Mechanistic-Empirical Flexible Pavement Design software : i3c-me

User's manual

Guy Doré, ing., Ph.D.
Damien Grellet
Caroline Richard
J.-P. Bilodeau, ing., Ph.D.
Erdrick L. Pérez-González
Maria F. Barón H

Department of Civil and Water Engineering
Université Laval

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i3C.gci.ulaval.ca
i3c-me@gci.ulaval.ca

E_1^*, h_1, μ_1

ε_t

E_{r2}, h_2, μ_2

ε_v

E_{r3}, μ_3
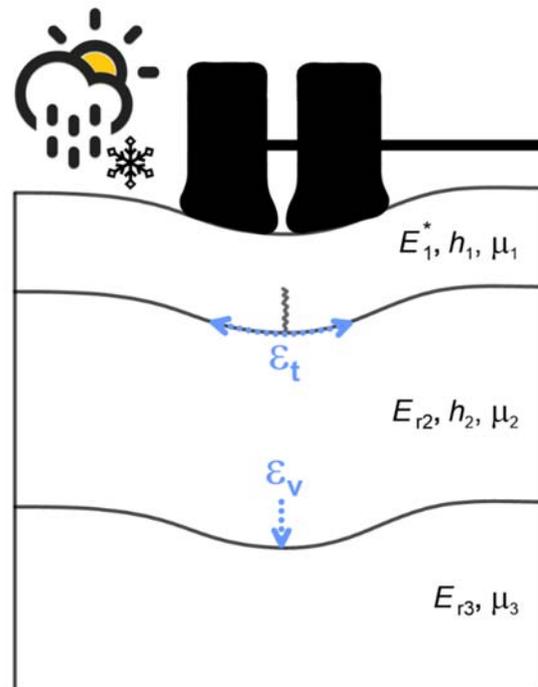
ABSTRACT

After several years of development, the i3c Chair team proposes a new software for the mechanist-empirical design of flexible pavements developed as part of its activities. This tool was developed to provide a new design tool adapted to the operating conditions, both rural and municipal, specific to Quebec. Developed in close collaboration with the Chair's partners and incorporating content based on several years of research at Laval University and in Quebec, this new tool aims to meet the needs of rural and urban network managers.

The software consists of seven modules corresponding to the different stages of pavement design:

1. General information about the project;
2. Design objectives;
3. Definition of the load;
4. Determination of climatic data;
5. Definition of the pavement structure;
6. Choice of performance models;
7. Calculation of frost action.

The software offers the user several choices of estimation and analysis methods of varying levels of complexity and precision. The design can therefore be adapted according to the importance of the project, the information available and the designer's preferences. The software performs a seasonal damage calculation to take into account the variation of the mechanical properties of materials for the different periods of the year. The user is guided through the design process to complete all the calculation steps. The mechanical response of the materials is based on an iterative linear elastic calculation. A frost module completes the analysis to determine the frost depth and the heave associated with winter conditions. At each step, the choice is left to the designer to select the level of precision of the calculations and also the relationships that will be integrated into them.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND SYMBOLS

%F :	Fine particles
σ:	Stress (kPa)
P :	Density (kg/m^3)
P_d :	Dry density (kg/m^3)
P_{dmax} :	Maximum dry density (kg/m^3)
P_s :	Density of soil solids (kg/m^3)
Υ :	Poisson's coefficient
AASHTO :	American Association of State Highway and Transportation Officials
Abs :	Absorption (%)
ASTM :	American Standard of Testing Materials
TF :	Truck factor (ESAL)
ATF :	Average truck factor (ESAL)
CBR :	California bearing ratio (%)
Cu :	Uniformity coefficient
AADT :	Annual average daily traffic number
E :	Modulus of elasticity (MPa)
ESAL :	Equivalent single axle load
A :	Incremental factor for heavy vehicles
g :	Growth factor (%)
FI :	Freezing index (°C ·days)
FI_n :	Normal freezing index (°C ·days)
FI_s :	Surface freezing index (°C ·days)
LI :	Liquidity index
IRI :	International roughness index (m/km)
MPa :	Megapascal
Mr :	Resilient Modulus (MPa)
MTQ :	Ministère des Transports du Québec
Sr :	Degree of saturation (%)
SP :	Segregation potential (mm^2/°C·day)
SP_0 :	Segregation potential without vertical load (mm^2/°C·day)
T :	Temperature (°C or K)
T :	Time (second,minutes,hours or years)
USCS :	Unified Soil Classification System
W :	Water content (%)
W_{opt} :	Optimum moisture content (%)

i. INTRODUCTION

The i3c-ME software is a software for mechanistic-empirical flexible pavements design. It was created as part of the activities of the i3c Research Chair at Laval University (Québec, Canada). Figure i.1 shows the main screen of the software. It contains seven specific modules allowing to enter or define general information, design objectives, load characteristics, climatic data, pavement structure and performance models, as well as for calculating the frost action.
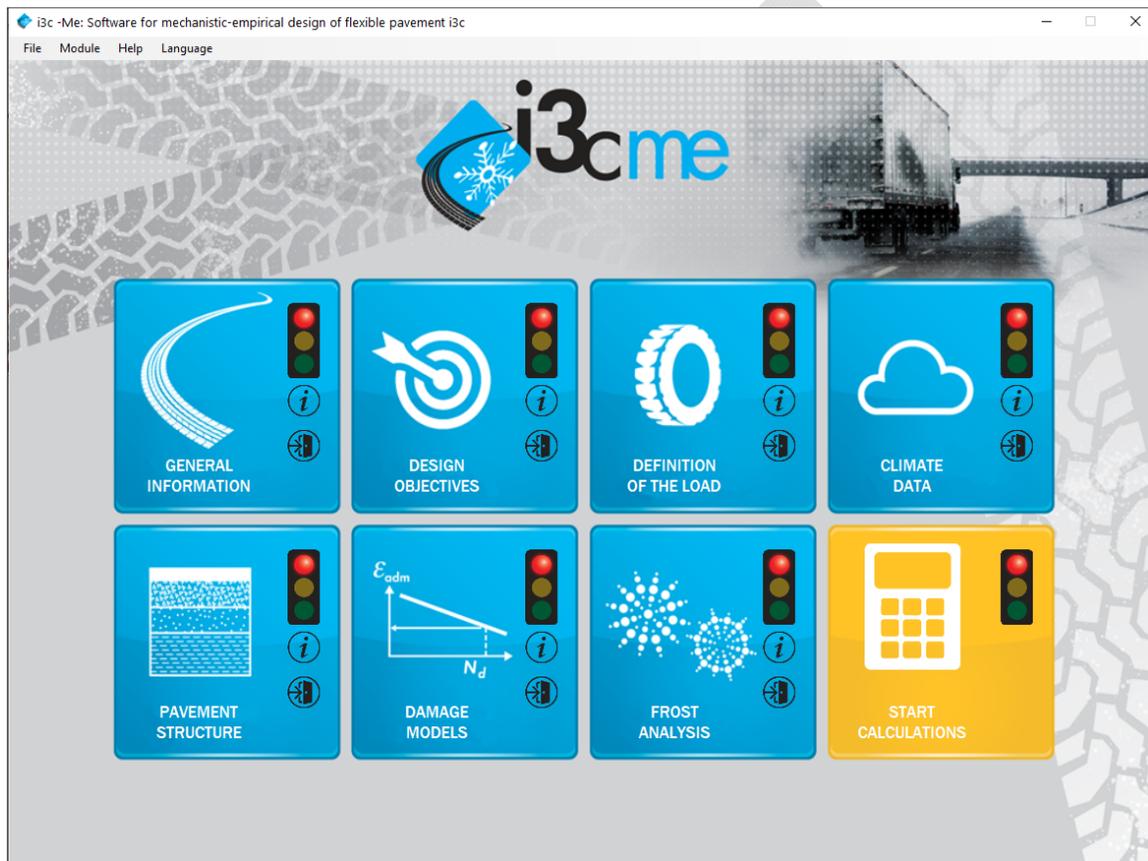
Figure i.1: Main screen of the software i3c

The software performs a seasonal damage calculation by dividing the year by up to 5 seasons: summer, fall, winter, beginning of thaw and end of thaw. The cumulative damage, based on Miner's law, allows the calculation of the service life of the pavement. The user must enter the duration of each season and provide the average air or asphalt temperature corresponding to the identified period. The user also has access to a library of climate stations and can create his own database. All types of vehicles can be considered in the study using a

calculation based on the truck factor specific to each vehicle. This approach offers the possibility of integrating, among other things, vehicles such as standard and articulated urban buses. Several options are available to the user to convert vehicle and traffic information into Equivalents Single Axle Load (ESAL), used as an input to the mechanistic calculation utility. In terms of damage laws, the user has the choice between several existing empirical transfer functions for fatigue and structural rutting that are integrated into the software. A calculation tool on the effect of frost penetration, programmed by the Ministère des Transports, has also been added to the software. It allows calculating the evolution of the frost depth with the help of temperature data coming from the climatic stations and from the properties of the materials. With regard to the definition of the pavement structure, the user can choose to use default values or to enter values estimated or measured by different tests, in order to define the mechanical properties of the materials. The software offers the user several choices of methods of estimation and analysis of levels of complexity and varying precision. The design can therefore be adapted according to the importance of the project, the information available and the designer's preferences. For example, to determine the mechanical properties of pavement materials, the user may choose to use default module values, estimate modules from CBR, LWD test results, or use advanced modelling parameters (Huet-Sayegh, Witczak, Uzan) obtained in laboratory tests on materials.

A progress indicator in the form of traffic lights is included for each step. It turns green when the module is completed or is displayed orange if data is missing. When the indicator turns green at the calculation launch level, they can be performed. Service life in terms of fatigue and rutting for each season, as well as the frost depth and frost heave, are determined by iterative calculations. Service life with respect to roughness performance is also calculated. The results are presented in a new window. The user can then modify each module and restart the calculations to optimize the design of the structure.

Figure i.2 shows the structure of the software and the interactions that can take place between the modules. The number at the top of the boxes in the flowchart refers to the module numbers. The cells without number are software-specific calculation blocks. For each use, the operator must provide general information on the project. Thereafter modules 3, 4 and 5 must be completed in order to perform the calculations associated with the mechanical response of the materials. This is done by iteration since the properties of the materials may depend on the response of the structure. An iterative calculation is therefore automatically performed by the software until a convergence of the mechanical response of

the structure is obtained. This calculation is performed for a given season. Module 4 is used to define the associated temperatures for each season and their duration. On exit, once module 6 is completed, the software determines the seasonal damage. A law of cumulative damage makes it possible to determine the lifetime of the pavement. Once Module 2 is completed, the lifetime information is compared to the design objectives. The result is displayed at the output of the software, allowing the operator to modify the data in the modules to adjust the design if necessary. Module 5 and Module 7 also allow the frost resistance of the structure to be verified by determining frost penetration and associated lifting.
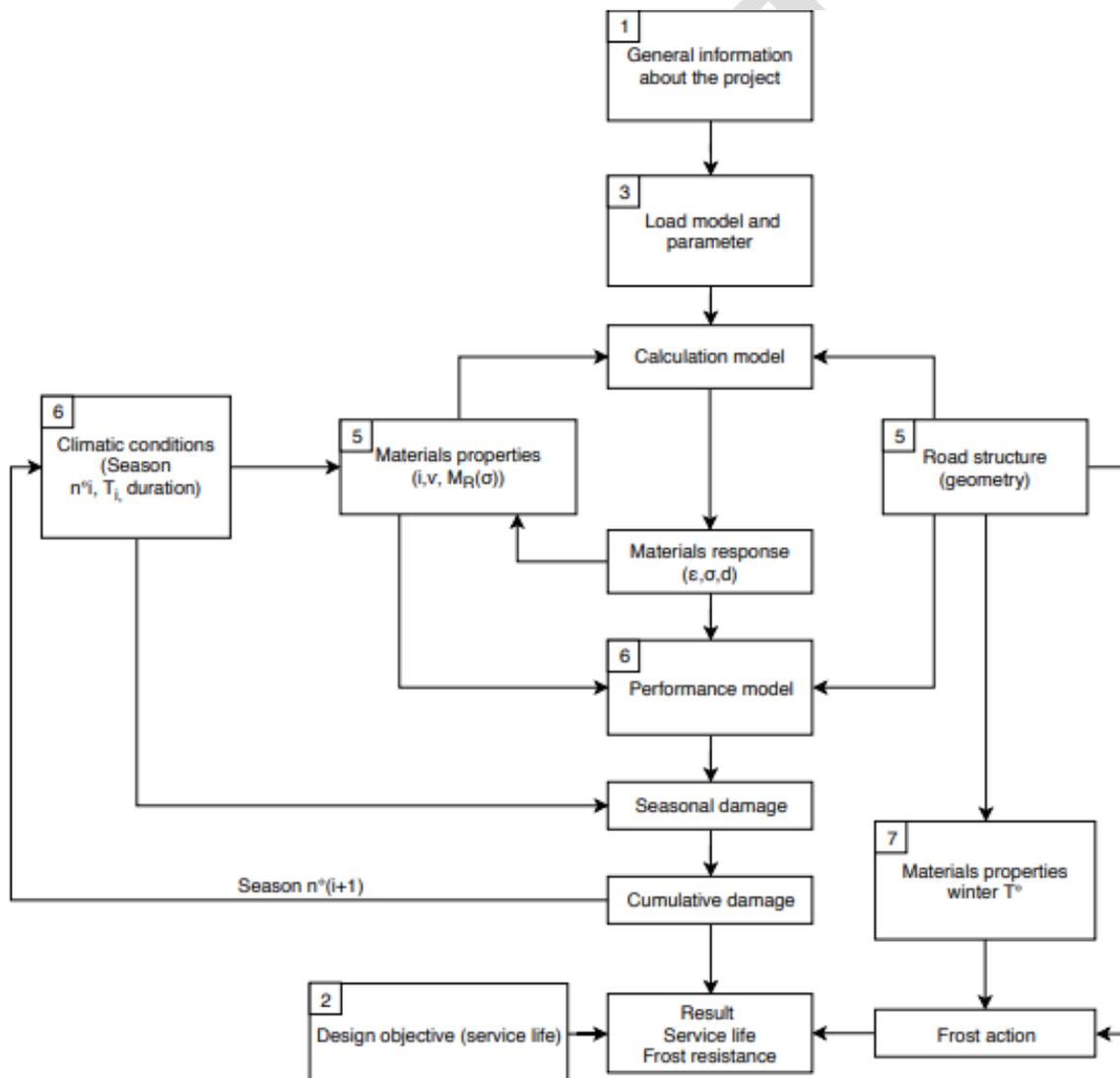
Figure i.2: Software flowchart

MODULE 1 : GENERAL INFORMATION

The first module concerns the general information of the project. The module screen is shown in Figure 1.1. The user registers a name to the project and completes the information of the location of the project. The city, sector, street name, mile marker are part of the information that can be saved after validation of the form. For all the information additional to the project, the "notes" tab allows you to save this data.

Figure 1.1: General information about the project

MODULE 2 : Design objectives

2.1 General calculations

The second module concerns the design objectives, i.e. the number of ESAL (equivalent single axial load) that the pavement will meet during its service life. The software will ensure that the number of permissible load applications before pavement failure is greater than or equal to the design objective. Figure 2.1 shows the home window of this module. First, the operator must select the type of road from the following choices: highway, national, regional, collector and local. Then, the determination of the number of admissible passages is done either by calculation or by direct entry of the value. The general equation (Doré, 2014) for calculating the total number of load applications in ESAL is based on equation (1)

$$N\ (ESAL) = AADT\ x\ D\ x\ L\ x\ T\ x\ TF\ x\ d\ x\ A \tag{1}$$

Where: N (ESAL) = Number of ESAL (million),

      AADT = Average daily traffic number (vehicle/day in both directions),

      D = Proportion of vehicles by direction (%),

      L = Proportion of vehicles per lane (when more than 2 lanes in one direction, %),

      T = Proportion of heavy vehicles (%),

      TF = Truck factor (ESAL),

      d = Number of days of commercial traffic per year,

      A = Incremental factor for heavy vehicles.

The number of ESAL obtained makes it possible to quantify the truck factor The AADT is an estimate of vehicles (all categories) travelling in both directions for all traffic lanes on the road. The number of days corresponds to the number of days in a year. It is generally chosen equal to 300 to take into account only days worked (year minus weekends and holidays) for heavy transport. The incremental factor for heavy vehicles is calculated according to equation (2) and depends on the expected growth factor (g) and the design period (n) in years.

$$A = \frac{(1 + g)^n - 1}{g} \tag{2}$$

Where: A = Incremental factor for heavy vehicles,

        g = Growth factor (%),

        n = Design period (years).

Figure 2.1: Determination of the number of Equivalent Single Axle Load (ESAL)

2.2   PROPORTION OF VEHICLES PER LANE (FACTOR L)

The proportion of heavy vehicles on multi-lane roads is automatically determined from Table 2.1 (Darter et al., 1985). The software returns the data from the table corresponding to the number of lanes and the AADT.

Table 2.1 Estimation of factor L

AADT (one way)	Two lanes in one direction		Three or more lanes in one direction		
	Inner	Outer	Inner	Center	Outer
2000	6	94	6	12	82
4000	12	88	6	18	76
6000	15	85	7	21	72
8000	18	82	7	23	70
10 000	19	81	7	25	68
15 000	23	77	7	28	65
20 000	25	75	7	30	63
25 000	27	73	7	32	61
30 000	28	72	8	33	59
35 000	30	70	8	34	58
40 000	31	69	8	35	57
50 000	33	67	8	37	55
60 000	34	66	8	39	53
70 000			8	40	52
80 000			8	41	51
100 000			9	42	49

2.3   TRUCK FACTOR

The truck factor can be estimated using the calculation tool integrated in the software, entered directly or used according to a default value.

2.3.1   CALCULATION TOOL

The calculation tool is used to determine the average truck factor as a function of the number of vehicles and their proportion in total traffic. To do this, the calculation tool determines the average truck factor of vehicles according to their configuration and axle load. Figure 2.2

shows the calculation tool as a whole. In each tab, the truck factor for each vehicle is evaluated according to equation (3).

$$TF = \sum TF_i = \sum \left(\frac{m_i}{m_{ref}} \right)^4 \tag{3}$$

Where: m_i = weight of axle or axle group i.

m_{ref} = weight of the reference axle or group of axles equivalent to 1 ESAL,

= 8.16 tonnes for a single axle,

= 15.20 tonnes for a double axle,

= 21.80 tonnes for a triple axle,

= 28.50 tonnes for a quadruple axle (extrapolated)

Figure 2.2: Calculation tool for the truck factor

Several vehicle classes are present in the database. Three types of buses are used as an example of calculation: the GMC classic bus, the Novabus LFS bus, the Novabus LFS Artic bus. The truck factor is 3.35 ESAL for the GMC Classic bus shown in Figure 2.3. The calculation of the truck factor is presented in Table 2.2 (Gauthier, 2012).

Figure 2.3: GMC Classic

Table 2.2 Calculation of the TF for the GMC Classic bus

Weight (with 75 passengers)	16 440 Kg				TF
Load distribution		66%		34%	**3.35 ESAL**
Weight per axle (kg)	Rear axle	10 850	Front axle	5 590	
TF (ESAL)		3.13		0.22	

The truck factor is 4.48 ESAL for the Novabus LFS bus shown in Figure 2.4. The calculation of the truck factor is presented in Table 2.3.

