Design of a specific bituminous surfacing for orthotropic steel bridge decks : application to the Millau Viaduct

B. Héritier
APPIA, Directeur Technique, Issy-les-Moulineaux, France

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

M. Saubot
APPIA, Laboratoire Central, Corbas, France

S. Krafft
APPIA, Direction Régionale Méditerranée, Vitrolles, France

ABSTRACT: This paper presents a rational approach for the performance-based design of bituminous wearing surfacings on orthogonally anisotropic steel bridges. Basically, the behavior of bituminous surfacings on steel orthotropic decks, under heavy truck traffic and environmental conditions, is highly complex. Both the geometry of the structure and the very high flexibility of metallic plates make the deformations and stresses very severe in steel bridge surfacings. In particular, the repeated loading make the fatigue strength be an important parameter for the design of such bituminous wearing courses. In addition, these specific surfacings must also have durability over the expected temperature range: it must be resistant to thermal cracking at low temperature and to rutting at high temperature. The technical studies led in parallel to the construction of the Millau Viaduct (France) –the tallest bridge in the world– have provided in particular the opportunity of new progress in the development of appropriate laboratory testing equipment and of original polymer-modified surfacing. Indeed, APPIA pulled the socks up and led a comprehensive research program including both a large laboratory testing campaign and a Finite Element analysis so as to develop a handy tool for design of plate surfacings. Eventually, as regards the realization of this one-off work, the bringing into play of considerable resources made APPIA succeed in delivering within the deadlines a surfacing of the highest standard for the Millau Viaduct.

KEY WORDS: orthotropic steel bridge deck, bituminous surfacing, Millau Viaduct.

1 INTRODUCTION AND PRESENTATION OF THE MILLAU VIADUCT PROJECT

This paper describes a project for choosing the most suitable pavement system for the Millau multiple-cable-stayed Viaduct (over the Tarn river, in the south of France), the highest bridge in the world (343 meters high at the top of the towers) constructed by EIFFAGE Group. This super-structure is a bridge with orthotropic steel deck plate. A heavy traffic is involved (≈20,000 vehicles/day). Our company APPIA, subsidiary of EIFFAGE Group, was in charge with the development and the construction of the specific bituminous surfacing.

Figure1: Overall view of the Millau Viaduct.

2 REQUIREMENTS FOR THE BITUMINOUS SURFACING DESIGN

2.1 Usual technical constraints

Technical constraints usually met for wearing courses under severe traffic are: *i)*workability (measured from the gyratory shear compacting press, NF P 98-252), *ii)*resistance to rutting (characterized with the French pavement rutting tester, NF P 98-253-1), *iii)*water resistance (measured from the Duriez test, NF P 98-251-1), and *iv)*macrotexture HSv (measured with the sandpatch test, NF EN 13036-1). Regarding the Millau Viaduct, the reduced means of compaction and an additional goal of waterproofing lead to seek a high workability. This results in the following values:

    *i)*PCG test   : percentage of voids to 60 gyrations $\approx$ 5 %,
    *ii)*rutting test   : in 10cm thick, 60C, rut depth at 30 000 cycles $\leq$ 6 %,
    *iii)*Duriez test   : r/R $\geq$ 0.75,
    *iv)*sandpatch test : HSv $\geq$ 0.8 mm.

2.2 Unusual technical constraints

What should be established at the very outset is that bridge deck pavements undergo frequent and severe climatic variations, so that a good resistance to thermal cracking (single event thermal cracking and/or thermal fatigue cycling) is an unquestioning prerequisite for a long service life.

Moreover, the steel plate deck structure is characterized by large local deformations due to its low thickness (12 and 14 mm respectively for the express way and the slow way) and its longitudinal ribs separated by 30 cm (Fig. 2 & 3.a), so the need for a great deformability of the surfacing as well (Fig. 3.a). Unlike traditional pavements, this particular constructive work, anisotropic along the longitudinal axe (direction of longitudinal ribs) and the transverse axe (direction of floorbeams) –hence the term of "orthotropic" plate– generates, during the passing of live loads, tensile stresses in the higher part of the flooring sheet as in that of the bituminous wearing course, bringing about a risk of top-down cracking (Fig. 3.b). Strain levels can exceed $5 \cdot 10^{-4}$, which is much higher than those in standard flexible pavements. Most problems reported in the literature (Hameau et al. 1981, Méhue 1981, Wøhlk 1985, Kolstein and Dijkink 1989, Hulsey et al. 1999, Hicks et al. 2000, Edwards and Westergren 2001, Wolchuk 2002, Nishizawa et al. 2004) are related to fatigue cracking of the pavement

or, to some extent, to low bond strength between the pavement and the steel deck at the "hard spots" above longitudinal stiffeners and main girder connections.

