Asphalt mixture performance and testing

STATISTICAL ANALYSIS OF THE EFFECT OF TEMPERATURE, LOAD FREQUENCY AND AIR VOID ON DYNAMIC MODULUS OF ROAD BASE ASPHALT CONCRETE

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Abstract

Road pavements placed in cold regions are subjected to harsh changes of temperatures both seasonally and daily which in turn influences the stiffness behavior of asphalt mixes through freeze-thaw cycling. This effect plays an important role on the performance of asphalt pavements, which is not taking into consideration in current methods of pavement design. Previous studies confirmed that after 300 freeze- thaw cycles, the stiffness behavior of a base asphalt concrete with a nominal maximum aggregate size of 20 mm (GB20) can change depending on the temperatures and frequencies of the freeze-thaw cycles. However, the effect of air void on the dynamic modulus under freeze-thaw cycles is not decisive. The main objective of this research is to perform a statistical analysis in order to identify the effect of air void content on dynamic modulus of asphalt in different freeze-thaw cycles in cold regions and also to find out a suitable tool to predict dynamic modulus based on influential factors.The results of this study showed that at very cold or hot temperature, The drop in dynamic modulus after high number of freeze-thaw cycles is tangibly influenced by the increase in air void content. Also, a linear regression model can be employed as a reliable tool to predict the dynamic modulus of asphalt in high freeze-thaw cycles based on temperature, frequency and air void content.

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1. INTRODUCTION

Canada is ranked seventh in the world in terms of network length, and more than 90 percent of roads constructed in Canada are bituminous pavements [1]. In cold areas like Quebec (a province in Canada) bituminous pavements are subjected to seasonal temperature fluctuations of 60°C and daily rapid variations of temperature that may run as high as 30°C [2]. In this context, freeze-thaw cycles are a very common phenomenon [3-5] which in turn result in the appearance of premature failures on the surface in terms of low temperature or thermal fatigue cracking.

Thermal cracks allow the ingress of moisture into the pavement system, which may exacerbate the distress because of the pumping of the supporting materials [6]. In addition, by introducing de-icing materials through the cracks during the cold months, thawing at the crack may occur which leads to a localized depression. Also, thermal cracks provide passageways for water to reach the granular based layers of the pavement structure, which can cause upward inflation induced by the formation of ice lenses. All of these consequences result in poor riding quality and reduced pavement service life and also imposes many strains from economic and constructional point of view on pavement authorities.

Furthermore, it is well known that the size and amount of air void content, to a high extent, dictate the thermal behavior of asphalt mixture and plays a pivotal role in analysis of bituminous pavement performance, especially in cold regions [7]. On the one hand, high level of air void in asphalt mixture means higher water flow through the mixture [8] and, on the other hand, as the size of air voids reduces the water freezes at lower temperature [9].

In addition, previous studies showed that based on linear viscoelasticity, the complex modulus values can be related to the thermal cracking in the pavement [10] by transforming into creep compliance values. It was also indicated that when temperature drops sharply or under the combined effect of temperature and vehicle loading, dynamic modulus of bituminous mixture is a rational indicator to analyze the thermal stresses [11-13].

The main objective of this research is to perform a statistical analysis of the influence of air void of GB20 mixes on the dynamic modulus, defined as the norm of the complex modulus, under three different freeze-thaw cycle conditions: a reference condition without freeze-thaw cycle and after 150 and 300 freeze-thaw cycles. Such study helps to accurately predict the mechanical performance of bituminous mixture subjected to severe fluctuations in temperature.

2. BACKGROUND

Many research projects have been performed on the influence of freeze-thaw cycles on the early distress of asphalt mixes [14-20]. The freeze-thaw mechanism is defined as water penetration inside the asphalt pores accompanied by the variation of positive and negative environment temperatures. Information about freeze-thaw cycles in the United States and Canada is available in the Long-Term Pavement Performance (LTPP) databases. Figure 1 is an example of the data gathered from the LTPP.

