Prediction of thermal cracking resistance of some SBS modified binders and mixes

F. Olard
APPIA, Direction de la Recherche et du Développement, Corbas, France

J-C. Vaniscote
APPIA, Direction Technique, Issy-les-Moulineaux, France

F. Loup
APPIA, Laboratoire Central, Corbas, France

ABSTRACT: The most recent addition to bituminous binder low-temperature specification in the US is AASHTO MP1a standard which uses a thermo-visco-elastic model to calculate induced thermal stress using binder creep compliance (determined from the Bending Beam Rheometer) and the empirical "Pavement Constant" 18. The predicted thermal stress curve is compared with binder tensile strength data obtained from the Direct Tension Test to determine a "critical cracking temperature" (T_{cr}) below which thermal cracking occurs. This paper presents an approach, both alternative and rational, to predict the thermal cracking resistance of bituminous materials. The complex modulus and DTT tests were respectively used, at the APPIA laboratory, to investigate the linear viscoelastic and failure properties of different SBS modified binders (with or without cross-linking). A recent method, introduced by Olard & Di Benedetto in 2003, was used to predict the mix complex modulus from the binder one so that the empirical Pavement Constant 18 is not needed in the binder specification anymore. The thermal stress was then calculated using the mix complex modulus properties predicted from those of the binders. The mix tensile strength was supposed to be close to that of the binder in the brittle domain. This experimental campaign and the proposed numerical analysis was performed to develop a handy tool for predicting the thermal cracking resistance of bituminous materials as an alternative to the current Superpave specification. Eventually, some restrained cooling tests confirmed the efficiency of the proposed new methodology.

KEY WORDS: low temperature performance, thermal cracking resistance, SBS modifiers.

1 INTRODUCTION

1.1. Background

As testing bituminous mixes is expensive and time-consuming, one of the current great issues is to determine (when possible) methods in which the mix performance could be evaluated with enough accuracy from the binder properties and from the mix composition.

The developments of this paper rely on two main experimental findings :

i) A lot of experimental work has already been done and presented in the literature to relate binder and mix moduli for a given mix composition (Heukelom and Klomp 1964, Ugé et al. 1977, Francken 1991, Shell Bitumes 1991, Lytton et al. 1993, Boussad and Dony 1996, Di Benedetto and Des Croix 1996, Franken and Vanelstraete 1996, Witczak et al. 1999, Goacolou and Mazé 2000, Zeng et al. 2001, Olard et al. 2003-04, Di Benedetto et al. 2003-04).

ii) In the brittle domain, at very low temperatures, a first approximation allows to consider that the binder tensile strength equals the mix tensile strength whatever the strain rate (Olard et al. 2003-04). This statement is of the utmost importance since the failure in mixes could be predicted, in a first approximation, from the failure in binders.

The two assumptions *i)* and *ii)* are based on many experimental results obtained on very different bituminous materials and are thus reliable. This approach implies that there is a simple uncomplicated relationship between the binder characteristics and the performance of the corresponding mixture and hereby negligible interactions between the aggregate and the binder. Nevertheless, a study of Wegan and Brûlé (1999), using optical microscopical investigation, has shown that a specific interaction between one type of polymer (EVA and SBS) used for the binder modification and the aggregate in the bituminous mix may occur.

1.2. Research objectives and study approach

The recent addition to binder low temperature specification (AASHTO MP1a standard) uses a thermo-visco-elastic model to calculate induced thermal stress (during a restrained cooling test) from the binder creep compliance (determined from the Bending Beam Rheometer) and the empirical "Pavement Constant" 18 (AASHTO 2002). The predicted thermal stress curve is compared with binder tensile strength data obtained from the Direct Tension Test to determine the so-called "critical cracking temperature" (T_{cr}) below which transverse thermal cracking occurs in the pavement (Anderson et al. 2000, Bouldin et al. 2000, Rowe et al. 2000, D'Angelo and Dongre 2002-04, Marasteanu 2004, Ho and Zanzotto 2004).

According to us, the introduction of an empirical "Pavement Constant" 18 is not sensible since only one constant can not be sufficient to convert the binder properties to those of the mix (cf. e.g. Heukelom and Klomp 1964, Ugé et al. 1977, Francken 1991, Shell Bitumes 1991, Lytton et al. 1993, Boussad and Dony 1996, Di Benedetto and Des Croix 1996, Franken and Vanelstraete 1996, Witczak et al. 1999, Goacolou and Mazé 2000, Zeng et al. 2001, Olard et al. 2003-04, Di Benedetto et al. 2003-04).

