Mechanistic-empirical flexible pavement design using i3C-me

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Abstract: Mechanistic-empirical (ME) flexible pavement design is now the recommended practice in Canada. Yet, the complexity and the costs associated with the integration of the recent American design method may limit the integration of this approach. The NSERC Research Chair i3C undertook the development of a ME flexible pavement design software as part of its activities. The software, named i3C-me, allows performing ME design, for both structural capacity (using a Linear Elastic Analysis of pavement response) and frost protection (combined Saarelainen-Konrad method), of flexible pavement structures. The objective of the paper is to present and describe the software. This design tool is user-friendly and free and uses three levels of precision depending on the available data, budget and the importance of the project. It also uses seven different modules associated with project identification, design objectives, load characteristics, climate, structure and materials, transfer functions and frost penetration calculations. It includes a fully editable database for the vehicle configurations, material properties, transfer function, etc., therefore the users can add their specific parameters for their local materials or calibrated transfer functions. Among other things, the software is well adapted to the urban context as it can easily consider the effect of vehicle speed and vehicle configuration, such as urban bus.

Keywords: Flexible pavement, design software, mechanistic-empirical procedure, structural design, frost protection design

1 Introduction

Flexible pavement design methods in North America have been evolving quite fast in the past few decades. The AASHO project initiated in the late 50's is among the most important milestone for pavement engineering and design. The empirical design procedure that emerged from this project led to significant improvements regarding the general and specific engineering practices used in North America. It also provided a very large database of pavement response and performance that were used for several years for research and developments. The AASHTO empirical design method, implemented in 1961 and regularly upgraded up until 1993, was intensively used by transportation agencies and designers. The method is still being used today. Nevertheless, the approach has some limitations due to its empirical nature. One can mention the specific soil and climate conditions encountered in Ottawa, Illinois, where the tests took place. Other parameters such as vehicles configuration and moderate speed were specific to the test. In order to improve the work that was undertaken through the AASHO project, the Long Term Performance Program (LTPP) was initiated in 1986. It involves the monitoring of response and performance of numerous pavement sections across North America. In combination of the data collected at the AASHO test site, the data collected through this type of performance monitoring programs allows to develop damage laws, or empirical transfer functions, that are at the heart of modern mechanistic-empirical pavement design procedures that are extensively developed in North America since the 90's.

Mechanistic-empirical (ME) flexible design procedures are now the recommended practice in Canada. In contrast with the empirical procedure, through which the optimized structure is solely determined based on general performance models developed through field observations, the mechanistic-empirical method combines physical and mechanical models to empirical transfer functions to make the process more versatile and adaptable to any specific conditions, materials and vehicles, among others. Several years of development, combined with the improvement of computing capacities, led the Strategic Highway Research Program (SHRP) in the United States to release one of the most complete design procedure available today, the Mechanistic-Empirical Pavement Design Guide (MEPDG). This method and components are the state-of-the-art of pavement engineering and design. Canadian transportation agencies are in the process of evaluating the potential of the method for the Canadian context and are working on the calibration and validation of the input parameters, damage functions, among others, so the approach can be efficiently used in Canadian Provinces. However, even at low levels of precision, the MEPDG is a complex design procedure, requires significant computation time and requires a lot of input parameters that are not always easily available. It is also a costly product.

This emphasizes the need for a ME design software that is user friendly, free and already adapted to the Canadian context. Such development efforts were undertaken as part of the research activities of the industrial research Chair on the interaction between heavy loads, traffic and climate (i3C), funded by the National Sciences and Engineering

Research Council (NSERC) of Canada and numerous industrial partners. A new flexible pavements ME design software, i3C-me, was proposed in 2015 and was first only available to the Chair partners. An updated version was made available in 2016 and is now available for free download on the web (http://i3c.gci.ulaval.ca/i3c-me/). This paper aims to introduce i3C-me, its main characteristics and functioning process, as well as to compare the software with other similar options. Design examples are also provided as part of the paper.

2 Software description

The software i3C-me is a flexible pavement design software developed using VisualBasic coding. Figure 1 presents the software home screen, which gives access to seven input modules and the calculation launcher. The software allows performing ME design for structural capacity using a Linear Elastic Analysis of pavement response based on Burmister equations and using empirical transfer functions. For structural design, i3C-me uses a seasonal analysis based on Miner’s law (Doré and Zubeck 2009). A ME calculation is also performed for frost protection using the combined Saarelainen-Konrad method, which is described in Saint-Laurent (2012). Three levels of precision are proposed depending on the available data, budget and the importance of the project. It also uses seven different modules associated with project identification, design objectives, load characteristics, climate, structure and materials, transfer functions and frost penetration calculations. It includes a fully editable database (Microsoft Access Database) for the vehicle configurations, material properties, transfer function, etc., therefore the users can add their specific information on their local materials or calibrated transfer functions.

Figure 1. i3C-me home screen

3 Input windows (modules)

3.1 General information

This input window is used to enter information about the project, such as the client, the cities and counties, typical pavement sections and chaining, for example. A comment window is available to enter any specific details worth documenting as part of the trial pavement structure. Any information entered in this window is going to be available in the software text file provided as an output after the calculations are performed.

3.2 Design objectives

The objectives are defined as the traffic magnitude to be encountered for the design period. Figure 2 presents the main screen of this input window. The traffic is expressed as Equivalent Single Axle Loads (ESALs) *N* determined with

$$\mathrm{N}\left(\mathrm{ESAL}\right)=\mathrm{DJMA}\times\mathrm{D}\times\mathrm{V}\times\mathrm{C}\times\mathrm{CA}\times\mathrm{J}\times\left(\frac{\left(1+\mathrm{g}\right)^{\mathrm{n}}-1}{\mathrm{g}}\right) \qquad [1]$$