Figure 2.4: Novabus LFS

Table 2.3 Calculation of the TF for the Novabus LFS bus

Nominal weightl	17 690 Kg				TF
Load distribution		66%		34%	**4.48 ESAL**
Weight per axle (kg)	Rear axle	11 669	Front axle	6 021	
TF (ESAL)		4.18		0.30	

The truck factor is 6.32 ESAL for the Novabus LFS Artic bus shown in Figure 2.5. The calculation of the truck factor is presented in Table 2.4.

Figure 2.5 : Novabus LFS Artic

Table 2.4 Calculation of the TF for the Novabus LFS Artic bus

Nominal weightl	27 020 Kg						TF
Load distribution	Rear axle	45%	Center axle	30%	Front axle	25%	**6.32**
Weight per axle (kg)		12 120		8 100		6 800	**ESAL**
TF (ESAL)		4.87		0.97		0.48	

Default values are used depending on the vehicle class and are integrated into the database. Table 2.5 groups the average truck factor by truck type (St-Laurent, 2006)

Table 2.5 Average truck factor by vehicle type

Vehicle		**ATF (ESAL)**
Truck 1 unit	2 axles	0.3
	3 axles	1.5
	4 and more axles	5.7
Truck 2 units	4 and less axles	0.5
	5 axles	1.7
	6 and more axles	6.8
Truck 3 units	5 axles	1.7
	6 and more axles	7.3

2.3.2 *THE DEFAULT VALUE*

Table 2.6 assembles the default average truck factor and can be used in the absence of vehicle classification data (Ministère des transports du Québec, 2006). This table depends on the road class and the percentage of heavy vehicles.

Table 2.6 Default average truck factor

Road classification	% of heavy vehicles			
	0 - 10	10 - 20	20 - 30	> 30
Local	0.8	12	-	-
Collector road	1.2	1.9	-	-
Regional	1.4	2.6	-	-
National to highway or urban	1.2	1.3	-	-
National rural	2.1	3.1	3.7	5.3
Urban highway	1.1	1.3	-	-
Peri-urban highway	1.7	2.0	-	-
Rural highway	2.1	2.7	3.4	-

MODULE 3 : LOAD DEFINITION

In this module, it is possible to define the load characteristics that will be applied while calculating the stress and strain distribution in each layer of the structure. Figure 3.1 shows the home screen of this module. The load is considered circular and the contact pressure is uniformly distributed. The three load parameters, i. e. circle radius, load and contact pressure, are linked by equation (4).

$$P(kPa) = \frac{F}{\pi a^2} \tag{4}$$

Where: P = pressure (kPa),

F = force (kN),

a = radius of the plate (mm).
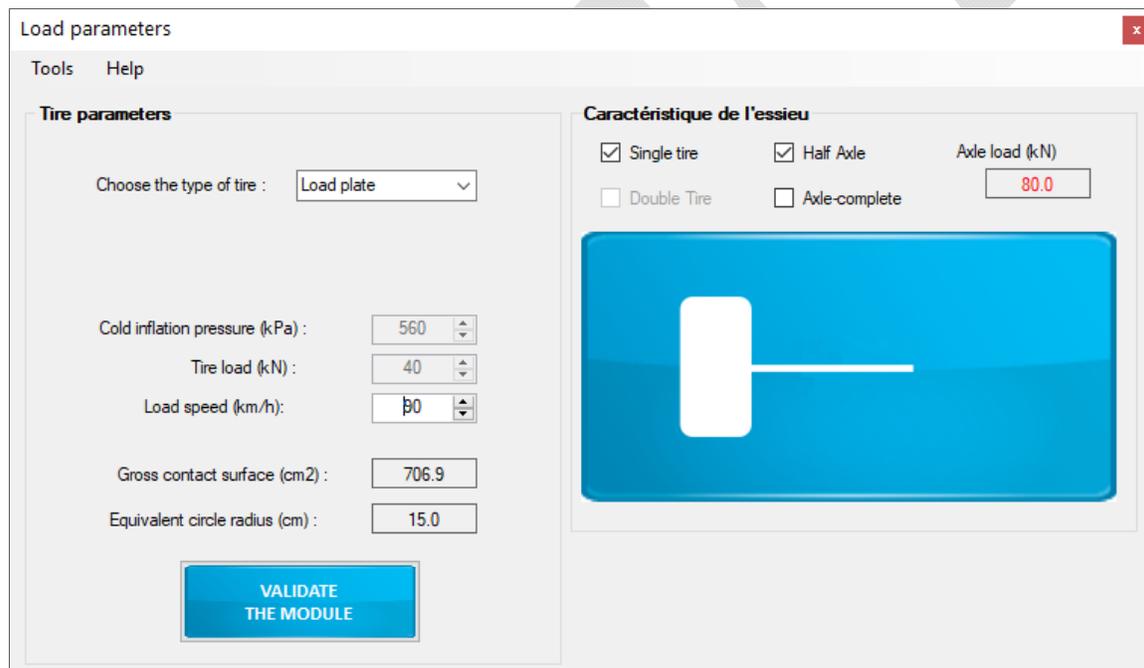
Figure 3.1 : Setting up the load parameters

Two different tire configurations are available: (1) Considering a standard load plate, and (2) considering of a particular tire type. In the first case (load plate) the tire configuration defined by a single equivalent axle is used, with a 40 kN load applied on a circular plate with a radius of 150 mm. This configuration should be considered for pavement design, as it is the reference load on the traffic module.

For the second option of tire configurations, the equations of the Tire and Rim Association (TRA) are used, the average contact pressure (CP) is defined by the following equation:

$$CP = \frac{L}{A_{nc}} \qquad (5)$$

Where L is the maximum load and A_{nc} is the net contact area. To calculate an approximation of the net contact area the following equations are used:

$$A_{nc} = A_{gc} \times NG \qquad (6)$$

$$A_{gc} = 39.8 \times (0.315 \times P) + (0.00887 \times L) + (0.000938 \times V_t) \qquad (7)$$

Note: The gross contact area equation is appropriate for highway speed and loads, and inflation pressure for truck-bus tires shown in the TRA tables.

Where A_{gc} is the gross contact area, NG is tire tread footprint net/gross, P is the tire cold inflation pressure and V_t is the tire volume, approximated using the following formula:

$$V_t = 3.14 \times (H + D_r) \times (S \times H) \qquad (8)$$

Where, H is the TRA design section height, D_r is the rim diameter, and S is the TRA design section width of the tire. The following table summarizes the values considered for the tire configurations normally used in Canada, and which are included in the software:

Table 3.1 TRA parameters for tire configurations normally used in Canada

	11R24.5	11R22.5	385/65R22.5	275/70R22.5
H (in.)	9.49	9.49	9.85	7.58
Dr (in.)	24.5	22.5	22.5	22.5
S (in.)	11.0	11.0	15.2	10.9
Vol. (in³)	11147	10491	15178	7815

An important aspect of the definition of the load is that it is possible to adapt the loading speed. These data allow the viscoelasticity of the materials to be taken into account when calculating the mechanical properties. In the toolbar, the user can change the frequency of request to which the asphalt will be subjected.

A relationship linking vehicle speed to solicitation frequency is used by default in the calculations (Mollenhauer et al., 2009). An option in this module allows imposing a frequency to be considered for calculations. Figure 3.2 shows the two available options.

Figure 3.2: Determination of the frequency of solicitation

MODULE 4 :   CLIMATIC CONDITIONS

Module 4 is organized around the establishment of the climatic conditions that the structure will encounter over the course of a year. The year is divided into a maximum of five seasons. A season is characterized by a duration (number of days) and an average temperature of the coating. For each season, the modulus of the asphalt mix will vary according to temperature (viscoelasticity of the material). Figure 4.1 displays the module's home screen and has two tabs either for manual data entry or for selecting a climate from the database.

Figure 4.1 : Setting up of climatic conditions

4.1   MANUAL ENTRY OF TEMPERATURES

First, by choosing a manual temperature entry, it is necessary to determine the number of days for each season and the temperature of the asphalt pavement. If the coating temperatures are known, it is possible to choose a direct input of the values otherwise these values are calculated from the air temperatures. In cases where the coating temperature is calculated from the air temperature, the relationship, defined by equation (9), is used. Temperatures are automatically converted from °C to °F. The calculation depth is set by the software to 4 cm for display purposes. This depth is adjusted when the calculations are started to 1/3 of the total thickness of the asphalt pavement layers.

$$T_p = T_A \left(1 + \frac{1}{z+4} \right) - \frac{34}{z+4} + 6 \qquad (9)$$

Where: T_p = Calculated asphalt mix temperature (°F),

T_A = Air temperature (°F),

z = Depth at which the temperature is calculated (in inches).

z= 1/3 of the total thickness of the bituminous layers.

To ensure proper data entry, an alert message will appear in red if errors are made (for example, if the total number of days in a year exceeds 365). It is also possible to save the manually entered climates in order to integrate them into the database.

4.2   PROCEDURE FOR DETERMINING CLIMATIC PARAMETERS

The procedure proposed here is for information purposes only and is not a rule to follow.

1. Acquisition of climate data

In order to divide the year into representatives seasons of the climate, it is recommended to have daily averages of air temperature. To do this, climate data can be obtained, for example, from the Government of Canada's climate database (Government of Canada, 2019). An example of the daily data for January 2015 at the "Quebec/Jean lesage intl" weather station is shown in Figure 4.2. In our case, for each city defined in the database, the average daily temperatures for all years between 1986 and 2015 (i.e. 30 years of data) were extracted. In some cases, missing data or the absence of measures over an extended period may require that certain years be ignored.
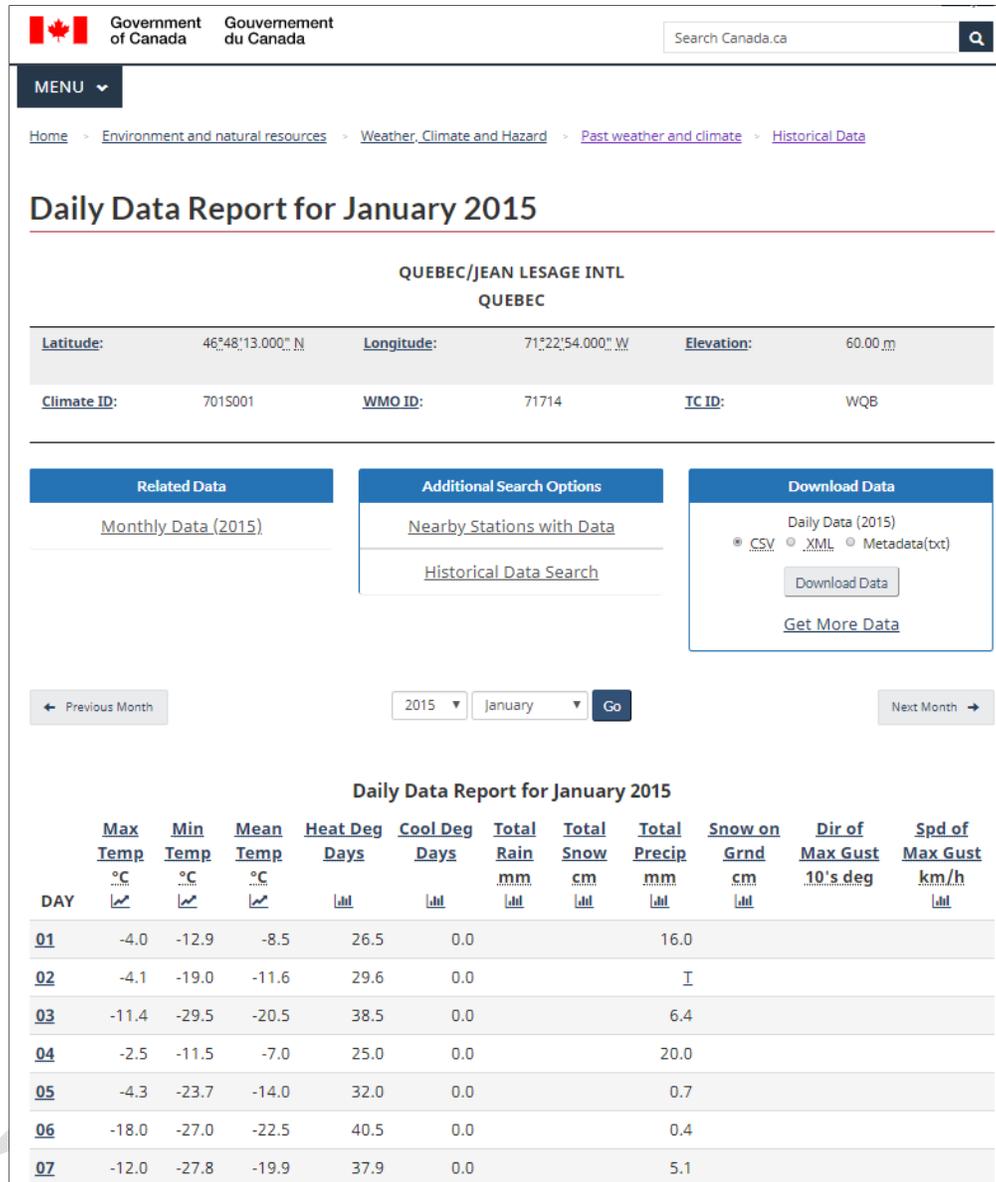
Figure 4.2: Extract from the Government of Canada website (2019) for daily climate data.

2. Determination of a sinusoidal interpolation

Using the daily data, it is possible to determine a sinusoidal curve checking equation (10) for each year measured. The optimization of the sine curve is determined by a calculation by minimizing the least square residue between the measured and modelled values. The modeling thus makes it possible to obtain the average annual temperature, the amplitude of the sinusoidal signal and the phase shift of the sine curve. By assumption all years are considered to have 365 days.

$$T_A = T_m + T_0 . \mathrm{Sin}[w \cdot (t - t_0)] \qquad (10)$$

Where: T_A = modelled air temperature (°C),

T_m = mean annual temperature (°C),

T_0 = modeling sine amplitude (°C),

W= period of the sine function (= $2 \cdot \pi / 365$),

T_0= time of signal initialization
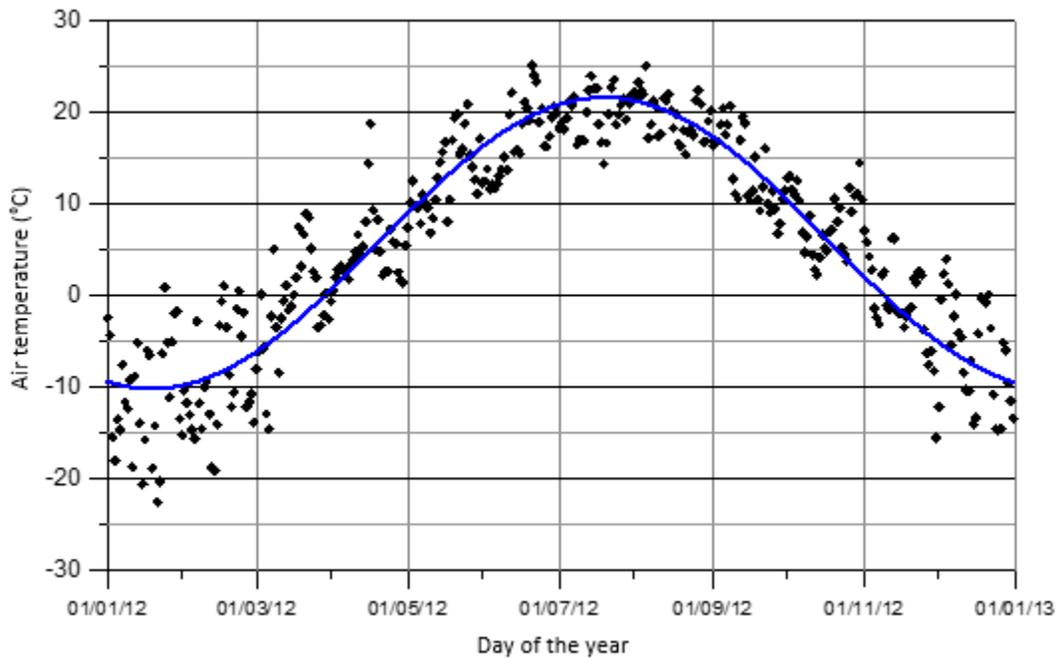
Figure 4.3 shows an example of modelling. In this figure, the average daily temperatures are represented by diamonds. The blue curve corresponds to the sine interpolation associated with this measurement year. The measurements shall begin on 1 January of the year and end on 31 December of the same year. An annual average temperature value of T_m= 5.77°C is calculated. The amplitude of the sine is T_0=15.9°C.
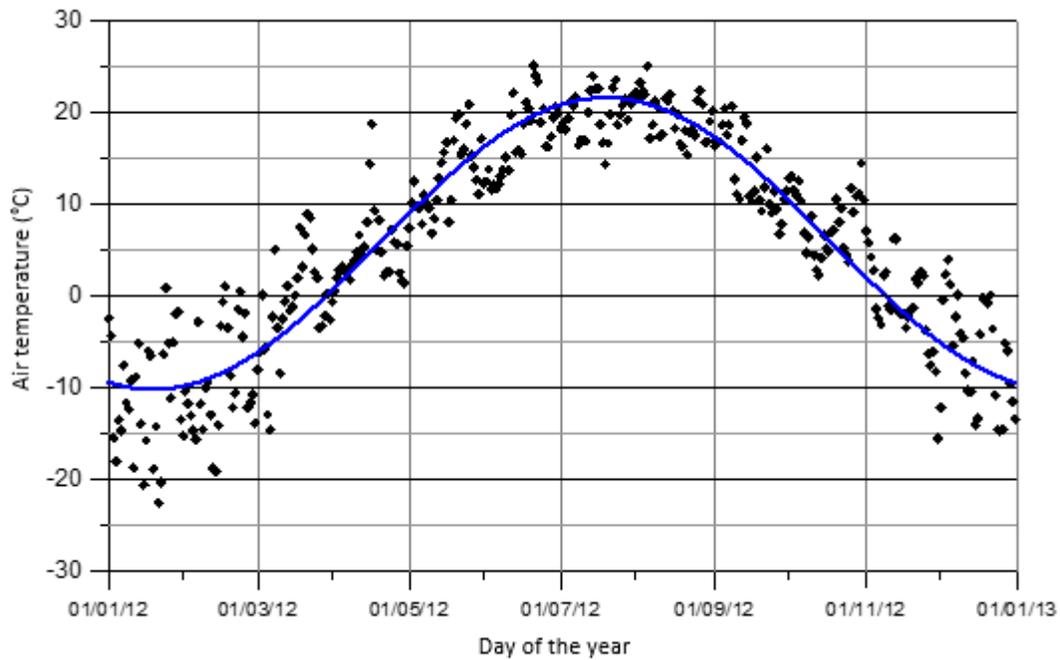
Figure 4.3 : Modelling of the annual climate by a sine function.