In a context of continuing development and innovation, and in order to contribute to characterization of PMB's, the objectives of this work are to present an alternative and rational approach that enable realistic and accurate prediction of the cracking temperature of asphalt pavement in the binder specification. Restrained cooling tests confirm the efficiency of the proposed new methodology (see sections 4.1 and 4.2).

2. EXPERIMENTAL DETAILS

2.1. Equipment

Complex modulus tests were performed at the APPIA laboratory with a Metravib Viscoanalyzer 2000 over a range of frequencies from 1.6 to 250Hz. From -30 to +20°C, compression/tension tests were conducted on cylindrical samples (diameter=10mm, height=22mm). From +20 to +80°C, the tests consisted of annular shearing of hollow cylindrical samples (inner diameter=8mm, outer diameter=10mm, height=20mm). The relation $|E^*|=3|G^*|$ (incompressibility and isotropy) is assumed, which allows all results to be plotted as a function of E^* only.

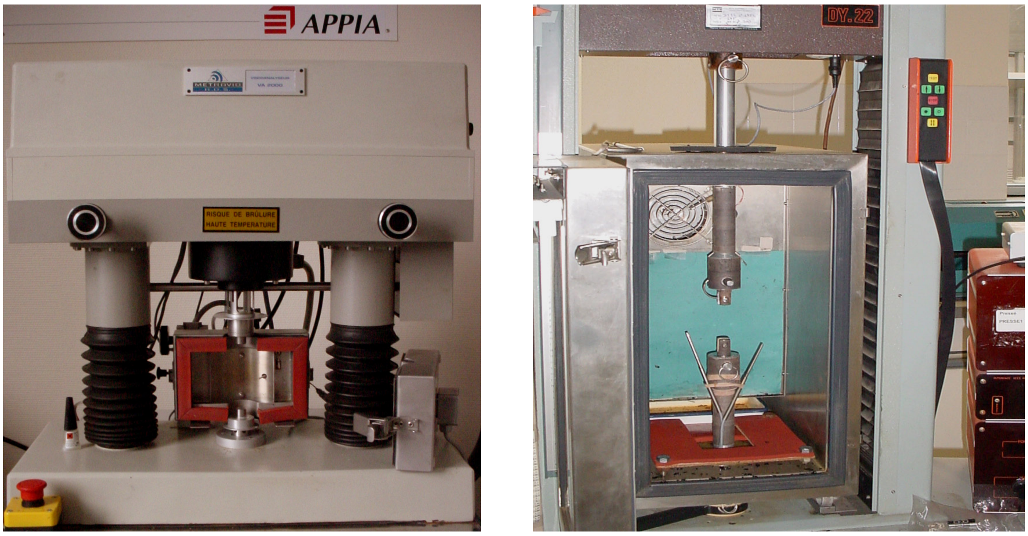

Figure 1: a) Metravib Viscoanalyzer VA 2000, b) MTS press for DTT tests.

As described in AASHTO TP3 and in Superpave Series (1997), the SHRP Direct Tensile Tests consisted in elongating 27mm high bitumen samples at 1mm/min and at constant temperatures. Six repeats were realized at each temperature at the APPIA laboratory.

Restrained cooling tests –also called Thermal Stress Restrained Specimen Tests (TSRST)– were carried out at the APPIA lab on a servo-hydraulic press at a cooling rate of -10°C/h from an initial temperature of +5°C (AASHTO 1993). Tests were run in duplicate on 160mm high samples (55mm in diameter) which were cored from parallelepipedic slabs (L*W*H = 60*40*15cm) prepared using the LCPC slab compaction method (NF P 98-250-2). The strain ε can be modeled as the sum of a thermal strain ($\varepsilon^{thermal}$) and a mechanical strain ($\varepsilon^{mechanical}$) :

$$\varepsilon = \varepsilon^{mechanical} + \varepsilon^{thermal} \qquad \text{Equation 1}$$

$\varepsilon^{thermal}$ equals $\alpha.\Delta T$, with α the thermal contraction coefficient of the mix. As the total strain ε is kept equal to zero during the whole test, Equation 1 becomes :

$$\varepsilon^{mechanical} = -\varepsilon^{thermal} = -\alpha\Delta T \qquad \text{Equation 2}$$

Thus, TSRST introduces a coupling between the thermal and mechanical effects.

Figure 2: Mix sample to be tested on the hydraulic press.

2.2. Materials

The linear viscoelastic and failure properties of one pure 10/20 pen grade base bitumen and of four APPIA PMB's (SBS modified binders with or without cross-linking, Vaniscote 2003) were investigated. Table 1 presents the composition of these five binders along with their conventional characteristics.

Table 1: Conventional results on the five studied binders (Penetrability at 25°C, Softening Point Ring & Ball).

