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Abstract : In cold regions, climate affects flexible pavement performance, such as frost heave. In the context of a changing climate, air freezing index can no longer be considered as fixed for pavement design. Climate simulations were performed for Quebec conditions in order to determine the evolution of the air freezing index over the coming decades. Using a relationship between average frost heave and the yearly roughness deterioration rate and a proposed method to consider decreasing air freezing index, the effect of climate change was quantified with respect to the 1971-2000 conditions. Thinner pavement structures are obtained with the calculation approach, and its effect was quantified in terms of materials and pavement life. It was shown that a reduction of 100 mm could be considered for pavements built on frost sensitive soils. In addition, the proposed method showed an increase of pavement life, quantified with roughness, for most of the cases considered.

Keywords : Climate change, air freezing index, flexible pavements, roughness, frost heave

1. Introduction

In the past few decades, signs of an evolving climate were discussed among the scientific community. While a couple of years ago, the subject of climate changes did not make a full consensus, it is now difficult to deny the various proofs of climate change around the globe (IPCC 2013). The obvious changes in climate are usually associated with the beginning of the industrial era. This period is characterized by a massive increase in emissions of greenhouse gases such as CO₂, CH₄ and NO₂. Indeed, the warming observed from the mid-20th century is unequivocal and IPCC (2013) states that it is extremely likely that human influence is the dominant cause of that warming. Climate change also manifest as increases in ocean temperatures, an increase of sea level and a decrease of sea ice extent. Global warming also affects frozen ground, as permafrost temperature increases of up to 3°C in parts of Northern Alaska between the mid-1980s and mid-2000s were documented (IPCC 2013). Moreover, non-uniform changing pattern regarding the precipitation regimes were observed all over the globe (IPCC 2013). The work of Collins et al. (2013) states that warming is likely to continue over the 21st century if greenhouse emissions associated with human activity continue to rise. The projected increase by the end of the century is expected to reach 1.8 to 3.8 °C depending on the emission trend considered. The warming may, however, not be uniform all over the globe (Maloney et al. 2014), with greater changes expected at higher latitudes.

When it comes to pavement performance, the temperature is among the most influential factors associated with climate to consider (Byram et al. 2012), and its variation is among the most probable climate variations for future climates (Emery 2010). Climate change is likely to influence pavement performance and response in many ways., The main manifestations of its

effect are rutting, longitudinal cracking, fatigue cracking, transverse cracking or roughness (Tighe et al. 2008; Kim et al. 2005; Graves et al. 2006; Dawson 2010; Carrera et al. 2009). In North America, climate changes are expected to be more significant during the winter period (Desjarlais et al. 2010; Thiam 2014; Perron Drolet 2015; Emery 2010). Increase of temperature, precipitation and number of winter partial thaws is the effect of climate change expected to occur in the winter period (Chaumont and Brown 2010; Logan et al. 2011). Moreover, climate change will also have a significant effect on the length of the freezing season (decrease) or even on the number of days to reach a critical freezing index (increase) (Mills et al. 2009). The research work of Logan et al. (2011), Emery (2010), Dawson (2010) and Chaumont and Brown (2010) showed that future climate conditions will likely be associated with more frequent freeze-thaw cycles during the winter period.

For many types of engineering projects, climate is an important factor to take into consideration in order to ensure a long-lasting performance. This is the case in pavement engineering, where many climatic data, such as temperatures and moisture, are considered when designing pavement structures (NCHRP 2004; Huang 2004; TAC 1997). In northern countries, air temperature is essential to quantify the length and severity of the winter period. This is usually done using the air-freezing index FI_a which, expressed in °C*day, represents the sum of the average daily temperatures throughout the sub-zero time period, or the average temperature of the freezing period multiplied by the length of the freezing period (Doré and Zubeck 2009). Many design methods use this parameter for frost protection of pavement structures. The frost protection principles are usually based on the limitation of frost action in the most frost sensitive component of the pavement system, the subgrade soil. Frost heaving problems are likely to occur if the subgrade is frost sensitive and if water is available in the system; soils are

