LVE properties of asphalt mixtures with glass aggregates subjected to water exposure and freeze-thaw cycles

Éric Lachance-Tremblay[1], Daniel Perraton[2], Michel Vaillancourt[3], Hervé Di Benedetto[4]
（[1] École de Technologie Supérieure (ÉTS)，Montréal, Canada,
eric.lachance-tremblay.1@ens.etsmtl.ca）
([2] ÉTS，Montréal, Canada, daniel.perraton@etsmtl.ca)
([3] ÉTS，Montréal, Canada, michel.vaillancourt@etsmtl.ca)
([4] Université de Lyon/ENTPE，Lyon, France, herve.Dibenedetto@entpe.fr)

ABSTRACT

In cold regions such as Canada, asphalt pavements are exposed to water and to numerous freeze-thaw cycles (FT). To evaluate the degradation of materials used in cold regions, we must consider two specific states: 1) high temperatures, 2) low temperatures. To do so, a methodology has been developed at Laboratoire des Chaussées et Matériaux Bitumineux (LCMB) to quantify the degradation of asphalt samples with the variation of the linear viscoelastic properties (LVE) based on complex modulus measurements. In this study, one reference mixture and two mixtures with 20 % glass aggregates were tested. One of the mixture with 20 % glass also contained hydrated lime. For each sample, three complex modulus tests were done in the following sequence: 1) in dry condition first, 2) in wet condition after 14 days curing in a hot water bath at +60°C and, 3) in wet condition after an additional 3 FT cycles. Overall, a variation of the LVE due to hot water conditioning was found for mixture without hydrated lime. For the mixture with glass and hydrated lime, a variation of the LVE was observed mostly after FT cycles.

Keywords: recycled glass aggregate, complex modulus, linear viscoelastic properties (LVE), moisture susceptibility, freeze-thaw cycles, hydrated lime.

1 INTRODUCTION

In Quebec province of Canada, multiple research projects are ongoing to find recycling and/or reusing possibilities for recycled glass. At the *Laboratoire sur les Chaussées et Matériaux Bitumineux* (LCMB) of the École de Technologie Supérieure (ÉTS) located in Montréal, Canada, the idea of using recycled glass as an aggregate in asphalt mixtures is part of many research projects since 2013 [1-5]. Main advantage of using recycled glass as an aggregate in asphalt mixtures is that glass absorption values are lower than conventional aggregates. This means the optimal binder content of a mixture may significantly decrease [4]. However, an increase in terms of moisture susceptibility is generally reported when using glass aggregates [4, 6, 7]. Some researches have shown that using an optimal glass aggregate content with hydrated lime increase the mixture stiffness compared to a conventional mixture [8-10]. Other research conducted on mastic also showed the stiffening effect of using a glass filler in replacement of a conventional filler [11, 12]. On the other hand, another research showed that glass aggregates had a negligible effect on the mixture stiffness [6].

Due to the Quebec province climate, pavements are subjected to severe conditions such as rain showers, melting snow and severe change in temperature which lead to multiple freeze-thaw cycles [13]. In fact, we can consider that pavement structures are exposed to over 40 freeze-thaw cycles per year [14]. Repeated freeze-thaw cycles, especially in presence of water, is considered one of the main sources of pavement degradation in cold regions such as Quebec [15].

The objective of this paper was to evaluate the moisture susceptibility and degradation due to freeze-thaw cycles based on the linear viscoelastic properties (LVE) measurements. Three asphalt mixtures were studied, a conventional asphalt mixture (REF) and two asphalt mixtures with 20 % glass aggregates, one containing hydrated lime (20G and 20G-HL). LVE properties were measured with the complex modulus test.

2 MATERIALS AND EXPERIMENTAL PROCEDURE

2.1 Materials

Three asphalt mixtures with nominal aggregate maximal size of 10 mm as well as a PG70-28 binder modified with polymers (Table 1) were fabricated for this study: 1) reference mixture with limestone aggregates (REF), 2) mixture with substituting 20 % glass aggregates (by volume) (20G), 3) mixture with substituting 20 % glass aggregates (by volume) and 2 % hydrated lime (by mass) (20G-HL). Mixtures characteristics are presented in Table 2. The 20 % glass content was chosen in order to maximize the amount of glass aggregates reused while achieving good mechanical performances, according to a recent study conducted at the LCMB [4]. Various sizes of glass aggregates was used ranging from 0.315 mm to 2.5 mm. Hydrated lime was used because it is known to improve mixture moisture durability.