3. Determination of the five seasons

First, winter is defined as the period when the modeled temperatures (points on the sine curve) are below 0°C. The two points of the sinusoidal curve crossing the axis at a temperature of 0°C delimit the beginning and end of winter. In the example shown in Figure 4.4 winter begins on November 10 and ends on March 28, a period of 140 days. Over this period, the average temperature is -6.04°C. The average temperature is calculated from the modelled data and not the raw data.
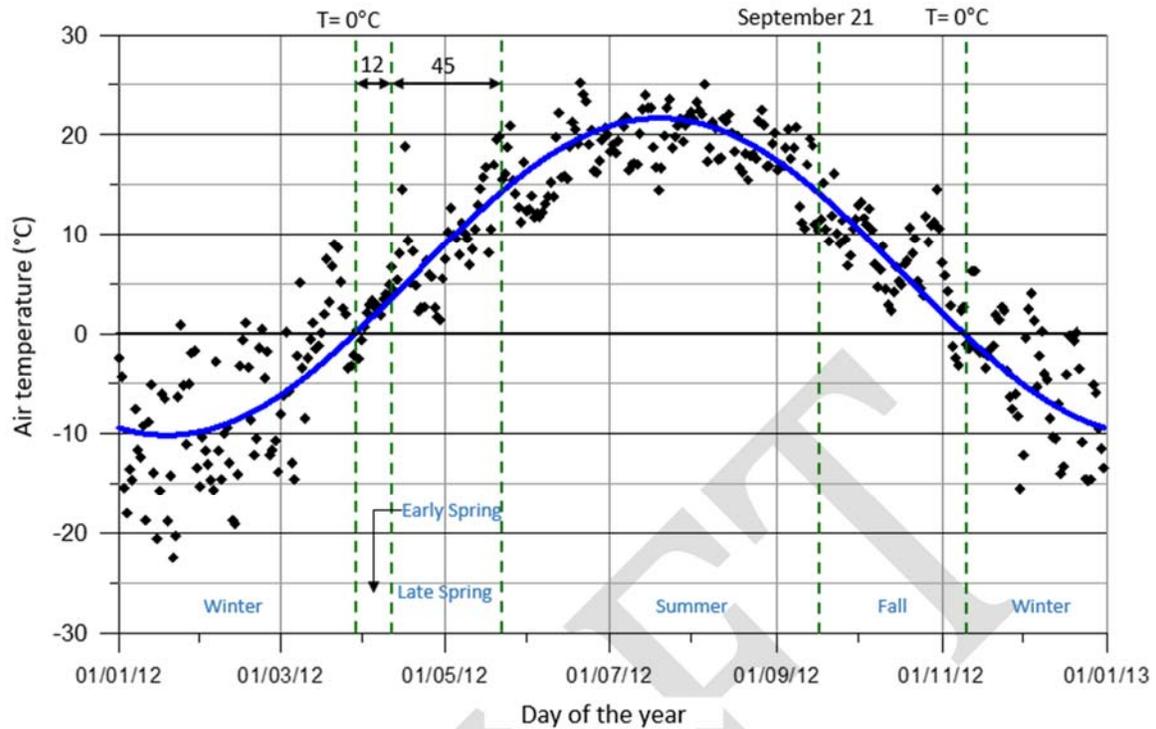
Figure 4.4 : Determination of seasons according to temperature

Thereafter, spring is divided in two. Early spring consists of the first 12 days of thawing following the end of winter, then late spring corresponds to the next 45 days. The average temperatures for each period are also calculated. For the example, the beginning of spring is from March 29 to April 9 and the end of spring from April 10 to May 24.

The summer period begins when the late spring ends and lasts until September 20. In our case, it lasts 119 days. Finally, the fall is between September 21 and the beginning of winter for a total duration of 48 days in the example considered. All the results are detailed in Table 4.1

Table 4.1 Determination of the seasons

Winter		Early spring		Late spring		Summer		Fall	
Nb Days	**AT (°C)**	**Nb Days**	**AT (°C)**	**Nb Days**	**AT (°C)**	**Nb Days**	**AT (°C)**	**Nb Days**	**AT (°C)**
140	-6.6	12	1.59	45	9.22	120	19.01	48	6.57

4. Generalization of the approach for the thirty years considered

The determination of the seasons, defined by the average temperature and the number of days must then be carried out for all the years to be taken into account. For the cases in the database, the sine curve and the determination of the seasons were carried out for the years between 1986 and 2015. As an example for the city of "Quebec/Jean lesage intl", Table 4.2 shows the average duration and temperature for the years 1986 to 2015. The final results show that on average winter lasts 146 days for an average temperature of -7°C, early spring lasts 12 days with an average temperature of 1.55°C, late spring lasts 45 days with a temperature of 9°C, summer lasts 112 days with an average temperature of 18.77°C and finally fall lasts 50 days with an average temperature of 8.85°C. From these data it is also possible to determine the normal FI. The latter is FI_n =1030 °C. Days with a standard deviation of =200.3 °C. Days. These last two climatic information are necessary for the probabilistic analysis of the rigorous frost calculation in MODULE 7 :Frost criteria.

Table 4.2 Determination of the 1986-2015 seasons for Quebec City

Year	Winter Nb Days	Winter AT (°C)	Early spring Nb Days	Early spring AT (°C)	Late spring Nb Days	Late spring AT (°C)	Summer Nb Days	Summer AT (°C)	Fall Nb Days	Fall AT (°C)
2015	152	-8.07	12	1.63	45	9.63	102	19.74	54	10.03
2014	153	-8.07	12	1.64	45	9.54	104	19.35	51	9.51
2013	148	-7.13	12	1.60	45	9.05	114	18.58	46	8.40
2012	137	-6.13	12	1.52	45	8.84	118	19.31	53	9.04
2011	138	-6.28	12	1.41	45	8.74	111	19.26	59	9.69
2010	125	-4.86	12	1.39	45	8.14	129	18.83	54	8.39
2009	148	-7.05	12	1.63	45	9.03	111	18.56	49	8.72
2008	147	-6.92	12	1.59	45	8.96	109	18.64	52	9.08
2007	149	-7.36	12	1.70	45	9.30	108	19.04	51	9.16
2006	130	-5.21	12	1.31	45	8.05	121	18.41	57	8.76
2005	146	-7.28	12	1.67	45	9.49	111	19.81	51	9.48
2004	154	-7.88	12	1.65	45	9.35	107	18.76	47	8.90
2003	154	-8.07	12	1.59	45	9.44	104	19.13	50	9.43
2002	145	-6.70	12	1.48	45	8.65	112	18.16	51	8.55
2001	140	-6.23	12	1.53	45	8.75	112	18.87	56	9.30
2000	146	-6.75	12	1.60	45	8.79	114	18.13	48	8.24
1999	136	-6.07	12	1.57	45	8.88	119	19.37	53	8.95
1998	131	-5.24	12	1.27	45	8.02	123	18.31	54	8.56
1997	155	-7.85	12	1.50	45	9.03	105	18.23	48	8.82
1996	144	-6.45	12	1.53	45	8.64	112	18.19	52	8.71
1995	148	-7.46	12	1.54	45	9.24	112	19.18	48	8.88
1994	153	-8.18	12	1.57	45	9.50	106	19.29	49	9.22
1993	156	-8.34	12	1.81	45	9.74	108	19.09	44	8.69
1992	155	-7.75	12	1.52	45	8.93	106	17.91	47	8.49
1991	148	-7.31	12	1.62	45	9.28	115	19.11	45	8.61
1990	142	-6.29	12	1.36	45	8.38	113	18.05	53	8.70
1989	160	-9.20	12	1.81	45	10.16	108	19.63	40	8.74
1988	150	-7.55	12	1.53	45	9.18	112	18.86	46	8.66
1987	144	-6.55	12	1.44	45	8.63	118	18.26	46	8.22
1986	154	-7.21	12	1.54	45	8.60	112	17.10	42	7.62
Average.	**146.3**	**-7.05**	**12**	**1.55**	**45**	**9.00**	**111.9**	**18.77**	**49.9**	**8.85**
Standard deviation	8.41	1.00	0	0.13	0	0.51	6.06	0.62	4.38	0.49

4.3   SELECTING A CLIMATE FROM THE DATABASE

The climate module allows you to select a weather station from the database available when the software is installed. Several cities in the province of Quebec are by default included in the database.

The database is customizable. Once the data has been recorded manually, it is possible to save it in the database in order to save it for future projects. The complete database can be consulted in the "tools" tab of the climate module.

MODULE 5 : PAVEMENT STRUCTURE

The fifth module defines the pavement structure and the home screen is shown in Figure 5.1. This module allows the integration into the design method of certain research work carried out at Laval University and the Ministère des Transports. The pavement structure is composed of a maximum of 10 layers. For each one, it is necessary to enter the material class, their thickness and define their mechanical properties. For each type of layer, asphalt, granular materials and soil, three levels of accuracy are available. The three levels are: 1) level 1 - laboratory data; 2) level 2 - an estimate based on physical data; 3) level 3 - typical value of material modules. For asphalt mix, Witczak or Huet-Sayegh models can be used. For granular materials, Uzan's model (1985), Mellizo et al. (2010), based on a material characterization or finally an estimation from CBR are the available models. For soils, Uzan's model (1985), FWD measurements, Rahim and George's model (2005), Soto et al. (2013) or an estimate from the CBR are the five characterization options available. The characterization levels are then detailed according to the material class.

Figure 5.1: Determination of pavement structure and mechanical properties

5.1 ASPHALT CONCRETE

Three types of asphalt are included in the software. ESG-10 and ESG-14 asphalt mixes are semi-granular asphalt mixes with a maximum nominal particle size of 10 and 14 mm respectively. The third asphalt is a gravel asphalt with a maximum nominal aggregate size of 20 mm, called GB-20. Bitumen classes follow the nomenclature "PG H-L", where PG represents the performance class, H is the upper temperature limit of the class at which the bitumen is likely to undergo permanent deformation and L is the lower temperature limit of the class at which the asphalt concrete is likely to crack by thermal contraction. The choices integrated into the software are PG 58-28, PG 58-34, PG 64-28, PG 64-34 and PG 70-28. The home screen for determining the mechanical properties of a bituminous asphalt mix is presented in Appendix 1.

The Ministère des Transports du Québec (MTQ) recommends minimum, maximum and optimal thicknesses depending on the type of bitumen. These data are presented in Table 5.1. If the minimum or maximum thicknesses are not respected, an alert message will appear in red, leaving the input value accessible.

Table 5.1 Asphalt selection criteria (extracted from Quebec, 2012)

Thickness of laying	Type of asphalt		
	ESG-10	ESG-14	GB-20
Maximum (mm)	40	60	80
Optimal (mm)	60	70	100
Minimum (mm)	70	80	120

5.1.1 LEVEL 1: LABORATORY MEASUREMENT, WITCZAK MODEL AND HUET-SAYEGH MODEL

Level 1 is the most accurate level and requires laboratory tests to determine the coefficients associated with the Witczak model (Witczak, M. Et Fonseca, 1996) or the Huet-Sayegh model (Huet, 1963, Sayegh, 1965). Dynamic modulus tests on specimens characteristic of the asphalt layers of the pavement structure must be carried out according to MTQ standards (LC 26-700 standard). The values obtained following the modelling of the results are then manually entered in the boxes associated with each coefficient. Figure 5.2 shows the parameters for level 1.

Figure 5.2 : Laboratory measurement of the mechanical properties of an asphalt mix

5.1.1.1 WITCZAK MODEL

Witczak's entire model is detailed for typical formulations of Quebec (Doucet and Auger, 2010). It corresponds to the model currently used in the United States in the MEPDG (Mechanistic Empirical Pavement Design Guide) design method. Equations (11), (12) and (13) describe the Witczak model, which can be used to model the influence of temperature and frequency on the dynamic modulus (Witczak, M. Et Fonseca, 1996; Witczak, Matthew, 2005).

$$Log|E^*| = \delta + \frac{\alpha}{1 + e^{(\beta + \gamma \cdot \log(f_r))}} \tag{11}$$

Where: $|E^*|$ = dynamic modulus (Mpa),

F_r = reduced frequency (Hz),

$\alpha, \beta, \gamma, \delta$ = regression coefficients.

$$f_r = a_T \cdot f \ \rightarrow \ log(f_r) = \log(f) + log(a_T) \tag{12}$$

Where: f_r = reduced frequency (Hz),

f = frequency (Hz),

a_T = translational factor (Hz).

$$Log(a_T) = a_1 \cdot (T - T_r) + a_2 \cdot (T - T_r)^2 \tag{13}$$

Where: a_t = translational factor (Hz),

a_1, a_2 = regression coefficients,

T = temperature (°C),

T_r = reference temperature (=10°C).

Table 5.2 summarizes the regression coefficients of the Witczak model for a reference temperature of 10 ° C. These values are present in the software database and available at level 2.

Table 5.2 Regression coefficients of the Witczak model

Asphalt	Bitumen	Regression coefficients, $\log |E^*|$ (Mpa)					
		δ	α	β	γ	a_1	a_2
ESG-10	PG 58-28	-0.480	5.011	-1.718	-0.412	-0.150	6.28E-4
	PG 58-34	-0.051	4.548	-1.325	-0.386	-0.144	7.20E-4
	PG 64-28	-0.083	4.627	-1.615	-0.321	-0.151	6.74E-4
	PG 64-34	0.539	3.953	-1.323	-0.377	-0.148	7.34E-4
	PG 70-28	-0.693	5.238	-1.829	-0.265	-0.160	6.11E-4
ESG-14	PG 58-28	-0.330	4.877	-1.766	-0.430	-0.149	6.72E-4
	PG 58-34	0.399	4.092	-1.295	-0.399	-0.148	8.23E-4
	PG 64-28	-0.177	4.756	-1.748	-0.313	-0.152	6.68E-4
	PG 64-34	0.480	4.056	-1.517	-0.350	-0.148	5.88E-4
	PG 70-28	0.496	4.038	-1.652	-0.304	-0.157	6.49E-4
GB-20	PG 58-28	-0.309	4.870	-1.781	-0.435	-0.149	6.36E-4
	PG 58-34	0.266	4.252	-1.345	-0.405	-0.145	8.23E-4
	PG 64-28	0.130	4.421	-1.678	-0.346	-0.150	7.14E-4
	PG 64-34	1.035	3.502	-1.284	-0.400	-0.145	6.73E-4
	PG 70-28	-0.932	5.497	-1.888	-0.279	-0.157	5.34E-4

5.1.1.2   HUET-SAYEGH MODEL

The entire Huet-Sayegh model is detailed for typical formulations of Quebec (Doucet and Auger (2010). The Huet-Sayegh analog model is represented by equations (14), (15) and (16). The complex modulus depends on pulsation and relaxation time, which are themselves a function of the material's temperature and stress frequency (Huet, 1963 and Sayegh, 1965).

$$E^* = E_0 + \frac{E_\infty - E_0}{1 + \delta \cdot (i\omega\tau)^{-k} + (i\omega\tau)^{-h}} \qquad (14)$$

Where: E^* = complex modulus (MPa),

τ = relaxation time (s),

ω = pulsation [2πf] (rad/s),

E_0, E_∞ , δ, k, h, = regression coefficients.

$$\tau = a_T \cdot \tau_0 \ \rightarrow \ \log(\tau) = \log(\tau_0) + \log(a_T) \qquad (15)$$

Where: τ = relaxation time (s),

a_T = facteur de translation (Hz),

τ_0 = regression coefficients.

$$log(a_T) = a_1 \cdot (T - T_r) + a_2 \cdot (T - T_r)^2 \qquad (16)$$

Where: a_t = translation factor (Hz),

T = temperature (°C),

T_r = reference temperature (=10°C),

a_1 et a_2= regression coefficients.

Table 5.3 shows the regression coefficients of the Huet-Sayegh model for a reference temperature of 10°C. These values are present in the software database and available at level 2.

Table 5.3 Regression coefficients of the Huet-Sayegh model

Asphalt	Bitumen	Regression coefficients, E* (Mpa)							
		E_0	E_∞	δ	K	H	τ_0	A_1	A_2
ESG-10	PG 58-28	0.4	36 100	2.512	0.177	0.545	0.044	-0.149	7.41E-4
	PG 58-34	3.9	36 700	2.740	0.166	0.494	0.006	-0.139	7.75E-4
	PG 64-28	0.1	39 100	2.627	0.143	0.415	0.024	-0.149	8.18E-4
	PG 64-34	10.1	36 900	2.370	0.149	0.441	0.009	-0.142	8.07E-4
	PG 70-28	0.1	39 800	2.742	0.119	0.365	0.033	-0.154	7.27E-4
ESG-14	PG 58-28	2.3	37 500	2.685	0.188	0.569	0.089	-0.157	1.00E-4
	PG 58-34	8.2	37 000	2.568	0.163	0.479	0.008	-0.142	8.60E-4
	PG 64-28	0.1	39 600	2.390	0.143	0.410	0.056	-0.149	8.54E-4
	PG 64-34	4.5	40 000	2.450	0.139	0.422	0.026	-0.143	7.03E-4
	PG 70-28	0.1	42 400	2.428	0.116	0.362	0.036	-0.151	7.66E-4
GB-20	PG 58-28	1.1	39 000	2.584	0.188	0.571	0.086	-0.154	9.36E-4
	PG 58-34	4.3	38 500	2.424	0.164	0.491	0.009	-0.139	8.56E-4
	PG 64-28	0.1	39 700	2.408	0.149	0.434	0.047	-0.145	8.25E-4
	PG 64-34	38.6	40 700	2.350	0.153	0.450	0.018	-0.139	7.85E-4
	PG 70-28	0.1	36 600	2.472	0.137	0.397	0.060	-0.152	7.19E-4

5.1.2 *LEVEL 2: DEFAULT SELECTION, WITCZAK MODEL AND HUET-SAYEGH MODEL*

At level 2, the mechanical properties of the material can be selected from the software database. The models used are the same as in level 1. The values proposed by the software correspond to the data available in the publication "Determination of the complex modulus of asphalt mixes at the Ministère des Transports du Québec" (Doucet and Auger, 2010). It is

possible to add new values to the database. The drop-down list shows the materials available in the database according to the type of asphalt and grade of bitumen that have been selected. Figure 5.3 shows an example of selected parameters.
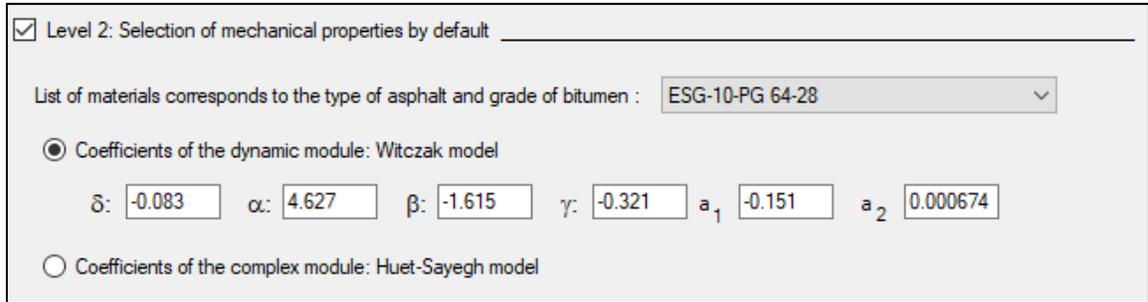
Figure 5.3 : Default selection of the mechanical properties of a bituminous asphalt mix

5.1.3 LEVEL 3 : DEFAULT RELATIONSHIP

Level 3, corresponds to a default relationship linking the mechanical properties of the material to temperature. This relationship is presented in equation (17). This equation represents the variation of the modulus of asphalt as a function of its temperature (Croney and Croney, 1998). The relationship was determined for a load frequency of 10 Hz.

$$Modulus\ (GPa) = 11{,}437 \cdot e^{-0.0594 \cdot T} \tag{17}$$

Where: T = Temperature (°C).