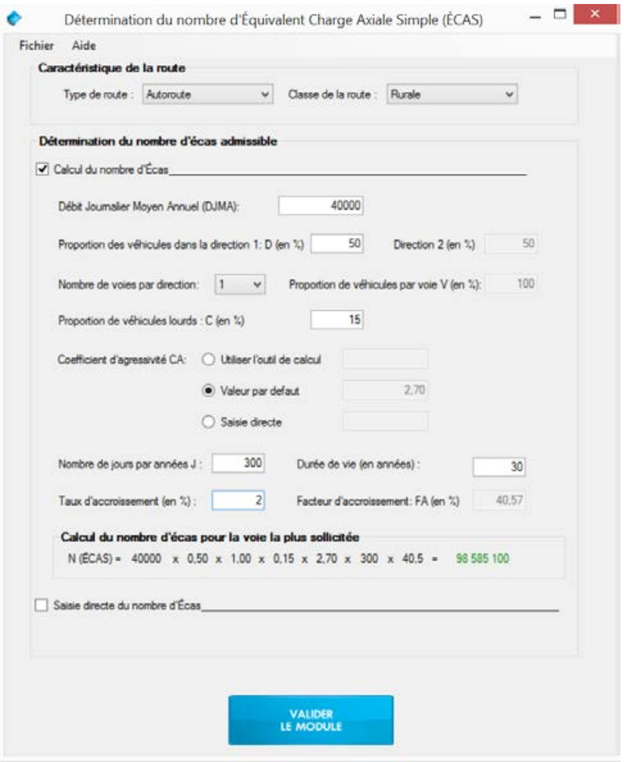
in which DJMA is the average annual daily traffic (AADT), *D* is the percentage of vehicles in each direction, *V* is the percentage of vehicles for a considered lane when 2 or more lanes are encountered in one direction, *C* is the heavy vehicle percentage, *CA* is the truck factor (ESAL), *J* is the number of days, *g* is a traffic growth factor and *n* the design period in years. The *N* value can be entered directly if available or calculated using the software interface. The heavy vehicles truck factor (*CA*) can be either directly entered by the user, defined by a default value based on the road functional class, or a calculation tool is also provided. This latter tool is similar to what is found in Chaussée2, the flexible pavement design software used in Quebec. The results of a traffic counting survey can be entered for various types of heavy vehicles and the weighted truck factor can be calculated. The default vehicles configurations and axle loads are found in an editable database, and vehicles can be added, edited or removed easily in the database. Typical heavy vehicles configuration are available in the database with the software installation, including many types of urban bus, which makes the software adapted to municipal pavement design.

The ESAL value determined is proportionally separated through the year using the season lengths that are entered in the climate analysis design window.

3.3 Load characteristics

The load characteristics are defined as the force applied, the radius of the circular plate assumed and the surface contact pressure, as well as the vehicle speed. The default values entered are the ones associated with the ESAL, which are a force of 40 kN applied on a circular plate having a radius of 150 mm, for a surface contact stress of 566 kPa.

Those values can be modified for specific analysis, considering the relationship between the three parameters. The speed is used when some specific models are considered for the asphalt concrete in the pavement structure window. The models are used to determine the dynamic modulus of the asphalt concrete mixtures. The speed is converted into a loading frequency using the equation provided by Mollenhauer et al. (2009). The user can also choose to enter manually a specific loading frequency.



Détermination du nombre d'Équivalent Charge Axiale Simple (ÉCAS)

Caractéristique de la route

Type de route : Autoroute
Classe de la route : Rurale

Détermination du nombre d'écas admissible

☑ Calcul du nombre d'Écas

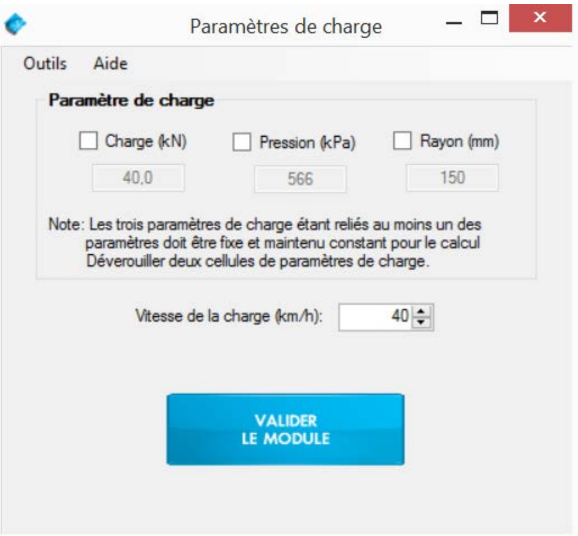
Débit Journalier Moyen Annuel (DJMA): 40000
Proportion des véhicules dans la direction 1: D (en %) 50
Direction 2 (en %) 50
Nombre de voies par direction: 1
Proportion de véhicules par voie V (en %): 100
Proportion de véhicules lourds : C (en %) 15
Coefficient d'agressivité CA:
○ Utiliser l'outil de calcul
● Valeur par defaut 2,70
○ Saisie directe
Nombre de jours par années J : 300
Durée de vie (en années) : 30
Taux d'accroissement (en %) : 2
Facteur d'accroissement: FA (en %) 40,57

Calcul du nombre d'écas pour la voie la plus sollicitée

N (ÉCAS) = 40000 x 0,50 x 1,00 x 0,15 x 2,70 x 300 x 40,5 = 98 585 100

☐ Saisie directe du nombre d'Écas

Figure 2. Design objectives window



Paramètres de charge

Paramètre de charge

☐ Charge (kN) 40,0
☐ Pression (kPa) 566
☐ Rayon (mm) 150

Note: Les trois paramètres de charge étant reliés au moins un des paramètres doit être fixe et maintenu constant pour le calcul Déverouiller deux cellules de paramètres de charge.