Table 1. PG70-28 binder characteristics

Specific gravity	1.022
Viscosity at 135°C/165°C (Pa·s)	1.097/0.312
Ring & Ball temperature (°C)	58.2
Penetration at 25°C (dmm)	130
Elastic recovery (%) at 10°C$^{\text{(ASTM D6084-13)}}$	75

Table 2. Mixture characteristics and volumetric properties

Mixture	b (%)^1	Limestone volume (%)	Glass volume (%)	Voids content (%)^2
REF	5.4	100	20	5.4
20G	5.3	80	20	5.7
20G-HL	5.3	80	20	5.1
^{1} Binder content by mass, ^{2} For the E* sample				

2.2 Testing equipment

For this research, complex modulus of asphalt samples was measured with a servo-hydraulic press with using an environmental chamber for samples thermal conditioning. Samples (ϕ75 x 150mm^3) were submitted to sinusoidal tension-compression loading. Axial stress was measured with a 100kN load cell while the axial strain was measured by three extensometers (50 mm length) placed mid-height at 120° intervals around the sample. Three temperature probes were placed on the sample surface to monitor the temperature.

2.3 Testing procedure

Complex modulus tests were performed in strain controlled mode. From axial strain (ε_0) and axial stress (σ_0) given by Equations 1 and 2, the complex Young's modulus is expressed as Equation 3. Here, the complex modulus is characterized by the norm of the modulus ($|E^*|$), which is the stiffness of the material, and the phase angle (ϕ_E), which corresponds to the delay between the strain and the stress under sinusoidal cyclic loading. Axial strain amplitude was maintained to 50µm/m to stay within the linear viscoelastic domain. Depending on the testing condition, testing temperature ranged from -35°C to +35°C by 10°C increments. For each temperature, samples were tested at the following frequencies: 0.01, 0.03, 0.1, 0.3, 1, 3 and 10 Hz.

$$\varepsilon\ (t) = \varepsilon_0 \sin(\omega t) \tag{1}$$

$$\sigma\ (t) = \sigma_0 \sin(\omega t + \phi_E) \tag{2}$$

$$E^* = \frac{\sigma_0}{\varepsilon_0} e^{j\varphi_E} = \left|E^*\right| e^{j\varphi_E} \tag{3}$$

2.4 Samples preparation and conditioning

For complex modulus test, the samples were cored (ϕ75 x 150mm^3) from samples compacted with a Superpave Gyratory Compactor (SGC). SGC samples were compacted to a target void content of 5.5 ± 0.5 %. Three complex modulus tests (E*) were performed in sequence on each sample. A summary of the testing for each sample is presented in Table 3.

Table 3 Summary of the complex modulus tests performed on REF, 20G and 20G-HL

	E* test series	Test name	Conditioning	Testing temperature (°C)[1]	Testing frequencies (Hz)
Test performed on each mixture	1st	DRY	None	-35 to +35	0.01, 0.03, 0.1, 0.3, 1, 3 & 10
	2nd	WET	14 days in 60°C water bath	+5 to +35	
	3rd	3 FT	14 days in 60°C water bath + 3 freeze-thaw cycles	-35 to +35	
[1] Testing temperature were by 10°C increases					

The first E* was done in dry condition to evaluate the initial LVE properties. LVE were measured in the temperature range of -35°C to +35°C. Then, samples were saturated with water (degree of saturation targets between 70 % and 80 %, using a vacuum system) and placed for 14 days in a hot water bath at 60°C. A sand bed was used to limit the creep of the samples. The second E* test series were done following hot water curing and only for temperature over freezing point (+5°C to +35°C). Following that, the samples were submitted to an additional 3 freeze-thaw cycle under partially saturated condition which consisted of 24 hours at -18°C and 24 hours at 25°C prior being tested for the third E* test series (-35°C to +35°C). For WET and 3 FT testing, the samples were kept in a latex membrane to prevent any water loss during testing.

3 MODELLING OF COMPLEX MODULUS TEST RESULTS FOR DRY SAMPLES

The LVE properties of mixture were modelled with 2S2P1D model developed at University of Lyon/ENTPE [16]. This rheological model widely used to simulate LVE properties of asphalt mixtures [1, 14, 17-20]. The equation of the model as well as more information can be found in other researches [1, 4].