5.1.4 POISSON RATIO CALCULATION

For asphalt mixtures, the influence of the stiffness can be take in to consideration in the Poisson ratio using the following equation:

$$\mu_{calc} = 0.15 + \frac{0.35}{1 + \exp(-12.452 + 2.291 \times \log(145.038 \times |E^*|))} \tag{18}$$

In the i3C-ME, you can use this option (selected by default), or enter a user-defined Poisson ratio value by deselecting the "Poisson ratio calculated" checkbox.

5.2 GRANULAR MATERIALS

Different classes of granular material are included in the software, such as MG 20, MG 56, MG 112, MR 1, MR 2, MR 3, MR 4 and MR 5, MG 112-A (excluding poorly graduated sands "SP") and infra improved MG 112-C (up to 20% fines). These different classes are based on the data in the database. The home screen for determining the mechanical properties of a granular

material is presented in Appendix 2. As with asphalt mixes, there are three levels of characterization of the mechanical properties of materials.

Minimum and maximum thicknesses are recommended depending on the foundation materials. These data are presented in Table 5.4. If these criteria are not met, an alert message appears in red, leaving the value entered accessible.

Table 5.4 Minimum layer thicknesses for granular materials

Thickness of laying	Foundation material					
	MG 20	MG 56	MG 112	MR 1 MR2	MR 3 MR4	MR 5
Maximum (mm)	200	200	300	150	150	150
Optimal (mm)	225	225	500	200	300	150
Minimum (mm)	600	600	3000	600	600	200

5.2.1   *LEVEL 1 : LABORATORY MEASUREMENT, UZAN MODEL*

Level 1 corresponds to a characterization of the mechanical properties following laboratory tests carried out on the materials used during the construction or rehabilitation of the pavement. These tests consist of triaxial tests to determine the coefficients of the Uzan model (1985). These data must be entered manually, as shown in Figure 5.4.

Figure 5.4 : Laboratory measurement of the mechanical properties of a granular material

Uzan's model (1985) used in the software calculations is defined by equation (19). The resilient modulus is a function of the total stress (equation (20)), the octahedral shear stress (equation (21)) and the material characteristics constants k_1, k_2 and k_3. Laboratory tests are used to determine these model calibration constants. The stresses are calculated by iteration by the software according to the load conditions imposed.

$$M_R = k_1 \cdot p_a \cdot \left(\frac{\theta}{p_a}\right)^{k_2} \cdot \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3} \qquad (19)$$

Where: M_R = resilient modulus (MPa),

k_1, k_2, k_3 = calibration constant,

P_a = atmospheric pressure (=101.325 kPa),

θ = total stress (kPa), defined by the equation (20),

τ_{oct} = octahedral shear stress (kPa), defined by the equation (21).

$$\theta = \sigma_1 + \sigma_2 + \sigma_3 = \sigma_1 + 2 \cdot \sigma_3 \qquad (20)$$

Where: θ = total stress (kPa),

σ_1 = major main stress (kPa),

σ_2 = minor main stress (kPa),

σ_3 = minor main stress (kPa).

$$\tau_{oct} = \frac{1}{3} \cdot \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2} \qquad (21)$$

Where: τ_{oct} = octahedral shear stress (kPa)

σ_1 = major main stress (kPa),

σ_2 = minor main stress (kPa),

σ_3 = minor main stress (kPa).

In the case of triaxial tests, the stresses are axisymmetric. The octahedral shear stress formula then has the simplified form

$$\tau_{oct} = \frac{1}{3} \cdot \sqrt{2} \cdot (\sigma_1 - \sigma_3) \qquad (22)$$

5.2.2 LEVEL 2: DEFAULT SELECTION, MELLIZO ET AL. MODEL AND MODEL FROM CBR TESTS

Level 2 analysis consists of estimating the properties of materials indirectly. Having as first option (level 2.1) the use of databases of material properties, and at lower levels (level 2.2 and 2.3) estimates from physical properties. Very few laboratory tests are required to calculate with good accuracy the reversible modulus of the granular layers. Two estimation models are proposed in the software: the model by Mellizo et al. (2010), proposed following work within the i3c Chair, and a model allowing the calculation of the resilient modulus from CBR tests. Figure 5.5 shows the level 2 screen for granular materials. If tests have been

performed on similar materials, it is possible to save these parameters in the database so that they can be selected from the drop-down list.

Figure 5.5 : Estimation from the physical properties of a granular material

5.2.2.1   MELLIZO, BILODEAU, DORÉ MODEL

The Mellizo et al. (2010) model allows to calculate the resilient modulus of a granular material according to its stress state and physical properties. The entire model is available at reference: Mellizo et al, 2010. The resilient modulus of granular materials can be calculated from the saturated modulus to which a correction is applied. This correction depends on the sensitivity of the material to its water content. The resilient modulus can therefore be calculated from equation (23):

Where: M_R = resilient modulus (MPa),

$$M_R = M_{R,SAT} + \Delta M_R \qquad (23)$$

$M_{R, SAT}$ = saturated resilient modulus (MPa),

ΔM_R = sensitivity of the MR as a function of water content (MPa).

The saturated resilient modulus can be defined according to the equation (24):

$$M_{R,SAT} = C_1 \cdot \theta + C_2 \qquad (24)$$

Where: $M_{R, SAT}$ = saturated resilient modulus (MPa),

C_1 and C_2 = regression parameters in the saturated state

θ= total stress (kPa).

The regression coefficients C_1 and C_2, of the Mellizo et al. (2010) model are calculated according to the physical characteristics of the material according to equations (25) and (26).

$$C_1 = -8.9762 - 0.50796 \cdot \left(\frac{C_U}{nf}\right) + 0.02717 \cdot S_r + 7.72547 \cdot \left(\frac{\rho_{d\,max}}{\rho_d}\right)$$
$$- 0.10661 \cdot w + 0.16825 \cdot w_{opt} \tag{25}$$

Where: C_1 = regression parameter in the saturated state,

C_U = uniformity coefficient (no units),

nf = porosity of the fine fraction (%), defined according to the equation (27)

S_r = degree of saturation (%),

$P_{d\,max}$ = maximum dry density (kg/m³),

P_d = dry density (kg/m³),

W = water content (%),

W_{opt} = optimum moisture content (%).

$$C_2 = 672.4762 + 14.35277 \cdot n - 6.21307 \cdot nc + 2.06996 \cdot Sat$$
$$+ 0.25323 \cdot \rho_{d\,max} - 0.55721 \cdot \rho_d - 27.53324 \cdot w \tag{26}$$

Where: C_2 = regression parameter in the saturated state,

n = porosity (%),

n_c = porosity of the coarse fraction (%), defined according to the equation (28),

S_r = degree of saturation (%),

$P_{d\,max}$ = maximum dry density (kg/m³),

P_d = dry density (kg/m³),

W = water content (%),

The porosity of the fine fraction is calculated according to the equation (27).

$$n_f = \frac{n}{n + (1-n) \cdot \%F} \cdot 100 = \frac{n}{n_c} \cdot 100 \tag{27}$$

Where: n_f = porosity of the fine fraction (%),

n_c = porosity of the coarse fraction (in decimals),

n = porosity (in decimals),

%F= fine particles (in decimals).

The porosity of the coarse fraction is calculated according to the equation (28).

$$n_c = n + (1-n) \cdot \%F \tag{28}$$

Where: n_c = porosity of the coarse fraction (in decimals),

n = porosity (in decimals),

%F= fine particles (in decimals).

The dry density is calculated according to the equation (29).

$$\rho_s = \frac{\rho_d}{1-n} \tag{29}$$

Where: ρ_s = density of soil solids (kg/m³),

                ρ_d = dry density (kg/m³),

                n = porosity (in decimals).

The absorption is calculated according to the equation (30).

$$Abs = w - \frac{Sat \cdot e \cdot \rho_w}{\rho_s} \tag{30}$$

Where: Abs = absortion (%),

                W = water content (%),

                S_r = degree of saturation (%),

                e = void index (in decimals),

                ρ_s = density of soil solids (kg/m³),

                ρ_w = density of water (kg/m³).

ΔM_R is defined as the product of the slope S by the deviation of the degree of saturation according to the equation (31).

$$\Delta M_R = S \cdot (Sat - 100\%) \tag{31}$$

Where: ΔM_R = sensitivity of the M_R as a function of water content (MPa),

                S = slope (MPa/%),

                S_r = degree of saturation (%).

The slope S can be defined according to the characteristics of the material according to equation (32)(Mellizo, 2010)

$$S = 3x10^{-5} \cdot \theta \cdot n_f + 0.0206 \cdot n_f - 0.0034089 \cdot \theta - 2.022597 \tag{32}$$

Where: S = slope (MPa/%),

                θ = deviator stress (MPa),

                n_f = porosity of the fine fraction (%),defined according to the equation (27).

The calculation steps are automatically performed by the software for each season according to the total stress calculated in the middle of each sublayer.

5.2.2.2   *ESTIMATION FROM CBR*

It is possible to estimate the resilient modulus of a material from a CBR (California Bearing Ratio) test. According to Figure 5.6, taken from the *Chaussée 2* software user guide (St-Laurent, 2006), the proposed relationship has three different slopes depending on the value

of the Californian lift index. Equation (34) calculates the resilient modulus for a smaller CBR 2, equation (33) for a CBR between 2 and 15 and finally equation (36) for a CBR greater than 15.
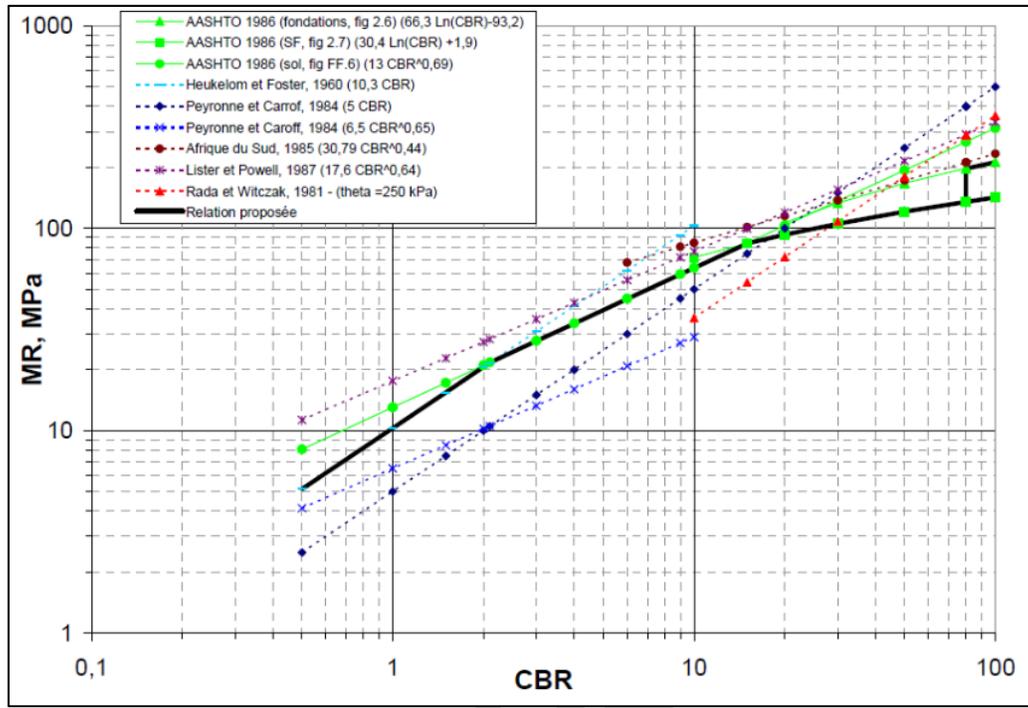
Figure 5.6 : Correlation between the resilience modulus and the CBR index (MTQ 2002)

$$If\ CBR < 2 : M_R = 10.3 \cdot CBR \tag{34}$$

$$If\ 15 > CBR \geq 2 : M_R = 13 \cdot CBR^{0.69} \tag{35}$$

$$If\ CBR \geq 15 : M_R = 30.4 \cdot Ln(CBR) + 1.9 \tag{36}$$

Where: CBR = California Bearing Ratio,

M_R = resilient modulus (MPa).

5.2.3   LEVEL 3: TYPICAL MATERIAL VALUE

In level 3, the user can enter a typical material value of the resilient modulus. This value must correspond to the modulus for an optimal water content.

5.3   SOIL

The soil types included in the manual are described according to the symbols used in the *Unified Soil Classification System* (USCS) (ASTM D2487-11, 2011). They correspond for clays on the soil CL and CH, for silts on the soil ML and MH, for sands on the soil SM, SC, SP and SW and finally for gravels on the soil GM and GC.

Where   Soil symbols: C = clay,

                       G = gravel,

                       M = silt,

                       S = sand,

        Spreading symbols: W = well graded,

                       P = poorly graded,

        Symbols of liquid limits: H = high,

                       L = low.

Appendix 3 presents the home screen for determining the mechanical properties of a soil.

5.3.1   LEVEL 1: LABORATORY MEASUREMENT, UZAN MODEL

First, level 1 allows you to enter the measurements obtained from laboratory tests or measurements with a portable deflectometer in the field (Figure 5.7). In the first case, the parameters k1, k2 and k3 obtained in the laboratory allow the resilient modulus to be calculated according to the equation presented in section 5.2, page 35. These data are obtained following triaxial tests. This model, as for granular materials, is in the form of Uzan's (1985) model. In the absence of laboratory measurements, it is possible to enter the modulus measurement obtained directly during a portable deflectometer test.

Figure 5.7 : Laboratory measurement of the mechanical properties of a soil

5.3.2 LEVEL 2: DEFAULT SELECTION, RAHIM ET GEORGE MODEL, SOTO ET AL. MODEL AND CORRELATION WITH THE CBR INDEX

Level 2 allows you to enter physical characteristics of the materials in order to obtain, using different models, an estimate of the soil modulus. Level 2 estimates mechanical properties from either the Rahim and George model (Rahim and George, 2005), the Soto et al. (2013) or from a correlation with the CBR index. Figure 5.8 shows the level 2 window.

Figure 5.8 : Estimation from the physical properties of a soil (level 2)

5.3.2.1 ESTIMATION FROM THE RAHIM AND GEORGE MODEL

Rahim and George model (Rahim and George, 2005) determines the resilient modulus of soils according to their state of stress and physical characteristics. The model distinguishes two categories: fine and coarse soils. The soil classification method follows the AASHTO method: a soil is considered fine if the fine particles have a percentage passing greater than 35% through the #200 sieve.

The resilient modulus for fine soils is found according to equation (37).

$$M_{R,fine\ soils} = k_1 \cdot p_a \cdot \left(1 + \frac{\sigma_d}{1 + \sigma_c}\right)^{k_2} \tag{37}$$

The resilient modulus for coarse soils is found according to the equation (38).

$$M_{R,coarse\ soils} = k_1 \cdot p_a \cdot \left(1 + \frac{\theta}{1 + \sigma_d}\right)^{k_2} \tag{38}$$

Where: M_R = resilient modulus (MPa),

k_1 and k_2 = model parameters,

P$_a$ = atmospheric pressure (=101,325 kPa),

σ$_d$ = deviator stress (kPa),

σ$_c$ = confinement pressure (kPa),

θ = total stress (kPa).

The parameters of model k1 and k2 for fine soils are calculated according to the equations (39) and (40).

$$k_{1,fine\ soils} = 1.12 \cdot (\gamma_{dr})^{1.996} \cdot \left(\frac{LL}{w_c}\right)^{0.639} \tag{39}$$

$$k_{2,fine\ soils} = -0.27 \cdot (\gamma_{dr})^{1.04} \cdot (w_{cr})^{1.46} \cdot \left(\frac{LL}{\#200}\right)^{0.47} \tag{40}$$

The parameters of model k_1 and k_2 for coarse soils are calculated according to the equations (41) and (42).

$$k_{1,coarse\ soils} = 0.12 + 0.90 \cdot \gamma_{dr} - 0.53 \cdot w_{cr} - 0.017 \cdot (\#200) + 0.314 \cdot \log(c_u) \tag{41}$$

$$k_{2,coarse\ soils} = 0.226 \cdot (\gamma_{dr} \cdot w_{cr})^{1.2385} \cdot \left(\frac{\#200}{log\,c_u}\right)^{0.124} \tag{42}$$

Where: k_1 and k_2 = model parameters,

Γ$_{dr}$ = density ratio,

Γ$_{dr}$ = dry density/ maximum dry density

LL = liquid limit (%),

W$_c$ = water content (%),

W$_{cr}$ = water content ratio ($water\ content(current/optimum)$),

#200 = passing through a #200 sieve (%),

C$_u$ = uniformity coefficient (no units).

5.3.2.2   ESTIMATION FROM THE SOTO ET AL. MODEL (2013)

The model of Soto et al. (2013) estimates the mechanical properties of a soil using simple laboratory tests. The complete experimental procedure and model results are available at the reference: Soto et al. (2013). The resilient modulus is determined from tests performed at the optimum moisture content. Subsequently, a correction corresponding to the effects of saturation is calculated according to the model developed by Drumm et al. (1997) according to equation (43). The model of Soto et al. (2013) will simplify this equation to determine the

resilient modulus of the material based on the physical properties and a portable deflectometer test performed on the ground previously placed in a mold.

$$M_{R(wet)} = M_{R(opt)} + \frac{dM_R}{dS} \cdot \Delta S \qquad (43)$$

Where: $M_{R(wet)}$ = resilient modulus with high water content (MPa),

$M_{R(opt)}$ = resilient modulus with optimum moisture content (MPa),

dM_r/dS = slope of the resilient modulus according to saturation,

ΔS = deviation of the degree of saturation (decimal).

The drop mass deflectometer is used to calculate the deflections caused by a vertical stress applied to the sample compacted in the mold. The tests shall be carried out with a cylindrical mold with the following dimensions: diameter and height of 300 mm and 350 mm respectively. Equation (44) expresses the back-calculated modulus in the mold as a function of the Poisson's coefficient, the vertical stress applied, the plate radius and the deflection measured by the sensors.

$$E_{mold} = \frac{2 \cdot (1 - v^2) \cdot \sigma_v \cdot a}{d_0} \qquad (44)$$

Where: E_{mold} = back-calculated modulus in the mold (MPa),

v = Poisson's coefficient,

σ_v = vertical stress (kPa),

a = plate radius (m),

The model distinguishes two soil classes: Group I and Group II. Group I includes sands with a positive parameter b, and group II includes clays and sands with a negative parameter b. Parameter b is a data specific to laboratory tests with the portable deflectometer. During the deflectometer tests, since the soil is stressed in the elastic range, the curve between the applied stress and the deflection is a straight line. This line has a slope m and an ordinate at origin b. It is this value b which corresponds to the parameter b previously stated. A tool for determining this parameter is programmed in the software. When a sand is selected in the software's soil class, a new box appears to determine parameter b, see Figure 5.9.

Figure 5.9 : Estimation from the Soto, Bilodeau and Doré model for the case of sands.