For these reasons, the performance of the wearing surfacings on steel plate decks mainly depends upon deck plate flexibility, temperature variations, volume of heavy truck traffic, and also the type and thickness of the surfacing. Basically, in order to ensure circulation conditions of motorway level for any environmental conditions, suitable wearing surfaces on steel deck plate should :

- be lightweight, while having sufficient thickness to cover deck irregularities,
- ensure skid-resistance,
- have durability over the expected temperature range (in particular it must be resistant to thermal cracking at low temperatures and to rutting at high temperatures),
- be impervious to water, motor fuels, oils, and chemicals agents (lasting corrosion protection of the steel deck is necessary),
- have high bond strength to the steel deck to avoid extreme fatigue stresses in the surfacing and in the deck, and to resist delamination from shear stresses,
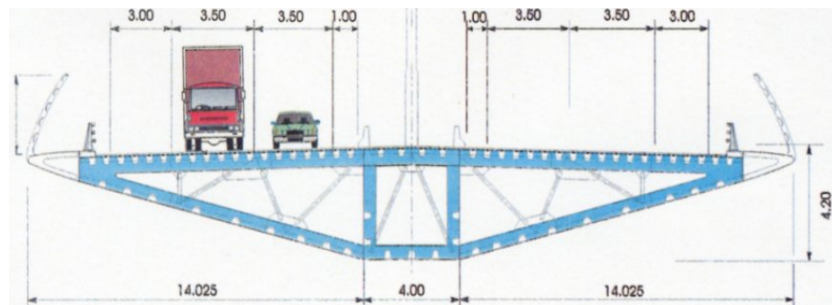- have an excellent fatigue resistance.

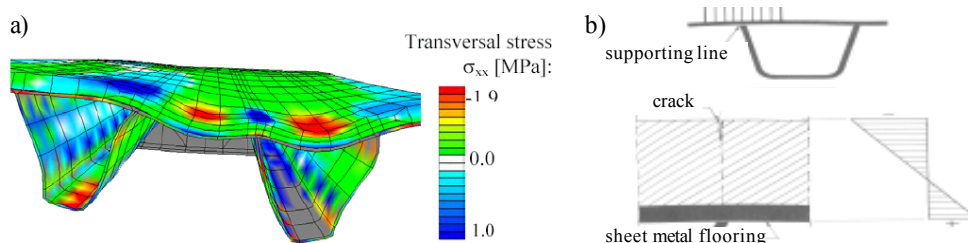Figure2: Transversal cross section of the Millau Viaduct deck.

Figure 3: a)Example of deformed bridge deck (250x) with transversal stress (Huurman et al. 2003); b)Bituminous mix on orthotropic plate (Méhue 1981).
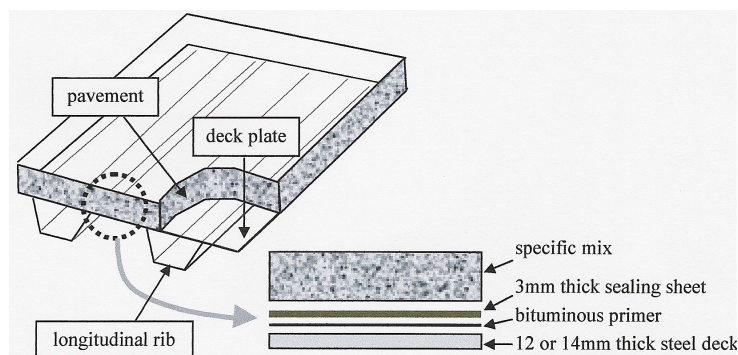

Figure 4: Bituminous surfacing laid on the Millau Viaduct.

3 DESCRIPTION OF THE BITUMINOUS PAVEMENT SYSTEM

Figure 4 represents the composite system laid on the Millau Viaduct which consists of *i)*a bituminous primer, intended to protect metal from corrosion, *ii)*a 3mm thick bituminous sealing sheet which provides an impermeable barrier to absorb differential movements between the surface course and the steel plate, and *iii)*a 60mm thick bituminous mixture specifically formulated by the APPIA laboratory.

4 FIVE-POINT BENDING FATIGUE TEST

Many a laboratory test was carried out on several waterproofing and paving systems so as to choose the right system for the Millau Viaduct.