In this project, the 2S2P1D model was calibrated for each sample in DRY condition. Then, the ability of the 2S2P1D model to simulate the 1D mixture LVE properties was verified. To do so, an equivalent frequency (f_{eq}) for a given reference temperature (10°C) is calculated for each temperature frequency testing combination. The f_{eq} are calculated with Equation 4 where a_T are the experimental shift factors and f the testing frequency. The a_T are calculated by minimizing the difference between $|E^*_{measured}|$ and $|E^*_{2S2P1D}|$.

$$f_{eq} = a_T \times f \tag{4}$$

For each temperature frequency testing combination, simulated values of the norm of the complex modulus are calculated with 2S2P1D model calibrated in dry state ($|E^*_{2S2P1D\_DRY\_simulated}|$). Then, the relative difference values between simulated values and experimental values ($|E^*_{experimental}|$) of the complex modulus norms are calculated with Equation 5. This procedure has been used in others researches and has proven to be very effective to compared E* test results [1, 17].

$$\frac{\left|E^*\right|_{experimental} - \left|E^*\right|_{2S2P1D\_DRY\_simulated}}{\left|E^*\right|_{2S2P1D\_DRY\_simulated}} x100 \tag{5}$$

Figure 1 shows the relation between equivalent frequencies and the relative difference values of experimental results and simulated values, both in DRY condition. For the three samples, relative difference values are quite low (under 20 %), which means that the 2S2P1D model is adequate to simulate the mixtures LVE properties.

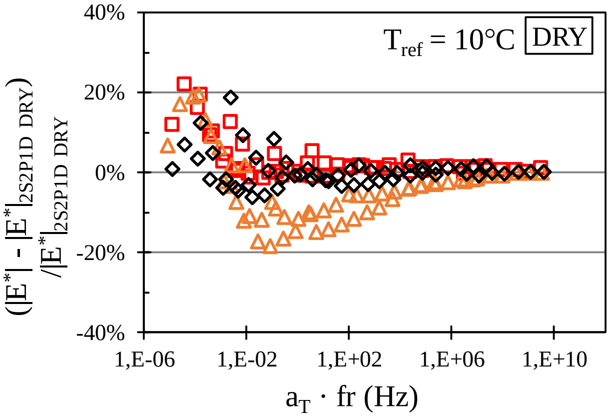

Figure 1. Relative difference values between norms of the complex modulus (|E*|) test in DRY condition and |E*| simulated values of 2S2P1D calibrated with samples in DRY condition.

4 VARIATION OF THE LVE PROPERTIES USING 2S2P1D SIMULATED VALUES

When comparing E* results from different tests, small differences are observed regarding testing temperature and frequency. This is true even if the same apparatus is used for all tests. For that reason, E* results cannot be directly compared between all tests. WET and 3 FT tests shall be compared with a reference state given by the 2S2P1D model calibrated in DRY condition, which is called 2S2P1D simulated values.

Figure 2 shows the relative difference values calculated with Equation 5 between experimental complex modulus norm (|E*|) for DRY, WET and 3 FT test series with |E*| simulated values of 2S2P1D calibrated on DRY condition. On Figure 2.a), the difference values for WET and DRY tests are plotted. For WET test series, the 20G-HL has the smallest difference values (up to -20%). However, for this same sample, the relative difference values between norms of the measured and calculated as expressed in accordance to the calculated norms for DRY condition and reported in Fig. 2 also has differences values up to -20 %. Consequently, to properly evaluate the effect of hot water curing on the LVE properties, instead of looking at the differences values of the WET tests, we shall observe the gap between the cloud of points from WET and DRY test series. The gap between those two clouds of points represents a change of the LVE properties which in this case is a decrease of the |E*|. With that in mind, comparing the cloud of points from WET test with the one from DRY test of 20G-HL, there is no significant gap which means that no variation of the LVE properties has been observed. In comparison, the 20G and REF for WET test series have differences values respectively up to -80 % and -40 % and the gap with their respective DRY cloud of points is very significant. This means that for both samples a decrease of the |E*| has been observed which can be attributed to hot water curing.

