A new pavement design procedure for frost protection in seasonal frost areas

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ABSTRACT: Differential frost heave and uneven degradation of flexible pavements surface profile in cold climate significantly affects the serviceability of these important civil engineering structures. Among the factors influencing this phenomenon, subgrade soils variability is documented as a significant parameter to consider, especially regarding differential frost heave. Subgrade soils variability may increase in urban area because of the buried utilities and the numerous cuts, both usually filled with granular materials. Therefore, past researches were revisited to implement a design methodology for frost heave protection of flexible pavements in northern environment based on the risk of differential frost heave caused by subgrade soils variability. Previous data were used to 1. Propose a relationship between the maximum pavement IRI, usually encountered at the end of the winter period, the design period and the subgrade soils longitudinal variability index, and 2. Quantify the effect of the replacement of in situ subgrade soils with granular fill on the coefficient of variation of frost heave. The relationship was used as a reference to identify allowable average frost heave based on subgrade soils variability conditions. This is specifically applicable in the urban context for which granular fills, and consequently supplementary induced soil variability, is the main factor contributing to the determination of the allowable frost heave. Working examples of various classes of urban pavements allowed obtaining allowable frost heave criteria that take into account subgrade soils variability, design period and maximum allowable roughness, which are also in good agreement with available data in the literature.

KEY WORDS: Flexible urban pavements, pavement design, soil variability, geostatistics, differential frost heave.

1 INTRODUCTION AND BACKGROUND

Frost heave of flexible pavements during winter in northern environments significantly affects the performance of such civil engineering structures. This phenomenon typically occurs when a frost sensitive subgrade soil is submitted to subzero temperature with an access to a water source, such as the water table (TAC 1997; Doré and Zubeck 2009). Because unfrozen adsorbed and capillary water films exist at subzero temperatures within fine grained soils, the thermodynamic instability causes important suction stresses in the frozen fringe towards which available water flows and freezes at the segregation front, causing the growth of an ice lens (Konrad 1999; Doré and Zubeck 2009). Frost heave, if not considered properly through design, significantly contribute to surface profile degradation in the winter period and thaw weakening in the spring period (Doré and Zubeck 2009; Doré 1997; TAC 1997; Konrad et Roy 2000).

Frost heave may contribute more drastically to surface profile degradation if the subgrade soils are not uniform with respect to their physical characteristics, such as water content and grain-size distribution, as this may result in differential frost heave (Doré et al. 2001; Vaillancourt 2004; Flamand 2000). Doré (1997) investigated this problem using a geostatistical approach based on the semivariogram, which is a mathematical function that allows representing and quantifying the spatial variability of a phenomenon (Clark 1979). This function is expressed

(1) $$\gamma^*(d) = \frac{1}{2N}\Sigma\left[g(x) + g(x+d)\right]^2$$

in which N is the number of pair samples, g(x) is the value measured at a distance x, g(x+d) is the value measured at a distance d of the measurement at x and $\gamma^*(d)$ is the experimental semivariogram (Figure 1). Various models, which allow determining the sill, nugget and range, are used to fit experimental semivariogram with distance. The sill is the value of the semivariogram obtained when the variation of the studied parameter becomes independent from the distance. Based on the fact that the surface distortion wavelength of 8 m is critical in terms of user comfort (OCDE 1987, Doré and Zubeck 2009), the research done by Doré (1997) and Doré (2002) documented several flexible pavement test sites, which were characterized for physical characteristics of subgrade soils at a distance of 4 m (half of the critical wavelength). Because of its relationship with the frost heave, the percentage passing 80 µm sieve was used to assess the variability. An index of longitudinal variability V_L was proposed, which can be related to the typical differential heave between 4-m spaced measurement points. The V_L value is obtained with

(2) $$V_L = \frac{\sqrt{\gamma(4)}}{\bar{x}} \times h = CV_G \times h \simeq \Delta h_{4m}$$

in which h is the average frost heave (measured or calculated), $\bar{x}$ is the mean of the physical parameter considered (percent passing 80 µm), Δh_{4m} is the differential heave at a distance of 4 m and $\sqrt{\gamma(4)}$ is the square root of the semivariogram measured at a distance of 4 m (the standard deviation). The ratio of $\sqrt{\gamma(4)}$ to $\bar{x}$ therefore represents the coefficient of variation CV_G which, when multiplied by the average frost heave, allows obtaining the differential frost heave.