considered to have low sensitivity to frost action if the degree of saturation is below 70% (Konrad and Roy 2000). The thickening of the pavement structure is the most common way to protect the subgrade against frost action. Frost penetration is then be affected by the thermal properties of the pavement materials, which are influenced by mineralogy, water content and density among other things (Kersten 1949; Côté and Konrad 2005). When severe frost heaving and/or significant differential frost heaving are anticipated, pavement insulation is an interesting solutions to counter frost action and to prevent heat loss in the pavement system (Doré and Zubeck 2009). Extruded (most common) or expanded polystyrene, lightweight concrete or lightweight aggregate, wood residues and peat, are the most common materials used in pavement insulation layers. When designing an insulated pavement, the designer must take into account the low stiffness of the insulation layer, its thermal effectiveness, the risk of differential icing at the pavement surface and the differential behaviour at the end of the insulated areas.

In Quebec, frost protection design method is an important part of the flexible pavement design procedure. Two alternatives are offered in the pavement design method proposed by the Quebec Ministry of Transportation. The first is a minimum thickness design used to ensure that adequate partial protection against frost is obtained through the use of an empirical criterion (Saint-Laurent 2006; Saint-Laurent 2012; Armstrong and Csathy 1963). This empirical criterion, adapted for the context of Quebec Province, suggests the minimum thickness of the pavement as a function of the normal FI_a and other considerations such as pavement functional class and subgrade soil. The empirical partial frost protection allows to determine a pavement structure thickness based on the experience in Canada which suggests that the pavement performance against frost is generally acceptable when a thickness protection corresponding to 50% of the

typical frost depth is used. The second approach is a mechanistic-empirical design procedure for frost protection that uses the Saarelainen-Konrad method to calculate frost penetration and associated frost heave at a daily time step using iterative calculations (Saarelainen 1992; Saint-Laurent 2012; Saarelainen 1992). At each time step, the heat balance at the frost front and the associated frost heave are calculated. The basic thermal balance equation is defined by

$$[1] \quad q_- = q_+ + q_f + q_s$$

in which q_- is the heat flux from the frost front towards the surface through the frozen layer, q_+ is the geothermal heat flux, q_f is the heat flux generated by the phase change from water to ice and q_s is the additional heat flux induced in the system by the freezing of water that migrates upward due to cryosuction and which feeds the growing ice lenses. Solving this heat balance thermal equation gives the frost penetration at each time step. After each iteration, the frost heave associated with the freezing of a given sublayer is calculated considering the 9% volume increase of water when changing to ice, as well as the heave induced by ice segregation. The latter is obtained from frost heave mechanics theory (Konrad and Roy 2000; Konrad and Morgenstern 1981) and is expressed as

$$[2] \quad dh = 1.09 \times SP \times GradT_- \times dt$$

in which dh is the frost heave of a sublayer, SP is the segregation potential, $GradT_-$ is the thermal gradient of the frozen soil at the segregation front and dt is the time interval. The frost heave calculated for a given winter is then compared to the allowable frost heave, which have been determined based on previous field performance observations. The Finnish Road Administration

and the Quebec Ministry of Transportation are among the few agencies proposing allowable frost heave criteria (Doré and Zubeck 2009; Saint-Laurent 2006; Saint-Laurent 2012; Tammirinne et al. 2006), mostly ranging from 30 to 100 mm depending on road functional class. The Saarelainen-Konrad calculation method requires many thermal parameters for the pavement soils and materials, such as heat capacity, thermal conductivity and latent heat. One of the main parameters needed for thermal calculations is the thermal boundary condition at the pavement surface, which is the surface freezing index FI_s . This input parameter can be obtained directly from the FI_a using the n-factor simplified approach (Andersland and Ladanyi 2004; Ladanyi 1996; Doré and Zubeck 2009). Therefore, the FI_a is of great importance for pavement design in northern countries where undesirable effects, such as differential frost heave, associated with frost action are likely to occur (Bilodeau and Doré 2013; Doré 1997; Doré and Zubeck 2009).