Binder	10/20	PMB1	PMB2	PMB3	PMB5
composition	10/20	35/50 + 3% SBS	50/70 + 3% SBS	70/100 + 5% SBS	160/220 + 7% SBS + coss-linking
Pen @ 25°C (mm/10)	16	35	50	55	90
Softening Point R&B (°C)	67	58	50	70	90

3. METHODOLOGY

During TSRST, as the material is restrained, its tendency to shorten results in the development of a tensile stress that produces fracture when it equals the mix tensile strength. The different following steps were followed to predict the thermal cracking of the studied materials.

3.1. Prediction of the mix complex modulus from the binder one

A recent method, introduced by Olard and Di Benedetto, was used to predict the mix complex modulus from the binder one (Olard and Di Benedetto 2003, Olard 2003, Olard et al. 2004, Di Benedetto et al. 2004) so that the empirical Pavement Constant 18 is not needed in the binder specification anymore. The thermal stress was then calculated using the mix complex modulus properties predicted from those of the binder (linear visco-elastic calculation).

This relationship between the binder and the mix complex moduli is as follows (both the phase angle and the norm of the complex moduli are herein considered) :

$$E^*_{mix}(\omega,T) = E_{0\_mix} + \left[E^*_{binder}(10^{\alpha}\omega,T) - E_{0\_binder}\right]\frac{E_{\infty\_mix} - E_{0\_mix}}{E_{\infty\_binder} - E_{0\_binder}} \qquad \text{Equation } 3^*$$

If the binder complex modulus is known at a given temperature T, Equation 3 gives the mix complex modulus at this temperature T. It requires only three constants (E_{0_mix}, E_{∞_mix} and α) which depend on the considered mix composition. The two first constants have a simple physical meaning : E_{0_mix} and E_{∞_mix} respectively correspond to the minimum and maximum asymptotic values of the norm of the mix complex modulus, respectively at very low frequencies and high frequencies. The meaning of the parameter α is given in the above references. Olard and Di Benedetto checked with success the efficiency of Equation 3 for data obtained on different binders and various mastic and mix compositions. In fact, Equation 3 corresponds to an isotropic expansion plus a translation of the binder curve in the Cole-Cole

* Considering the experimental data, $E_{0\_binder} << E_{\infty\_binder}$ and $E_{0\_mix} << E_{\infty\_mix}$. Equation 3 can be thus simplified in a first approximation :

$$E^*_{mix}(\omega,T) = E_{0\_mix} + E^*_{binder}(10^{\alpha}\omega,T)\frac{E_{\infty\_mix} - E_{0\_mix}}{E_{\infty\_binder}}$$

plane. Figure 3 allows to explain how to obtain practically the mix modulus from the binder one. Starting from binder complex modulus $E^*_{binder}(\omega,T)$, three geometrical transformations have to be carried out to obtain the mix modulus $E^*_{mix}(10^{-\alpha}\omega,T)$:

i) negative translation along the real axis of value E_{0_binder} (E_{0_binder} is often equal to 0).

ii) homothetic expansion from the origin with a $(E_{\infty\_mix}-E_{0\_mix})/(E_{\infty\_binder}-E_{0\_binder})$ ratio.

iii) positive translation along the real axis of value E_{0_mix}.

For simplicity, we have decided to study the mix composition already used by Olard et al. & Di Benedetto et al. in the above references. The mix has a dense 0/10mm grading, a 3±1% void content and a binder content of 6% by weight of aggregate. Regarding the three needed parameters E_{0_mix}, E_{∞_mix} and α, their respective values are 100MPa, 43000MPa and 2.82.

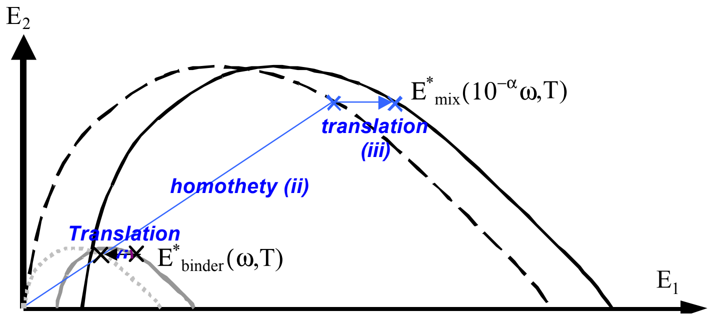

Figure 3: Prediction of the mix modulus from the binder one in the Cole-Cole plane.