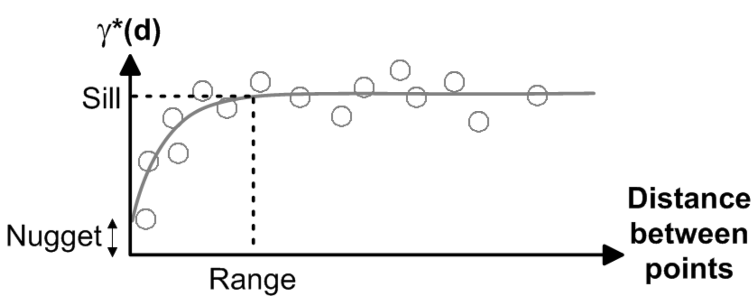

Figure 1. Example of a semivariogram

In the urban context, subgrade soils variability is often created “artificially” because of the numerous buried utilities, which are frequently filled with granular soils with low fine content. Consequently the approach proposed by Doré (1997) appears to be adequate and applicable to the urban context, as it considers differential frost heave through the subgrade soils variability using fine particles content as an indicator. Differential frost heave has an important impact on the seasonal and long term evolution of roughness (IRI). Thus the objective of this paper is to propose an adapted design methodology for differential frost heave protection of flexible pavements based on subgrade soils variability.

2 DATABASE AND MODEL IMPLEMENTATION

The database assembled from observations at various experimental sites by Doré (1997) and Doré (2002) was revisited to come up with a model that relates V_L to winter increase of roughness (ΔIRI_s) and to long term deterioration of the IRI (IRI_{LT}, corresponding to the summer value of IRI). Table 1 presents the database used for the model development. The fine particles content was used as the physical indicator of frost heave (Konrad 1999). The test sites are located in Minnesota (4) and Quebec (19). The frost heave sensitivity of the selected test sections varies from low (33% of the test sections), medium (42% of the test sections) and high (25% of the test sections). The pavement types considered varies from highways (21%), national (33%), regional (29%) and local (17%). The values of $\gamma(4)$, x and h represent the variance of the fine particles content at a distance of 4 m, the mean fine particles content and the average frost heave on the test sections, respectively. The analysis of this database allowed identifying a relationship between the maximum winter IRI obtained (IRI_{Max}), pavement age and V_L. It appears to be important to consider IRI_{Max} in the analysis, because it corresponds to the worst case of roughness experienced during a year, which usually occurs at the end of the winter period. As a matter of fact, as pavements may exhibit degraded but acceptable roughness in the summer time, the riding quality may decrease significantly due to the frost action. The identified relationship, illustrated in Figure 2 and Figure 3, for pavement age in years and V_L in mm, is defined by

$$\text{(3)} \qquad \mathrm{IRI}_{\mathrm{Max}} = \mathrm{AGE}^{0.2323}\left(0.0788\mathrm{V}_{\mathrm{L}} + 1.2431\right)$$

for which the coefficient of determination value (R^2) is 0.49. The R^2 value is relatively low but is considered satisfactory, considering that several factors can influence IRI_{Max}. For example, a surface phenomenon such as a crack heaving is independent of frost susceptibility and variability of subgrade soils but contributes significantly to winter and long-term roughness. Other parameters, such as the freezing index, pavement thickness and drainage conditions may also influence the response of such a model. This model also gives a similar relationship, in terms of coefficient of determination and model type, to the one proposed by Doré (1997) which relates the seasonal variation of the IRI to V_L. Nevertheless, the main research hypothesis involves that seasonal and long-term increase of roughness is significantly influenced by subgrade soils variability.