As air temperatures, and thus the FI_a , have a strong influence on pavement performance during the winter period, a question then arises of how to take future winter climate changes into consideration for the determination of this design parameter. The following sections present a method that takes into account climate changes as part of pavement design for frost protection.

2. Climatic simulations

Climate change predictions were performed by Ouranos, a consortium which specializes in climate science research, to assess the evolution of the air-freezing index (FI_a) with respect to a reference period, which was set from 1971 to 2000. The simulations performed consist of a group of future climate determinations based on various climatic scenarios. A climatic scenario

consists of a choice of tools (climatic models), simulation methods, variables, regions, periods, frequency of analysis, statistical approach, etc. In this project, the use of delta climatic simulations was selected to partly eliminate some bias associated with the imperfections of climatic simulations. The effects of increasing greenhouse gases are predicted in different scenarios throughout the literature using various assumptions on demography, technology, economics, politics, etc. The magnitude of the expected climate change is directly associated with the particular scenario, which can vary from optimistic (low magnitude climate change) to pessimistic (high magnitude climate change). The work from Nakicenovic et al. (2000) and IPCC (2007) analyzes the effect of various scenarios of increasing greenhouse gases on global surface warming. The selected scenario A1B approximately represents the statistical median, in terms of global surface warming, of the scenarios initially considered, and is used in this paper to simulate the evolution of greenhouse emissions over the next few decades. However, prior to 2050, the effect of increasing greenhouse gases is limited to global surface warming. In order to adequately incorporate natural climate variability in climate modelling for future periods, five members of the Canadian Global Circulation Model (CCMA_CGCM version 3.1), as well as one member of the German model (SCIRO version mk 3.5) and one member of the Australian model (MPI_ECHAM version 5), were used in the analysis.

The simulations were performed and the averages for over 30 years periods were calculated in order to minimize bias and annual variability, as previously described. This period length is considered sufficient to include in the analysis a significant number of abnormal conditions, such as atypically mild winters, the important quantity of liquid precipitations during the winter period, etc. In order to simulate the expected climate for various time horizons, the following

periods were selected for climatic modelling: 2001-2030, 2011-2040, 2021-2050, 2031-2060, 2041-2070 and 2051-2080. Depending on various parameters, such as proximity of the sea, altitude, latitude, dominant winds, the climate change predictions are likely to differ depending on the geographical position in the province of Quebec. Therefore, as presented in Figure 1, the southern part of the Quebec map was divided into 3 different zones, all characterized by an expected evolution of the climate. This division was based on three different documents. The first document was the map used by the Quebec Ministry of Transportation to define three distinct spring load restriction zones. This map shows a division of Quebec's territory with respect to the period of the year during which spring thaw occurs (<https://www.mtq.gouv.qc.ca/usagers/vehiculelourd/degel/Pages/Zones-de-d%C3%A9gel.aspx>). The second document is the map of the historical air-freezing index over Quebec's territory, currently used for flexible pavement design at MTQ. This map clearly shows a northwest-southeast gradient of the index over the province, and a northeast-southwest gradient with respect to the St-Lawrence River (Ladanyi 1996). The third document was based on the study of Chaumont and Brown (2010) that presented a map of air-freezing index variations for the period 2041-2070 with respect to the period 1971-2000. The combination of the three documents allowed obtaining the climatic zone divisions considered for this study as presented in Figure 1.

