Laboratory Characterization of the Evolution of the Thermal Cracking Resistance with the Freeze-thaw Cycles

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ABSTRACT: The harsh climate and extreme temperature variations in Québec (Canada) have a significant effect on the performance of bituminous pavement mixtures. Traverse cracks caused by thermal contraction are generally the first cracks to appear in pavement.

The Ministère des Transports du Québec (MTQ) and the École de technologie Supérieure (ÉTS) worked together on a research project using the Thermal Stress Restrained Specimen Test (TSRST) and freeze-thaw cycles in order to characterize the thermal cracking resistance of hot-mix asphalt (HMA).

In this project, which was divided into three phases, it was first shown that the cracking temperature measured using the TSRST is equal to the low temperature grade of the binder for the s (60) = 300 MPa criteria (Phase I). Freeze-thaw cycles in air, in water and in a de-icing solution were carried out in Phase II and III. The evolution of the glass transition temperature, the cracking temperature, and the maximum thermal stress were studied at different numbers of cycles.

The application of many freeze-thaw cycles did not change the thermal cracking resistance of the HMA, which means that the thermal cracking that is observed on the roads is also affected by traffic. The thermal stress in the material increases with the decrease in temperature, which limits the tension resistance that is available to sustain traffic. However, it should be noted that freeze-thaw cycles in de-icing solution decrease the thermal cracking resistance of HMA.

KEY WORDS: Thermal cracking, TSRST, Freeze-thaw cycles

1 INTRODUCTION

The harsh climate and extreme temperature variations in Québec (Canada) have a significant effect on the performance of bituminous pavement mixtures. Transverse cracks caused by thermal contraction are generally the first cracks to appear in pavement.

Since the mid-1990s, in an effort to identify and prevent this type of contraction cracking, the MTQ has been testing its pavement mixtures using a restrained specimen testing system known as the TSRST (Thermal Stress Restrained Specimen Test), which was developed as part of the SHRP (Strategic Highway Research Program). The École de technologie supérieure (ÉTS) uses a MTS system to perform the same test.

In order to properly characterize this type of cracking, a large-scale research program that was divided into 3 phases was carried out in the 2000s. The MTQ research team carried out the first 2 phases. Although the results that were obtained were highly instructive and promising with respect to the mechanisms by which thermal cracking develops, a 3rd phase was required to isolate various characteristics of pavement mixtures and testing parameters in order to identify and measure their influence on cracking resistance. Phase 3, which was carried out by ÉTS, is the result of a research collaboration between the MTQ and ÉTS. This article deals mainly with the results obtained during this final phase of the project.

1.1 Factors that influence thermal cracking

The various parameters that influence thermal cracking can be divided into three categories:

- Factors related to materials
- Environmental factors
- Factors related to road geometry

1.1.2 Factors related to materials

The materials that are used possess a number of characteristics that can influence thermal performance. Although bitumen represents only 5% of the total composition of a pavement mixture, the grade of bitumen used plays a major role in the resistance of the pavement to thermal contraction. Bitumens become brittle at lower temperature. In order for a failure due to thermal contraction to occur, the temperature of the pavement only has to drop below the bitumen's critical temperature once. Pavement binders become more brittle with age, and over the years, this brittleness occurs at higher and higher temperatures.

Not all binders age at the same rate, and their performance at a given age can also vary. In addition, the bitumen content of pavement mixtures and the thickness of the bitumen film may affect the impact of successive thermal cycles.

Studies have demonstrated that the gradation of a pavement mixture does not affect significantly thermal cracking resistance (Isacsson et al., 1997).

1.1.3 Environmental factors

Temperature and the cooling rate are the major factors that influence low-temperature cracking of pavement mixtures. The lower the temperature of the pavement surface, the greater the likelihood of reaching the cracking temperature of the pavement mixture. A brief period of 24 hours of exposure to low temperature will not necessarily cause thermal cracks to appear on a pavement surface. However, prolonged exposure to low temperatures close to the low-temperature grade of the bitumen contained in the pavement mixture can have a more serious impact in terms of thermal cracking.