By clicking on the box of parameter b, a new window appears. It allows the calculation of the linear relationship of the applied vertical stress as a function of the deformation obtained. An example in Figure 5.10 is presented.
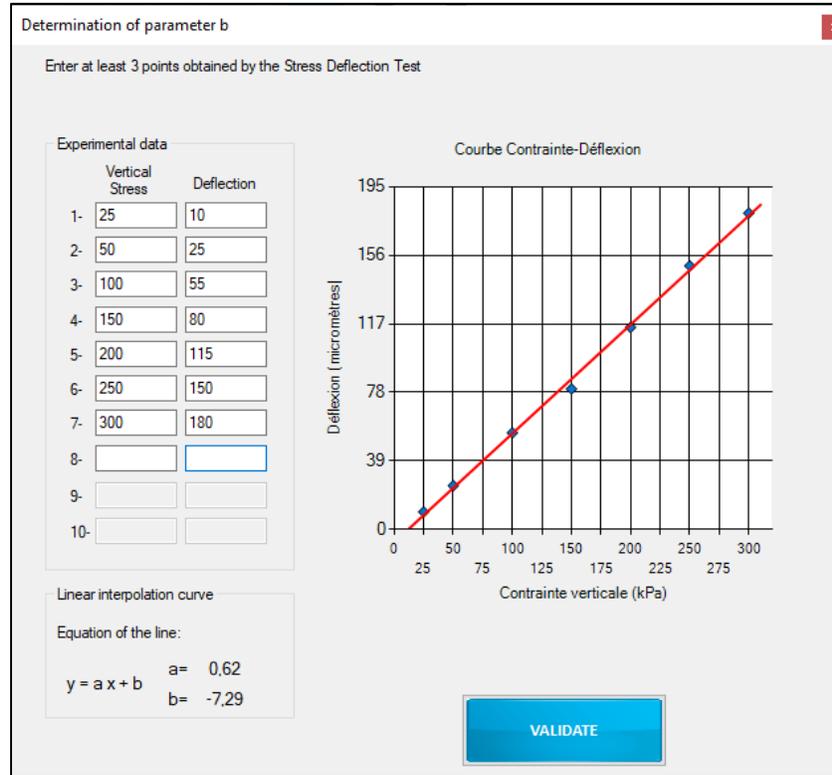
Figure 5.10 : Determination of parameter b

Only three parameters are required to calculate the soil modulus: its degree of saturation, percentage of fine particles and the back-calculated modulus in the mold. Equations (45) and (46) allow the calculation of the resilient modulus with high water content for the two defined groups.

$$log(M_{R(wet)_{Groupe\ I}}) = 0.00514 \cdot E_{mold} + 0.8278 \cdot S_r$$
$$-0.298 \cdot (P080)^{0.615} + 1.288 \tag{45}$$

Where:　　　　$M_{R(wet)}$ = resilient modulus with high water content (MPa),

　　　　　　　E_{mold} = back-calculated modulus in the mold (MPa),

　　　　　　　S_r = degree of saturation (decimal),

　　　　　　　$P080$ = percentage of fines (decimal).

$$log(M_{R(wet)_{Groupe\ II}}) = 0.2967 \cdot Log(E_{mold}) - 3.0152 \cdot S_r{}^{10}$$
$$-0.3642 \cdot (P080)^3 + 1.505 \tag{46}$$

Where: $M_{R(wet)}$ = resilient modulus with high water content (MPa),

E_{mold} = back-calculated modulus in the mold (MPa),

S_r = degree of saturation (decimal),

$P080$ = percentage of fines (decimal).

5.3.2.3   ESTIMATION FROM THE CBR INDEX

The approach for the soil is identical to that used for granular materials. It is therefore recommended to refer to section 5.2.2.2 for the estimation of the reversible module as a function of the CBR index.

5.3.3   LEVEL 3: TYPICAL MATERIAL VALUE

In level 3, the user can enter a typical material value of the resilient modulus. This value must correspond to the modulus for an optimum moisture content.

5.4   OTHER LAYER

Three types of layers that can be integrated into pavement design are presented in this section; first the insulation layer, then the draining layer and finally the reinforcement layer.

5.4.1   INSULATING LAYER

The action of frost in infrastructure soils can have significant impacts on the road network. For example, the formation of ice lenses in frost-sensitive underlying soils may cause irregular pavement lifting During the dimension calculation, the addition of an insulating layer is an interesting solution since it limits the penetration of the frost into the subgrade ground and thus reduces problems related to the action of the frost, such as differential lifting and loss of lift during thawing. On the other hand, the addition of such a layer increases the risk of frost formation on the pavement since it is possible for pavement cooling to occur when the frost front reaches the insulating layer. The installation of an insulation layer requires checking that there is sufficient protection against icing and that the stress applied at the top of the insulation layer is less than the maximum permissible stress for the insulation element. Additional information is available in Chapter 8 of the reference: Doré and Zubeck (2009). The materials commonly used for pavement insulation are extruded polystyrene and expanded polystyrene. These two elements are available in the list of materials available in the software database. Protection against icing on the pavement surface requires the application of a granular layer thick enough to limit this effect. Granular protection can be achieved by imposing a minimum thickness of 450 mm of foundation above

the insulation. This thickness can be adjusted according to the materials and characteristics of the pavement construction site. Details of these methods are presented in section 5.4.1.1. Finally, section xxx allows for a structural check to ensure that the stresses applied to the insulation are acceptable.

5.4.1.1 PROTECTION AGAINST ICING

This section summarizes the work presented by Côté and J.M. (2003) and Québec (2003). In order to reduce the risk of icing of isolated pavements, the layer of granular material must be thick enough to avoid being completely frozen before the end of the high-risk period. Protection against icing requires a minimum granular covering of 450 mm. The accuracy of this recommendation can be improved by following the method below. The minimum thickness of granular material of type MG 20 can be determined from equation (47):

$$e_{MG-20} = F \cdot \alpha_n \cdot \left(f_g - d_G\right) \cdot e_{pav} \tag{47}$$

Where: e_{MG-20} = thickness of MG-20 to be placed above the insulation (mm),

F = growth factor of the ice propagation rate due to the presence of a thermal insulator,

α_n = frost propagation rate in the upper part of a pavement (mm/day),

f_g, d_G = dates of the end of the high risk period for uniform icing and the beginning of the freezing period when the surface temperature becomes equal to 0°C

e_{Pav} = paving thickness (mm).

The rate of frost penetration in the upper part of a pavement can be calculated using equation (48).

$$\alpha_n = 23.737 \cdot w_f^{-0.134} - 1.105 \cdot (T_{ma} - 4) + (k_s - 2.5) + 2 \tag{48}$$

Where: α_n = frost propagation rate in the upper part of a pavement (mm/day),

w_F = water content in the foundation (%),

T_{ma} = average annual air temperature (°C),

k_s = thermal conductivity of the stone composing the granular material (W/m·°C).

Equation (49) describes an empirical relationship for calculating the growth factor.

$$F = 1.335 - 0.032 \cdot w_f + 0.02(T_{ma} - 4)$$
$$-0.023(k_s - 2.5) + 0.0016(e_{iso} - 50) \tag{49}$$

Where: F = growth factor of the ice propagation rate due to the presence of a thermal insulator,

w_F = water content in the foundation (%),

T_{ma} = average annual air temperature (°C),

k_s = thermal conductivity of the stone composing the granular material (W/m·°C).

e_{iso} = insulation thickness (mm).

Equation (50) is used to determine the probable start date of the frost.

$$d_G = 3 \cdot T_{ma} + 300.5 \tag{50}$$

Where: d_G = date in Julian day number (1 to 365),

T_{ma} = average annual air temperature (°C).

These equations are presented in the form of charts in the reference Quebec (2003)

5.4.1.2   STRUCTURAL VERIFICATION

Polystyrene is a type of dry insulation and offers low thermal conductivity. This material has a compressive strength that depends on the type of insulation and these manufacturing techniques. Insulating panels made of extruded polystyrene with a compressive strength of 400 kPa are very resistant and generally suitable for all situations. In order to reduce design costs, polystyrene panels with a compressive strength of 250 kPa can also be used in road construction, provided that the necessary checks are carried out. For each insulator, the vertical load imposed by the loads must not exceed a limit value that depends on the compressive strength of the insulator.

The insulation used must comply with the requirements of standard 14301 (Polystyrene for road construction, Ministère des transports du Québec, 2010). The three types of polystyrene insulation included in the software are presented in Table 5.5 and Table 5.6.

Table 5.5 Physical and mechanical characteristics of polystyrene for thermal insulation of pavements (400 kPa specification)

Properties	Test methods	Requirements
Compressive strength (minimum)	ASTM D 1621	400 kPa
Compressive modulus (minimum)	ASTM D 1621	15 MPa
Thermal resistance (minimum)	ASTM C 177	0,86 m²·°C/W

	ASTM D 2842	0,7 %
Water absorption as volume (maximum)		

Table 5.6 Physical and mechanical characteristics of polystyrene for thermal insulation of pavements (250 kPa specification)

Properties	Test methods	Requirements	
		Extruded	Expanded
Compressive strength (minimum)	ASTM D 1621	250 kPa	250 kPa
Compressive modulus (minimum)	ASTM D 1621	9 MPa	9 MPa
Thermal resistance (minimum)	ASTM C 177	0.86 m²·°C/W	0.69 m²·°C/W
Water absorption as volume (maximum)	ASTM D 2842	0.7 %	2.5 %

It is important to ensure that the loads applied to the insulating layer do not cause excessive deformation. To do this, the thickness of the granular layer required to protect the insulation layer can be determined using equation (51) (Doré and Zubeck, 2009).

$$Z_{min} = \sqrt{\frac{P/\pi \cdot \sigma_0}{\left[1 - (\sigma_a/\sigma_0)\right]^{-2/3} - 1}} \qquad (51)$$

Where: Z_{min} = minimum protection thickness (m),

P = wheel load (40 kN),

σ_0 = tire-road contact pressure (700 kPa),

σ_a = admissible pressure (kPa),

= $0.50 R_c$, if the number of permissible load applications is N = 10^3,

= $0.12 R_c$, if N = 10^6,

= $0.10 R_c$, if N = 10^8,

R_c = compressive strength of the insulating material specified by the manufacturer (kPa).

The software calculation module determines stresses and strains for the specified depths. The software therefore does not use equation (51) which is an approximation of the stress applied to the insulation. The software calculates the vertical stress for each season and

validates if it is less than the maximum permissible stress. Table 5.7 presents several types of materials that can be used as insulation and their associated thermal properties (Doré and Zubeck, 2009). Only the first two are available in the software database.

Table 5.7 Insulation materials and their thermal properties

Insulation material	Thermal conductivity, W/m·°C	Heat capacity, kJ/m³·°C	Typical water content, %	Compressive strength, kPa	Comments
Extruded polystyrene	0.03 – 0.04	≃ 40	0.3 – 5.0	200 – 700	Widely used and documented.
Expanded polystyrene	0.03 – 0.05	≃ 40	1.0 – 10.0	150 – 400	Low-cost alternative to extruded polystyrene. Risk of higher water intake in insulation material must be compensated by an increased layer thickness.
Lightweight concrete	0.50 – 0.70	1 500 – 1 700	1.0 – 5.0	2 000 – 4 000	High stiffness material; easy to lay down
Expanded clay	0.15 – 0.25	350 – 500	5.0 – 20.0		Separation geotextile needs to be used to protect the insulation layer against contamination
Foam glass aggregate	0.15 – 0.25	300 - 360	5.0 – 20.0		
Sawdust and wood bark	0.15 – 0.50		110 - 130	E modulus between 5 and 10 MPa	Structural design of pavement layers above the insulation layer is critical

5.4.2 *DRAINAGE LAYER*

The drainage layer analysis is based on the experience and models developed in the i3C research group at Laval University. In this section, the improvement in resistance to granular

materials resulting from the inclusion of a drainage layer in the pavement system is determined analytically.

The following equation, develop in the MEPDG, is used to predict changes in modulus due to changes in moisture:

$$\log \frac{M_r}{M_{opt}} = a + \frac{b - a}{1 + \exp\left(\beta + k_s \times \left(S - S_{opt}\right)\right)} \tag{52}$$

Where, M_r/M_{opt} is the resilient modulus ratio, and $\left(S - S_{opt}\right)$ is the variation in degree of saturation, and a, b, β, k_s are regression parameter whose default parameters are shown in Table 5.8.

Table 5.8 Default parameters for granular materials

a	b	β	k_s
-0.3123	0.30	-0.0401	6.8157

It was defined in an experimental project that the S/S_{ref} ratio when having a drainage layer was in average 0.931, where S_{ref} and S are the saturation degree in a pavement without drainage layer (reference) and with drainage layer respectively.

Using the AASHTO1993 approximation (calibrated by MTQ) to establish the period during the structure is exposed to conditions close to saturation, and based on equation 52, with $S/S_{ref} = 0.931$, it is possible to estimate the increase of stiffness in the granular layers in late spring, summer and fall. The stiffness increase (M_r/M_{opt}) is applied to the seasonal factors. The increase of stiffness is, for each season considered, weighted according to the time duration were the materials are exposed to conditions close to saturation. For example, this value is set to approximately 25% for Quebec conditions. Figure 5.11 shows the window for entering information on saturation conditions to consider when including drainage layers in the pavement structure.

Figure 5.11 : Form to include information related to the drainage layer

5.4.3   REINFORCEMENT LAYER

The software is in constant development and this section is still to come.

5.5   LAYERS SUBDIVISION

The i3C-ME performs a layer subdivision automatically in cases where materials with properties that are dependent on stresses are used. For this, the following conditioning is used:
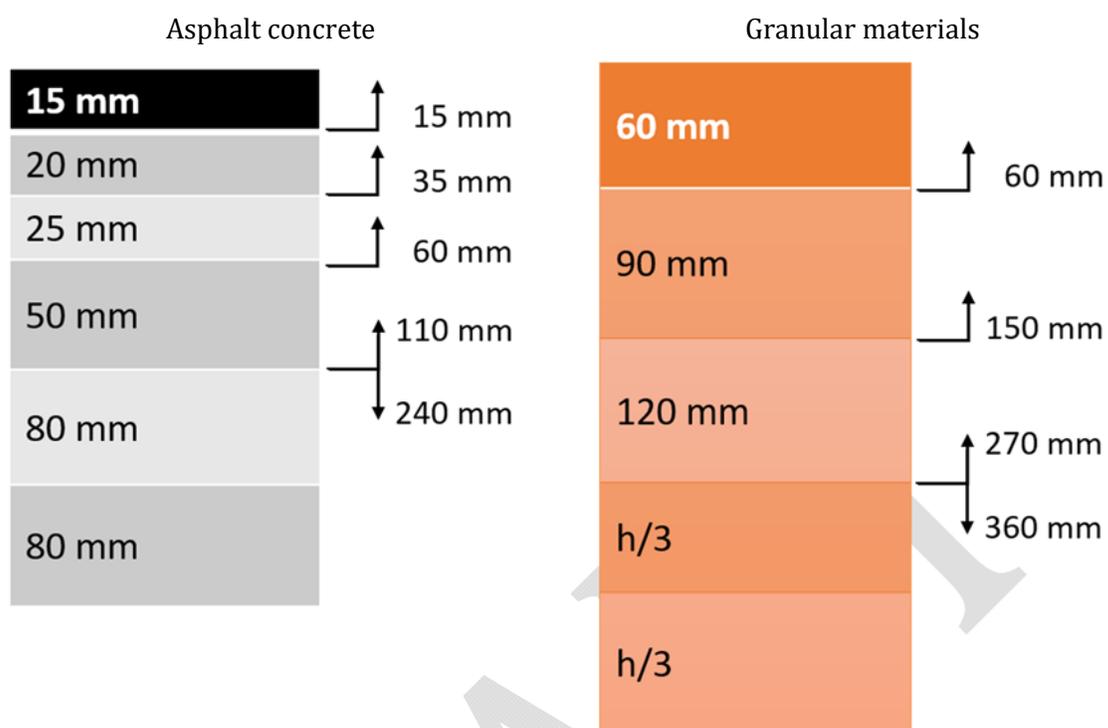
Figure 5.12 : Schematic representation of the criterion of subdivision of layers.

MODULE 6 : DAMAGE LAW

The sixth module corresponds to the definition of performance models. Several damage laws are available, related to fatigue and permanent deformation models. Deformations and lifetimes are calculated for each season. Figure 6.1 shows the home screen of the module.

Figure 6.1 : Selection of damage law parameters

6.1 FATIGUE MODEL

The six fatigue models integrated into the software are: *Asphalt Institute* (Carpenter, 2007), *ILLI-Pave* (Al-Qadi and Wang, 2009), *ASSHTO MEPDG 2002* (ARA, 2004), *NCAT 2005* (Timm and Newcomb, 2003), *Norwegian fatigue criteria* (Myre, 1992) and *Sweden PMS objekt* (Winnerholt, 2001). All these models are presented in the form given by equation (53). The operator can integrate new performance models into the database if they are in this form.

$$N_f = C \cdot K_{F1} \cdot \left(\frac{1}{\varepsilon}\right)^{K_{F2}} \cdot \left(\frac{1}{E}\right)^{K_{F3}} \tag{53}$$

Where: N_f = the allowable number of load repetitions prior reaching fatigue failure (loads equivalent to one single 8165 kg axle with twin tires),

ε = tensile strain at the bottom of the asphalt layer (m/m),

E = elastic modulus of asphalt layer (MPa),

C, K_{F1}, K_{F2}, K_{F3} = Calibration coefficient of the model.

The calibration coefficients of the model can be functions of the void and the bitumen content. The different models integrated into the program are detailed below.

6.1.1 *ASPHALT INSTITUTE*

The fatigue model developed by the *Asphalt Institute* is presented in equation (54) and uses the anglo-saxon unit system (Carpenter, 2007).

$$N_f = 18.4 \cdot (C) \cdot (4.325 x 10^{-3}) \cdot (\varepsilon_t)^{-3.291} \cdot (E)^{-0.854} \qquad (54)$$

Where: N_f = the allowable number of load repetitions prior reaching fatigue failure (loads equivalent to one single 8165 kg axle with twin tires),

C = parameter depending on void and bitumen content,

ε = tensile strain at the bottom of the asphalt layer (in/in),

E= elastic modulus of asphalt layer (PSI).

In order to properly integrate this model into the software, the transformation of the units into the international system has been completed. In addition, the shape of equation (54) had to be changed to match that shown in equation (53). Thus, the calculation of N_f is presented in equation (55). The parameter K_{F1} used depends on the void content (%) and the bitumen content (%), depending on the level of accuracy selected in the structure definition module, default values are proposed. These values can be modified by the operator. Figure 6.2 shows an example calculation for parameter K_{F1}.

$$N_{f(Asphalt\ Institute)} = 0.001135 \cdot K_{F1} \cdot \left(\frac{1}{\varepsilon}\right)^{3.291} \cdot \left(\frac{1}{E}\right)^{0.854} \qquad (55)$$

Figure 6.2 : Determination of parameter K_{F1}

6.1.2 ILLI-PAVE

The *ILLI-Pave* structural model is defined by equation (56) and uses the anglo-saxon unit system (Al-Qadi and Wang, 2009).

$$N = 2.65x10^{-9} \cdot \left(\frac{1}{\varepsilon}\right)^{4.0} \tag{56}$$

Where: N_f = the allowable number of load repetitions prior reaching fatigue failure (loads equivalent to one single 8165 kg axle with twin tires),

ε = tensile strain at the bottom of the asphalt layer (in/in).