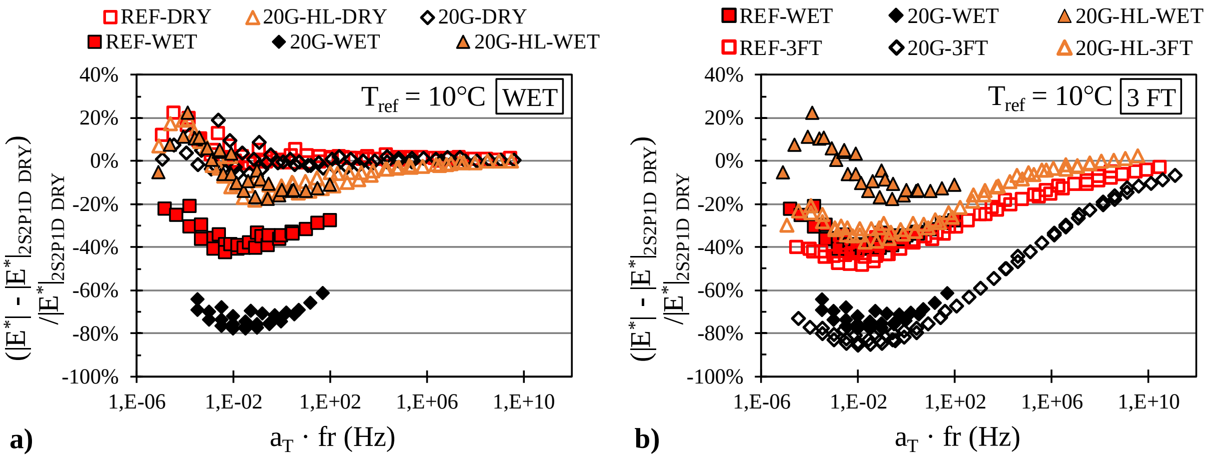

Figure 2. Relative difference values between the experimental complex modulus norms (|E*|) and |E*| 2S2P1D simulated values calibrated with samples in DRY condition: a) WET and DRY tests, b) 3 freeze-thaw cycles (3 FT) and WET tests.

To evaluate the effect of repeated freeze-thaw cycles (FT) on LVE properties, one shall keep in mind that the difference values between 3 FT test and 2S2P1D simulated values are the results of both hot water curing and repeated FT cycles. To differentiate the effect of FT cycles with the effect of hot water curing, the cloud of points of the difference values from 3 FT test shall be compared with the cloud of points from WET test. On Figure 2.b), the difference values for 3 FT and WET tests are presented. First, it can be seen that the higher difference values seem to be located for equivalent frequencies lower than 1,E+02. Then, moving along the X axis increasing the equivalent frequencies, the difference values decrease until reaching values close to 0 %. From this observation, it can be concluded that LVE properties variation is mainly for equivalent frequencies lower than 1E,+02 Hz (high temperatures). Looking at low equivalent frequencies for the three samples, it is 20G-HL which has the smallest difference values (up to -40 %). For 20G and REF, the differences value reaches a maximum value of respectively -85 % and 50 %. To differentiate the effect of water curing and FT cycles, we shall refer to the gap between the cloud of points of 3 FT and WET test. With that in mind, for 20G and REF, the gaps between 3 FT and WET clouds of points are very small, which means a low variation of the LVE properties due to FT cycles. For 20G-HL, there is a bigger gap which means that FT cycles has an effect on the LVE properties.

From those observations, we can conclude that for REF and 20G (without hydrated-lime), most of the LVE variation (i.e. |E*| decrease) was caused by hot water curing. For 20G-HL, no significant |E*| decrease was observed following hot water curing. This proves that hydrated lime is a very effective anti-stripping additive, especially for mixtures with glass aggregates. Looking at the effect of FT cycles on the |E*|, a significant decrease was found for 20G-HL.

5 CONCLUSION

In this paper, linear viscoelastic (LVE) properties of three mixtures (reference (REF), 20 % glass (20G) and 20 % glass with hydrated lime (20G-HL) for different conditioning (DRY, WET and 3 FT) were measured with the complex modulus (E*) test. To evaluate the effect of conditioning on LVE properties, E* experimental results were compared with 2S2P1D simulated values. Overall, it was found that:

1. 2S2P1D model is effective to simulate the mixture LVE properties in DRY condition;
2. Most of the LVE properties variation for REF and 20G (without hydrated lime) was found following hot water curing. For 20G-HL, no significant variation was observed after hot water curing;
3. Freeze-thaw cycles had a significant effect on the LVE properties for 20G-HL, but not for REF and 20G mainly because most of the variation has been induced from the water conditioning;
4. Hydrated-lime is a very effective anti-stripping additive especially for asphalt mixture with glass aggregates.

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