In addition, the higher the rate of cooling, the greater the chance that thermal cracking will occur (Jung and Vinson, 1994).

1.1.4 Factors related to road geometry

The dimensions of the pavement affect the development of thermal cracking. On site observation reveals that temperature-induced cracks occur closer together on narrow pavements than on wider pavements. In addition, as a general rule, the greater the thickness of a layer of pavement is, the lower the incidence of low-temperature cracking.

1.2 Thermal Stress Restrained Specimen Testing (TSRST)

The testing procedure is based on the hypothesis that contraction of the surface layer of the pavement structure during cooling is longitudinally restrained (the length of the road can be considered to be infinite).

The TSRST (Thermal Stress Restrained Specimen Test) involves placing a sample of pavement mixture in a temperature-controlled enclosure in which the temperature is lowered at a constant rate while restricting the movement of the test specimen (Jung and Vinson, 1994). The restrained thermal contraction of the pavement mixture results in stresses within the test specimen that intensify as the cooling process progresses. When the stress induced by the restrained thermal contraction exceeds the tensile strength of the pavement mixture, the sample breaks. The variation of the temperature of the sample and the stress in the pavement mixture are recorded from the beginning of the cooling process until failure. The test parameters are shown in Table I.

Table I - Parameters for the Thermal Stress Restrained Specimen Test (TSRST)

Parameters	Requirement according to AASTHO Standard TP10-93
Diameter of sample (mm)	60 ± 5
Length of sample (mm)	250 ± 5
Cooling rate (°C/h)	10 ± 1
Initial temperature (°C)	5 ± 2
Duration of conditioning (h)	6 ± 0.5

The results of a TSRST make it possible to graph the temperature and stress of the sample up to the point of failure (Figure 1). The description of the data collected is as follows:

- Slope no.1: This curve represents performance during the relaxation period.

- Slope no.2: This curve represents a value analogous to the modulus of elasticity in a diagram of stress versus deformation of an elastic material.

- Glass transition temperature (T_g): This temperature represents the end of the relaxation and the beginning of a linear relation with temperature.