Equation (57) reveals the ILLI-PAVE fatigue model in the form used by the software.

$$N_{f(ILLI-PAVE)} = 1 \cdot 2.65x10^{-9} \cdot \left(\frac{1}{\varepsilon}\right)^{4} \cdot \left(\frac{1}{E}\right)^{0} \tag{57}$$

6.1.3 AASHTO MEPDG 2002

The *AASHTO MEPDG 2002* model is presented in equation (58) and uses the anglo-saxon unit system (ARA, 2004).

$$N_f = 0.00432 \cdot k_1' \cdot C \cdot \left(\frac{1}{\varepsilon}\right)^{3.9492} \cdot \left(\frac{1}{E}\right)^{1.281} \tag{58}$$

Where: N_f = the allowable number of load repetitions prior reaching fatigue failure (loads equivalent to one single 8165 kg axle with twin tires),

$$k_1' = \frac{1}{0,000398+\frac{0,003602}{1+e^{(11,02-3,49\cdot h_{ac})}}},$$

ε = tensile strain at the bottom of the asphalt layer (in/in),

E= elastic modulus of asphalt layer (PSI),

h_{ac} = thickness of asphalt mix (in).

Parameter C depends on the void content (%) and the bitumen content (%). The calculation of N_f, according to the form previously described with the parameters displayed, is presented in equation (59) and uses the International System for units. The i3c software calculates a new K_{F1} which is based on the void and bitumen content (Figure 6.2). Depending on the level of accuracy selected in the structure definition module, default values are proposed. These values can be modified by the operator.

$$N_{f(AASHTO\ MEPDG\ 2002)} = 7.35574x10^{-6} \cdot K_{F1} \cdot \left(\frac{1}{\varepsilon}\right)^{3.9492} \cdot \left(\frac{1}{E}\right)^{1.281} \tag{59}$$

6.1.4 NCAT 2005

The NCAT 2005 model (Timm and Newcomb, 2003) is presented in equation (60).

$$N = 2.83x10^{-6} \cdot \left(\frac{1}{\varepsilon}\right)^{3.148} \tag{60}$$

In order to satisfy the formula used by the software, equation (61) sets out the calculation in the desired form.

$$N_{f(NCAT\ 2005)} = 1 \cdot 2.83x10^{-6} \cdot \left(\frac{1}{\varepsilon}\right)^{3.148} \cdot \left(\frac{1}{E}\right)^{0} \tag{61}$$

6.1.5 NORWEGIAN FATIGUE CRITERIA

The *Norwegian fatigue criteria* (Myre, 1992) is based on the results of tests performed on a center-point loaded beam (CPB). The data analysis produced a relationship corresponding to the fatigue criteria (equation (62)).

$$Log(N_f) = 34.5326 - 6.1447 \cdot log(\varepsilon) - 3.395 \cdot log(E)$$
$$+ 0.3864 \cdot log(VB)(MF) - 0.0788V_V \tag{62}$$

Where: N_f = total number of cycles until fatigue failure,

ε = tensile strain at the bottom of the asphalt layer (μm/mm),

E = elastic modulus of the asphalt mix (MPa),

VB = bitumen content (%),

V_V = void content (%),

MF = Model factor obtained according to equation (63).

$$MF = 1.99 - 3.37\frac{A}{B} - 0.00342 \cdot B + 0.004 \cdot A + 0.00153 \cdot Esg \qquad (63)$$

Where: $A = \sum_{i=1}^{i=n}(h_i \cdot \sqrt[3]{E_i})$,

$B = \sum_{i=1}^{i=m}(h_i \cdot \sqrt[3]{E_i})$,

h_i = thickness of the numbered layer i (cm),

E_i = elastic modulus of the numbered layer i (MPa),

Esg = elastic modulus of the infrastructure layer (MPa),

n = the lowest asphalt layer below the surface,

m = foundation soil.

For the season: "early spring", the MF factor is expressed according to equation (64):

$$MF = 2.56 - 4{,}03\frac{A}{B} - 0.006555 \cdot B + 0.00743 \cdot A \qquad (64)$$

Where: $A = \sum_{i=1}^{i=n}(h_i \cdot \sqrt[3]{E_i})$,

$B = \sum_{i=1}^{i=m}(h_i \cdot \sqrt[3]{E_i})$,

h_i = thickness of the numbered layer i (cm),

E_i = elastic modulus of the numbered layer i (MPa),

n = the lowest asphalt layer below the surface,

m = foundation soil.

The calculation of N_f according to the Norwegian fatigue criteria model is shown in equation (65). Again, parameter K_{F1} depends on the void content (%) and bitumen content (%), but also on the thickness of the layers and modules of each layer. For each season, the coefficient is recalculated to take into account the variations in modulus of each layer.

$$N_{f(Norwegian\ fatigue\ criteria)} = 3.408788x10^{34} \cdot K_{F1} \cdot \left(\frac{1}{\varepsilon}\right)^{6.1447} \cdot \left(\frac{1}{E}\right)^{3.395} \qquad (65)$$

6.1.6   *SWEDEN PMS OBJEKT*

The *Sweden PMS objekt* model (Winnerholt, 2001) is presented according to equation (66).

$$N_{bb,i} = f_s \frac{2.37x10^{-12} \cdot 1.16^{(1.8 \cdot T_i + 32)}}{\varepsilon_{bb,i}^4} \qquad (66)$$

Where: $N_{bb,i}$ = total number of allowable axle passages equivalent to a standard axle loaded at 100 kN

f_s = safety factor,

T_i = temperature of the season i (°C),

$\varepsilon_{bb,i}$ = tensile strain at the bottom of the asphalt layer (mm/mm).

Equation (67) presents the model according to the form used by the software. Parameter K_{F1} therefore depends on the temperature of the asphalt mix at each season and the safety factor f_s applied.

$$N_{f(Sweden\ PMS\ objekt)} = 2.37x10^{-12} \cdot K_{F1} \cdot \left(\frac{1}{\varepsilon}\right)^4 \cdot \left(\frac{1}{E}\right)^0 \tag{67}$$

6.2   PERMANENT DEFORMATION DAMAGE MODEL

The permanent deformation models integrated into the software are: *Asphalt Institute* (1982), *MNPAVE* (Minnesota Department of Transportation, 2012), *Huang* (1993) and *Roadent* (Timm et al., 1999). Equation (68) presents the form used for the calculation. Figure 6.3Figure 6.2 shows an example calculation for parameter K_{F1}.

$$N_R = C_R * K_{R1} \cdot \varepsilon_V^{K_{R2}} \tag{68}$$

Where: N_R = number of loading cycles applied for a reference axle until failure by permanent deformation (structural rutting),

C_R = correction factor,

ε_v = vertical deformation at the top of the infrastructure ground (m/m),

K_{R1}, K_{R2} = design parameters.

Figure 6.3 : Determination of parameter K_{r1}

6.2.1 ASPHALT INSTITUTE

The model proposed by Asphalt Institute (1982) is presented in equation (69). Structural failure is achieved when the rut has reached a depth of 12.7 mm.

$$N_{R(Asphalt\ Institute)} = 1 \cdot 1.365 x 10^{-9} \cdot \varepsilon_V^{-4.477} \tag{69}$$

6.2.2 MNPAVE

The mnpave software (Minnesota Department of Transportation, 2012) calculates the permanent deformation according to equation (70).

$$N_{R(MnPave)} = 1.39 \cdot 0.0261 \cdot \varepsilon_V^{-2.35} \tag{70}$$

6.2.3 HUANG (1993)

Equation (71) presents Huang's (1993) model (Al-Qadi et al., 2004). Structural failure is achieved when the rut has reached a depth of 12.5 mm.

$$N_{R(Huang\ 1993)} = 1 \cdot 1.077 x 10^{-8} \cdot \varepsilon_V^{-4.483} \tag{71}$$

6.2.4 ROADENT

Equation (72) presents one of the models proposed in the mnpave software. The original formulation has been modified to correspond to the generalized form proposed by the i3c software. The experimental approaches leading to this equation are available at reference: Timm et al. (1999)

$$N_{R(Roadent)} = 1 \cdot 1.11 x 10^{-8} \cdot \varepsilon_V^{-3.949} \tag{72}$$

6.3 OTHER DAMAGE MODELS

The "tools" tab allows access to the consultation of the entire database concerning damage models. It is possible to record all damage laws in the same form as those proposed in the software through the form presented in Figure 6.4. This form is available in the "tool" tab.

Figure 6.4 : New damage law

6.4 IRI

For IRI prediction, the model developed by Sylvestre (2017) is considered. This model has been developed to analyze pavements in cold regions, including the effect of frost heave of subgrade soils as one of the main mechanisms involved in the rate of degradation of flexible pavement. The equation is built to take into consideration the initial roughness, the frost heave and its variability, the effect of transversal cracking (estimated through age and asphalt concrete thickness) and traffic. The model is described by the following equation:

$$
(73)
$$

$$
\Delta IRI_{LT} = 0.6 \left[.001 IRI_0^2 + .399 h^{0.164} CV_G^{0.055} + .07 \log\left(\frac{age}{\sqrt{H_{BB}}}\right) + 1.813 \cdot 10^{-8} \left(\frac{ECAS_A^2}{ECAS_{AD}}\right) - .648 \right]
$$

Where, ΔIRI_{LT} : Long-term IRI rate (m/km/yr)

IRI_0 : Initial IRI (m/km)

h : Frost heaving (mm)

CV_G : Coefficient of variability of frost heave (See Table 6.1)

age : Age, design period, analysis period (yr)

H_{BB} : Asphalt layer thickness (mm)

$ECAS_A$: Average annual number of ESAL

$ECAS_{AD}$: Average annual ESAL's of pavement (AASHTO93 design)

Table 6.1 GV$_G$ as function of variability and type of road (Bilodeau and Doré 2013).

Variability	CV$_G$	
	Rural	Urban
Uniform (Alluvial terrace, Delta deposit, marine or Lacustrine Flood Plain)	< 0.1	< 0.5
Moderate (deposition basin border, Alluvial deposit, Fluvio-glacial deposit)	> 0.1 and < 0.3	< 0.5
High (Glacial till, varved clay, soil with silt layers, soil/rock contact)	< 0.3	< 0.5

Figure 6.5 shows the input screen for the IRI damage model. Note that no data will be provided for pavement designed with an insulation layer.

$$\Delta IRI_{LT} = 0.6\left[0.001 \times IRI_0^2 + 0.399 \times h^{0.164} \times CV_G^{0.055} + 0.07 \times \log\left(\frac{age^3}{\sqrt{H_{BB}}}\right) + 1.813 \cdot 10^{-8}\left(\frac{ECAS_A^2}{ECAS_{AD}}\right) - 0.648\right]$$

International Regularity Index

h: 0   H$_{BB}$: 60   ECAS$_A$: NaN   Road class:

% with maximum IRI: 70%   IRI$_0$: 1.2   CV$_G$: 0.1

Variability: Uniform (Alluvial terrace, Delta deposit, Marine or Lacustrine Flood Plain)

Figure 6.5 : Determination of IRI

MODULE 7 : FROST CRITERIA

The frost module is based on the SSR model (Saarelainen, 1992) developed in Finland. The frost module allows, for a previously defined pavement structure, to calculate the frost depth and associated lifting. The calculation of the frost depth is based on the balance of the heat balance at the frost front. The calculation of frost heave is performed by combining the heave generated by the increase in volume of water turning into ice and the formation of ice lens. Calculations are performed by iteration for each temperature data included in the winter season. The equations associated with the calculations are detailed in the Chaussée 2 software user guide (St-Laurent, 2006). The design and programming of the calculation module was carried out by Denis St-Laurent of the pavement department at the Ministère des Transports du Québec. Module 7 is the interface between the data that the user must enter and the calculation codes. It consists of two parts: the characteristics of the structure's materials and winter-specific climatic data. An example of the home screen of this module for a pavement structure consisting of 9 layers is shown in Figure 7.1.

Note: This module is independent of the other modules. Once the pavement structure is completed, the frost calculation can be completed and started without finalizing the other modules. It is therefore not necessary to complete this module to launch calculations of the pavement's mechanical response.
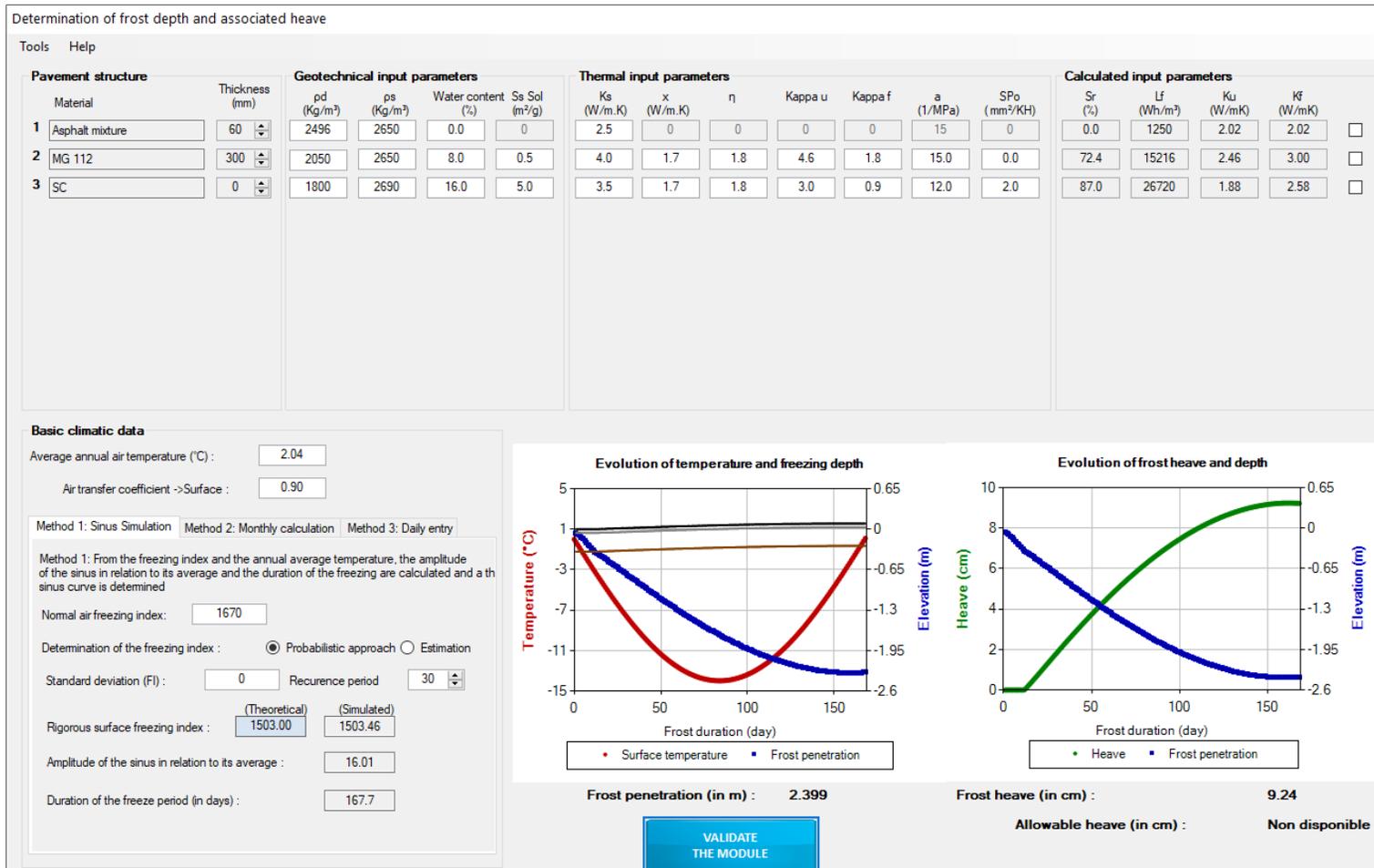
Figure 7.1 : Determination of frost depth and associated heaving

7.1 PAVEMENT STRUCTURE PARAMETER

The pavement structure is integrated into module 7 and is the same as that defined previously in module 5. The materials as well as the pavement thicknesses are automatically placed in the structure. The following geotechnical and thermal parameters must be completed:

ρ_s = density of soil solids (kg/m^3),

ρ_d = dry density (kg/m^3).

w = water content (%),

Ss = specific surface area of fine particles (m^2/g),

And k_S = thermal conductivity of soil solid particles (W/m·°C),

χ = material parameter that takes into account the effect of the particle shape (W/m·°C),

η = material parameter that takes into account the effect of the particle shape (no unit),

k_u = granularity factor for unfrozen thermal conductivity (k_u),

k_f = granularity factor for frozen thermal conductivity (k_f),

a = overload coefficient (in MPa^{-1})

SP_0 = segregation potential without vertical load (mm^2/°K.H),

Geotechnical and thermal conductivity parameters are used to calculate the degree of saturation (S_r), latent heat of fusion (L_f) and unfrozen (k_u) and frozen (k_f) thermal conductivity. The thermal conductivity parameters can be changed manually, otherwise the value is determined by the software. The grey boxes are not accessible and depend on the selected calculation model. In order to modify manually the conductivity of the materials, it is possible to tick the boxes in the last column making the boxes accessible. Default values are proposed from the database provided in the software. However, it is possible to vary the geotechnical and thermal parameters if the values do not correspond to the data of the materials constituting the structure to be analysed. The next sections detail the different equations used in the calculation of frost depth and associated heave.

7.1.1 SEGREGATION POTENCIAL

Segregation potential is a measure of the susceptibility of a soil to frost. It can be measured in the laboratory during frost tests on soil samples or estimated using empirical equations defined by Konrad's method (Konrad, 2005). Equations (74) and (75) determine the

reference parameters for a soil with an average fine particle diameter smaller than one micrometer (Konrad, 2005).

$$If \ d_{50}(FF) < 1\mu m \ ; \ Ss_{ref} = 25.95 \tag{74}$$

$$If \ d_{50}(FF) < 1\mu m \ ; \ SP_{0ref} = 489 \tag{75}$$

Where: d_{50}(FF) = average fine particle diameter (d < 80μm) (μm),

Ss_{ref} = specific surface area of the reference fine particles (m²/g),

SP_{0ref} = segregation potential without reference vertical load (mm²/°C·day).

Equations (76) and (77) define the reference physical properties of soils with an average fine particle diameter larger than one micrometer (Konrad, 2005).

$$If \ d_{50}(FF) > 1\mu m \ ; \ Ss_{ref} = 25.95 - 11.78 \cdot \log(d_{50}(FF)) \tag{76}$$

$$If \ d_{50}(FF) > 1\mu m \ ; \ SP_{0ref} = 489 - 232 \cdot \log(d_{50}(FF)) \tag{77}$$

Where: d_{50}(FF) = average fine particle diameter (d < 80μm) (μm),

Ss_{ref} = specific surface area of the reference fine particles (m²/g),

SP_{0ref} = segregation potential without reference vertical load (mm²/°C·day).

The calculation of SP_0 is based on equations (78), (79), (80) and (81) depending on the ratio of the specific surface area of fine particles to the specific reference surface area and the ratio of water content to the liquid limit (Konrad, 2005).

$$If \ \frac{S_S}{Ss_{ref}} < 1 \ ; \ \frac{SP_0}{SP_{0ref}} = \frac{S_S}{Ss_{ref}} \ si \ \frac{w}{w_L} = 0.7 \pm 0.1 \tag{78}$$

$$If \ \frac{S_S}{Ss_{ref}} < 1 \ ; \ \frac{SP_0}{SP_{0ref}} = 0.08 + 1.42 \cdot \frac{S_S}{Ss_{ref}} \ si \ \frac{w}{w_L} > 0.8 \tag{79}$$

$$If \ \frac{S_S}{Ss_{ref}} > 1 \ ; \ \frac{SP_0}{SP_{0ref}} = \left(\frac{S_S}{Ss_{ref}}\right)^{-0.85} \ si \ \frac{w}{w_L} = 0.7 \pm 0.1 \tag{80}$$

$$If \ \frac{S_S}{Ss_{ref}} > 1 \ ; \ \frac{SP_0}{SP_{0ref}} = \left(\frac{S_S}{Ss_{ref}}\right)^{-0.55} \ si \ \frac{w}{w_L} > 0.8 \tag{81}$$

Where: Ss = specific surface area of fine particles (m²/g),

Ss_{ref} = specific surface area of the reference fine particles (m²/g,

SP_0 = segregation potential without vertical load (mm²/°C·day),

SP_{0ref} = segregation potential without reference vertical load (mm²/°C·day)

w = water content(%),

w_L = liquid limit (%).