Table 1. Database

Site	γ(4) (mm²)	x (%)	h (mm)	V_L (mm)	IRI_{Max} (mm/m)	IRI_{LT} (mm/m)	ΔIRIs (mm/m)	Age (yrs)
SMC				26.6	3.38	1.9	1.48	0.5
MnRoad	1.01	11.2	11.8	1.06	1.35	1.15	0.2	2
MnRoad	1.22	4.6	1.2	0.23	1.1	0.76	0.34	2
MnRoad	0.02	4.9	12.6	0.38	1.85	1.24	0.61	2
MnRoad	0.07	9.9	16.1	0.48	1.96	1.54	0.42	2
St-Augustin N	28	13.4	40.6	15.56	4.06	1.49	2.57	2
St-Augustin S	18	20.4	38.9	7.74	6.01	2.19	3.82	20
Ste-Catherine	0.03	0.3	5	2.71	5.22	3.07	2.15	20
St-Prime N	5.8	30.76	80.7	6.31	2.86	1.46	1.4	20
St-Prime S	98	52.13	58.3	11.08	3.04	1.45	1.59	20
Dosquet	2.37	3.78	25	10.18	1.5	1.38	0.12	2.5
Victoriaville	5.5	16.22	37	5.35	3.3	2.9	0.4	15
SMC	12	7.8	60	26.65	5.3	3.02	2.28	6
St-Célestin	10.5	21.55	25	3.76	1.77	1.34	0.43	1.5
St-David	336	34.5	10	5.31	1.2	1.4	0.01	8
West Ditton	43	16.47	55	21.9	3.65	2.65	1	22
Donnaconna	10.7	14.7	6	1.34	1.9	2	0.01	18
Scott-Ste-Marie	2.2	10.45	26	3.69	1.5	1.3	0.2	16
Fleurimont	7	7.7	3	1.03	2.9	1.5	1.4	5
Champlain	0.1	0.52	0	0	1.1	0.8	0.3	9
La Prairie	56.6	100	2	0.15	1.1	1	0.1	0.5
St-Célestin	10.5	21.55	25	3.76	1.69	1.31	0.38	0.5
Plessisville			4		2.2	1.4	0.8	22

γ(4)=semivariogram at a distance of 4 m; V_L=longitudinal variability; ΔIRI_s=seasonal variation of IRI; ΔIRI_{LT}=long-term IRI; IRI_{max}= Maximum seasonal IRI; h= average frost heave; x=average fine particles content