3.2. Calibration of a "brittle" generalized Kelvin-Voigt model

First, the values of predicted mix complex modulus are fitted to a 15-element generalized Kelvin-Voigt model (cf. Figure 4) thanks to an optimization process in the frequency domain (cf. Figure 5). As it can be shown theoretically, only the 15 viscosities η_i depend on the temperature (T), to take into account the Time-Temperature Superposition Principle (valid only at low and intermediate temperatures (<10°C) for PMB's (Olard et al. 2003, Di Benedetto 2004).

Second, as the typical 15-element generalized Kelvin-Voigt model does not include the fracture of the samples under thermal stress, and in order to introduce a brittle failure criterion at low temperatures in the model, it is considered that the E_0 element has a brittle behavior. The brittle failure value is calibrated from the binder tensile strength (supposed to be equal to the mix tensile strength) in relation to temperature at very low temperatures. At least 12 tensile tests are needed (= 2 constant (low) temperatures x 1 loading rate x 6 repeats).

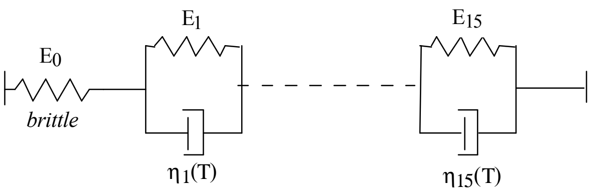

Figure 4: Analogical form of the modified 15-element generalized Kelvin-Voigt model used for the prediction of the thermally induced tensile stress during restrained cooling tests (the E_0 element has a brittle behavior).

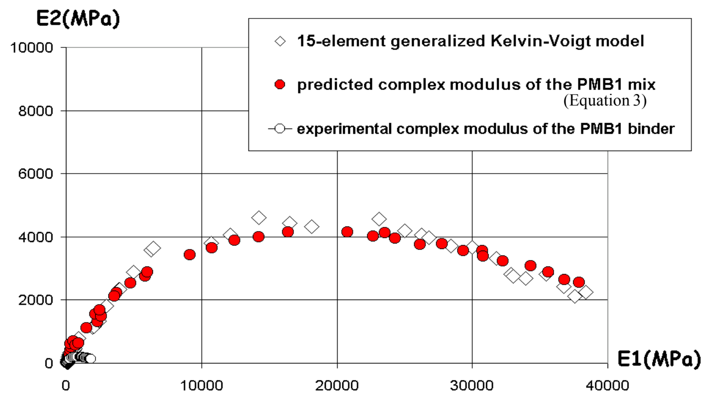

Figure 5: Example of experimental and modeled complex modulus at 15°C for PMB1 mix.

3.3. Prediction of thermally induced tensile stress

The developed and calibrated model can be used to simulate homogeneous tests. A computer program using the Visual Basic interface of MS Excel was used (Olard et al. 2003). It allows to simulate the response for any imposed strain or stress path (within a one-dimensional and linear visco-elastic framework).

Restrained cooling tests introduce a coupling between the thermal and mechanical effects (cf. Equation 2). The mechanical strain, $\varepsilon^{mechanical}$, can be described by the model introduced in this paper and the thermal strain, $\varepsilon^{thermal}$, is equal to $\alpha\Delta T$, where ΔT is the temperature variation and α is the thermal dilatation-contraction coefficient.

In the literature (Di Benedetto and Neifar 1997, Serfass et al. 2000, Olard 2003, Olard et al. 2004), a linear relationship between α and the temperature is generally obtained below 5°C, whereas α appears as nearly constant above 5°C (the creep of the sample makes the measurements inaccurate). For monotonic TSRST, α is hereafter supposed to vary linearly from around 26 to 20µm/m/°C while decreasing temperature from 5 to -30°C (Olard 2003, Olard et al. 2004), whereas, for cyclic TSRST between -20 and 20°C, α is arbitrarily supposed to be constant and equal to 23µm/m/°C (Olard 2003, Pucci et al. 2004).

4. SIMULATIONS OF RESTRAINED COOLING TESTS VS EXPERIMENTAL RESULTS

4.1 Case of a monotonic temperature variation

Figure 6 presents a comparison between the experimental results obtained for the five studied materials during TSRST at a cooling rate of -10°C/h and the simulated stress evolution, when considering a linear viscoelastic behavior described by the "brittle" generalized Kelvin-Voigt model with 15 elements, introduced in section 3.2 (see Fig. 4). Our linear computations lead to slightly higher thermally induced tensile stress. Two possible reasons may be given :

i) non-linearities should be considered in the large strain domain (Olard et al. 2003-04),

ii) difference between the numerical simulations and the experimental results can be partly due to the slight thermal gradient within the mix sample. Indeed, the temperature in the center of the mix sample (diameter of 55mm) is around 1.3°C higher than the surface temperature during TSRST.