Figure 2 presents the evolution of the variation of FI_a (ΔFI_a) from the reference period as a function of the climatic horizon considered for the median scenario. The decreasing rate of ΔFI_a with respect to time varies between -7.6 and -9.7 $^{\circ}\text{C}\cdot\text{d}\cdot\text{yr}^{-1}$. Table 1 presents the decreasing rates of ΔFI_a with respect to time for the median scenario. The variation of the air freezing index

is similar in zone 1 and zone 2, but the northern zone (zone 3) is more likely to be subjected to more significant climate changes during winter, as proposed by Desjarlais et al. (2010).

3. Effect of decreasing FI_a with climatic horizon

The evolving FI_a was used as an input for pavement design for the purpose of this project. The flexible pavement design software used in Quebec, CHAUSSEE 2, allows structural calculations using the AASHTO empirical method (AASHTO 1993) and uses the combined Saarelainen-Konrad method to calculate frost penetration and corresponding frost heave with an iterative thermal balance calculation at the frost front. A minimum frost protection is also ensured using an empirical criteria. First, the software was used to calculate a reference structure for the year 2010. The FI_a was adjusted for the year 2010 using the FI_a of each zone and the decreasing rates ΔFI_a . The 1971-2000 FI_a values are 1070, 1240 and 2004 °C*d and the corresponding 2010 FI_a values are 992, 1158 and 1907 °C*d, for zones 1, 2 and 3, respectively. In order to cover a wide range of likely situations representative of the Quebec conditions, three pavement functional classes (national, regional and local) and three type of soils (Low plasticity clay - CL, Silty sand - SM and Silty/Clayey gravel - GC-GM) were considered for each zone, as presented in Table 2 and Table 3. Table 2 presents the main characteristics of each pavement class, while the main soil parameters used as inputs in the design method are presented in Table 3. The following are found among the data presented in Table 3: the effective resilient modulus (M_{reff}), the segregation potential for the no vertical stress condition (SP_0), the coefficient of sensitivity to vertical stress for the segregation potential (α), the dry density (ρ_d), the frozen thermal conductivity (k_f), the degree of saturation (S_r) and the latent heat of fusion for the soil (L_f). Table

4 presents the structures obtained by the combined optimization process for the frost protection and structural design. It should be noted that Quebec specifications impose a minimum layer thickness for each pavement layer. When required, the design software imposed the minimum thickness. It can be observed that for a given pavement functional class, the thickness of the asphalt concrete layer and of the granular base are the same or very similar. In each case, only the subbase thickness varies significantly with the FI_a , soil type and functional class, due to the requirements for frost protection.

Since, as mentioned previously, the climate is evolving for the simulations presented in this paper, the pavement response to climatic conditions should also evolve with the climate. Doré and Zubeck (2009) presented an empirical relationship based on the work from Doré (1997, 2002) for the experience in Quebec that links the yearly increase rate of pavement roughness to the average frost heave encountered on a yearly basis h (mm). This relationship is expressed as

$$[3] \quad \Delta IRI = 0.0017h + 0.0297$$

in which ΔIRI is the yearly increase rate of the International Roughness Index (IRI) in $m\ km^{-1}\ yr^{-1}$. Using Equation 3, average frost heave values of about 40 to 80 mm will lead to a yearly IRI increase rate of about 0.1 to 0.15 $m\ km^{-1}\ yr^{-1}$. For example, a terminal IRI condition of 2.5 $m\ km^{-1}$, corresponds to a pavement at the end of its service life. Acceptable frost heave of 30 to 60 mm (Konrad 1998, cited in Saint-Laurent 2012), 30 to 100 mm (Gustavsson et al. (1999) and lower than 50 mm (Saint-Laurent 2012) were reported to be associated with adequate pavement performance depending on the pavement functional class. Therefore the associated pavement service life for this range of frost heave over typical values of the IRI terminal

condition implies that the empirical equation provides an approximate but realistic estimate of the annual rate of increase of the International Roughness Index.