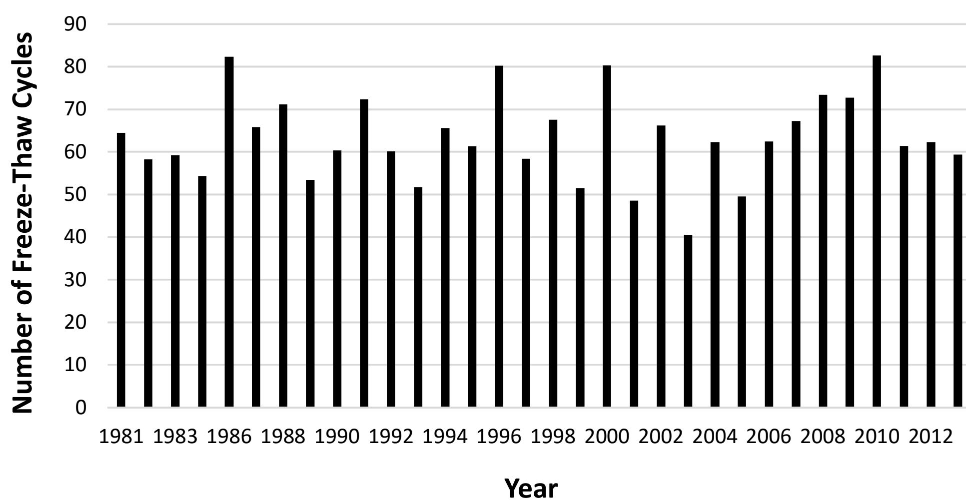

Figure 1: Number of freeze-thaw cycles in each year from 1981 to 2013 at Autoroute Félix-Leclerc, section 89-A310 in Canada (Adapted from [1])

It can be seen that, in cold regions, asphalt pavement undergoes a high number of daily freeze-thaw cycles. These severe temperature variations, in combination with other effective factors, can accelerate the evolution of distress.

Damage induced by freeze-thaw cycles is caused by changing the water into ice particles, which in turn leads to the expansion of water volume and the loss of adhesion between the asphalt and adjacent aggregates [20]. If the developed stress induced by ice expansion is lower than the tensile strength of the material, no damage is created [21]. However, after a large number of freeze-thaw cycles, stresses diminish the material tensile strength and cause micro damage on the surface [22]. The accumulation of this macro damage will deteriorate the asphalt-aggregate bond, allow water to enter into the pavement system, and increase the stripping of aggregates [21]. The stripping is due to the loss of adhesion at the asphalt cement-aggregate interfaces and/or in part by the failure of the cohesion within the binder [23-25]. Goh and You [20] performed an image-processing approach to investigate the stripping of aggregates on the surface of the asphalt mix after freeze-thaw cycles. It was shown that with each occurrence of the freeze-thaw cycle, the stripping and cracking grows increasingly. A previous study [26] confirmed that the stiffness behavior of an asphalt concrete (GB20), which is normally employed as a base course in Quebec roads, is dependent on temperatures, load frequencies, and air void variations especially in high freeze-thaw cycles.

Air voids are generally described as one of the most important parameters to explain mix characteristics and play a vital role in the analysis of asphalt mixes in cold regions. High levels of air voids always yield to the high possibility of moisture penetration into the mixture [19]. The air void content in an asphalt mixture is dependent on aggregate gradations, the effective asphalt content, and the compaction energy [27]. At the bottom of the asphalt base layer, higher tensile strain exists because of traffic, and a higher amount of air voids is expected mostly due to poor construction procedures in terms of required compaction. Besides, during thaw periods, water can pervade via a saturated base through capillary effect. Due to the melting of ice and insufficient pavement drainage, the structural capacity of underlying layers decreases substantially during the thaw periods [28]. Gong et al. [29] investigated the effect of freeze-thaw (FT) cycle on the low-temperature properties of the asphalt fine aggregate matrix. It was found that the fine air voids in the mixture does not provide enough space for volume expansion of freezing water, which in turn yields to higher compressive stresses in the asphalt structure. A laboratory study [30] performed to understand the effect of air void content on viscoelastic properties of Hot Mix Asphalt (HMA) indicated that for a constant temperature and frequency, the mechanical behavior of asphalt mix can be described by an Air Void-Time-Temperature Superposition (AVTTSP) principle.