4.1 Test principle (Lau 1978, Hameau et al. 1981, Cadic 1999, Saubot and Loup 2004, Héritier et al. 2005, Olard et al. 2005)

This atypical pavement behavior –bending under negative moment– had led the French Laboratoire Central des Ponts et Chaussées (LCPC) to develop in the 70's a five-point bending fatigue test, making it possible to assess the fatigue resistance of steel bridge pavement to deformation over stiffeners (Cadic 1999). The construction of the Millau Viaduct has provided APPIA with the opportunity of fitting out a MTS servo-hydraulic press of the central laboratory with this test (cf. Fig. 5 and Table 1). Only the steel quality of the sample support (E36 quality 4) and its roughness are those of the Millau Viaduct deck and not those of the LCPC procedure (Cadic 1999).

4.2 Calibration phase

Testing procedure begins with a calibration phase to determine the F_{max} load corresponding to a strain of 625µm/m (resp. 450µm/m) for a 12mm (resp. 14mm) thick steel plate on the steel surface over the central web welds. For a 12mm thick steel plate, the force measured over the central support is : F_{max}=21,740N. One can then deduce by calculation the reaction of the extreme supports (R_E = 6,560N) and the force applied to the sample (F = 2 x 17,430N).
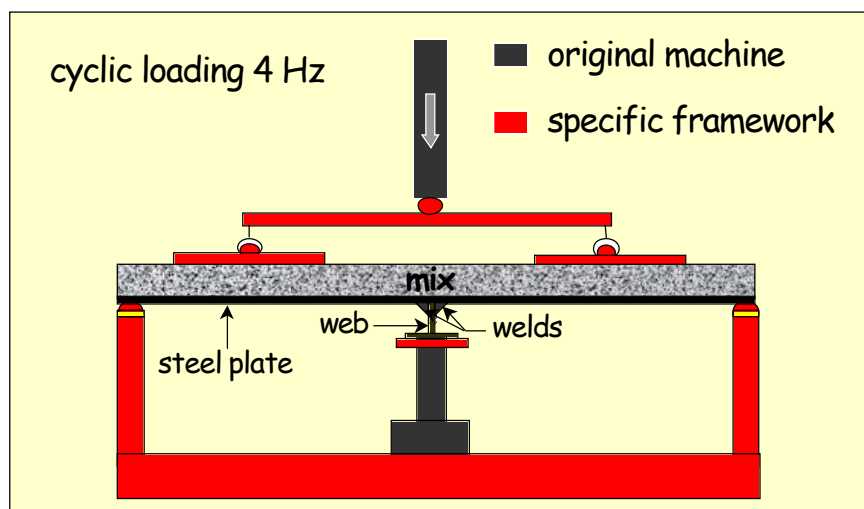

Figure 5: Testing machine for five-point bending fatigue test (Saubot and Loup 2004, Héritier et al. 2005, Olard et al. 2005).

Table 1: Testing parameters.

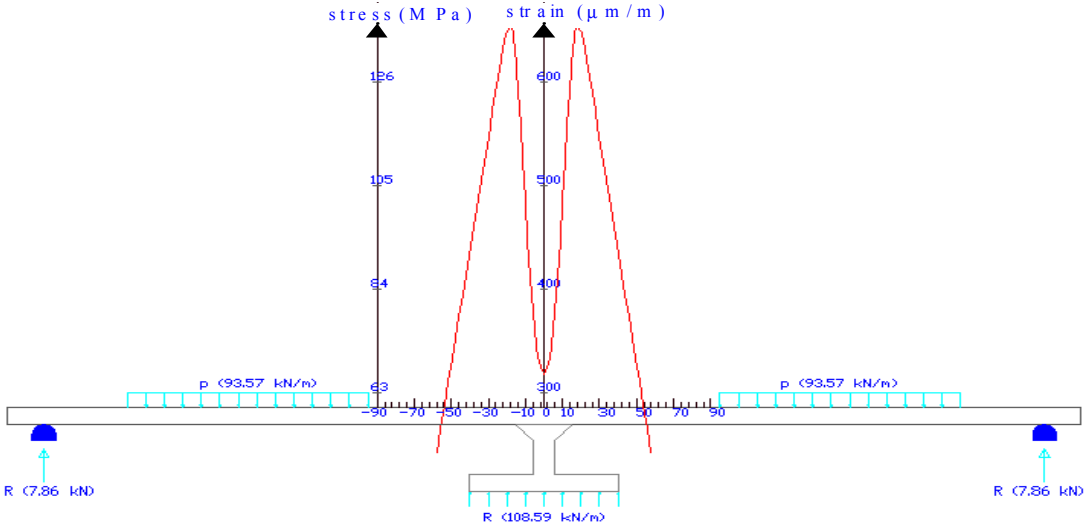| Geometry :	
- sample dimensions	580 x 200mm
- support positions	270mm between extreme and central supports
- shoe dimensions	130 x 220mm
- shoe positions	65mm from the ends of the samples
Loading :	sinusoidal compression ranging between F_{max} and $0,1 \times F_{max}$, at a frequency of 4Hz
Temperatures :	+10C and -10C
Number of cycles :	2 million at +10C and 1 million at -10C