As pavement performance is associated with frost heave, CHAUSSEE 2 (Saint-Laurent 2006; Saint-Laurent 2012) was used to compute the frost penetration and the corresponding frost heave during the years 2010 to 2050. With the calculated frost heave, a ΔIRI value was obtained for each year of the analysis period. Figure 3 presents the calculated frost penetration (X), frost heave (h) and ΔIRI with respect to time for the CL soil example. It can be observed that the decreasing FI_a is associated with decreasing frost penetration, frost heave and ΔIRI . This information is noteworthy, as it implies that the effect of climate change will likely cause an overdesign of flexible pavement structures against frost action over time. This is explained by the fact that the pavement design process is usually based on historical climatic conditions, which are likely to evolve from the moment the pavement is built.

3.1 Adjusted air freezing index

Because of the evolving climate, it was proposed to modify the design FI_a to take into account the future climate changes that will likely occur during the selected design period, which is a function of the pavement classification. As the design year FI_a may not be representative of the average climatic conditions that will likely occur during the design period n , an adjusted FI_a , identified as FI_{a-adj} , was proposed. This value of FI_{a-adj} is the FI_a that occurs in the middle of the design period ($n/2$). It is expressed as

$$\begin{aligned}
 & FI_{a-adj} = FI_{a-ref} - \Delta FI_a \\
 [4] \quad & \Delta FI_a = \frac{(Y_{ini} - Y_{ref})}{m} + \frac{n \times m}{2}
 \end{aligned}$$

in which FI_{a-ref} is the air freezing index of the reference period, ΔFI_a is the variation of the air freezing index, Y_{ini} is the design year, Y_{ref} is the reference year, n is the design period and m is the slope of the variation of FI_a with respect to time. Figure 4 presents the calculation and the approach proposed to calculate FI_{a-adj} . This adjustment method for the air freezing index was used to determine a new pavement design using the FI_{a-adj} as an input for the design procedure. This is likely to reduce the thickness of the frost protection layer for some of the cases considered.

3.2 Assessment of the economy of granular materials

Table 5 presents the comparison of the response of the pavement structures regarding frost heave h for the case where the standard FI_a is used and for the case where the FI_{a-adj} is used. As a reminder, FI_a is the air-freezing index used in the reference period and FI_{a-adj} is the adjusted air-freezing index, which occurs in the middle of the design period, calculated using the procedure introduced in Equation 2. The comparison is made on the basis of the obtained frost heave h and the average frost heave h_{av} , which are calculated using the Saarelainen-Konrad method. The h value is calculated with a reference freezing-index FI_a , which is fixed at the beginning of the design period. The use of a lower air freezing index (FI_{a-adj}) when the adjustment method is used implies that a lower frost heave is likely to be encountered. In that case, the frost heave is identified as the average frost heave that occurs throughout the pavement life h_{av} . Therefore,

through the design procedure that uses FI_{a-adj} , the thickness of the subbase D_{sb} can be modified to meet the allowable frost heave for a given pavement functional class. As a result, when using FI_{a-adj} , there may be a variation in the subbase thickness ΔD_{sb} , and corresponding cost savings in terms of granular materials. These savings are based on average material costs considered for a preliminary design at the Ministry of Transportation of Quebec. The results presented in Table 5 show that significant savings can be obtained for pavements built on frost susceptible soils. In the case of pavements built on clayey subgrade soil, the thickness of the subgrade layer can decrease by approximately 100 mm for all the climatic zones and pavement classes. The corresponding average savings in materials is about 0.9 \$ m⁻². For the other soil types less sensitive to frost action, it is generally observed that no cost savings are achieved because the frost heave is always below the allowable limit for each pavement functional class. The thickness of the subbase in these cases is fixed at a minimum value of 300 mm according to the requirements of the Ministry of Transportation of Quebec. However, some cost savings can be made for the SM soils in zone 3 because of the higher air freezing index. Nevertheless, the benefits in this case are the lowest encountered among the others considered.