Another important factor is daily and seasonally temperature fluctuations which affect asphalt pavement performance in two different ways: i) thermal expansion and contraction of asphaltic materials due to the seasonal changes of temperature, and ii) the structural deflection due to the day-night temperature fluctuations [31, 32]. Biao and You-to [33] studied the influence of temperature and aggregate gradation on the flexural tensile strength of asphalt mixes. It was indicated that coarse aggregate gradation increases the flexural tensile strength of asphalt mixes at low temperatures. The results also demonstrated that temperature influences the flexural tensile characteristics of mixes. Another study performed by Tarefder and Islam [34] showed that more than 98% of overall fatigue damage in asphalt mixes is created by thermal damage due to the effect of yearly and daily temperature variations.

Variable traffic speeds is another influential parameter, which is normally taken into account by the load frequency. Traffic speed can range from zero to the road speed limit, which is controlled by the traffic jam or bad weather conditions. Maadani and Abd El Halim [35] conducted a research to study the effect of traffic loading speed on flexible pavement stiffness. The results revealed that distresses such as rutting of bounded materials decreases while the traffic speed increases. In addition, most of the pavement performance problems occurred at locations with frequent bus stop and areas close to traffic signals. This finding highlighted the importance of traffic speed and load frequency on stiffness behavior, which is expected for pavement built with viscoelastic materials.

3. METHODOLOGY

3.1. Material preparation

A base course asphalt mixture with a nominal maximum aggregate size of 20 mm (GB20) and PG 64-28 bitumen was studied in this research. Four test slabs (two slabs as reference in dry condition and two in saturated condition) with dimensions of $500 \times 180 \times 100$ mm^3 compacted with the French laboratory slab compactor based on Quebec Standard LC 26-400 (MTQ 2016) were prepared.

After 2 weeks of conditioning at ambient temperature, 6 cylindrical specimens with a height of 150 mm and a diameter of 74 mm were cored from each slab. Two specimens were tested for each air void level in 3 different conditions: dry, after 150 F-T cycles, and after 300 F-T cycles. The level of air voids of test samples ranges between 0.8 to 6 percent.

The saturation process of the test specimens was performed according to LC 26-001(MTQ2005) standard through vacuum pressure in which water particles are directed into the pores by the pressure caused by vacuum effect and then surrounding the specimens in a rubber membrane to mitigate water evaporation during the test. The range of saturation was limited between 50-70% for the specimens tested after 150 and 300 freeze-thaw cycles.

3.2. Test equipment and procedures

To simulate the daily rapid freeze-thaw cycles, 150 and 300 freeze-thaw cycles as set out in ASTM C666.92 (ASTM 2008) were applied on each GB 20 test specimen in a cooling and heating rate of 4.5°C/min by taking advantage of a servo hydraulic press (MTS 810, TestStar II, Eden Prairie, Minnesota) with an electronic monitoring system.

For each freeze-thaw cycle, two temperature levels were selected, −18 and 6°C and the temperature was kept fixed at each level of temperature for a time duration of 1.5 h. The changes of temperature on the surface and inside the sample and also the cabinet temperature variations were recorded through embedded sensors.

Dynamic modulus of asphalt mixes are achievable by Quebec's LC 26-700 test method, which is recommended by the MTQ. The dynamic modulus |E*| is the norm of the complex modulus that explains the material's stiffness. The tests were done in a servo-hydraulic press (MTS 810) at 8 different temperatures (−32.5, −23.2, −13.6, −4, ,17.6 ,7.7 27.1, and 37.8°C), 6 different frequencies (10, 3, 1, 0.3, 0.1, and 0.03 Hz) and at 4 different air voids (0.8, 2.0, 3.5, and 6.0 %). The temperature was recorded during the test by taking advantage of three surface thermal sensors (PT100). At every temperature change, 6 hours waiting period was observed which is necessary to have a homogeneous temperature throughout the test specimen [36].