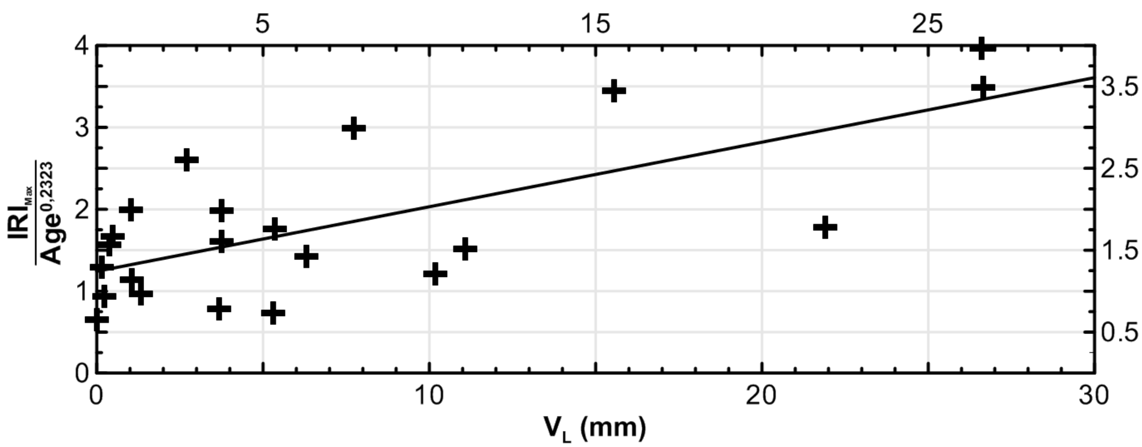

Figure 2. Relationship between IRI_{Max}, pavement age and V_L

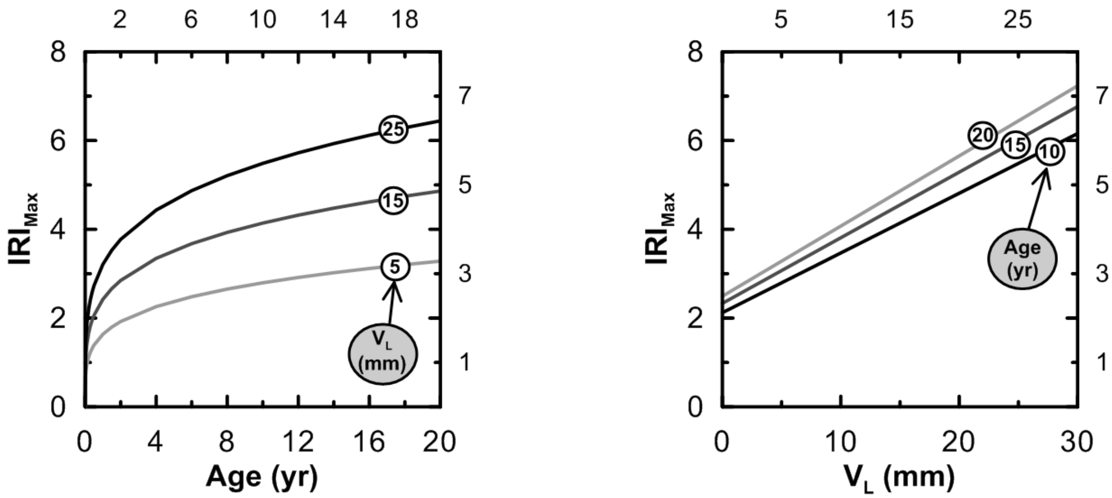

Figure 3. Model representation of the effect of V_L and age on IRI_{Max}

3 FROST HEAVE DESIGN CRITERIA FOR URBAN PAVEMENTS

Equations 2 and 3 were used for the development of the design procedure taking into consideration frost heave for urban pavements. For a given pavement classification, the approximate maximum allowable roughness can be established by highway agencies. The maximum pavement roughness, defined as IRI_{Max}, for which a V_L value may be determined given the design period. Applying equation 2, this V_L value may be used to determine a maximum allowable average frost heave h, given that the CV_G value is a known input. Doré (1997) and Doré (2002) gathered data from the literature to propose typical CV_G values, which are mostly based on the geological context. However, the best way to determine CV_G is by field sampling of the subgrade soils at a distance of 4 m and to perform grain-size analysis of the collected samples. Usually, 6 to 7 pairs of 4 m spaced samples are considered sufficient to determine the CV_G value for a specific site. In the urban context, CV_G remains the key parameter to obtain as significant additional variability may be added because of the numerous cuts and fills and buried public utilities encountered in that particular context.

Additional test sections were analyzed using variograms to determine the spatial correlation between fine particles content of the soil (< 80 μm) and distance. This allowed obtaining the standard deviation using the square root of $\gamma(4)$ and the average fine particles content, which allowed determining CV_G values for the considered test sites. In addition, in order to determine the impact on CV_G of cuts filled with granular soils, the same soil characteristics were also analyzed with a simulated trench containing granular materials with a uniform fine particles content of 8% at distances of 10, 12 and 14 m. The results of this simulation are referred to as "modified" variograms and CV_G in the following paragraphs. Figure 4 and Table 2 present the results of the analysis for the Donnaconna test site. As presented in Figure 4, the spherical variogram model was used. Given the $\gamma(4)$ values obtained on the fitted spherical variogram and the average fines content for the observed and modified conditions, it was possible to calculate the CV_G values. Table 3 presents a summary of the results of this analysis, classified using the soil variability classification Uniform/Moderate/High based observed fine content.

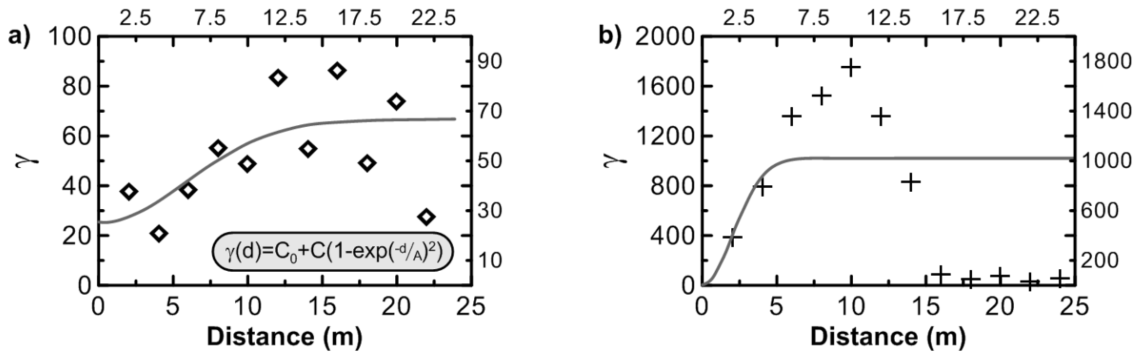

Figure 4. a) Observed and b) modified variogram for the soil fine particles content for the Donnaconna test site

Table 2. Observed and modified variogram data for the soil fine particles content for the Donnaconna test site

Distance (m)	Soil characteristics longitudinal profile (observed) < 80 μm (%)	Soil characteristics longitudinal profile (observed) γ(d) (m²)	Soil characteristics longitudinal profile (modified)* < 80 μm (%)	Soil characteristics longitudinal profile (modified)* γ(d) (m²)
0	71.2	-	71.2	-
2	72.5	37.78	72.5	382.2
4	67	20.77	67	795.75
6	71.3	38.32	71.3	1356.53
8	63.7	55.1	63.7	1523.94
10	76.2	48.7	8*	1753.66
12	64.3	83.68	8*	1358.6
14	79	54.87	8*	832.96
16	83.5	86.41	83.45	86.41
18	76.2	49.2	76.2	49.2
20	85.7	73.95	85.7	73.95