Figure 6: Stress diagram over the central web welds for a 12mm thick steel plate.
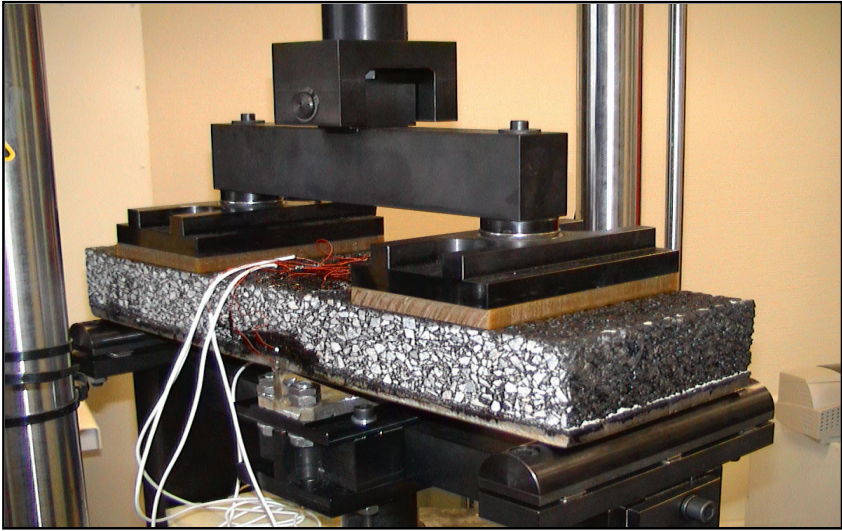

Figure 7: Machine used for the performance of the five-point bending fatigue test.

4.3 Observations during the test and acceptance criterions

The observations are carried out thanks to rupture witnesses and to strain gauges placed in the central zone, on the upper side of the mix (detection of the appearance of a crack in the central zone, follow-up of its propagation towards the edges of the sample) and on the lateral sides

5

(detection of delamination at the steel/sealing and sealing/mix interfaces, crack depth measurement in the bituminous mixture) (Fig. 7). Requirements for this constructive work were to obtain at the end of the test : *i)*no separation at steel/sealing and sealing/mix interfaces, *ii)*least crack depth in the mix at 10C and 2 million cycles, and at -10C and 1 million cycles.

4.4 Bituminous mixtures tested in laboratory

Various PMB's (different crudes, different polymer types and levels) were tested with one type of aggregate and grading. The mix samples had a continuous 0/10mm amphibolite grading, a 6% void content and a binder content of 5.8% by weight of the aggregate. The tested materials can be divided into three groups :
    - A group : 70/100 pen grade bitumens modified with SBS,
    - B group : 160/220 pen grade bitumens modified with SBS,
    - C group : 160/220 pen grade bitumens modified with EVA.
   A binder of the B group was selected, allowing the mix to satisfy all the criteria given in section 2 and to have a strong resistance to fatigue. This specifically developed binder is a "special" 160/220 pen grade base bitumen modified with a very high content of SBS and with in-situ cross-linking. The corresponding mix is called Orthochape®. Eventually, in parallel to this work, the low-temperature failure properties of the bitumen, selected by the previous performance-based methodology, were evaluated in accordance with the AASHTO MP1a standard. The so-called critical cracking temperature (T_{cr}) of the selected highly polymer modified bitumen (HPMB) equals -30C, which ensures a very good resistance to thermal cracking.

Table 2: Main results of rutting and fatigue resistance for groups A, B and C.

Group	A	B	C
Rut depth at 60C/30 000 cycles	4 to 5%	3 to 8%	12 to 14%
5-point bending fatigue at 10C : - separation at the interface - onset of cracking at	no <300,000 cycles	no >400,000 cycles	no <100,000 cycles
- crack depth at the end of the test	-	0 to 40mm	40 to 50mm

Table 3: Five-point bending fatigue results obtained on the selected material.