It is worth mentioning that, although the first asphalt layer is subjected to severe temperature fluctuations, the focus of this study is on the asphalt base layer for following reasons:

- Fatigue cracking is initiated from the first underlying asphalt base layer by the appearance of micro-cracks.
- Asphalt base layer (GB20) has much less quality than other mixes because of less bitumen and higher air voids which results in low durability and high moisture sensitivity.
- There is a high possibility of segregation for asphalt base layer (GB20) during production and construction process because of the large nominal maximum aggregate size (20mm) of the mix, which can reduce the long-term performance of the mix and in turn the pavement structure.
- Lack of studies on the effect of freeze-thaw cycles on the asphalt base layer.

4. FINDINGS

In this research, the dynamic modulus of specimens made of GB20 before and after freeze-thaw cycle test was studied in relation to changes in air voids of test specimens. Figure 2 shows the changes in dynamic modulus for each level of air void content for three test conditions: dry without F-T cycles, after 150 F-T cycles and after 300 F-T cycles. To this end, first, the values of the dynamic modulus were analyzed in a constant value of frequency of 10 Hz and three different temperatures of -32.5 °C, 7 °C and 37.8 °C.

The test results revealed that the dynamic modulus after 300 F-T cycles were noticeably lower in each level of temperature compared with two other test conditions as the air void contents went up. Furthermore, at very cold temperature (-32.5 °C) or high temperature (37.8 °C) the drop in dynamic modulus from the reference case with no F-T cycle was significant while in median temperature (7.7 °C), the differences in the dynamic modulus among the test conditions were not outstanding. In addition, the differences between dynamic modulus in dry condition and after 150 F-T cycles were not significant.

In the next step, in order to predict the dynamic modulus after 300 F-T cycles based on the independent variables studied in this research, the results in 8 different temperatures, 6 different frequencies and 4 different air voids were analyzed statistically with Minitab software (version 19) to seek for a meaningful relationship, which justifies the changes in dynamic modulus. In this context, according to the coefficient of determination (R=0.917) indicated in Table 1, a linear regression is able to predict the dynamic modulus based on the changes in temperature, frequency and air void. In addition, Table 2 shows the regression coefficient of independent variables introduced in linear model. As shown in Figure 3, the developed linear regression model is a suitable tool to predict the measured dynamic modulus at high number of freeze-thaw cycles.