Vitesse de la charge (km/h): 40

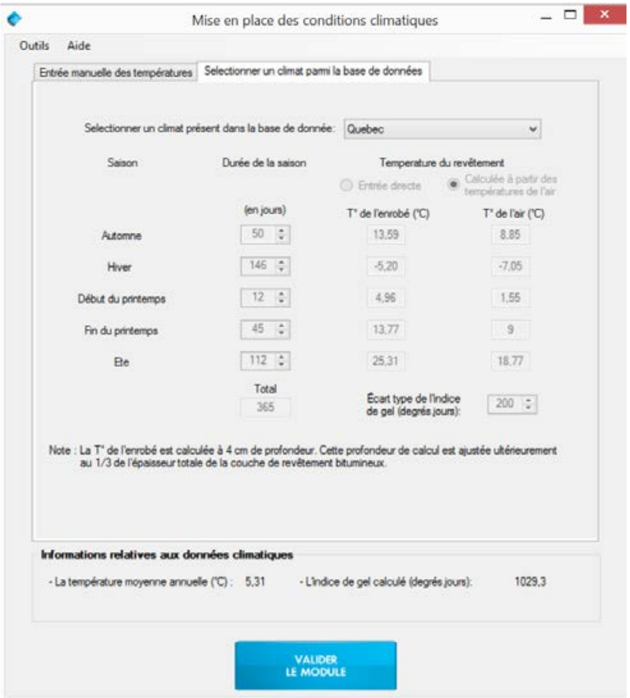
Figure 3. Load characteristics window

3.4 Climatic data

The software works using the seasonal analysis principles, as introduced in Figure 4. Five seasons are used, which are summer, fall, winter, early spring and late spring. The average air temperature and length for each season are defined in the main climate analysis window. The air temperature (T_A) is converted into asphalt concrete temperature (T_P) (Huang 2004) at a depth *z* corresponding to 1/3 of the layer thickness using the equation

[2] $$T_P = T_A\left(1+\frac{1}{z+4}\right)-\frac{34}{z+4}+6$$

for which imperial units are used. The user can either manually enter the length and temperature of each season and save the values in the database for future needs and analysis, or select a climate that is already defined in the database. Air temperatures or asphalt concrete temperatures, if available, can be entered in the database. A specific procedure that uses the sinusoidal modelling of yearly air temperatures is presented in the user’s manual to divide the yearly cycle into specific seasons, but the user can also use its own analysis techniques. The only requirement is that total number of days in a year equals to 365. If the users prefers to perform an analysis using only one season, it is possible to enter data (length and average temperature) only for the summer, using 365 as the number of days. The actual software database contains 28 weather stations in Quebec analyzed over a 30 years period. The next update will add about 30 more analyzed weather stations to the database. The average season lengths and average temperatures are calculated for this 30 years average, as well as the average annual temperature. The historical data and the climate analysis are also used to define the average air-freezing index and its standard deviation, which are used in the frost protection calculations.



Selectionner un climat présent dans la base de donnée: Quebec

Temperature du revêtement: ○ Entrée directe ● Calculée à partir des températures de l'air

Saison	Durée de la saison (en jours)	T° de l'enrobé (°C)	T° de l'air (°C)
Automne	50	13,59	8,85
Hiver	146	-5,20	-7,05
Début du printemps	12	4,96	1,55
Fin du printemps	45	13,77	9
Ete	112	25,31	18,77
Total	365		

Écart type de l'indice de gel (degrés.jours): 200

Note : La T° de l'enrobé est calculée à 4 cm de profondeur. Cette profondeur de calcul est ajustée ultérieurement au 1/3 de l'épaisseur totale de la couche de revêtement bitumineux.

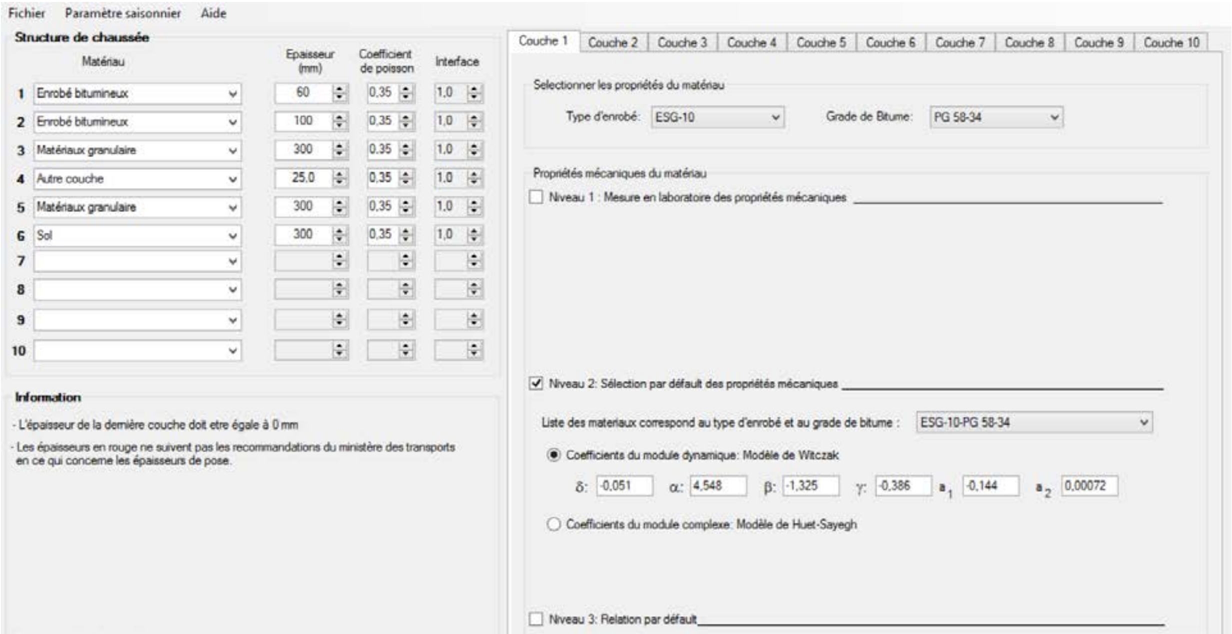
Informations relatives aux données climatiques

- La température moyenne annuelle (°C) : 5,31
- L'indice de gel calculé (degrés.jours): 1029,3

Figure 4. Main climate analysis window

3.5 Pavement structure

The pavement structure main window is presented in Figure 5. Up to 10 layers of materials can be used in the trial pavement structure. The materials categories available are: asphalt concrete, granular materials, soils and other materials (insulation, reinforcement or drainage). The software allows to use multiple layers of any materials and provide guidance with respect to the recommended thickness to be used for each layer of different materials. The layers thickness can be adjusted for the trial structure in this input window. The Poisson ratio is 0.35 for each material, but can be easily changed in the main input window. For design purposes, the algorithm detects the last layer of asphalt concrete, as well as the first layer of subgrade soil, in order to compute the tensile elastic strain at the bottom of the asphalt concrete layer and the compressive elastic strain at the top of the subgrade.