Despite the two drawbacks above, our rational methodology is appropriate to give quickly a good description of the thermal stress during TSRST and a realistic fracture temperature T_{TSRST}. The case of a cyclic temperature variation during the restrained cooling tests is treated in the following paragraph.

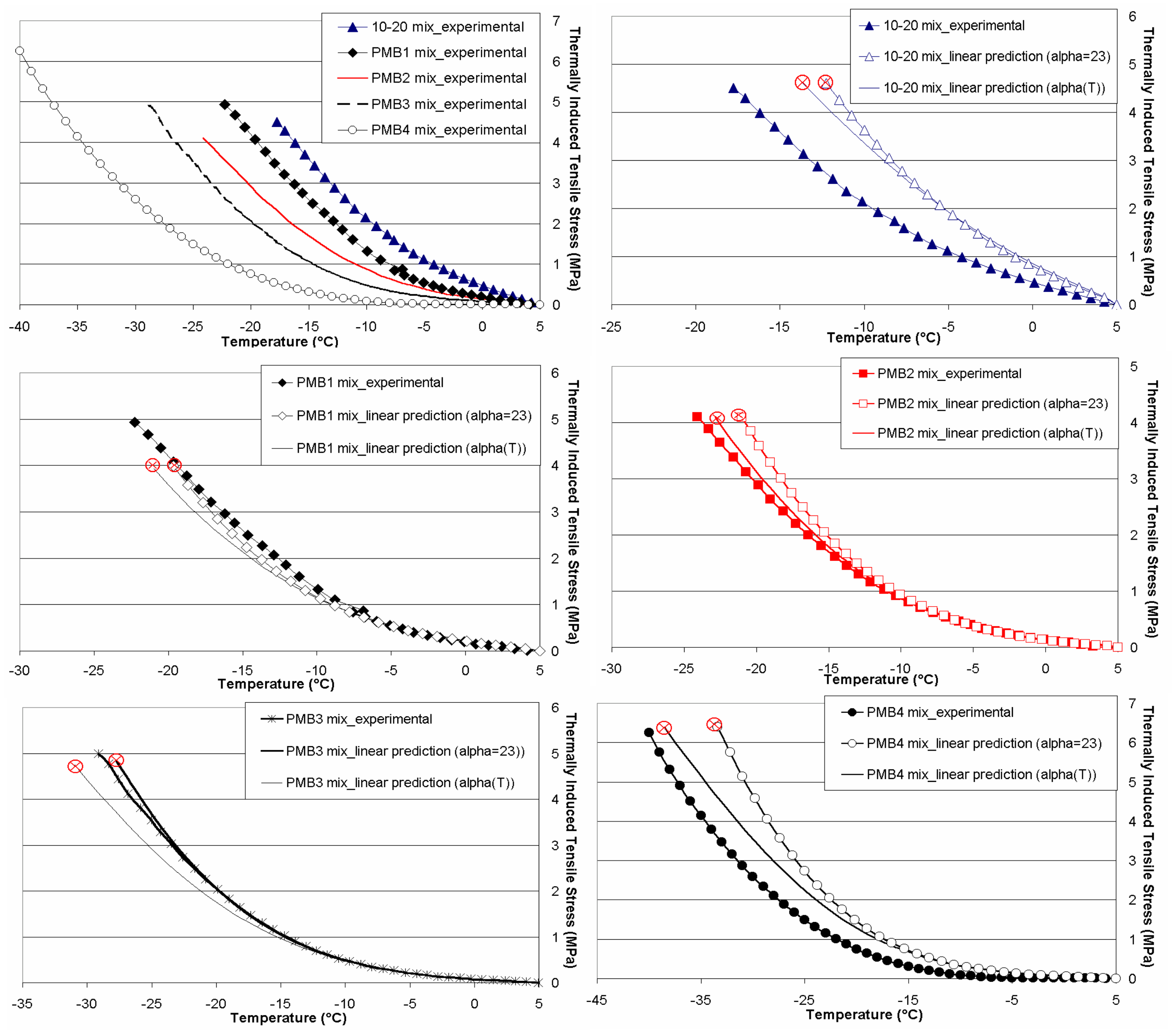

Figure 6: Experimental TSRST Vs predicted TSRST in the case of a monotonic temperature variation (-10°C/h). Symbol ⊗ indicates the low-temperature brittle failure of the E_0 body.