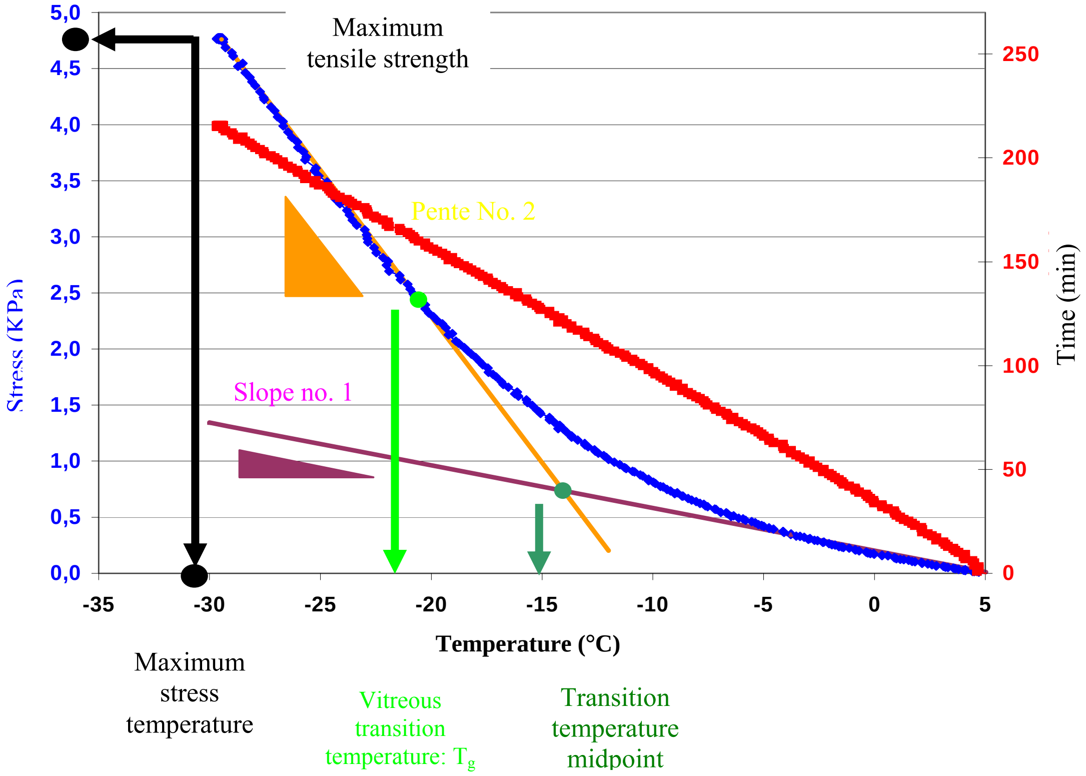

Figure 1: Data collected and analyzed for the TSRST

- Transition temperature midpoint: This temperature corresponds to the intersection of Slope no.1 and Slope no.2, and indicates the transition temperature between two perpendiculars of simplified bilinear performance of a material.

- Maximum tensile strength: This value represents the maximum stress applied to the test specimen just before it fails.

- Maximum stress temperature: This temperature is simply the value obtained when the maximum stress is reached.

It is important to note that, on many occasions, the temperature associated with tensile strength is relatively close to the low temperature of the PG.

2 REVIEW OF THE VARIOUS PHASES OF THE RESEARCH PROJECT

2.1 Phase I

Phase I of this research project demonstrated that the cracking temperature of a pavement mixture was approximately the same as the low temperature for an asphalt s-value (60) = 300 MPa. In light of this, there is no question that the most important factor that affected thermal cracking in the laboratory was the grade of bitumen used. The degree of compaction of the samples also influences the failure stress values and the stress accumulation slopes, but has little or no effect on the transition and cracking temperatures.

2.2 Phase II

Pavement mixtures are also affected by a thermal «fatigue» phenomenon. Therefore, the TSRST was adapted for this study in order to attempt to reproduce freeze-thaw cycles in the laboratory and to subject a sample pavement mixture to these cycles while keeping the length of the sample constant. A 10 mm semi-coarse graded surface pavement mixture (ESG-10), which is routinely used on highways in Québec, along with PG 58-28, PG 58-34, and PG 58-40 binders. Several samples were subjected to one or two freeze-thaw cycles using the TSRST device.

Applying one or two freeze-thaw cycles did not adequately simulate that aging of pavement mixtures and thermal fatigue. The difference in the failure stress and stress/temperature slope values was quite small. Therefore, a larger number of cycles will be required in order to create thermal fatigue. However, it is not possible to run numerous freeze-thaw cycles using the TSRST device. The quantity of nitrogen required is excessive, which makes this approach impractical and expensive. The use of an invar-steel jig (in order to avoid contraction of the sample during cooling) and running the cycles using a programmable freezer has been suggested as an alternative.

Laboratory-aged bitumen could be used to simulate the aging of pavement mixtures. Pavement mixture samples containing aged bitumen demonstrate the reduced resistance to thermal contraction more clearly than samples that are subjected to freeze-thaw cycles in the laboratory. Comparison with tests on freezer-aged pavement mixtures using the method described above is a promising avenue.

Finally, the study showed that the TSRST could be accelerated by using a cooling rate of 20°C/hr and applying a correction factor in order to make the resulting curve equivalent to the curve obtained for a test conducted using the standard rate of 10°C/hr. Additional tests on pavement mixtures comprising various grades of bitumen are required in order to better document the possibility of using a rate of 20°C/hr.

2.3 Phase III

The objectives of this third and final phase of the project were: 1) to determine the effect of the water content of samples on the thermal cracking measured by the TSRST; 2) to establish a protocol for measuring the effects of the freeze-thaw cycle on bituminous pavement mixtures; and 3) to evaluate the effect of thermal cycling on bituminous pavement mixtures that are dry or wet (water only or water + salt).