The segregation potential without vertical load allows the software to calculate the soil segregation potential using the relationship (82)

$$SP = SP_0 \, e^{-a \, \sigma} \tag{82}$$

Where: SP = segregation potential (mm²/°C·day),

SP$_0$ = segregation potential without vertical load (mm²/°C·day),

a = overload coefficient (in MPa^{-1})

σ = Overload applied to the soil (in MPa),

And the coefficient a is a function of the percentage of fine particles according to equation (83)

$$a = 13.455. \, e^{-0.0289. \, \%Fine} \tag{83}$$

7.1.2 THERMAL CONDUCTIVITY OF UNFROZEN AND FROZEN SOIL

Three options are available in the software to determine the conductivity of frozen and unfrozen soil. The first option is to enter manually a value, the second is to use Kersten's (1949) model and the third option is to use Côté and Konrad's (2005a) and (2005b) model. By default, the Coté and Konrad model is used. An option in the software toolbar allows you to select one or the other of the methods. The two models are detailed below.

7.1.2.1 KERSTEN'S MODEL

Kersten's (1949) model estimates the thermal conductivity of frozen and unfrozen soils. It is an empirical model developed for fine soils, such as silts and clays, and coarse soils, such as medium and fine sands (Doré and Zubeck, 2009). Equations (84) and (85) determine the thermal conductivity of frozen and unfrozen fine soil.

$$k_{u(fine \, unfrozen \, soils)} = 0.1442 \cdot (0.9 \cdot \text{Log}(w) - 0.2) \cdot 10^{0.6243 \cdot \rho_s} \tag{84}$$

$$k_{f(fine \, frozen \, soils)} = 0.001442 \cdot 10^{1.373 \cdot \rho_s} + 0.01226 \cdot w \cdot 10^{0.4994 \cdot \rho_s} \tag{85}$$

With: ρ_s = density of soil solids (g/cm³),

w = water content (%), valid for w > 7%

The Kersten's model for frozen and unfrozen coarse soils (medium and fine sand) is defined by equations (86) and (87).

$$k_{u(unfrozen \, coarse \, soils)} = 0.1442 \cdot (0.7 \cdot \text{Log}(w) + 0,4) \cdot 10^{0.6243 \cdot \rho_s} \tag{86}$$

$$k_{f(frozen \, coarse \, soils)} = 0.01096 \cdot 10^{0.8115 \cdot \rho_s} + 0.00461 \cdot w \cdot 10^{0.9115 \cdot \rho_s} \tag{87}$$

With: ρ_s = Density of soil solids (g/cm³),

w = water content (%), valid for w > 1%

The thermal conductivity of soils is therefore a function of water content and dry density. For example, typical values for different soils and materials are presented in Table 7.1

Table 7.1 Thermal properties of different soils and materials

Soil or material	Thermal conductivity, k (W/m°C)	Volumetric heat capacity, c_v (MJ/m^3·°C)
Fresh snow	0.06-0.10	0.21
Compacted snow	0.3-0.6	0.42-1.05
Bituminous asphalt mix	1.50	2.0-2.5
Granular material	1.3-1.7	2.0
Polystyrene	0.03-0.06	0.04-0.06
Peat	0.6	3.0
Sand-gravel	1.2-3.0	2.4-3.0
Silt	1.2-2.4	2.5-3.1
Clay	0.9-1.8	2.6-3.4

7.1.2.2 CÔTÉ AND KONRAD'S MODEL

The generalized model by Côté and Konrad (2005a) and (2005b) allows thermal conductivity to be calculated by integrating the properties of frozen and unfrozen soils, such as porosity, degree of saturation, mineralogy, grain size distribution and particle shape. This model is valid for natural soils and materials used in construction, such as crushed stone, gravel, sand, silt and clay.

First, the normalized thermal conductivity can be defined according to equation (88) according to the concept proposed by Johansen (1975)

$$k = (k_{sat} - k_{dry})k_r + k_{dry} \qquad (88)$$

Where: k = real thermal conductivity (W/m·°C),

k_{sat} = thermal conductivity of saturated soil (W/m·°C),

k_{dry} = thermal conductivity of dry soil (W/m·°C),

k_r = normalized thermal conductivity (W/m·°C).

The concept of normalized thermal conductivity, recently developed by Côté and Konrad, is proposed in equation (89). This general equation is valid for all types of soils.

$$k_r = \frac{\kappa \cdot S_r}{1 + (\kappa - 1)S_r} \qquad (89)$$

Where: k_r = normalized thermal conductivity (W/m·°C),

                    k = empirical parameter used to take into account the different types of soils in unfrozen and frozen conditions,

                    S_r = degree of saturation (%).

The limit conditions described in equations (90) and (91) must be respected.

$$Lower\ limit\ condition : \ S_r = 0 \ \rightarrow k_r = 0 \tag{90}$$

$$Upper\ limit\ condition : \ S_r = 1 \ \rightarrow k_r = 1 \tag{91}$$

The degree of saturation is obtained according to equation (92).

$$S_r = \frac{w}{100} \cdot \frac{\rho_s}{n \cdot \rho_w} \tag{92}$$

Where: S_r = degree of saturation (%),

                    w = water content (%),

                    ρ_s = density of soil solids (kg/m³),

                    n = porosity,

                    ρ_w = water density (=1000 kg/m³).

Examples of the empirical parameter for typical soils by unfrozen and frozen condition are presented in Table 7.2

Table 7.2 Empirical parameters κ for different soil types

Soil types	K	
	Unfrozen	Frozen
Gravel and coarse sand	4.60	1.70
Fine and medium sands	3.55	0.95
Silty and clay soils	1.90	0.85
Fibrous organic soils, peat	0.60	0.25

Also, it is possible to calculate the saturated thermal conductivity of the ground according to equation (93) for unfrozen soils, and according to equation (94) for frozen soils.

$$k_{sat\ (unfrozen\ soils)} = k_s^{1-n} \cdot k_w^{n} \tag{93}$$

$$k_{sat\ (frozen\ soils)} = k_s^{1-n} \cdot k_i^{n-\theta_u} \cdot k_w^{\theta_u} \tag{94}$$

Where: k_{sat} = thermal conductivity of saturated soil (W/m·°C),

                    k_s = thermal conductivity of solids soil (W/m·°C),

k_w = water thermal conductivity (=0.6 W/m·°C),

k_i = ice thermal conductivity (=2.24 W/m·°C),

n = porosity,

θ_u = volume fraction of unfrozen water in frozen fine-grained soils

The porosity of a soil is obtained by using equation (95)

$$n = 1 - \frac{\rho_s}{\rho_d} \tag{95}$$

Where: n = porosity,

ρ_s = density of soil solids (kg/m³),

ρ_d = dry density (kg/m³).

The volume fraction of unfrozen water in frozen fine-grained soils is presented in equation (96).

$$\theta_u = \frac{w_u \cdot \rho_s}{100 \rho_w} \tag{96}$$

Where: θ_U = volume fraction of unfrozen water in frozen fine-grained soils,

w_u = unfrozen water content (%),

ρ_s = density of soil solids (kg/m³),

ρ_w = water density (=1000 kg/m³).

The unfrozen water content in frozen ground can be estimated, for a given temperature, by the empirical relationship proposed by Anderson and Tice (1972) presented in equation (97).

$$\text{Ln}(w_u) = 0.2618 + 0.5519 \, \text{Ln}(S_s) - 1.449\ln(-T) \cdot S_s^{-0.264} \tag{97}$$

Where: w_u = unfrozen water content (%),

S_S = specific surface area of fine particles (m²/g),

T = temperature (°C).

The thermal conductivity of solid soil particles can be found using equation (98) when the complete mineral composition is known. Average values are also presented in Table 7.3.

$$k_s = \prod_j k_{m_j}^{x_j} \tag{98}$$

Where: k_s = thermal conductivity of solids soil (W/m·°C),

k_m = thermal conductivity of the minerals forming the rock (W/m·°C).

Table 7.3 Average values of thermal conductivity of solid particles for different materials

Material	P_s	K_s

	(g/cm³)	(W/m·°C)
Rocks		
Anorthosite	2.73	1.8
Basalt	2.90	1.7
Limestone	2.70	2.5
Diabase	2.98	2.3
Dolomite	2.90	3.8
Gabbro	2.92	2.2
Gneiss	2.75	2.6
Granite	2.75	2.5
Sandstone	2.80	3.0
Marble	2.80	3.2
Quartzite	2.65	5.0
Schist	2.65	1.5
Shale	2.65	2.0
Syenite	2.80	2.0
Trapp (Trop rock)	2.90	2.0
Soil and organic matter		
Coal	1.35	0.26
Teat	1.50	0.25
Silt and clay	2.75	2.90

The thermal conductivity of dry soil can be calculated using equation (99).

$$k_{dry} = \chi \cdot 10^{-\eta \cdot n} \tag{99}$$

Where: k_{dry} = dry thermal conductivity (W/m·°C),

χ = material parameter that takes into account the effect of the particle shape (W/m·°C),

η = material parameter that takes into account the effect of the particle shape (no unit),

n = porosity.

Material parameters for some soils are presented in Table 7.4.

Table 7.4 Material parameters for different soil types

Soil types	χ	η
Crushed rocks and gravel	1.70	1.80

Natural mineral soils	0.75	1.20
Fibrous organic soils, peat	0.30	0.87

7.1.3 THERMAL CONDUCTIVITY OF BITUMINOUS MATERIALS

Côté et al. (2013) measured the thermal conductivity of different bituminous concretes normally used in the province of Quebec. The results show that the thermal conductivity of the materials depends on the mineralogy of the particles, the amount of intergranular voids and the amount and type of bitumen in the bitumen mixture. The thermal conductivity of asphalt mixes can be calculated from equation (100).

$$\lambda = \frac{(\kappa_{2P} \cdot \lambda_{sm} - \lambda_a).\rho + \rho_{max}.\lambda_a}{\rho_{max} + (\kappa_{2P} - 1).\rho} \tag{100}$$

Where: κ_{2P} = empirical parameter as a function of the material structure (particle shape and degrees of cementation),

λ_{sm} = average conductivity of the solids in the bituminous mixture (aggregate, filler and bitumen) (W/m·°C),

λ_a = thermal air conductivity (=0.0024 W.m^{-1}.K^{-1}),

ρ = density (kg/m^3),

ρ_{max} = maximun density (kg/m^3).

The empirical parameter κ_{2P} can be related to the mean conductivity λ_{sm} by the relationship defined in equation (101). Similarly, the conductivity λ_{sm} can be calculated using the geometric means of each component according to equation (102).

$$\kappa_{2P} = 0.205.\lambda_{sm}^{-0.34} \tag{101}$$

$$\lambda_{sm} = \lambda_{agg}^{\chi_{agg}}.\lambda_{fil}^{\chi_{fil}}.\lambda_{bit}^{\chi_{bit}} \ avec \ \chi_{agg} + \chi_{fil} + \chi_{bit} = 1 \tag{102}$$

Where: λ_i = thermal conductivity of component i (aggregate, filler and bitumen) (W/m·°C),

χ_i = volume fraction of component i.

Côté et al. (2013) proposes a simplified relationship of equation (100) that is used in the frozen module to calculate the thermal conductivity of asphalt mixes. The conductivity is only a function of the density of the asphalt mix as shown in equation (103).

$$\lambda = \frac{0.35.\rho + 62}{2585 - 0.85.\rho} \tag{103}$$

7.2 CLIMATIC CONDITIONS PARAMETERS

Three calculation options are available to the user to estimate frost depth and frost heave. First, the sine simulation allows to create a sine function from the freezing index representative of winter. For the second option, the operator has the option of entering the average temperature and duration of the month on a monthly basis in order to perform a monthly calculation. Finally, the third option is to specify the average daily temperatures for the whole winter. These three methods offer different levels of accuracy for calculating frost depth and heave.

In order to calculate the frost depth and frost heave, some basic climatic data must be entered such that:

- The average annual air temperature (°C),
- The air-surface transfer coefficient (decimal).

The air-surface transfer coefficient also called the n-factor and noted n is defined as the ratio between the surface temperature in freezing conditions and the air temperature in freezing conditions. Equation (104) presents the relationship between the factor-n and temperatures. Table 7.5 summarizes the typical values used for pavement design purposes (Doré and Zubeck, 2009).

$$n = \frac{T_S}{T_a} = \frac{Surface\ Temperature}{Air\ Temperature} \tag{104}$$

Table 7.5 Typical values of the n-factor

Surface material	n-factor	
	Order of magnitude	Suggested value range in design
Bituminous asphalt mix	0.25-2.50	0.8-0.95
Gravel	0.60-1.50	0.9-1.0
Trees, shrubs, moss, peat	0.25-0.50	0.30-0.35
Snow		1.00

The three calculation options proposed in the frost module are detailed below.

7.2.1 DETERMINATION OF THE SEVERE FREEZING INDEX

The severity of a winter is taken into account in a frost calculation using the normal frost index of the study site. The normal freezing index (FI_n) varies according to the geographical position where the project is carried out. The normal freezing index is defined by the area between the negative temperature curve and the 0°C line for a fixed period of time. In the software this time period is equal to one year. The freezing index proposed in the calculation module is defined by the relationship (105). The freezing index is a positive value. The

negative sign in the equation gives a positive frost index since the average temperature during the winter is a negative value.

$$FI_n = -Tm_H . D_H \tag{105}$$

Where: FI_n = normal freezing index (°C.days)

   Tm_H = average temperature during the winter (°C)

   D_H = winter duration (days)

The freezing index can also be defined by the equation

$$FI_n = \sum_{i=1}^{n} -Tm_i . D_i \tag{106}$$

Where: Tm_i = average temperature of day i (°C),

   D_i = duration of day i (=1 day),

   i = winter days with a negative average temperature,

   n = number of days in the winter when the average daily temperature is negative.

The normal freezing index represents an average value calculated over a given period of time. For pavement design, an increased value is used to account for colder than average winters. A rigorous frost index (FIᵣ) is therefore calculated from the normal frost index and serves as a reference for pavement heave calculations.

The frozen module offers two options for determining the rigorous freezing index. The first option is an estimate representing a winter that would correspond to the average of the three coldest winters over a thirty-year period (equation (107)).

$$FI_r = 1.143 \cdot FI_n + 220 \tag{107}$$

Where: FI_r = rigorous freezing index (°C·days),

   FI_n = normal freezing index (°C·days).

The second option is a probabilistic approach that takes into account the history of winters for a defined period of time. The standard deviation and the average of the distribution of freezing indexes for a given region must be available or calculated. The user must define the normal freezing index (corresponding to the average of the freezing indexes for the given period) as well as the standard deviation of the values. Thereafter it is necessary to define a return period (P_r). Choosing P_r=10 years means that the severity of winter will correspond to the most severe winter encountered once every 10 years. The return period is used to define the reliability level from equation (108).

$$R = 100 - {100}/{P_R} \tag{108}$$

Where: R = reliability level (%),

               P_R = return period (years).

Considering that the freezing indices follow a normal distribution, it is possible to define the normal deviation associated with the reliability level. An excerpt from the standard statistical table is presented in Table 7.6.

Table 7.6 Normal deviation as a function of reliability level

Return period, (years)	Reliability level, %	Normal deviation
2	50	0.000
5	80	0.841
10	90	1.282
20	95	1.645
30	97	1.881

The rigorous freezing index is calculated from these parameters by equation (109)

$$FI_r = FI_n + Z_r \cdot \sigma \tag{109}$$

Where: FI_r = rigorous freezing index (°C·days),

               FI_n = normal freezing index (°C·days),

               Z_R = normal deviation associated with the calculation risk,

               σ = standard deviation.

The calculation module proposes a return period varying between 2 and 100 years. The normal freezing index is calculated from the data entered in the climate module. However, this value may be adjusted if other methods of calculating the FIn are used.

7.2.2 SINE SIMULATION

The first method allows the software to determine a sine curve from the rigorous air freezing index (°C-day), the average annual air temperature (°C) and the air-surface transfer coefficient. The sinusoidal function obtained gives the freezing time as a function of temperature. Figure 7.2 shows the input parameter screen for this method.
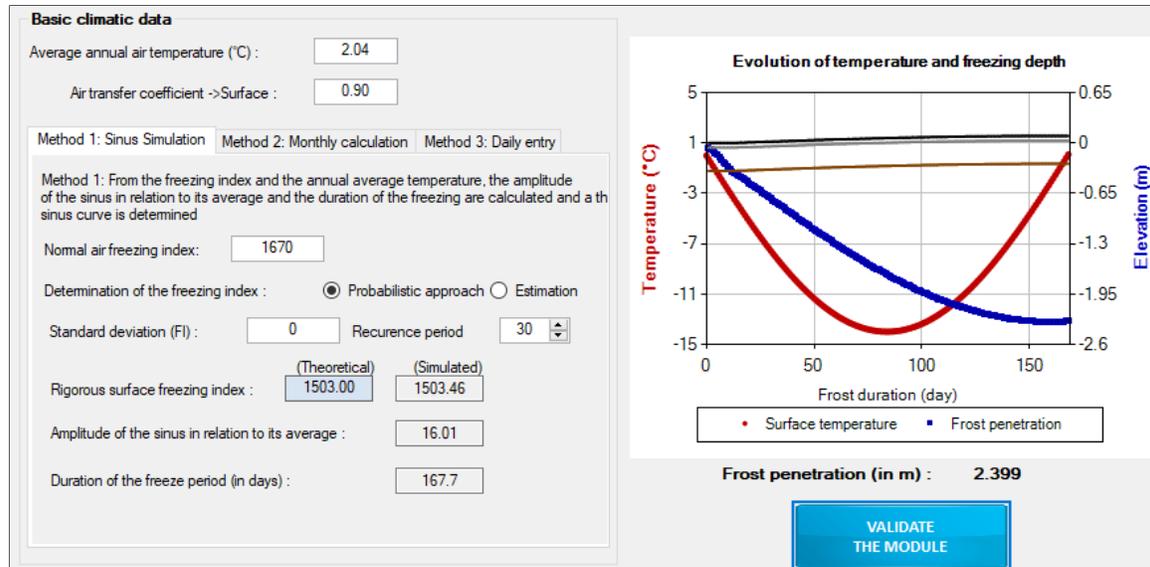
Figure 7.2 : Method 1 - Sine simulation and example of result

Figure 7.2 also shows an example of the sine curve obtained when entering the following variables:

- - Average annual air temperature: 2.04°C
- - Air-surface transfer coefficient: 0.95
- - Normal air freezing index: 1670 °C-days
- - Probabilistic approach with P_R= 30 years and σ=200 °C.days.