4.2 Case of a cyclic temperature variation

The previous calculations only take into account single event thermal cracking whereas traffic and thermal cycling have a great influence upon thermal cracking. Thus, it appears as interesting to quantify the effect of this type of variation on the thermal stress during TSRST. In this section, a sinusoidal variation of the temperature between -20 and +20°C, with a period of 24 hours, is considered. Figure 7 shows, for the 10/20 and PMB1 mixes, a comparison between the experimental results and the thermal stress evolution with temperature calculated thanks to the "brittle" 15-element generalized Kelvin-Voigt model illustrated in Figure 4.

Note that the strong non-symmetry between the tension phases (negative temperatures) and the compression phases (positive temperatures) is due to the great variation of the viscous properties with the temperature. The difference in stress levels between these two mixes is to underline : the 10/20 mix develops particularly high tensile stresses as soon as the first cycles. Figure 7 makes it possible to predict the thermal cracking of this mix (3rd day). One can finally observe that at the end of two to three thermal cycles (two to three days), the minimum and maximum stress levels are stabilized for the PMB1 mix.

Cyclic restrained cooling tests on the three other mixes will be soon carried out at the APPIA central laboratory to validate the efficiency of the simulations.

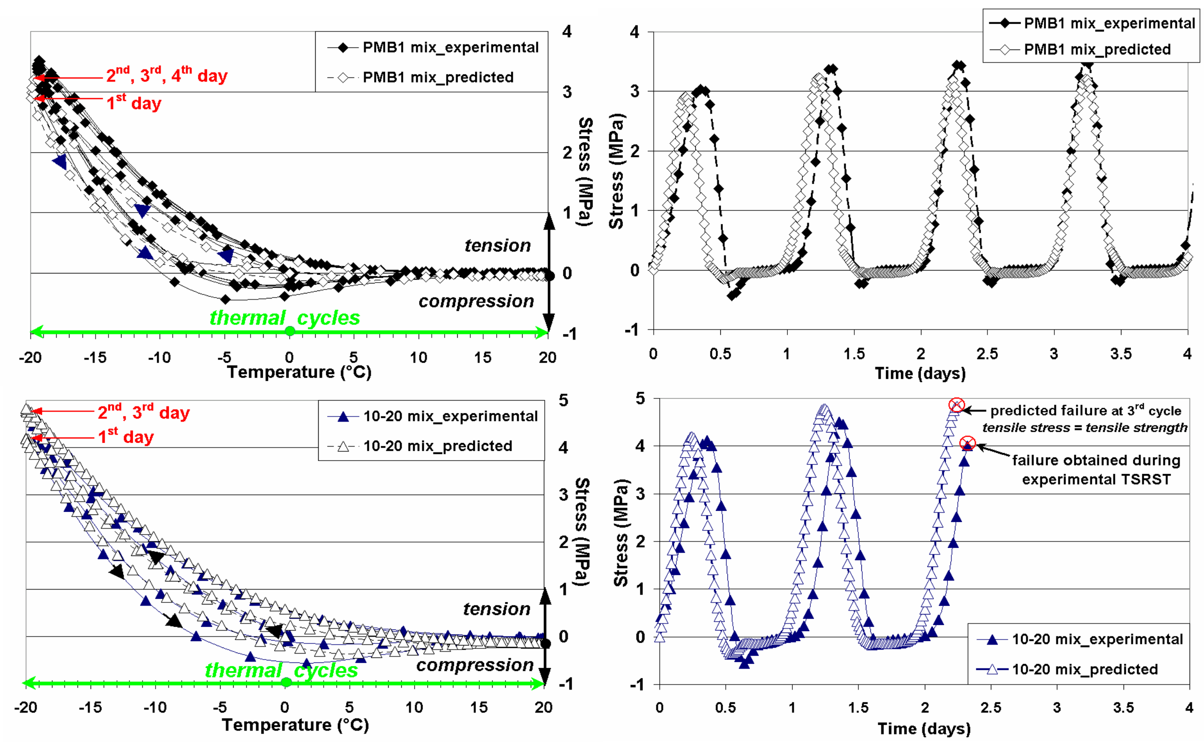

Figure 7: Experimental and predicted thermal stress evolution for the 10-20 and the PMB1 mixes during a cyclic TSTRST (sinusoidal temperature variation with a 24-hour period between -20 and +20°C) : the prediction of the 10/20 mix failure at the 3rd cycle is correct.

5. CONCLUSIONS / DISCUSSION

Based on the presented TSRST results obtained with five bituminous materials, the following conclusions and recommendations can be made :

• A comparison between TSRST experimental data and theoretical simulations based on a linear viscoelastic analysis has been presented. The experimental data and the modeling results are matching well with either a monotonic or a cyclic temperature variation. Even if our linear computations lead in most cases to slightly too high thermally induced tensile stress, this study is encouraging. Neifar and Di Benedetto (2001), Olard (2003), Olard et al. (2004), Chehab et al. (2004) and Olard and Di Benedetto (2005) and have recently shown that an increase in accuracy is possible by taking into account the viscoplastic properties of bituminous materials but additional monotonic tension tests on mixes are required to calibrate appropriate models (DBN model, Visco-Elasto-Plastic Continuum Damage model, *etc.*), which is time-consuming and cannot be done within the framework of a binder specification.