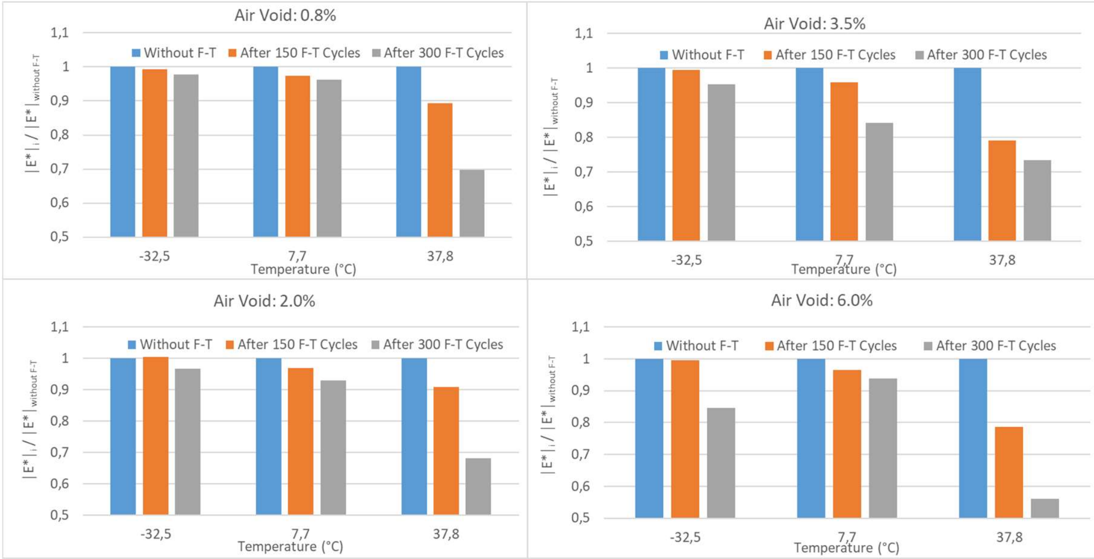

Figure 2: The changes in dynamic modulus at different air voids content at three different test conditions: dry, after 150 F-T cycles and after 300 F-T cycles at 10Hz and -32.5 °C, 7.7 °C and 37.8 °C

Table 1. Linear regression model summery for dynamic modulus

Model	R Square	Adjusted R Square	S
1	91.88 %	91.73%	3822.08

Table 2. Regression coefficients of independent variables used in linear regression model

Term	Coef.	SE Coef.	T-Value	P-Value	VIF
Constant	17343	768	22.59	0.000	
Percentage of air voids	-1119	179	-6.26	0.000	1.00
Temperature	-538.3	12.9	-41.81	0.000	1.00
Frequency	617.9	86.5	7.14	0.000	1.00

$$|E^*| = 17345.250 - 1119.595\ A - 538.231\ T + 618.460\ F \quad (1)$$

Where:

| E*| Stiffness value of GB20 mixture (MPa)
A The percentage of air void in the mixture (%)
T Temperature in (°C)
F Load frequency in (Hz)

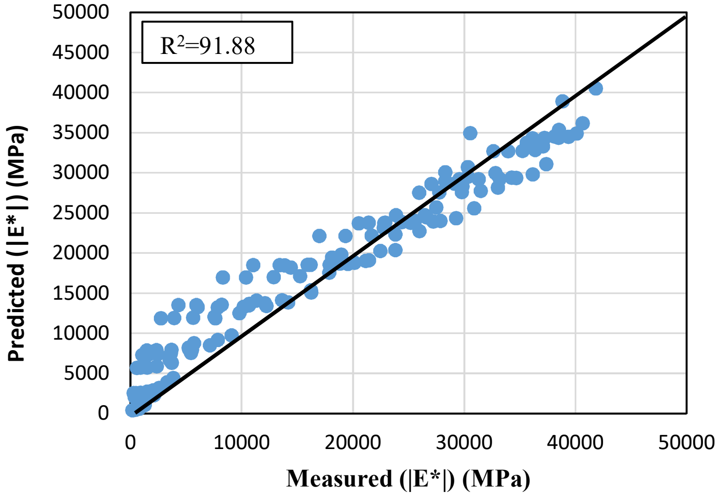

Figure 3: Comparison between measured and predicted dynamic modulus after 300 freeze-thaw cycles obtained from linear regression model

5. CONCLUSION

In this study, the effect of air voids on dynamic modulus of road base asphalt (GB20) located in cold regions was examined. To this end, the asphalt specimens were tested in three different conditions: one in dry condition with no freeze-thaw cycles as a reference case and two other in saturated conditions after 150 F-T cycles and after 300 F-T cycles. Direct tension-compression test on cylindrical samples was conducted to obtain dynamic modulus in 8 different temperatures, 6 different frequencies and 4 different air voids. Based on the results obtained from this experimental study, the following conclusions are listed:

- In cold regions, a large number of freeze-thaw cycles considerably influence the dynamic modulus of road base asphalt, while this effect in dry condition and low number of freeze-thaw cycles is negligible.
- At higher levels of air voids in asphalt mixes, dynamic modulus is tangibly lower in very cold or hot temperatures. While in temperatures near to freezing point, this difference is not meaningful.
- Linear regression model is a suitable tool to predict the dynamic modulus of road base asphalt with great certainty in any combinations of temperature, frequency and air void content in high number of freeze-thaw cycles.

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