3.3 Assessment of the relative damage

In order to verify the reliability of the proposed approach to adjust the air freezing index in terms of pavement performance, a comparative analysis of pavement deterioration (assessed in terms of road roughness) was carried out between identical pavement structures. This was done using the previously developed relationship between the observed frost heave and the annual roughness deterioration. The pavement structures considered are the same as the ones

presented in section 3.2, which are the pavements designed with FI_a and FI_{a-adj} , respectively. For national roads, the period 2010-2040 was considered, while the period 2010-2035 was considered for regional and local roads (Table 2). For the pavements designed with FI_{a-adj} , the total damage was obtained from the damage rate, which was determined using the frost heave that occurred in the middle of the design period. This damage rate value was then multiplied by the design life of the pavement structure.

Table 6 presents the results of this analysis. In order to validate the proposed correction approach, the ratio between the sum of the roughness damage for the pavement structures designed with FI_a and the sum of the roughness damage for the pavement structures designed with FI_{a-adj} was calculated. This ratio is expressed as

$$[5] \quad \text{Ratio}(\%) = 100 \frac{\sum \Delta IRI}{\sum \Delta IRI_{adj}}$$

in which $\sum \Delta IRI$ is the sum of roughness damage for the pavements designed with FI_a and $\sum \Delta IRI_{adj}$ is the sum of roughness damage for the pavements designed with FI_{a-adj} . For adequate interpretation of this analysis, it should be recall that only the pavement structures built on clayey soils and the pavement structure built on an SM subgrade soil show a decreased subbase thickness when the approach for the correction of the air freezing index is used. Ratios lower than 100% are observed for each pavement functional class of the CL subgrade soil. This means that the roughness damage is slightly higher when the FI_{a-adj} is used for the design. The average roughness damage ratio is found to vary between 93.08 and 97.02 for all the zones considered. This is associated with an average total roughness damage of 0.25 m km^{-1} higher when the FI_{a-adj}

is used; both damages are therefore very similar. The ratio values are generally higher but close to 100% for the pavement structures in which the subbase thickness did not have to be adjusted between methods for considering the air freezing index for the pavement design (SM and GC-GM subgrade soils). This is related to the fact that, for a given total pavement thickness, the frost heave is lower for the cases where FI_{a-adj} is used, as it is a lower value than the FI_a . The corresponding damage is therefore lower. When the subbase thickness varies, this variation is likely to have an impact on the calculated roughness damage ratio. Nevertheless, as presented in Table 6, the calculated roughness damage ratios are all close to 100%, which means that the proposed adjustment method for the air freezing index may be adequate to predict future winter period climate changes. In some cases, the proposed method may lead to some cost benefits associated with a decrease in the subbase thickness.

4. Conclusion

Climatic data are necessary inputs for adequate pavement design against frost action in northern environments. The air freezing index is extensively used to describe the length and the severity of the winter period. Considering the expected climate changes over the next few decades, which imply evolving climatic data, and the typical service life of flexible pavement structures, the constantly changing air freezing index should be taken into account in the pavement design process. This paper introduced the results of a comprehensive study to establish a correction method of the air freezing index to take into account future climate changes. The results were presented for a median scenario of greenhouse gases increase. The study allowed concluding that, because of the reduction of the air freezing index in the frost

protection design inputs, a thickness decrease of about 100 mm can be considered for the subbase when flexible pavements are built on frost sensitive subgrade soils. The roughness damage ratio was used to quantify the effect of the proposed air freezing index correction method on pavement performance. The proposed method showed an increase of pavement life, quantified with roughness, for most of the cases considered (soil types and road functional class). The roughness damage ratio showed a slight decrease of pavement life of maximum value of about 7% for roads built on clayey soils.