3 PHASE III: TESTING PROGRAM

3.1 Effect of water content

To measure the effect of water content, pavement mixture samples (PG58-28) were subjected to water conditioning. The samples to be tested were submerged in water at 5°C for a minimum of 24 hours before the start of the restrained specimen test. Because the TSRST starts with a period during which the sample is subjected to conditioning in air at 5°C, it was thought to be important that this period take place in water so that the water would be retained in the sample. The results of the TSRST testing are shown in Figure 2.

For these samples, slope 1 is difficult to analyze. It seems that the expansion of the water as the temperature drops offsets the contraction of the sample. This change in the volume of the water accounts for the compression measured by the press (negative portion of the stress values). On the other hand, beyond a certain level, probably the glass transition temperature, water no longer seems to have as much of an effect, although it is enough to reduce the failure temperature and stress compared to the dry samples.

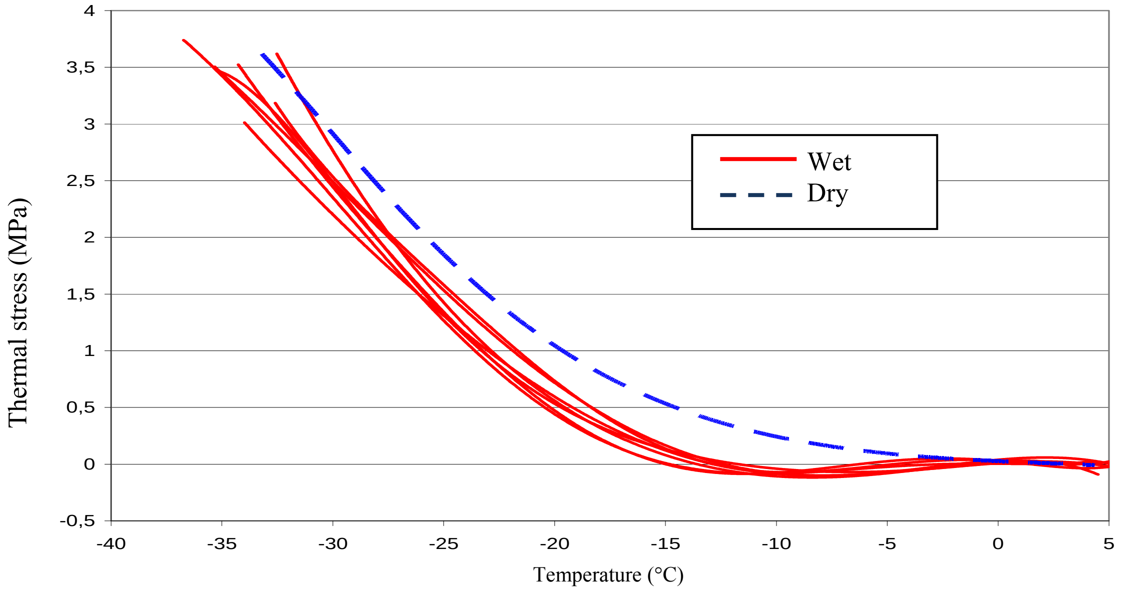

Figure 2: Results of TSRST testing for samples subjected to wet curing, and an average curve of the results for dry curing

3.2 Freeze-thaw cycle

During this phase of the testing program, the same pavement mixtures were used as for the previous phases. In order to properly simulate the effect of temperature on site, the test specimens of the bituminous pavement mixtures would need to be held in place during the freeze-thaw cycles. A steel and aluminium jig was used to accomplish this (Figure 3). The principle underlying the design of the jig is simply to use the thermal contraction of the two materials in such a way that they cancel out in order to create a setup whose dimensions do not change during the thermal cycles.