Structure de chaussée

	Matériau	Epaisseur (mm)	Coefficient de poisson	Interface
1	Enrobé bitumineux	60	0,35	1,0
2	Enrobé bitumineux	100	0,35	1,0
3	Matériaux granulaire	300	0,35	1,0
4	Autre couche	25.0	0,35	1,0
5	Matériaux granulaire	300	0,35	1,0
6	Sol	300	0,35	1,0
7				
8				
9				
10				

Information

- L'épaisseur de la dernière couche doit etre égale à 0 mm
- Les épaisseurs en rouge ne suivent pas les recommandations du ministère des transports en ce qui concerne les épaisseurs de pose.

Selectionner les propriétés du matériau

Type d'enrobé: ESG-10

Grade de Bitume: PG 58-34

Propriétés mécaniques du matériau

☐ Niveau 1 : Mesure en laboratoire des propriétés mécaniques

☑ Niveau 2: Sélection par défault des propriétés mécaniques

Liste des materiaux correspond au type d'enrobé et au grade de bitume : ESG-10-PG 58-34

● Coefficients du module dynamique: Modèle de Witczak

δ: -0,051 α: 4,548 β: -1,325 γ: -0,386 a_1 -0,144 a_2 0,00072

○ Coefficients du module complexe: Modèle de Huet-Sayegh

☐ Niveau 3: Relation par défault

Figure 5. Pavement structure main input window

The materials database can be modified at all times through the input window. New materials, modification to available materials, can be entered in the database.

The software works on the seasonal analysis principles. For asphalt concrete materials, the season stiffness is determined from the season input temperature. For the granular materials and soils, the optimum stiffness, which is associated to summer conditions, is determined. For the other seasons, seasonal multipliers function of soils and materials types, which can be modified at all times in the input window, are used to modify the optimum stiffness for the response calculations during the other seasons.

Three levels of characterization are used for each materials, level 1, 2 and 3, the first one being associated with a detailed and precise materials characterization, while the last one being associated with the use of default values, for example.

3.5.1 Asphalt concrete

When downloaded, i3C-me has three asphalt concrete mix entered in the database (surface course ESG-10; surface and base course ESG-14; base course GB-20) (Doucet and Auger 2012). The user can also input new materials in the database. The bitumen grade can be selected for each mix. These information are used to select appropriate typical dynamic modulus or complex modulus equations for each mixture (level 2), or the user can input directly test results at level 1. The available models are the Witczak (2005) or Huet-Sayegh (1963) and are expressed

[3]
$$Log|E^*| = \delta + \frac{\alpha}{1 + e^{(\beta + \gamma \cdot \log(f_r))}}$$
$$Log\ fr = Log\ f + Log\ aT$$
$$Log\ aT = a1(T - Tr) + a2(T - Tr)^2$$

[4]
$$E^* = E_0 + \frac{E_\infty - E_0}{1 + \delta \cdot (i\omega\tau)^{-k} + (i\omega\tau)^{-h}}$$
$$Log\ \tau = Log\ \tau 0 + Log\ aT$$

|E*| = Dynamic modulus (MPa),
E* = complex modulus
f = fréquence (Hz),
fr = reduced frequency (Hz),
α, β, γ, δ, a1, a2, E0, E∞, k, h, τ0 = regression coefficients
aT = shift factor (Hz).
T = Temperature (°C),
Tr = Reference temperature (=10°C).
τ = relaxation time (s),
ω = pulsation [2πf] (rad/s),
log(τ)=log(τ0)+log(aT)

If such models are used, the temperature and frequency are needed as inputs. For the temperature, the value at 1/3 of the trial asphalt concrete thickness is used, as it is also done when MnPave is used, which is the ME flexible pavement design software developed by Minnesota department of Transportation. The temperature in the asphalt concrete layer can either entered manually for each of the five seasons, or calculated using equation 2. For the loading frequency, it can either be entered manually, or calculated using a default relationship proposed by Mollenhauer et al. (2009), where the frequency is defined as 0.46**V*, with the speed *V* expressed in km/h. More options will be available for defining load frequency in a future update.

At level 3, a default relationship which defines the dynamic modulus as a function of temperature is used. This is the same function than the one used in Chaussée2, the flexible pavement design software used in Quebec.

3.5.2 Granular materials

The database available when the software is downloaded contains 8 types of granular materials: granular base (MG20), granular subbase (MG112), granular base and subbase (MG56), as well as 5 types of recycles materials (MR1, MR2, MR3, MR4 and MR5). At level 1, the resilient modulus (M_R) stress dependency is modelled using the Uzan (1985) model, which is expressed

[5] $$M_R = k_1 \cdot p_a \cdot \left(\frac{\theta}{p_a}\right)^{k_2} \cdot \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3}$$

M_R = resilient modulus (MPa),
k1, k2, k3 = regression coefficients
pa = atmospheric pressure (=101.325 kPa),
θ = total stress (kPa), définie par l'équation (15),
τoct = octahedral shear stress (kPa).

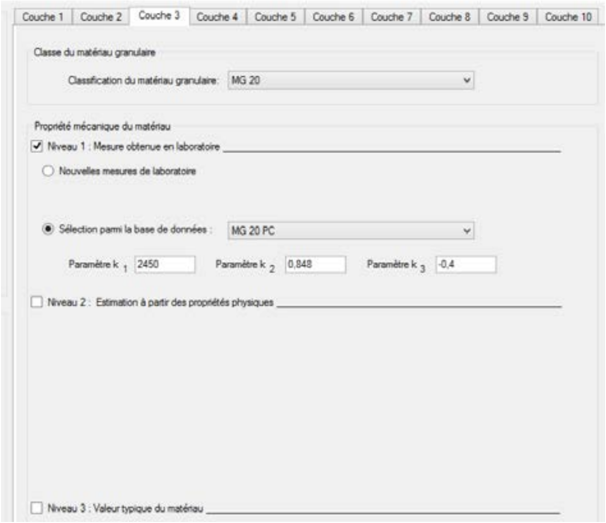
As shown in Figure 6, typical k1, k2 and k3 values are provided in the database for each material and can be used at level 1. However, at this level, the user can also enter directly the results of laboratory tests. At level 2, the stress dependency of the resilient modulus can be estimated using basic characterization (grain-size distribution, grain density and modified proctor) or using the results from a CBR test. At level 3, a typical elastic modulus for the considered granular material is entered in the software.

