Design and Rehabilitation of Urban Pavements

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ABSTRACT: Urban pavements are conceptually different from rural pavements in part because of the differences in the design speeds. The main objective of this research project is to develop a rational design methodology adapted for urban pavement structures. The proposed design method is developed in order to calculate the pavement layer thicknesses considering traffic, climate, soils and design speed. These parameters are used to determine the strain occurring in the pavement structures submitted to mechanical and thermodynamic solicitations. Viscoelastic models are included to take into account the mechanical response of pavement materials as a function of loading time. The consideration of traffic speed is of great interest for urban pavements design. Deterioration models are included in the design approach and consideration of seasonal effects was done through the use of five typical yearly seasons.

KEYWORDS: Design, speed, mechanical response, viscoelasticity, damage.

1. INTRODUCTION

Canadian pavement structures are essential for people's mobility and for the country economical development. Therefore, the importance of these structures should not be underestimated and there is a need to economically preserve these ageing national assets. The design methods used a few decades ago were conceptually adapted for national road network administration needs, which differ from the urban pavements manager needs. In most cases, the approaches are adapted for high traffic rural contexts. Therefore, these methods may not be suitable for the urban context, where the traffic volume is often low and the design speeds are much lower.

2. LITERATURE REVIEW

Mechanistic-empirical pavement design necessitates the determination of pavement materials mechanical properties. This approach allows dimensioning each layer thickness according to the stresses and strains occurring within the multilayered system submitted to traffic and climate (mechanistic part), as well as a function of deterioration models corrected for in situ conditions (empirical part). Using this approach, it is possible to evaluate the pavement performance prior its construction, knowing the material properties and the traffic level. Considering the asphalt concrete layer, as it is a viscoelastic material which mechanical response is time dependent (Huang 2004), it is suitable to use the viscoelasticity theory for this material analysis. Doucet and Doré (2004) have determined the dynamic modulus |E*| and phase angle of 11 asphalt concrete cores sampled on various sites of the C-LTPP project (Canadian Long Term Pavement Performance Project) in order to build a database of typical

Canadian asphalt concrete mechanical characteristics. Figure 1 summarizes the basic information on these samples. The determination of the master curves (dynamic modulus) and Black curves (phase angle) were performed at various temperatures and test frequencies.

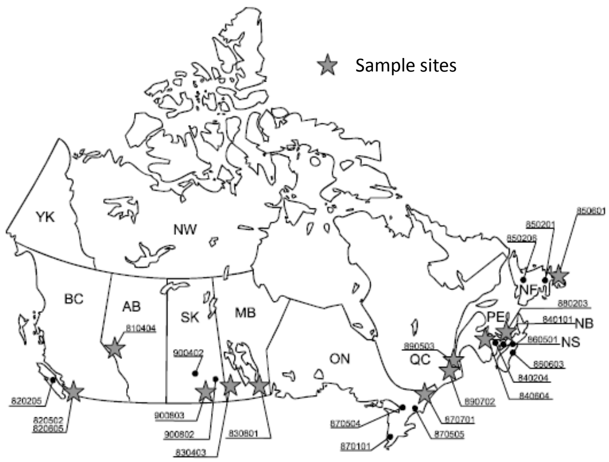

Figure 1: C-LTPP sampled sites (Doucet and Doré 2004)

The temperature and frequency influence on |E*| can be determined with a master curve using temperature-frequency equivalency that is usually applied to asphalt concrete (Di Benetto and De LaRoche 1998). This principle suggests that |E*| can be obtained for various temperature-frequency couples, which allows determining the frequency corresponding to |E*| for a reference temperature, even if some temperature-frequency couples were not characterized. The master curve for |E*| is generally well represented with a sigmoid model (Witczak and Fonseca 1996). The proposed model (Doucet and Doré 2004) for C-LTPP asphalt concrete is presented as a function of frequency and temperature and is expressed

$$\log|E*| = 0.95 + \frac{3.27}{1+e^{(-2.67-0.51\log f+0.07T)}} \quad (1)$$

in which |E*| is expressed in MPa, f is the frequency (Hz) and T is the temperature (°C).

In this research project, the Burger viscoelastic model is used to characterize the mechanical response of subgrade soils. For various traffic speeds, pavements show viscoelastic response that is not entirely explained by the viscoelasticity of asphalt concretes (Coulombe 2002). The use of such a model tends to explain adequately the load time effect on the mechanical response of pavements (Huang 2004). The Burger model is expressed with

$$\varepsilon(t) = \frac{\sigma 0}{E0} + \frac{\sigma 0 * t}{\lambda 0} + \frac{\sigma 0}{E1}\left(1 - e^{\frac{-t*E1}{\lambda 1}}\right) \quad (2)$$

in which t is the time, E0 is the modulus zero, E1 is the modulus 1, λ0 is the viscosity zero and λ1 is the viscosity 1. The first term of the model represents the instantaneous strain, the second represents the viscous strain and the last represents the retarded strain.