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Table 1. Rate of decreasing air freezing index with respect to time for the three climatic zones

Zone	FI_a decreasing rate ($^{\circ}\text{C}\cdot\text{d}\cdot\text{yr}^{-1}$)	R^2
1	-7.764	0.996
2	-8.219	0.967
3	-9.656	0.996

Table 2. Design objectives for the pavement functional classes considered

Pavement class	Traffic class MADT* (vehicle d ⁻¹)	Design life (year)	ESALs* ($\times 10^6$)	Allowable frost heave (mm)
National	5 000 – 20 000	30	5	55
Regional	2 000 – 3 000	25	2	60
Local	< 1 000	25	0.5	70

*MADT = Mean Annual Daily Traffic; ESAL = Equivalent Single Axle Load

Table 3. Subgrade soil properties used for structural and frost protection design

Soil type	M_{reff} MPa	SP_0 $\text{mm}^2 \cdot ^{\circ}\text{K}^{-1} \cdot \text{h}^{-1}$	a MPa^{-1}	ρ_d Kg m^{-3}	k_f $\text{J s}^{-1} \text{m}^{-1} \cdot ^{\circ}\text{K}^{-1}$	S_r %	L_f W h m^{-3}
CL ($I_p < 12$ and $I_L < 0.9$)	36	5.0	10.0	1300	2.29	99	42 265
SM ($P_{80\mu\text{m}} > 30\%$)*	45	4.0	11.0	1800	2.39	82	21 802
GC-GM	87	2.0	15	1800	2.14	79	21 519

* $P_{80\mu\text{m}} > 30\%$: percentage of particles finer than 80 μm lower than 30%

Table 4. Pavement designs for each case considered for the reference year using the normal air freezing index

Road type	Layer	Layer thickness (mm) Soil type : CL / SM / GC-GM		
		Zone 1	Zone 2	Zone 3
National	AC	170 / 170 / 170	170 / 170 / 170	170 / 170 / 170
	Base	250 / 250 / 250	250 / 250 / 250	250 / 250 / 250
	Subbase	850 / 300 / 300	1025 / 300 / 325	1725 / 700 / 300
Regional	AC	130 / 130 / 130	130 / 130 / 130	130 / 130 / 130
	Base	225 / 225 / 225	225 / 225 / 225	225 / 225 / 225
	Subbase	875 / 300 / 300	1050 / 300 / 300	1725 / 650 / 300
Local	AC	90 / 90 / 900	90 / 90 / 900	90 / 90 / 900
	Base	200 / 200 / 200	200 / 200 / 200	200 / 200 / 200
	Subbase	825 / 300 / 300	1000 / 300 / 300	1650 / 450 / 300

Table 5. Analysis of the economy in subbase granular materials using the adjusted air freezing index

Zone	Soil type	Pavement class	FI_a		FI_{a-adj}			Economy
			D_{sb}	h^*	D_{sb}	h_{av}^*	ΔD_{sb}	
			(mm)	(m)	(mm)	(m)	(mm)	(\$ m ⁻²)
1	CL	National	850	0.055	725	0.055	125	1.125
		Regional	875	0.059	775	0.059	100	0.900
		Local	825	0.070	725	0.070	100	0.900
	SM	National	300	0.048	300	0.044	0	0
		Regional	300	0.051	300	0.048	0	0
		Local	300	0.055	300	0.052	0	0
	GC-GM	National	300	0.022	300	0.021	0	0
		Regional	300	0.024	300	0.023	0	0
		Local	300	0.026	300	0.025	0	0
2	CL	National	1025	0.055	900	0.055	125	1.125
		Regional	1050	0.060	950	0.060	100	0.900
		Local	1000	0.070	900	0.070	100	0.900
	SM	National	300	0.053	300	0.049	0	0
		Regional	300	0.056	300	0.053	0	0
		Local	300	0.060	300	0.057	0	0
	GC-GM	National	300	0.025	300	0.023	0	0
		Regional	300	0.027	300	0.025	0	0
		Local	300	0.028	300	0.027	0	0
3	CL	National	1725	0.055	1625	0.055	100	0.900
		Regional	1725	0.060	1650	0.060	75	0.675
		Local	1650	0.069	1575	0.069	75	0.675
	SM	National	675	0.055	600	0.055	75	0.675
		Regional	625	0.060	550	0.060	75	0.675
		Local	450	0.070	375	0.070	75	0.675
	GC-GM	National	300	0.032	300	0.031	0	0
		Regional	300	0.034	300	0.033	0	0
		Local	300	0.035	300	0.034	0	0