All the material properties available in the database (k_1, k_2, k_3, Mr, CBR, etc.) are based on typical Quebec conditions, as found in Chaussée2.

3.5.3 Soils

For soils, level 1 is similar to what was previously described for granular materials. The stress dependent Uzan (1985) model is used. However, an option is also available to input a stiffness value measured using a deflectometer. At level 2, for which an example is provided in Figure 7, the user can still use the results of a CBR test, but can also express the stress dependency of the soil using either the approach proposed by Rahim and George (2005) (based on basic soil characterization) or Soto et al. (2013) (based on light weight deflectometer measurements). At level 3, a typical elastic modulus is used.

Once again, all the material properties available in the database (k_1, k_2, k_3, Mr, CBR, etc.) are based on typical Quebec conditions, as found in Chaussée2.



Classe du matériau granulaire

Classification du matériau granulaire: MG 20

Propriété mécanique du matériau

☑ Niveau 1 : Mesure obtenue en laboratoire

○ Nouvelles mesures de laboratoire

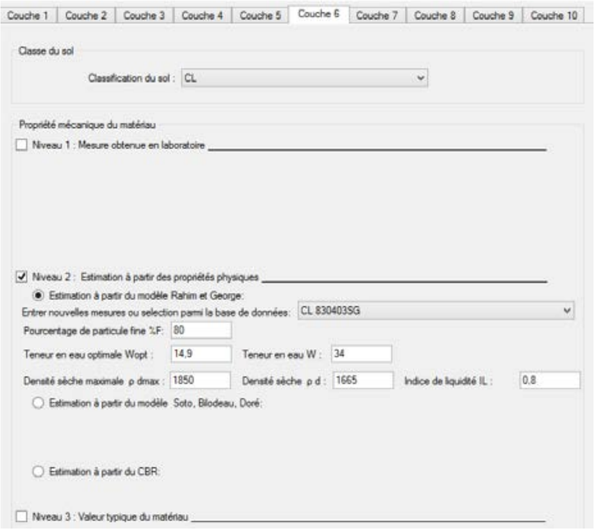
● Sélection parmi la base de données : MG 20 PC

Paramètre k_1 2450 Paramètre k_2 0,848 Paramètre k_3 -0,4

☐ Niveau 2 : Estimation à partir des propriétés physiques

☐ Niveau 3 : Valeur typique du matériau

Figure 6. Example of granular materials option window (level 1)



Classe du sol

Classification du sol : CL

Propriété mécanique du matériau

☐ Niveau 1 : Mesure obtenue en laboratoire

☑ Niveau 2 : Estimation à partir des propriétés physiques

● Estimation à partir du modèle Rahim et George:

Entrer nouvelles mesures ou selection parmi la base de données: CL 830403SG

Pourcentage de particule fine %F: 80

Teneur en eau optimale Wopt : 14,9 Teneur en eau W : 34

Densité sèche maximale ρ dmax : 1850 Densité sèche ρ d : 1665 Indice de liquidité IL : 0,8

○ Estimation à partir du modèle Soto, Blodeau, Doré:

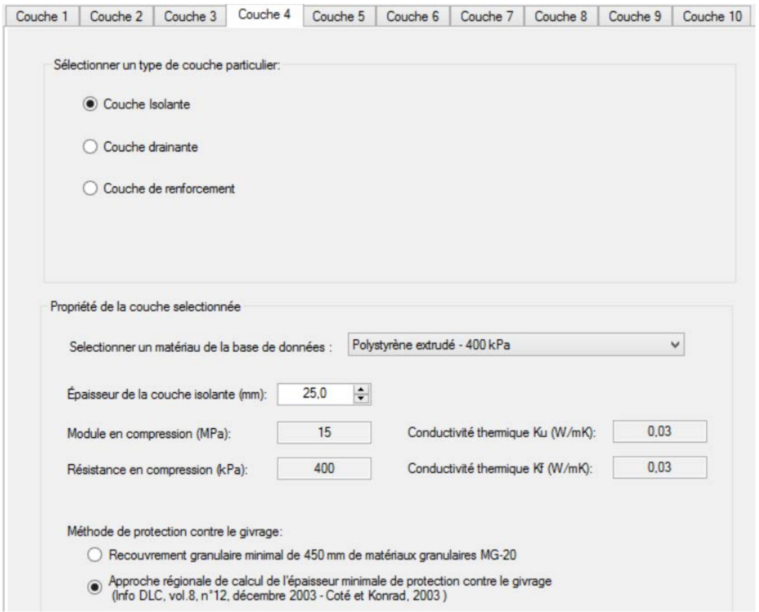
○ Estimation à partir du CBR:

☐ Niveau 3 : Valeur typique du matériau

Figure 7. Example of soils option window (level 2)

3.5.4 Other materials

In the current version, only insulation is available in this material category (Figure 8). An insulation layer can be used in the trial pavement structure as a design option for frost protection. The user is prompted to enter the type of insulation (expanded polystyrene or extruded polystyrene). Two level of compression resistance are available, 250 and 400 kPa, are available for the extruded polystyrene. The user can also add or modify the properties of the insulation materials in the database. Properties like elastic modulus, compression resistance and thermal conductivity, among others, are needed. The resistance is used in order to meet a mechanical criteria of allowable vertical stress applied on the polystyrene (Doré and Zubeck 2009), which is based on anticipated traffic and load characteristics. The use of an insulation layer can also create favorable conditions for frost hoar and therefore cause slippery surface. To prevent these conditions to develop, the software proposes two design options, which allow to adjust the thickness of the granular layer above the insulation layer to ensure that there is sufficient heat in the system that will keep the pavement surface warm enough during fall freeze-up (Doré and Zubeck 2009). The first one is a default granular protection value of 450 mm. The second one propose an adjustment of the granular protection layer based on the mean annual temperature, granular materials thermal conductivity and granular materials water content (Côté and Konrad 2003).