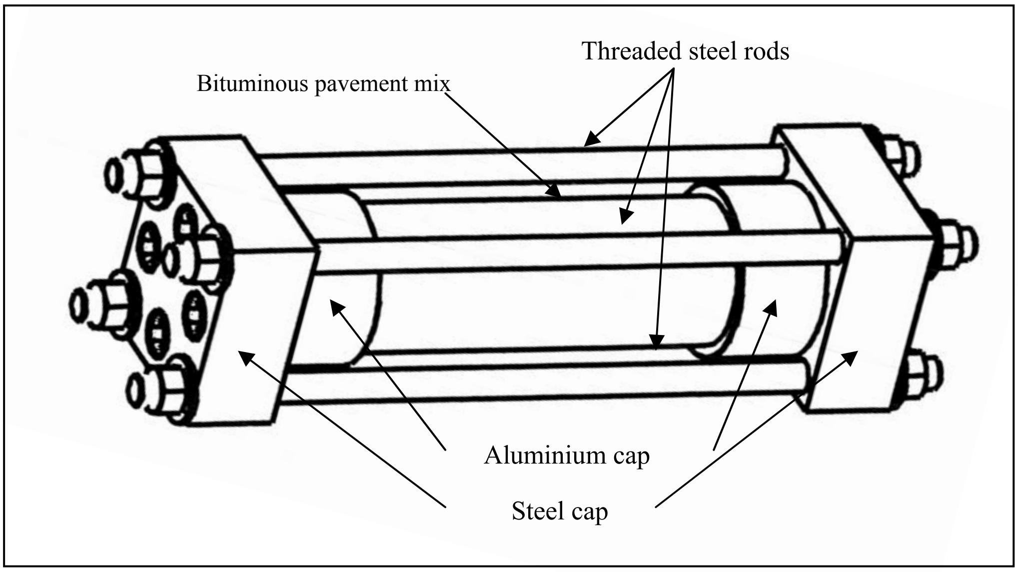

Figure 3. Jig for restraining the specimen during freeze-thaw cycles

The steel and aluminium caps are 38 mm thick. The thermal contraction coefficients for these two materials are: Steel 12.1 x10^{-6}/°C and Aluminium 22.5 x10^{-6}/°C. A number of different geometries were tested in order to eliminate movement of the pavement mixture during the cycles. Of the ones tested, this geometry is the one that allows the least movement. For cycles from 5 to -20°C, it was calculated that the sample would contract 16.5µm. According to tests conducted at LUCREB of ÉTS [Pavement, Roads and Bituminous Materials Laboratory], the thermal expansion coefficient of pavement mixtures in this temperature range is approximately 21 x10^{-6}/°C. Therefore, for a temperature delta of 25°C and a sample length of 120 mm, there should be 63 µm of contraction. The jig only allows for 16.5 µm of contraction, which means that approximately 75% of the contraction is prevented.

In order to confirm these calculations, bituminous pavement mixtures were installed in the jig and then inserted into the thermal chamber. Strain gauges (100mm) were glued to the pavement mixtures in order to allow their movement to be measured during the cycle. In addition, a gauge was mounted on a piece of titanium silicate in order to provide a reference that would make it possible to correct the thermal contraction of the gauges themselves. Titanium silicate is a material that is considered to be stable under temperature change (0.01 x10^{-6} /°C). In addition, in order to verify the sensitivity of the jig to the length of the test specimens and their installation, one bituminous pavement mix specimen was installed with no particular care, while a second one was installed as precisely as possible.

The test specimen that was not correctly installed had movements averaging 137μdef, or 13.7 μm. However, the deformation of the properly installed test specimen was 72 μdef, or 7.2 μm. In both cases, the measured movement is less than the theoretical movement. Therefore, the jig is considered to be effective, and was used for the rest of the testing.