* h and h_{av} are the frost heave calculated using the Saarelainen-Konrad method

Table 6. Roughness damage ratio for normal and adjusted air freezing index

Zone	Soil	Pavement class	FI_a		FI_{a-adj}		Ratio (%)	
			$\Sigma \Delta IRI$ (m km ⁻¹)	ΔIRI_{adj} (m km ⁻¹ yr ⁻¹)	$\Sigma \Delta IRI_{adj}$ (m km ⁻¹)	$\Sigma \Delta IRI_{adj}$ (m km ⁻¹)		
1	CL	National (30 yrs)	3.35	0.12	3.70		90.6	
		Regional (25 yrs)	3.07	3.32	0.13	3.25	3.56	93.3
		Local (25 yrs)	3.53		0.15	3.72		94.9
	SM	National (30 yrs)	3.21		0.11	3.14		102.5
		Regional (25 yrs)	2.89	3.05	0.11	2.78	2.96	103.1
		Local (25 yrs)	3.04		0.12	2.95		103.1
	GC-GM	National (30 yrs)	2.02		0.065	1.96		103.2
		Regional (25 yrs)	1.79	1.89	0.069	1.72	1.83	103.5
		Local (25 yrs)	1.87		0.072	1.81		103.4
2	CL	National (30 yrs)	3.37		0.12	3.70		91.3
		Regional (25 yrs)	3.08	3.32	0.13	3.29	3.57	93.1
		Local (25 yrs)	3.51		0.15	3.72		94.5
	SM	National (30 yrs)	3.49		0.11	3.39		103.0
		Regional (25 yrs)	3.13	3.30	0.12	3.00	3.18	103.6
		Local (25 yrs)	3.27		0.13	3.17		103.5
	GC-GM	National (30 yrs)	2.15		0.07	2.06		104.1
		Regional (25 yrs)	1.89	2.00	0.07	1.81	1.92	104.3
		Local (25 yrs)	1.96		0.08	1.89		103.9
3	CL	National (30 yrs)	3.51		0.12	3.70		94.8
		Regional (25 yrs)	3.21	3.45	0.13	3.29	3.55	97.0
		Local (25 yrs)	3.63		0.15	3.68		98.8
	SM	National (30 yrs)	3.62		0.12	3.70		97.8
		Regional (25 yrs)	3.27	3.54	0.13	3.29	3.57	99.2
		Local (25 yrs)	3.74		0.15	3.72		100.7
	GC-GM	National (30 yrs)	2.54		0.08	2.47		102.6
		Regional (25 yrs)	2.21	2.34	0.09	2.15	2.27	103.2
		Local (25 yrs)	2.28		0.09	2.19		104.2

Figures list

Figure 1. Climatic zones considered

Figure 2. Decreasing air freezing index with climatic horizon

Figure 3. Evolution of frost penetration (X), frost heave (h) and yearly rate of roughness increase (Δ/RI) with respect to time for 3 pavement functional classes and three climatic zones – Example for CL soil

Figure 4. Adjustment of the air freezing index

Climatic zones considered
42x46mm (200 x 200 DPI)

Decreasing air freezing index with climatic horizon
89x62mm (200 x 200 DPI)

191x138mm (200 x 200 DPI)

Adjustment of the air freezing index
92x72mm (200 x 200 DPI)