Sélectionner un type de couche particulier:

● Couche Isolante

○ Couche drainante

○ Couche de renforcement

Propriété de la couche selectionnée

Selectionner un matériau de la base de données : Polystyrène extrudé - 400 kPa

Épaisseur de la couche isolante (mm): 25,0

Module en compression (MPa): 15

Conductivité thermique Ku (W/mK): 0,03

Résistance en compression (kPa): 400

Conductivité thermique Kf (W/mK): 0,03

Méthode de protection contre le givrage:

○ Recouvrement granulaire minimal de 450 mm de matériaux granulaires MG-20

● Approche régionale de calcul de l'épaisseur minimale de protection contre le givrage
(Info DLC, vol.8, n°12, décembre 2003 - Coté et Konrad, 2003)

Figure 8. Example of options for insulation materials

3.6 Damage models

The load associated damage analysis is performed for bottom-up fatigue cracking and for structural rutting, as introduced in Figure 9. The former is associated with the tensile elastic strain (ε) developing at the bottom of the asphalt concrete layer, while the latter is associated with the compressive elastic strain (ε_V) developing at the top of the subgrade soil. For each damage mechanism, several models are available to calculate the number of load repetitions prior failure (N_F for fatigue and N_R for rutting), but the user can also define new models based on their preferences or test results, or modify the existing ones in the database. The models should always be defined using the same mathematical expression of the empirical transfer functions.

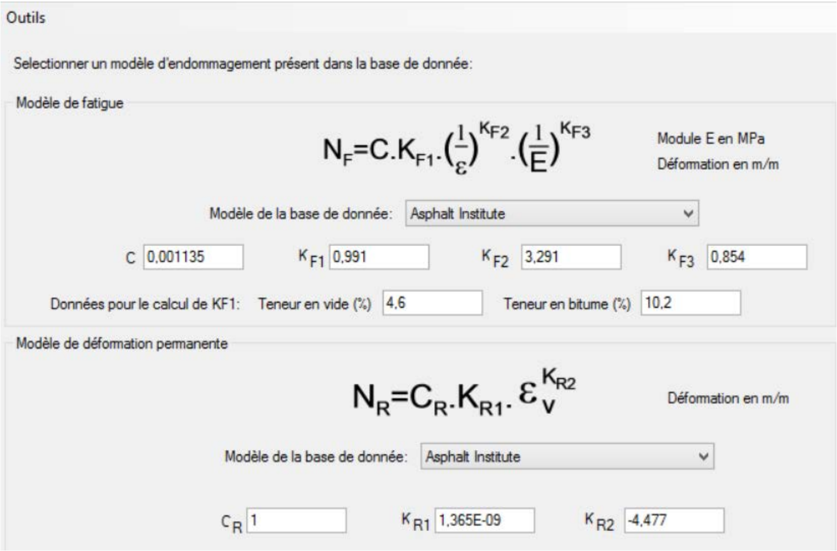
For bottom-up fatigue cracking, the general empirical transfer function model is expressed

$$N_f = C \cdot K_{F1} \cdot \left(\frac{1}{\varepsilon}\right)^{K_{F2}} \cdot \left(\frac{1}{E}\right)^{K_{F3}} \tag{6}$$

while, for structural rutting, it is expressed

$$N_R = C_R * K_{R1} \cdot \varepsilon_V^{K_{R2}} \tag{7}$$

N_f = allowable number of load repetitions for fatigue cracking,
N_R = allowable number of load repetitions for structural rutting,
ε = tensile strain at the bottom of asphalt concrete layer (m/m),
ε_V = vertical compressive strain at the top of the subgrade soil (m/m),
E = elastic modulus of the asphalt concrete (MPa),
C, KF1, KF2, KF3, KR1, KR2, C_R = adjusted model parameters.



Selectionner un modèle d'endommagement présent dans la base de donnée:

Modèle de fatigue

$$N_F = C.K_{F1}.\left(\frac{1}{\varepsilon}\right)^{K_{F2}}.\left(\frac{1}{E}\right)^{K_{F3}}$$

Module E en MPa

Déformation en m/m

Modèle de la base de donnée: Asphalt Institute

C: 0,001135

K_{F1}: 0,991

K_{F2}: 3,291

K_{F3}: 0,854

Données pour le calcul de KF1: Teneur en vide (%): 4,6 Teneur en bitume (%): 10,2

Modèle de déformation permanente

$$N_R = C_R.K_{R1}.\varepsilon_v^{K_{R2}}$$

Déformation en m/m

Modèle de la base de donnée: Asphalt Institute

C_R: 1

K_{R1}: 1,365E-09

K_{R2}: -4,477

Figure 9. Damage laws input window

For fatigue cracking, the available models in the software are the Asphalt Institute (Carpenter 2007), Illi-Pave (Al-Qadi and Wang 2009), Roadent, AASHTO MEPDG (ARA 2004), NCAT 2005 (Timm and Newcomb 2003), Norwegian Fatigue Criteria (Myre 1992) and Sweden PMS Objekt (Winnerholt 2001). For structural rutting, the available models are the Asphalt Institute (Asphalt Institute 1982), MnPave (Minesota Department of Transportation 2012), Huang 1993 (Al-Qadi et al. 2004) and Roadent (Timm et al. 1999). The user can use the models that are more adapted to his preferences or to context of the project.

It is worth mentioning that i3C-me can also be used as a calculation tool for unpaved roads. In order to be used as such, an appropriate structural rutting empirical transfer function shall be entered first by the user. In such pavement design exercise, the trial pavement structure would not have an asphalt concrete surfacing layer. Therefore, the user shall be aware that the calculations for fatigue cracking damage that will be provided by the software should not be considered, and focus should be put on the structural rutting damage in such case.