*Value of <80μm fixed at 8% at distance of 10, 12 and 14 m

Table 3. Average CV_G values for each soil variability classification

	CV_G (as observed)	CV_G (modified)	Increase (%)
Uniform	0.082	0.468	570
Moderate	0.142	0.435	307
High	0.556	0.655	118

The results presented in Table 3 reveal interesting information. As a matter of fact, the modification of the fine content in order to model cuts and trenches filled with granular soils has a significant impact on the CV_G values obtained. As it was expected, this impact is more pronounced for uniform soils. For non-uniform soils, the addition of supplementary variability due to granular material fills will therefore have a lesser impact on the overall soil variability. It can also be noticed that the addition of a trench filled with granular soils appears to be the primary influence factor on the obtained CV_G values as the CV_G values for the modified soil conditions range around a value of 0.5. Since the CV_G for pavements including cuts and trenches filled with granular is approximately 0.5, it is postulated that this value can be used for the implementation of frost heave criteria in an urban context. Table 4 synthesizes the available information for the CV_G values in both the rural and urban contexts.

Table 4. Suggested CV_G values for the rural and the urban context

Variability	CV_G

	Classification	Rural	Urban
Uniform -Alluvial terrace, Delta deposit, Marine or lacustrine Flood plain	SP, SW, GP, GW, CL	<0.1	<0.5
Moderate -Deposition basin border, Alluvial deposit, Fluvio-glacial deposit	SP-SM, GP-GM, CL-ML	>0.1 and <0.3	<0.5
High -Glacial till, Varved clay, Soil with silt layers, Soil/Rock contact	GM, GC, SM, SC, ML, CL	>0.3	<0.5

The rearrangement of equation 2 and equation 3, as well as the use of the CV_G values proposed in Table 4, lead to a six steps design methodology to determine admissible frost heave for pavement structures, especially for urban pavements were CV_G values are significantly influenced by trenches and buried utilities. Figure 5 is introduced as a tool to apply the design methodology and can be used to determine the allowable frost heave for a given CV_G value and a maximum allowable IRI_{Max}. The 6 steps design methodology is as follows:

1. Establish the design period (Age) and the maximum roughness (IRI_{Max}) that can be tolerated considering the classification of the road;

2. Determine V_L for the design period (AGE in years) and IRI_{Max} with the use of a rearranged equation 3 which is expressed

$$(4)\ V_L\left(\text{mm}\right)=12.69\left(\frac{IRI_{Max}}{AGE^{0.2323}}\right)-15.775$$

3. Determine CV_G to be used from Table 4 or by field sampling of the subgrade soil (at least 6 to 7 four meters spaced sample pairs);

4. Determine the allowable frost heave h_{adm} using Figure 5 or with the rearrangement of equation 2 (V_L in mm) which is expressed

$$(5)\ h_{adm}\left(\text{mm}\right)=\frac{V_L}{CV_G}$$

5. Calculate the theoretical frost heave h_{est} using an appropriate model, such as the Saaralainen-Konrad approach (Saint-Laurent 2006), for a trial pavement structure and typical conditions;

6. If $h_{meas} \leq h_{adm} \rightarrow$ Adequate protection against frost action
   If $h_{meas} > h_{adm} \rightarrow$ Modify structure (step 5) or modify design period and/or IRI_{Max} (step 1)

This procedure allows obtaining allowable frost heave h_{adm} based on the estimation of -surface distortion when pavements are submitted to frost action. The differential frost heave is associated with the longitudinal variability in the soil physical properties such as fine particles content. As presented in Figure 5, which shows the output of the calculation procedure to obtain h_{adm}, high allowable frost heave values are obtained when CV_G values are low. However, as this calculation method is based on differential frost heave and differential soil movement due to subgrade soils variability, the output of the method appear to be realistic. If surface heaving was uniform at any point of the pavement surface, frost heave would have little effect on the degradation of the surface profile. This is the main reason why very high h_{adm} are obtained using the calculation approach. Nevertheless, threshold values should be modified by transportation agencies based on their assessment of allowable IRI_{Max} and h_{adm}.