• The first advantage of our methodology lies in Equation 3, a very accurate and powerful relationship between the binder and the mix complex moduli that was found by Olard and Di Benedetto in 2003-04.

• The second advantage of our approach lies in the fact that it is possible to successfully predict the response of bituminous mixes for any imposed strain or stress path in the brittle domain, in particular cyclic TSRST which are too long to systematically perform in lab.

• The brittle failure criterion, introduced in the E_0 body of the "brittle" generalized Kelvin-Voigt model with 15 elements (Fig. 4), should also be considered as a function of the number of thermal cycles so that the thermal fatigue can be taken into account. This point needs further investigation.

REFERENCES

American Association of State Highway and Transportation Officials, 1993. *AASHTO Designation TP10-93*. Standard Test Method for Thermal Stress Restrained Specimen Tensile Strength, 1st Edition, Washington, DC.

American Association of State Highway and Transportation Officials, 2002. *AASHTO Designation MP1a-02*. AASHTO Provisional Standards, Washington, DC.

Anderson, D.A., Marasteanu, M.O., Champion-Lapalu, L., Le Hir, Y., Martin, D., Planche, J.P., 2000. *Low-temperature thermal cracking of asphalt binders as ranked by strength and fracture properties*. 2nd Eurasphalt & Eurobitume Congress, Barcelona.

Boussad, N., Dony, A., 1996. *Binder rheology : powerful predicting tool for mix modulus prediction*. Revue Gale des Routes et des Aérodromes, Supplement to n°739.

Bouldin, M.G., Dongré, R., Rowe, G.M., Sharrock, M.J., Anderson, D.A., 2000. *Predicting thermal cracking of pavements from binder properties : theoretical basis and field validation.* Association of Asphalt Paving Technologists.

Chehab, G.R., Kim, Y.R., Witczak, M.W., Bonaquist, R., 2004. *Prediction of thermal cracking behavior of asphalt concrete using the viscoelastoplastic continuum damage model.* 83rd Annual Meeting of the Transportation Research Board, Washington D.C..

D'Angelo, J., Dongre, R., 2002. *Development of a performance based binder specification in the United States.* 47th Annual Meeting of the Canadian Technical Asphalt Association.

D'Angelo, J., Dongre, R., 2004. *Development of a performance based binder specification in the United States*. 3rd Eurobitume and Eurasphalt Congress, Vienna.

Di Benedetto, H., Des Croix, P., 1996. *Binder-mix rheology : limits of linear domain, non linear behaviour.* Eurasphalt and Eurobitume Congress.

Di Benedetto, H., Neifar, M., 1997. *Coefficients de dilatation et de contraction thermiques d'un enrobé bitumineux avec et sans chargement mécanique*, Mechanical Tests for Bituminous Mixes, Proceedings of the 5th International Rilem Symposium, Lyon.

Di Benedetto, H., Olard, F., Sauzeat, C., Delaporte., B., 2004. *Linear viscoelastic behavior of bituminous materials : from binders to mixes*. Inaugural Meeting of the European Asphalt Technology Association, Nottingham. Published in the International Journal of Road Materials and Pavement Design, Vol.5, Special Issue.

Franken, L., 1991. *Propriétés mécaniques des enrobés. Influence de la composition*. Journées d'études AFREM sous la direction scientifique du Laboratoire Central des Ponts et Chaussées, Saint-Rémy-lès-Chevreuse.

Franken, L., Vanelstraete, A., 1996. *Complex moduli of bituminous binders and mixtures : interpretation and evaluation*. Eurasphalt and Eurobitume Congress.

Goacolou, H., Mazé, M., 2000. *Enrobés à haut module élastique. Relation entre les propriétés rhéologiques du bitume et celles de l'enrobé.* Revue Gale des Routes et des Aérodromes, n°787.

Heukelom, W., Klomp, J.G., 1964. *Road design and dynamic loading.* Association of Asphalt Paving Technologists, Vol. 33.

Ho, S., Zanzotto, L., 2004. *Low-temperature properties of asphalt binders studied by the Direct Tension Test and the Superpave MP1a specification.* 3rd Eurobitume and Eurasphalt Congress, Vienna.