3.7 Frost protection analysis

The frost protection analysis main window is presented in Figure 10. The analysis can be performed with a sinusoidal equation that uses the data utilized as inputs in the climate analysis window, or specific monthly or daily temperature data can be entered by the user if the information is available. A mechanistic-empirical design procedure for frost protection is programmed in the software. This procedure is similar to the one proposed in Chaussée2 in Quebec. The calculation method uses the Saarelainen-Konrad approach to calculate frost penetration and associated frost heave caused by ice lenses growth and volume variations due to phase change of water 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 general thermal balance equation is defined by

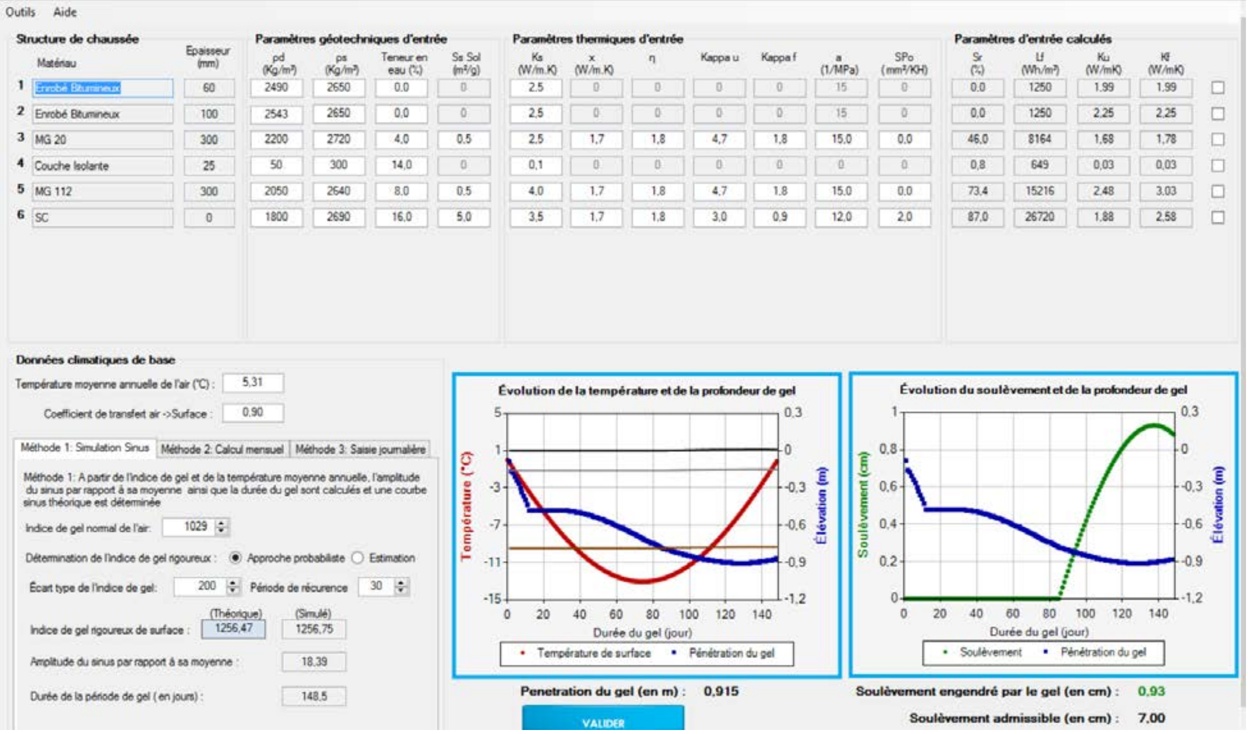
[8] $$q_{-} = q_{+} + q_{f} + q_{s}$$

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. The solving process of heat balance allows obtaining the frost penetration at each time step. After each iteration, the corresponding frost heave attributed to 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 the freezing of water migrating upward towards growing ice lenses. Heaving from segregation ice is calculated from frost heave mechanics theory (Konrad and Roy 2000; Konrad and Morgernstern 1981) and is defined as

[9] $$dh = 1.09 \times SP \times GradT_{-} \times dt$$

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 total frost heave obtained for the winter is compared to allowable frost heave values that were established using field performance observations. The Finnish Road Administration and the Quebec Ministry of Transportation are among the few agencies proposing allowable maximum frost heave criteria (Doré and Zubeck 2009; Saint-Laurent 2006; Saint-Laurent 2012; Tammirinne et al. 2006), generally in the range of 30 to 100 mm depending on road functional class. In Quebec, as programmed in i3C-me, the allowable frost heave are 50, 55, 60 and 70 mm, for highways, national roads, regional and collectors roads, and local roads, respectively. The Saarelainen-Konrad calculation method requires many thermal parameters for the pavement soils and materials in order to solve the thermal balance equation, such as heat capacity, thermal conductivity and latent heat. One of the important parameters needed to solve the equation is the thermal boundary condition at the pavement surface, which is defined with the surface freezing index (FIs) in the model. This input parameter can be derived from the air-freezing index (FIa) using the approach based on the n-factor (Andersland and Ladanyi 2004; Ladanyi 1996; Doré and Zubeck 2009). The climatic data used as inputs in the climate analysis window, such as the 30 years air-freezing index, are utilized to calculate the surface freezing index using an appropriate n-factor, which is in the range of 0.9 to 1.

The material parameters required to perform the frost design analysis are based on typical Quebec soils and materials and were extracted from the database available in Chaussée2. The database of i3C-me can easily be edited by the user, so the new materials can be added. The properties used in the calculations can also be modified easily.



Structure de chaussée			Paramètres géotechniques d'entrée				Paramètres thermiques d'entrée							Paramètres d'entrée calculés				
	Matériau	Epaisseur (mm)	ρd (Kg/m³)	ρs (Kg/m³)	Teneur en eau (%)	Ss Sol (m²/g)	Ks (W/m.K)	x (W/m.K)	η	Kappa u	Kappa f	a (1/MPa)	SPo (mm²/KH)	Sr (%)	Lf (Wh/m³)	Ku (W/mK)	Kf (W/mK)	
1	Enrobé Bitumineux	60	2490	2650	0.0	0	2.5	0	0	0	0	15	0	0.0	1250	1.99	1.99	☐
2	Enrobé Bitumineux	100	2543	2650	0,0	0	2,5	0	0	0	0	15	0	0,0	1250	2,25	2,25	☐
3	MG 20	300	2200	2720	4,0	0.5	2,5	1,7	1,8	4,7	1,8	15,0	0,0	46,0	8164	1,68	1,78	☐
4	Couche Isolante	25	50	300	14,0	0	0,1	0	0	0	0	0	0	0,8	649	0,03	0,03	☐
5	MG 112	300	2050	2640	8.0	0.5	4.0	1,7	1,8	4,7	1,8	15,0	0,0	73,4	15216	2,48	3,03	☐
6	SC	0	1800	2690	16,0	5,0	3,5	1,7	1,8	3,0	0,9	12,0	2,0	87,0	26720	1,88	2,58	☐