Miner (1945) linear damage model is widely used in pavement design to describe pavement damage accumulation under repetitive standard loading. This theory can be used to analyze pavement multilayered systems in terms of structure failure. Miner law is expressed

$$\sum_i Di = \sum_i \frac{ni}{Ni} \leq 1 \quad (3)$$

in which Di is the partial damage, ni is the number of solicitations applied during a period i, Ni is the admissible solicitations number prior failure for a period i.

3. EXPERIMENTAL RESULTS

The experimental data describing the variation with speed of pavement mechanical performance at the subgrade were obtained from two sources. First, the data from Coulombe (2002) were used. As part of this research, data was collected on the St-Célestin experimental site in the Province of Quebec (Canada). The second data source comes from tests performed in the fall 2009 at SERUL (Laval University Experimental Pavement Site), located 75 km north of Québec city. In both cases, a four-plate multidepth deflectometer (DMN) was used. Three plates are positioned at each layer interface, while the fourth is positioned deeply in the subgrade soil (2500 mm at the SERUL, 2080 mm at St-Célestin). This type of equipment was also used in other research projects carried by Imbs (2003) and DeBlois (2005). It allows measuring the relative displacement of each pavement layer interface under vehicle wheel loading. At each experimental site, a heavy vehicle carrying a standard load was driven over the DMN at various speeds (3 to 70 km/h). To obtain layer strains, the deflection measured at the bottom of a specific layer is substracted from the deflection measured at the top of the layer, and the results must be divided by the layer thickness. Figure 2 illustrates a typical pavement structure response with the DMN at the SERUL (autumn 2009). In this case, the vehicle speed was 3.38 km/h.

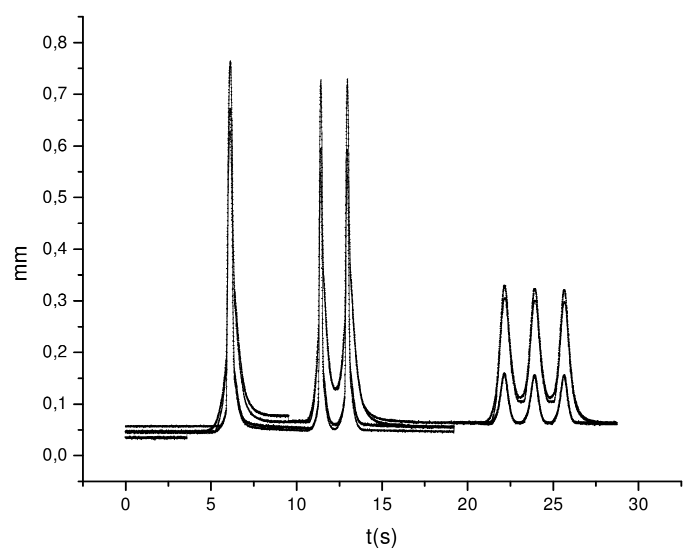

Figure 2: Experimental results at the SERUL (vehicle speed 3.38 km/h)

It is well known that climate and soils variations are major parameters to consider when it comes to calculating annual damage on pavements. Therefore, the proposed design method must consider the damage on a seasonal basis (early spring, late spring, summer, autumn and winter). In order to analyze the modulus variations for each period, a literature search was undertaken to identify typical modulus seasonal multipliers (Léon Fernandez 2000, Ovik et al. 2000, MnPave software database). In these researches, the layer moduli were backcalculated from FWD deflection basins. For the proposed method, the moduli are normalized according to the summer modulus.

4. PRINCIPLE OF THE DESIGN METHOD

Urban pavement design presents some specific challenges. The municipal context is characterized by slow design speed and, for some urban pavement classes, by low volumes of traffic. In order to take into account the loading time, the method is based on the use of viscoelastic models to determine the pavement mechanical response as a function of speed. The mechanistic design process is based on the hypothesis that a pavement structure can be modelled as a multilayered elastic (or viscoelastic) resting on an elastic (or viscoelastic) foundation (Huang 2004). The proposed design method will allow calculating layer thicknesses based on traffic volume, climate and soils. The climatic effects are taken into account by dividing the year cycle into five different periods: winter, partial thaw, total thaw, recuperation and summer/autumn.