7.2.3 MONTHLY CALCULATION

The second method allows you to enter the air freezing index (°C-days) and duration (days) for each month from November to April. The duration may differ from the number of days scheduled in the month in order to be able to start a freeze period at any time during the month. Figure 7.3 shows the table to be completed for the calculation of frost depth and frost heave. Three parameters are considered in the calculation. The length of the period, the freezing index over this period and the average temperature. As the three parameters are directly linked, the software automatically calculates the average temperature from the other two parameters. As illustrated in the example, the month of November only lasts 10 days since for the first 20 days of the month the temperature was positive and did not have to be taken into account. An example of a route is also shown in Figure 7.3
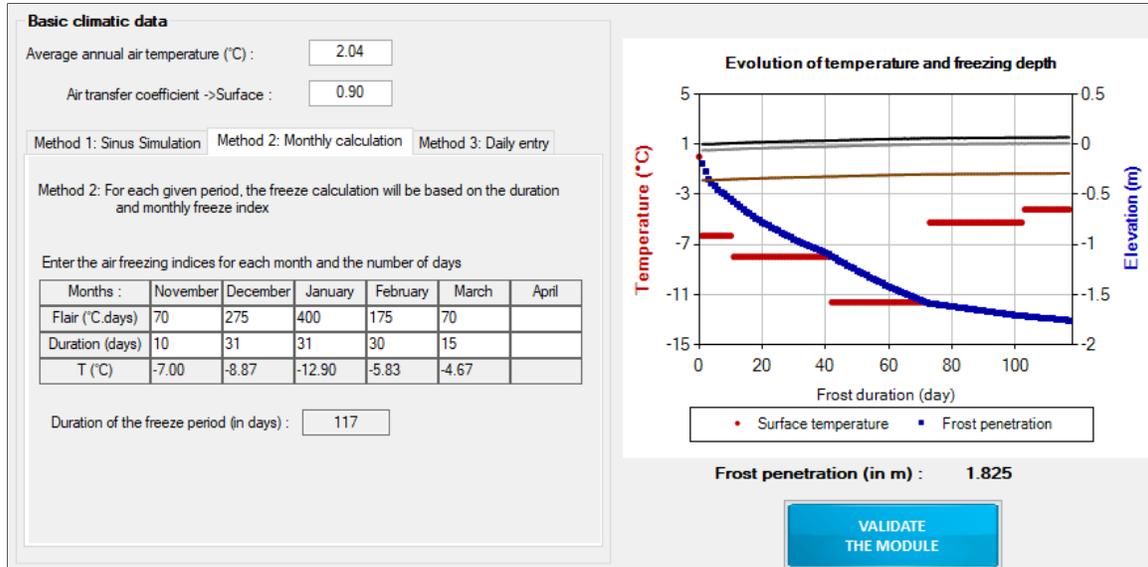
Figure 7.3 : Method 2 - Monthly calculation and example of result

7.2.4 DAILY ENTRY

The third method, called daily entry, opens a weather file (.txt). Figure 7.4 shows the home screen of this method and an example of a display.
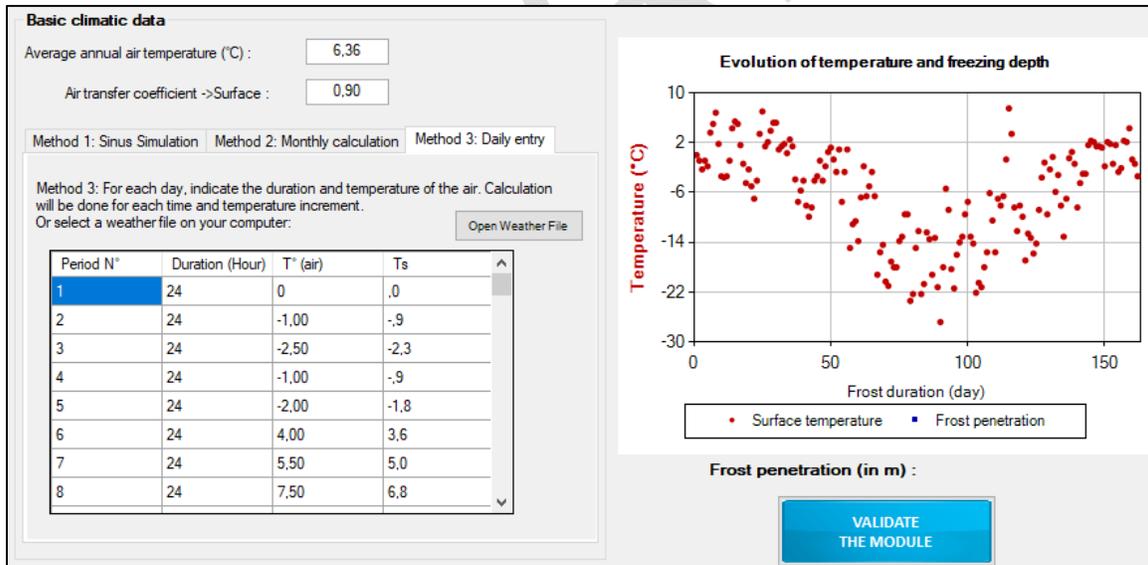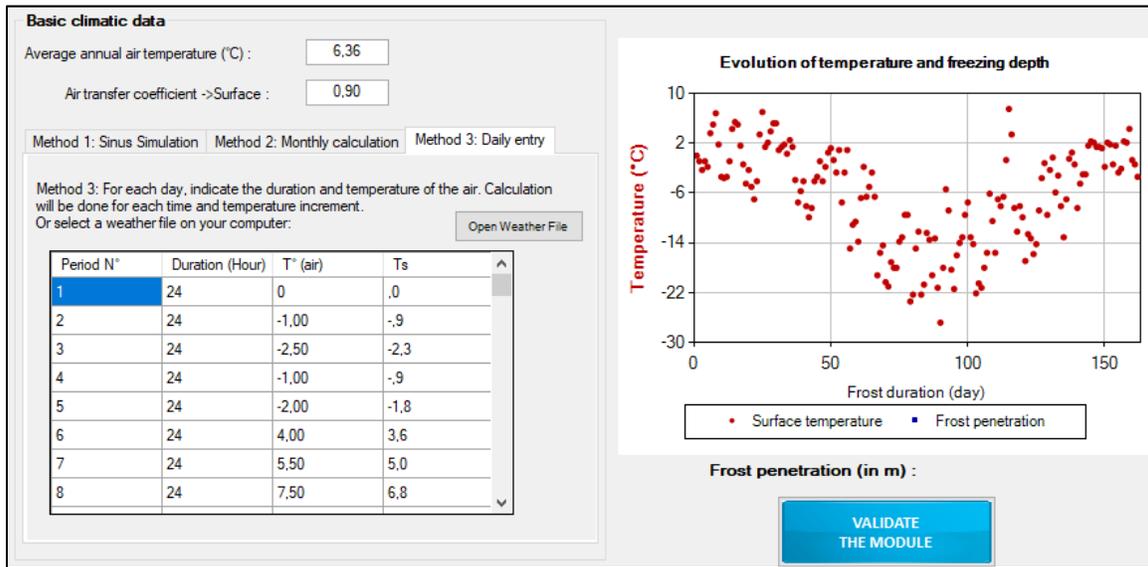
Figure 7.4 : Method 3 - Daily entry and example of result

It is recommended to use a.txt weather file or if it does not exist, to create it in an application such as "Notepad". The file format must be as shown in Figure 7.5. The first line allows you to name the file. The second line specifies the type of data and the third line gives the column header. The first column consists of the durations (in hours) of the period and the second column consists of temperatures (in °C).

Figure 7.5 : Example of a weather file

8. EVALUATION BETWEEN VERSIONS

Improvements between versions of the i3C-ME. To find out which version is installed on your computer, please refer to the help tab by clicking on the "About ..." option in the toolbar.

1. First version, dated January 30, 2015

2. First version (improved), dated February 29, 2016

2.1. Improvement of the MODULE 3 :Load definition. The radius of the applied load as well as the inflation pressure and load applied to the pavement structure can be adjusted.

2.2. Improvement of the MODULE 4 :Climatic conditions. The available database provides a larger number of cities and geographical locations. The calculation of average temperatures for each season and the duration of the seasons were calculated from available data on Environment Canada's website. These calculations take into account climate records over the last 30 years. When data are available, the value of the freezing index and the standard deviation of the values are directly integrated into the MODULE 7 :Frost criteria

2.3. Improvement of the MODULE 5 :Pavement structure. Addition of recommended minimum and maximum thicknesses for bituminous layers and granular material layers.

2.4. Add to the MODULE 5 :Pavement structure a new layer available for the pavement structure. In the *other layer* category, it is now possible to select the integration of an insulating layer. Three types of insulation are available. The calculation of the necessary protection to limit icing and the structural check are automatically calculated by the software. The software indicates by information messages in the synthesis of the calculations if the set of design conditions associated with the insulating layers is respected.

2.5. Improvement of the MODULE 7 :Frost criteria. Display results as two graphs. The first graph represents the evolution of the surface temperature as well as the frost depth. The interfaces between the different soil layers are also traced and the heave generated by the frost in the structure is integrated with the plots. The second graph represents the evolution of the heave and depth of penetration of the frost during the winter.

2.6. Improvement of the MODULE 7 :Frost criteria. Geotechnical and thermal parameters are proposed by default in the calculation module. These values can be modified. An alert message as well as a red or orange coloring of the boxes may appear when an incompatibility is detected by the software when calculating the degree of saturation or latent heat of fusion.

2.7. Add to the MODULE 7 :Frost criteria. Addition of a section for the determination of the rigorous freezing index using a probabilistic approach or by estimating this value.

2.8. Add to the MODULE 7 :Frost criteria. For the calculation of thermal conductivity the software now offers two calculation methods for non-frozen and frozen thermal conductivity. In previous versions, only Kersten's (1949) model was available. The Côté and Konrad (2005a) and (2005b) model has been added to the module. The selection of calculation methods is possible in the module toolbar. The thermal conductivity of bituminous materials is calculated from the physical parameters of the material. The calculation kernel remains unchanged from the previous version, only the estimation of the input parameters has been improved.

2.9. Improvement of the *Calculation core*. The calculation of the asphalt temperature for the seasonal analysis is performed at 1/3 of the total thickness of the asphalt pavement. Previously, the calculation was performed at a fixed depth. This change is operational when the calculations are started, i. e. by clicking on *Start calculations.*

2.10. Improvement of the *results sheet*. A new graphical output of the calculation results is now available. This graphical output allows a direct reading of the results associated with seasonal damage calculations.

2.11. Improvement of the *results sheet:* Design advice is provided when design objectives are not met or if the structure is oversized.

3. **Second version, dated December 20, 2019**

3.1. Inclusion of English version

3.2. Possibility to adjust the pavement structure in the frost analysis module

3.3. Consideration of a drainage layer

3.4. Subdivision of layers for non-linear analysis and temperature analysis

3.5. Updating the database of materials and laws of mechanical damage

3.6. Adaptation to the design of unpaved pavements

3.7. Adding 125 weather stations to the database

3.8. Addition of an IRI damage law

3.9. Possibility to perform analysis with double tires and complete axles, for different tire sizes

3.10. Temperature-dependent Poisson ratio for asphalt concrete layers

3.11. Possibility to insert or remove layers between existing layers

3.12.   More visual presentation of results

3.13.   Better organized and more detailed design report

APPENDIX

Appendix 1   HOME SCREEN MODULE 5 :ASPHALT

HOME SCREEN FOR DETERMINING THE MECHANICAL PROPERTIES OF A BITUMINOUS ASPHALT MIX

Appendix 2   HOME SCREEN MODULE 5 :ASPHALT GRANULAR MATERIALS

| Layer 1 | Layer 2 | Layer 3 | Layer 4 | Layer 5 | Layer 6 | Layer 7 | Layer 8 | Layer 9 | Layer 10 |

Granular material type

    Classification of granular material: [∨]

Mechanical property of the material

☐ Level 1: Laboratory measurement   _____

☐ Level 2: Estimation from physical properties   _____

☐ Level 3: Typical material value   _____

Information

HOME SCREEN FOR DETERMINING THE MECHANICAL PROPERTIES OF A OF A GRANULAR MATERIAL

Appendix 3   HOME SCREEN MODULE 5 :ASPHALT SOIL

HOME SCREEN FOR DETERMINING THE MECHANICAL PROPERTIES OF A OF A SOIL

BIBLIOGRAPHIE

Al-Qadi, I.L., Elseifi, M., Yoo, P.J., 2004. Pavement damage due to different tires and vehicle configurations. The roadway infrastructure group, Viginia Tech Transportation Institute, Blacksburg, VA,

Al-Qadi, I.L., Wang, H., 2009. Evaluation of pavement damage due to new tire designs. Research report FHWA-ICT-09-048, Illinois Center of Transportation, University of Illinois, Urbana-Champaign,

Anderson, D.M., Tice, A.R., 1972. Predicting unfrozen water contents in frozen soils from surface area measurements. Highway research record,

ARA, I., 2004. Development of the 2002 Guide for the Design of New and Rehabilited Pavements. NCHRP 1-37A, Transportation Research Board, Washington, DC ERES Division,

Asphalt Institute, 1982. Research and Development of the Asphalt Institute's Thickness Design Manual (MS-1). 9th ed., Research Report 82-2,

ASTM D2487-11, 2011. Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). ASTM International, West Conshohocken, PA,

Carpenter, S.H., 2007. Fatigue performance of IDOT mixtures. Research report FHWA-ICT-07-007, Illinois Center of Transportation, University of Illinois, Urbana-Champaign,

Côté, J., Grosjean, V., Konrad, J.-M., 2013. Thermal conductivity of bitumen concrete. Canadian Journal of Civil Engineering 40, pp. 172-180, 10.1139/cjce-2012-0159

Côté, J., J.M., K., 2003. Une nouvelle approche régionale de conception des chaussées avec isolant thermique tenant compte du risque de givrage différentiel, Rapport CREIG-S4, 32 pages. Département de génie civil, Université Laval,

Côté, J., Konrad, J.-M., 2005a. A generalized thermal conductivity model for soils and construction materials. Canadian Geotechnical Journal 42, pp. 443-458, 10.1139/t04-106

Côté, J., Konrad, J.-M., 2005b. Thermal conductivity of base-course materials. Canadian Geotechnical Journal 42, pp. 61-78, 10.1139/t04-081

Croney, P., Croney, D., 1998. The design and performance of road pavements. Mcgraw Hill, USA,

Darter, M.I., Becker, J.M., Snyder, M.B., Smith, R.E., 1985. Portland Cement Concrete Pavement Evaluation System (COPES). Transport Research Board NHRP Report 277,

Doré, G., 2014. Notes de cours GCI-3100: Conception et réhabilitation des chaussées. Université Laval, Québec,

Doré, G., Zubeck, H.K., 2009. Cold regions pavement engineering. Mcgraw-Hill, NY,

Doucet, F., Auger, B., 2010. Détermination du module complexe des enrobés au Ministère des transports du Québec. Service des matériaux d'infrastructures, Direction des laboratoires des chaussées, Ministère des transports du Québec, Québec.

Drumm, E., Reeves, J., Madgett, M., Trolinger, W., 1997. Subgrade resilient modulus correction for saturation effects. Journal of Geotechnical and Geoenvironmental Engineering pp. 663-670, Volume 123, Number. 7,

Gauthier, P., 2012. Conception et dimensionnement de chaussées municipales. Québec, Université Laval,

Gouvernement du Canada, 2015. Rapport de données quotidiennes (climat). Http://climat.meteo.gc.ca Consulté en 2015,

Huet, C., 1963. Étude par une méthode d'impédance du comportement viscoélastique des matériaux hydrocarbonés. Thèse de Docteur-Ingénieur, Faculté des sciences de l'Université de Paris, France,

Johansen, O., 1975. Thermal conductivity of soils. Ph. D. Thesis, University of Trondheim, Trondheim, Norway. CRREL Draft Translation 637 July 1977, US Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Kersten, M., 1949. Thermal Properties of Soils. Bulletin No. 28, University of Minnesota,

Konrad, J.-M., 2005. Estimation of the segregation potential of fine-grained soils using the frost heave response of two reference soils. Canadian Geotechnical Journal Volume 42, Number 1,

Mellizo, C., 2010. Estimation du module réversible des matériaux granulaires de chaussées.

Mellizo, C., Bilodeau, J.-P., Doré, G., 2010. Resilient modulus estimation for granular materials. 11th International Conference on Asphalt Pavements, Nagoya, Japan,

Ministère des transports du Québec, 2006. Logiciel de dimensionnement des chaussées souples: Chaussée Version 2.0. Service des chaussées, Québec, Canada,

Ministère des transports du Québec, 2010. Norme 14301: Polystyrène pour construction routière. Tome VII - Matériaux -Chapitre 14 - Matériaux divers.

Minnesota Department of Transportation, 2012. Mnpave Users's Guide.

Mollenhauer, K., Wistuba, M., Rabe, R., 2009. Loading frequency and fatigue: In situ conditions & impact on test results. 2nd Workshop on Four Point Bending,

Myre, J., 1992. Fatigue of asphalt materials for norwegian conditions. Seventh International Conference on Asphalt Pavements, Vol. 3 Proc., U.K.,

Québec, 2003. Info DLC: Prise en compte du givrage dans la conception des chaussées comprenant un isolant thermique. Vol. 12, N° 8, Septembre 2003. Transports Québec.

Québec, 2012. Info DLC: Nouvelles versions des tableaux de choix des composants et critères de sélection des enrobés. Vol. 17, N° 3, Septembre 2012. Transports Québec.

Rahim, A.M., George, K.P., 2005. Models to estimate subgrade resilient modulus for pavement design. International Journal of Pavement Engineering Volume 6, issue 2,

Saarelainen, S., 1992. Modelling frost heaving and frost penetration in soils at some observation sites in Finland The SSR model. VTT publication 95, technical research centre of Finland, Espoo,

Sayegh, G., 1965. Contribution à l'étude des propriétés viscoélastiques des bitumes purs et des bétons bitumineux. Thèse de Docteur-Ingénieur, Faculté des sciences de l'Université de Paris, France,

Soto, D., Bilodeau, J.-P., Doré, G., 2013. Estimation of subgrade soils mechanical properties and frost sensitivity through the use of simple tests. Bearing Capacity of Roads Railways and Airfields, Trondheim, Norway,

St-Laurent, D., 2006. Guide de l'utilisateur, Chaussée 2 : Logiciel de dimensionnement des chaussée souples. Ministère des transports, Québec, Canada,

Timm, D.H., Birgisson, B., Newcomb, D.E., 1999. Mechanistic-empirical flexible pavement thickness design: The minnesota method. Technical report MN/RC-P99-10. University of Minnesota, Department of Civil Engineering, Minneapolis, MN,

Timm, D.H., Newcomb, D.E., 2003. Calibration of flexible pavement performance equation for Minnesota road research project. Transportation research record : journal of the transportation research board, No. 1853, p134-142. Washington, D.C.,

Uzan, J., 1985. Characterisation of granular materials. Transportation research record 1022, Transportation research board, National research council,

Winnerholt, T., 2001. A new approach to pavement design in Sweden : new swedish road design manual. Swedish National Road Administration, Technological Development and Support Services Directorate, Road Engineering Division,

Witczak, M., 2005. Simple performance tests : summary of recommended methods and database. NCHRP Report 547, National cooperative highway research program, Transportation research board Washington, D.C., USA,

Witczak, M., Fonseca, O., 1996. Revised predictive model for dynamic (complex) modulus of asphalt mixtures. Transportation research record 1540, Transportation research board, National research council Washington, D.C., USA,