Lytton, R.L., Uzan, J., Fernando, E.G., Roque, R., Hiltunen, D., Stoffels, S.M., 1993. *Development and Validation of Performance Prediction Models and Specifications for Asphalt Binders and Paving Mixes.* SHRP-A-357, Strategic Highway Research Program , National Research Council, Washington.

Marasteanu, M.O., 2004. *The role of Bending Beam Rheometer in thermal stress calculations*. 83rd Annual Meeting of the Transportation Research Board, Washington D.C.

Neifar, M., and H. Di Benedetto, 2001. *Thermo-Viscoplastic Law for Bituminous Mixes*. International Journal of Road Materials and Pavement Design. Volume 2, Issue 1.

Olard, F., Di Benedetto, H., Dony, A., Vaniscote, J.C., 2003. *Properties of bituminous mixtures at low temperatures and relations with binder characteristics*. 6th International Rilem Congress on Performance Testing and Evaluation of Bituminous Materials, Zurich.

Olard, F., Di Benedetto, H., Eckmann, B., Triquigneaux, J-P., 2003. *Linear viscoelastic properties of bituminous binders and mixtures at low and intermediate temperatures*, International Journal of Road Materials and Pavement Design, Volume 4, Issue 1.

Olard, F., Di Benedetto, H., 2003. *General "2S2P1D" model and relation between the linear viscoelastic behaviors of bituminous binders and mixes.* International Journal of Road Materials and Pavement Design, Volume 4, Issue 2.

Olard, F., 2003. *Comportement thermomécanique des enrobés bitumineux à basses températures. Relations entre les propriétés du liant et de l'enrobé*. PhD Thesis, ENTPE.

Olard, F., Di Benedetto, H., Eckmann, B., Vaniscote, J-C., 2004. *Low-temperature failure behavior of bituminous binders and mixes* 2004., 83rd Annual Meeting of the Transportation Research Board, Washington D.C.

Olard, F., Di Benedetto, H., Eckmann, B., 2004. *Comportement visco-élastique linéaire des liants et des enrobés bitumineux à basse température*. Revue Gle des Routes et des Aérodromes, N°826.

Olard, F., Di Benedetto, H., Eckmann, B., Vaniscote, J-C., 2004. *Failure behavior of bituminous binders and mixes at low temperatures*. 3rd Eurobitume and Eurasphalt Congress, Vienna.

Olard, F., Di Benedetto, H., Maze, M., Triquigneaux, J-P., 2004. *Thermal cracking of bituminous mixtures : Experimentation and modeling.* 3rd Eurobitume and Eurasphalt Congress, Vienna.

Olard, F., Di Benedetto, H., Eckmann, B., 2004. *Comportement à la rupture des liants et des enrobés bitumineux à basse température.* Revue Gle des Routes et des Aérodromes, N°832.

Olard, F., Di Benedetto, H., 2005. *Experimental characterization and constitutive modeling of the thermo-visco-elasto-plastic behavior of bituminous mixes : the "DBN" law*. Association of Asphalt Paving Technologists.

Pucci, T., Dumont, A-G., Di Benedetto, H., 2004. *Thermomechanical and mechanical behaviour of asphalt mixtures at cold temperature*. International Journal of Road Materials and Pavement Design, Volume 5, Issue 1.

Rowe, G.M., Ibberson, C., Bouldin, M.G., 2000. *The effect of design parameters on the computation of thermal stress and critical cracking temperature*. 2nd Eurasphalt & Eurobitume Congress, Barcelona.

Serfass, J.P., Bense, P., Tessonneau, H., 2000. *Enrobés bitumineux modifiés au polyéthylène*, Revue Gale des Routes et des Aérodromes, n°787.

Shell Bitumes, 1991. *Techniques et Utilisations.*

Ugé, P., Gest, G., Gravois, A., 1977. *Nouvelle méthode de calcul du module complexe des mélanges bitumineux*. Bull. liaison des Laboratoires des Ponts et Chaussées, N° spécial V.

Vaniscote, J-C., 2003. *Liants modifiés d'enrobage : la nouvelle gamme APPIA*. Revue Gale des Routes et des Aérodromes, N°814.

Wegan, V., Brûlé, B., 1999. *The Structure of Polymer Modified Binders and Corresponding Asphalt Mixtures*. Danish Road Institute, Report 92.

Witczak, M.W., Andrei, D., Mirza, W., 1999. *Development of Revised Predictive Model for the Dynamic (Complex) Modulus of Asphalt Mixtures*. Interteam Technical Report, NCHRP Project 1-37A, University of Maryland.

Zeng, M., Bahia, H.U., Zhai, H., Anderson, M.R., Turner, P., 2001. *Rheological modeling of modified asphalt binders and mixtures.* Association of Asphalt paving Technologists.