5. LAYER MODULUS ANALYSIS

The mechanical response analysis of the pavement layers uses three different models specific to the material type. For asphalt concrete, a viscoelastic analysis is done using the Witczak and Fonseca model modified by Doucet and Doré (2004). The granular layers are analysed as elastic materials using Hooke's law. Finally, subgrade soils are considered to behave as viscoelastic materials (Lourens 1995, OCDE 1991), and analysed using the Burger's model.

5.1 Surface course analysis

The asphalt concrete layer is analyzed using the Doucet and Doré (2004) model, which takes into account the temperature and the frequency to obtain the dynamic modulus. Figure 3 presents a comparison, as a function of speed, between the predicted horizontal strains at the bottom of the asphalt concrete layer calculated with the Doucet and Doré (2004) model and the measured horizontal strains by Coulombe (2002) at the same level. Coulombe (2002) presented numerous data regarding the effect of speed on the strains occuring in flexible pavements at the St-Célestin experimental site, but also gathered the results from various studies. In Figure 3, the discontinuous line represents the data obtained by Coulombe (2002), while the continuous line represents the results obtained when the Doucet and Doré (2004) (see equation 1) model is used to calculate the horizontal strain at the bottom of the asphalt concrete layer. This comparison was performed for the same speeds (2, 30, 50 and 70 km/h). There is a good agreement between the two curves, especially at speed of 30 km/h or higher.

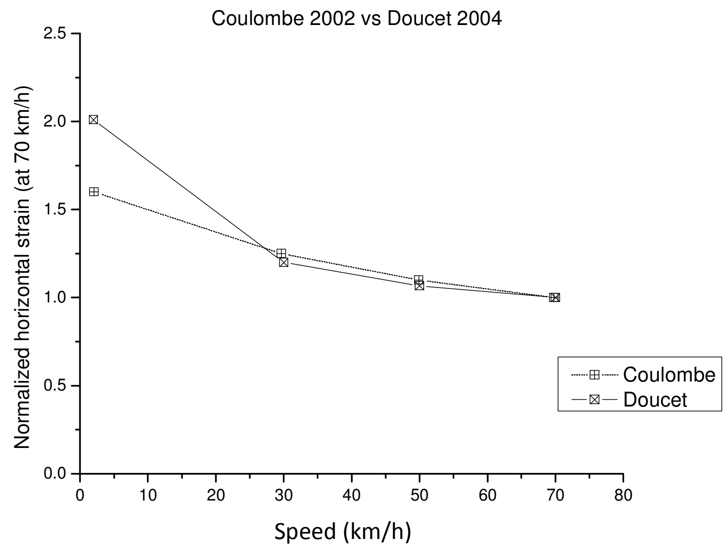

Figure 3: Comparison between work from Coulombe and the Doucet and Doré model

5.2 Granular layers analysis

Since loading time and frequency have no significant effect on granular materials mechanical behaviour (Lekarp and al. 2000), Hooke's law is used to analyze the granular layers. Hooke's law is expressed by

$$\sigma = E\epsilon \tag{4}$$

in which σ is the stress, ε is the strain and E is the elasticity modulus. Seasonal factors were used to quantify modulus variations through the yearly cycle. The modulus for the early spring, late spring, autumn and winter periods are computed based on the summer modulus using the seasonal factors. These moduli are necessary to compute stresses and strains using Odemark and Boussinesq theories. Table 1 presents the seasonal factors used in this study.

Table 1: Granular materials resilient modulus seasonal multipliers

	Granular materials				
AASHTO classification	Early spring	Late spring	Summer	Autumn	Winter
A-1 (> 15% crushed, < 7 % fines)	0,35	0,82	1,00	1,18	2,52
A-1 (> 10 % crushed, < 10 % fines)	0,35	0,82	1,00	1,17	2,85
Class 4	0,35	0,82	1,00	1,18	5,15

5.3 Subgrade soil analysis

The Burger viscoelastic model was used to analyze the subgrade soils for the design method, From the available experimental data, the model variables E0, E1, λ0 and λ1 were determined for two subgrade soils. Figure 4 shows an example of the experimental data obtained at St-Célestin, as well as the Burger model concept. From the experimental data, the measured strains were analyzed. When the loading speed tends toward zero, the strain tends toward σ0/E0 (perfect elasticity). For high loading time, the experimental data present an asymptote having a slope σ0/λ0 and an intercept point of σ0(1/E0 + 1/E1). The last parameter, λ1, is related to the strain rate at which the curve reaches the asymptote

$$\dot{\varepsilon} = \sigma 0 \left(\frac{1}{E1 * \lambda 1} e^{\frac{-E1*t}{\lambda 1}} + \frac{1}{\lambda 0} \right) \tag{5}$$

in which $\dot{\varepsilon}$ is the strain rate.

