in an idealized sinusoidal representation for time versus surface temperature relationships, whereas the use of new daily *n* factors provides relationships that capture diurnal variations. The surface indexes determined in this study using seasonal *n* factors (with daily average temperatures) and the daily *n* factors were similar (within 4% of each other). Therefore, the indexes determined using the two approaches can be used interchangeably for applications where solely surface indexes are required.

The average surface temperatures were within 2°C between the seasonal and daily *n* factors, whereas the maximum and minimum surface temperatures from daily *n* factors were significantly higher (up to 26°C) and lower (up to 20°C) than the corresponding temperatures from seasonal *n*-factor analyses. Similarly, the half-daily surface temperature differentials were significantly higher using daily *n* factors (up to 52°C) in comparison to seasonal *n* factors (less than 1°C). Near-surface ground temperatures obtained using daily *n* factors agreed better with measured data than temperatures obtained using seasonal *n* factors. Furthermore, onset of measured freezing and thawing conditions in the ground were better predicted using daily *n* factors than seasonal *n* factors for change-over months. The localized variations in measured data were captured using daily *n* factors, which provided representative time-variant surface and near-surface temperatures. The proposed daily *n* factor is recommended to be used to provide representative predictions of ground surface temperature in applications where near-surface thermal gradients, absolute temperature thresholds (maximum or minimum), time-critical events associated with temperature change, and/or short-term localized temperature fluctuations are required, particularly for locations undergoing repeated cycles of freeze/thaw.

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