The next step was to determine the rate of cooling and heating to be used for the cycles, along with the maximum and minimum temperatures. As a first step, it was decided to use continuous freeze-thaw cycles, without a rest period at the maximum or minimum temperature. This choice was made so that the pavement mixture would not have time to dissipate the stresses. The absence of a rest period would make it possible to increase the stresses in the sample during the cycles. Cycles from -5^{o}C to +20^{o}C with a cooling/heating rate of 10^{o}C/hr. were chosen. The ±10^{o}C/hr. rate was chosen because it is similar to the rate used in the TSRST tests. Also, it has been demonstrated that there is no difference in the results of TSRST testing when the rate is 10^{o}C/hr. or less. The maximum temperature is the initial temperature for the TSRST, while the minimum temperature is approximately equivalent to the glass transition temperature for PG58-28 binders. Analysis of the signal during the first thermal cycles that were conducted revealed that the internal temperature of the test specimen (measured using a thermocouple inserted into the sample) does not follow that of the chamber precisely (thermocouple installed on the surface of the sample). The only effect of this lag on the results is the fact that the actual temperature of the sample is not that of the chamber, and an adjustment to the temperature setting is all that is needed to achieve the desired temperature.

4 RESULTS

Due to time constraints, the test specimens were subjected to a maximum of 40 cycles with the jig shown on Figure 3. The results of the TSRST after 0, 8, and 40 cycles for the pavement mixtures with the three available binders (PG 58-28, PG 58-34, and PG 58-40) are presented in Table II. The first conclusion that can be drawn from the table is that 40 freeze-thaw cycles between 5 and -20^{o}C at a rate of +/- 10^{o}C/hr do not affect greatly the results of the TSRST. There are no observable trends in any of the following: failure temperature, failure stress, glass transition temperature, and slope of the final part of the test.

Table II. Results of TSRST testing after thermal cycles

Binder	No. of freeze-thaw cycles	Glass transition temp. (^{o}C)	Failure temperature (^{o}C)	Failure stress (MPa)	Slope 2 (MPa/^{o}C)
PG58-28	0	-16.9	-32.4	3.6	-0.212
	8	-16.8	-33.1	3.7	-0.214
	40	-16.4	-32.8	3.5	-0.212
PG58-34	0	-20.1	-36.4	4.9	-0.261
	8	-19.4	-36.6	5.0	-0.260
	40	-19.2	-37.1	5.2	-0.262
PG58-40	0	-23.2	-44.6	5.6	-0.269
	8	-23.7	-44.1	5.4	-0.267
	40	-25.1	-43.5	5.4	-0.264

In light of the fact that water affects TSRST results without a prior thermal cycle, water-saturated samples were subjected to 8 cycles. In order to saturate the samples, they were placed in water under vacuum (4kPa) for one day. Then, in order to lock in the water content, the samples were wrapped in a plastic film during the cycles, and during the TSRST. Cycles were also conducted in brine (8% salt). The averages of the results of the TSRST tests after 8 thermal cycles for pavement mixtures with PG58-28 are shown in Table III. The water content of the samples subjected to cycles in water was 0.96%, compared to 1.03% for those that were subjected to cycles in brine.

Table III. Results of TSRST testing after thermal cycles in water and brine

Binder	No. of freeze-thaw cycles	Vitreous transition (^{o}C)	Failure temperature (^{o}C)	Failure stress (MPa)	Slope 2 (MPa/^{o}C)
Water	8	-17.5	-31.8	4.0	-0.260
Brine	8	-15.3	-27.7	2.38	-0.082

The cycles in water did not produce results that differ significantly from the dry cycles. However, the cycles in brine produced interesting results in terms of failure stress and failure temperature. With respect to the glass transition temperature and Slope 2, the results are not very reliable because of the shape of the curve.

The glass transition temperature is difficult to determine, because there are two distinct slopes below -11^{o}C in the graph. There is a linear portion between -11 and -20^{o}C, and another linear portion between -20 and -27^{o}C that features a different slope.

5 CONCLUSION

Based on these results, it appears that thermal cycles alone are not the cause of failure of bituminous asphalts in winter. Instead, it is probably the combined effect of thermal stress and the action of traffic that results in stress that exceeds the tensile strength of the asphalt. Water alone does not seem to have a great effect, but adding salt to the water completely changes the results. After only 8 freeze-thaw cycles in brine, the failure temperature dropped 5^{o}C, and the failure stress decreased by 1.2 MPA, which corresponds to a 33% reduction.

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