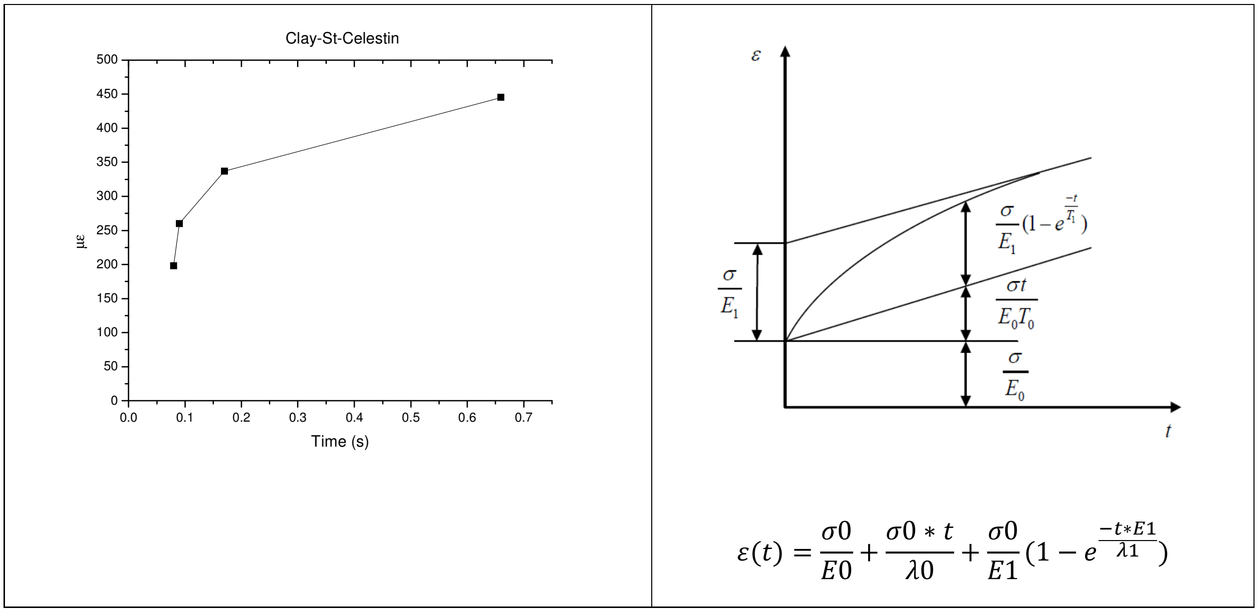

Figure 4: Experimental data fitted with the Burger model for St-Célestin site (left) and conceptual scheme of the Burger model (right) (Huang 2004)

The Burger model parameters were determined for three soil types (sandy silt, silty till and clay). The modulus values obtained using the Burger model values are normalized according to the modulus values obtained at a loading time of 0.05 s. This normalization allows identifying three types of behaviour: unsaturated granular soils, saturated granular soils and clayed soils. Figure 4 presents the evolution of the normalized modulus according to loading time.

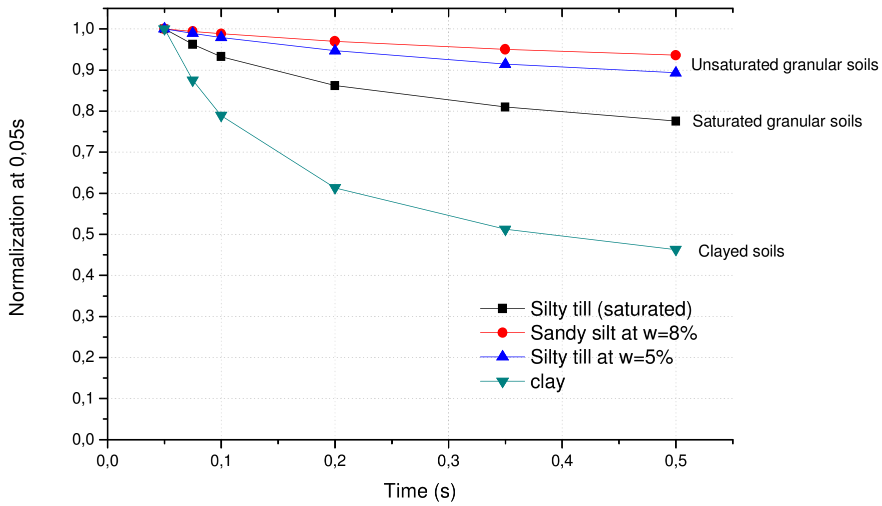

Figure 4: Normalized modulus at 0.05 second

The stress and strain analysis was performed using the Odemark-Boussinesq theories and the subgrade modulus was necessary to perform such a calculation. The modulus values for every season considered are obtained from the summer values using the seasonal multipliers found in the MnPave software database.Table 2 summarizes some examples of the subgrade seasonal modulus multipliers used for each season.