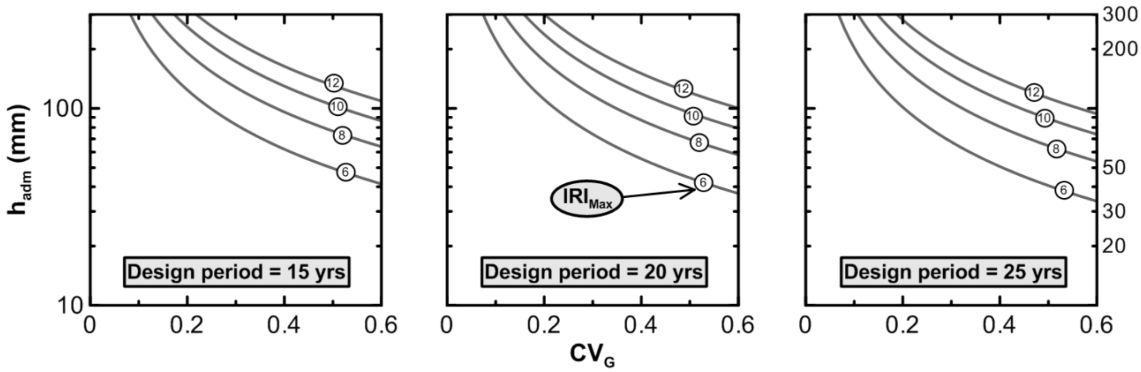

Figure 5. Design charts to determine allowable frost heave

As working examples of this design procedure, values of h_{adm} were calculated for an arterial, residential and a local road for a design period of 20 years. For these examples, adapted IRI_{Max} of respectively 7, 9 and 7 were selected for these three road classes.. These values of IRI_{Max} appear to be reasonable for urban pavements reaching the end of their design period as discussed in TAC (1997) and Carrier (2011). For the arterial and residential roads, buried utilities were considered and therefore, CV_G values were set at 0.5. For the last case, CV_G values were fixed for different soil variability conditions (uniform=0.09, moderate=0.28 and high=0.4). The analysis performed using the design approach allowed obtaining frost heave criteria for each of the typical urban road types proposed. Table 5 summarizes the h_{adm} values obtained using the proposed calculation approach. A high h_{adm} value of 317 mm was obtained for the case of local road built on uniform subgrade soil (CV_G=0.09). As previously discussed, this high value was expected because the calculation approach is based on differential soil movements, which are of low magnitude for uniform soil conditions. Nevertheless, a maximum value was set at 120 mm based on the available data found in the literature, as presented in Table 6, considering the fact that this calculation is made for uniform soil conditions. As it can be observed in the output from the calculation method proposed in Table 5, as well as the typical allowable frost heave values in Quebec and Finland in Table 6, the approach developed throughout this paper gives reasonable results that are in good agreement with actual standards. However, the proposed method has the advantage to propose allowable frost heave based on the soil variability conditions, which may vary from one site to another.

Table 5. Allowable frost heave for typical urban pavement conditions

Soil variability conditions	Allowable frost heave (mm)*		
	Arterial	Residential	Local
Uniform	60	90	120**
Moderate	60	90	100
High	60	90	70

*Rounded values
**Reduced from 317 mm

Table 6. Examples of allowable frost heave for various class of roads in Quebec and Finland (Doré and Zubeck 2009)

	Quebec	Finland
Freeways	< 50 mm	< 30 mm
Main Highways	< 55 mm	< 50 mm
Regional roads	< 60 mm	
Local roads	70 to 80 mm	< 100 mm

4 CONCLUSION

Differential frost heave and degradation of flexible pavement surface profile in cold climate significantly affects the serviceability of these important civil engineering structures. This degradation is believed to be mostly associated with subgrade soils variability. As this variability becomes an unavoidable issue for urban pavements because of the numerous cuts and fills and buried utilities, a design methodology for flexible pavements frost heave protection based on subgrade soils variability is proposed. The research work done in several countries was revisited in order to develop a design methodology based on subgrade soil variability. A relationship between the maximum IRI, pavement age and subgrade soils variability was proposed as the basis of the design approach. The design methodology was applied for three typical cases of urban flexible pavements as working examples in order to determine maximum admissible frost heave adapted to road classification. The maximum allowable frost heave values obtained using the proposed method appear to be reasonable and in good agreement with other frost heave criteria found in the literature. It was demonstrated that the proposed approach can reasonably take into account the road classification, subgrade soils variability conditions, design period and allowable maximum value of surface profile degradation.

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