Données climatiques de base

Température moyenne annuelle de l'air (°C) : 5,31

Coefficient de transfert air ->Surface : 0,90

Méthode 1: A partir de l'indice de gel et de la température moyenne annuelle, l'amplitude du sinus par rapport à sa moyenne ainsi que la durée du gel sont calculés et une courbe sinus théorique est déterminée

Indice de gel normal de l'air: 1029

Détermination de l'indice de gel rigoureux : ● Approche probabiliste ○ Estimation

Écart type de l'indice de gel: 200 Période de récurence 30

Indice de gel rigoureux de surface : (Théorique) 1256,47 (Simulé) 1256,75

Amplitude du sinus par rapport à sa moyenne : 18,39

Durée de la période de gel (en jours) : 148,5

Penetration du gel (en m) : **0,915**

Soulèvement engendré par le gel (en cm) : **0,93**

Soulèvement admissible (en cm) : **7,00**

Figure 10. Frost protection analysis main window

It is recommended to perform the frost protection analysis considering a severe winter to take into account reliability. The software suggests two approaches to determine a severe surface freezing index. The user can either use a default relationship that uses the normal air freezing index and its standard deviation (obtained from the climate analysis window for the thirty years period), or a probabilistic approach given a return period that is specified by the user. As part of the procedure recommended in Quebec's practices (Saint-Laurent 2006), a return period equals to half the design period is recommended for most cases. The results of the analysis will provide the frost penetration and corresponding frost heave with respect to time. The total frost heave for the climate conditions considered is obtained and then compared to the allowable value used for the pavement, considering its functional class.

3.8 Damage analysis and results

The structural damage calculations are performed for each season considered and each damage mechanism (bottom-up fatigue cracking and structural rutting). For each season, the linear elastic analysis returns the appropriate strain values to be used in the selected empirical transfer functions. The Miner's law is used (Doré and Zubeck 2009), which is expressed

[10] $$D_i = \frac{n_i}{N_i}$$

in which *i* represents a specific season, n_i is the anticipated traffic for the considered season, and N_i is the allowable number of load repetitions for the season *i* for either fatigue cracking or structural rutting. The total damage consumed, D_T, is calculated using

[11] $$D_T = \sum D_i$$

and represents the sum of each seasonal damage. Using this design principle, for each damage mechanism considered, the value D_T should be close to 1 but should not be greater. Values greater than 1 suggests an under designed pavement structure, while values significantly lower than 1 suggests an over designed pavement structure.

As for the frost protection, the software compares the calculated frost heave to the threshold values suggested according to the pavement functional class.

The user can modify the trial pavement structure and material properties in order to adequately meet the design objectives.

4 Comparison with CHAUSSÉE2

In this section of the paper, a design comparison between i3C-me and CHAUSSÉE2, the empirical flexible pavement design software used at Quebec's Ministry of Transportation, is performed. CHAUSSÉE2 performs a structural calculation based on an adapted AASHTO 1993 empirical design, and the frost protection design is based on the same The comparison is made for two cases a regional road and a highway. The calculations are performed for the Quebec city climatic station and for a high plasticity silt (MH) subgrade soil having a summer resilient modulus of 32 MPa and a segregation potential SP_0 of 2 $mm^2/(°C*h)$. For the regional road, the traffic was fixed at 5 million ESALs and a speed of 70 km h^{-1} was selected. For the highway, the traffic was set at 50 million ESALs and a speed of 100 km h^{-1} was selected. The Asphalt institute empirical transfer function were selected in i3C-me. Adjustment were made to parameters related to the stress dependency of the resilient modulus of the granular layers so both calculation tools would use the same parameters. The n-factor selected was 1 in both cases and return period was set to 12 years for the regional road and to 15 years for the highway. However, minor differences were observed in the database of both software regarding the freezing index. The physical properties of the subgrade soil (water content, dry density, etc.) were adjusted so they were the same in both software, as they have a significant impact on frost heave calculations.

The results of the comparison are presented in Table 1. Both software give comparable results, with i3C-me providing slightly thicker asphalt concrete course (differences of 15 to 20 mm). The total thickness is also in the same range, but differences of 70 to 90 mm are observed. These are attributed to the slightly different air freezing index, but also to the different calculation methods. While i3C-me performs seasonal mechanistic calculations based on the pavement structure system properties, CHAUSSÉE2 uses the AASHTO 1993 empirical equation and effective soils and materials resilient modulus. This is likely to induce some minor differences in the layer thickness.

Table 1. Comparison between i3C-me and CHAUSSÉE2

	Thickness (mm)			
	Regional road		Highway	
Layer	**i3C-me**	**Chaussée2**	**i3C-me**	**Chaussée2**
Asphalt concrete*	175	155	290	275
Granular base	200	200	200	200
Granular subbase	870	800	940	1025
Total thickness	1245	1155	1430	1500

*For i3C-me, combinations of surface and base course having different dynamic modulus master curve.

5 Conclusion

A new mechanistic-empirical design software for flexible pavements was programmed as part of the research activities of the i3C NSERC industrial Research Chair at Laval University. The software performs mechanistic-empirical design for structural capacity and frost protection design. The calculations performed by the calculation tool are based on seasonal damage analysis. This software is used as the main technology transfer tool to provide the research results in an easy and simple form for the research partners and the industry. The objective of this paper was to introduce this software and present an overview of its main functionalities and options. The calculation tool can be downloaded for free online on the website of the i3C research Chair. The actual version is in French, but an English version is currently developed. Such a software presents numerous advantages, such as the ease of use, mechanistic-empirical structural design, seasonal damage analysis, consideration of the effect of vehicles speed, the calculation of frost penetration using the general heat balance equation, as well as the easy access to a fully editable database for climate, vehicles, materials and empirical transfer functions, among others. It is particularly adapted to urban pavements design because of the consideration of the vehicle speed and the availability of most urban buses configuration and axle weight in the database. The software can also be used for the design of unpaved roads. A major update of the software is planned for fall 2017.

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