Table 2: Subgrade seasonal modulus multipliers

	Subgrade soils				
USCS classification	Early spring	Late spring	Summer	Autumn	Winter
SP-SM (Sand)	5,15	0,82	1,00	1,18	5,15
SM, SC (Silty or clayed sand)	5,93	0,83	1,00	1,17	5,93
ML, MH (Silty clay)	8,92	0,81	1,00	1,16	8,92
SC, SM (Silty or clayed loam)	7,61	0,83	1,00	1,17	7,61
CL (Clayed loam)	8,68	0,82	1,00	1,16	8,68
ML/CL, MH/CH (Silty clay)	11,11	0,81	1,00	1,19	11,11
CL, CH (Clay)	8,65	0,81	1,00	1,16	8,65

6. STRESSES AND STRAINS ANALYSIS

The pavement strains were computed using the Boussinesq theory and the equivalent height method proposed by Odemark. The analysis was performed using a standard contact stress $\sigma 0$ of 0.56 MPa uniformly distributed on a circular plate of 150 mm radius. The analyzed multilayered system consists of a bounded surface course and two granular layers resting on an infinite subgrade.

7. DAMAGE

Pavement damage accumulation is calculated using Miner's law. The tensile strain at the bottom of the asphalt concrete layer and vertical strain at the top of the subgrade criterion are used in the proposed design method for the pavement structural analysis. In order to design appropriate pavement layers, the well-known and widely used Asphalt Institute criterion were used to obtain admissible number of load applications using the tensile and compression strains with

$$N_f = 0.0796 \varepsilon_t^{-3.291} (145 x E^*)^{-0.854} \quad (6)$$

$$N_p = 1.365 x 10^{-9} (\varepsilon_c)^{-4.477} \quad (7)$$

where ε_t is the initial tensile strain, E* is the dynamic modulus, ε_c is the vertical compressive strain on the sugbrade soil (Doré and Zubeck 2009).

8. METHOD VALIDATION

The final step of this research will be the development of software adapted to the urban context. The preliminary version of this tool is a calculation sheet that includes pre programmed function in order to validate the proposed model. In order to demonstrate the interest of using the proposed design method, an analysis is made using a predetermined typical urban pavement structure. It is composed of four layers and the characteristics of this structure are presented in Table 3.

Tableau 3: Analyzed pavement structure

Layer	Thickness (mm)	Modulus (MPa)
Asphalt concrete	155	-----
Base	250	147
Subbase	300	74
Subgrade	Infinite	47

The surface layer modulus is not defined in Table 3, because it is dependent of the design speed. This structure was analyzed using the proposed design method and the KENLAYER software. The latter was used using the non linear elastic solution. The results of this comparison between both design methods for fatigue cracking and rutting are presented in Table 4. Two design speeds were used for the proposed design method.

Table 4 Fatigue and rutting damage for the proposed design method (PDM) and KENLAYER software

	Fatigue damage	Rutting damage
KENLAYER	1.433	0.23
PDM (100 km/h)	1.281	0.4
PDM (50 km/h)	1.444	0.93

In general, both design methods give similar results at 100 km/h. For the analysis with KENLAYER, the fatigue damage is slightly higher (1.433). However, the proposed design method gives slightly higher results for rutting damage (0.4). For the design at 50 km/h, the calculated fatigue damage with the proposed design method is closer to what is found using KENLAYER. However, the calculated values for the rutting damage are closer to unity (1) without getting passed this critical value.

9. CONCLUSION AND FUTURE RESEARCH

The proposed design method allows calculating, amongst others, the seasonal damage in order to take into account the northern climate which is characteristic of Quebec (Canada). However, this method differs from most of the other design methods because it considers the viscoelasticity of the entire pavements structure. As a matter of fact, the experimental results showed a clear viscous component of the mechanical performance of subgrade soils in the pavement structure context and its incidence on the pavement mechanical response. The data collected at the autumn 2009 still need to be completely included in the model to improve the design method. In addition, laboratory work will be undertaken in 2010 to quantify the viscoelastic behaviour of subgrade soils in the laboratory using cyclic triaxial tests performed at various load times and frequencies.

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