Temperature	+10C	-10C
separation at the interface	no	no
onset of cracking at	nothing	nothing
crack depth : at 1 million cycles	-	0mm
at 2 million cycles	0mm	-
at 3 million cycles	4mm	-

5   PARAMETRIC FINITE ELEMENT STUDY

Bi-dimensional computer simulations were performed by using the code CASTEM 2000, to evaluate the strain and stress levels in the considered pavement system whatever the material stiffness. In a first approximation, the steel along with the bituminous sheet and the mix were assumed as linear elastic materials. Some complex modulus tests were performed in parallel on Orthochape[®] and on the sealing sheet, at the APPIA laboratory, with a view to evaluating their stiffness for a broad temperature and frequency range. Because of a lack of place, these results are not presented in this paper (cf. Héritier et al. 2005, Olard et al. 2005).

Figure 9 shows contours of transverse strains in the bituminous mixture layer in the case of a 12mm thick deck plate. From this figure, it can be seen that large horizontal strains (up to 450μm/m at 10C-4Hz) are generated at the pavement surface over the central web. For such high strain amplitudes, the mix has a highly non linear behavior. Indeed, the viscoelastic linearity limit of mixes is around 10^{-4} (Doubbaneh 1995, Airey et al. 2002). Non linear computations remain to be done. Extensive work with non linear FE analysis has already been done in the literature (*e.g.* Huurman 2003).

Furthermore, these contours of transverse strains suggest that the fatigue cracking most likely starts from the surface in the pavement, which agrees with the remarks mentioned in section 2.2 and with experimental results.

Besides, a FE parametric study which investigated the influence of the surfacing rigidity has been performed for a 14mm thick deck plate (that used for the slow way of the Millau Viaduct). The maximum transversal strain and stress at the surface of the considered pavement system are given in Table 4 and illustrated in Figure 10.
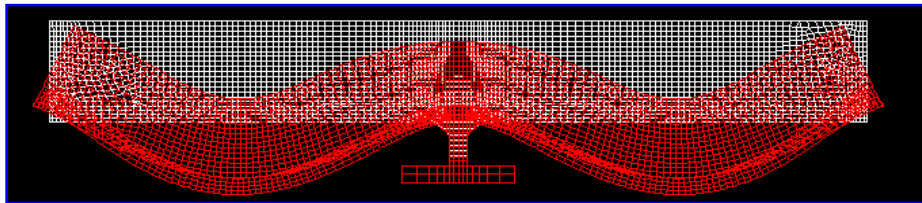

Figure 8: Cross section of the initial and deformed lab samp le (400x).
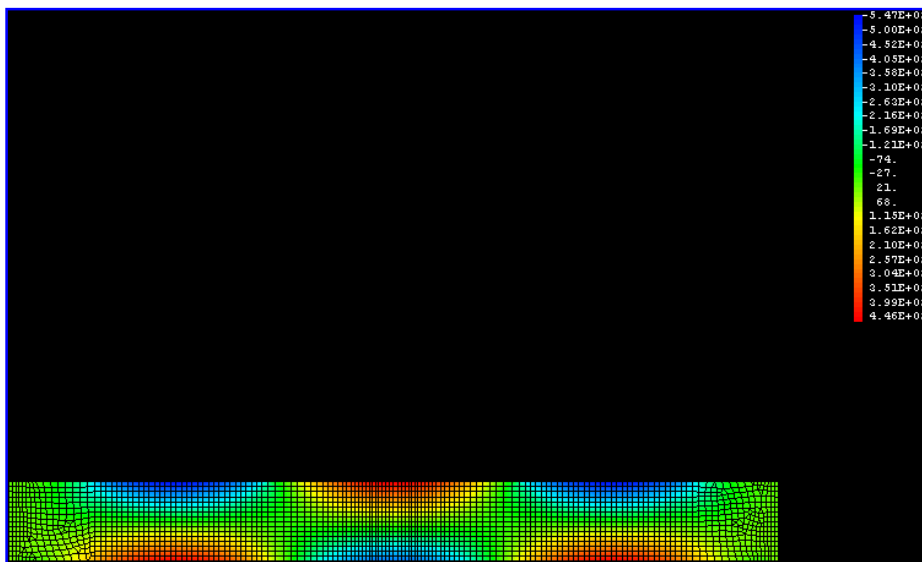

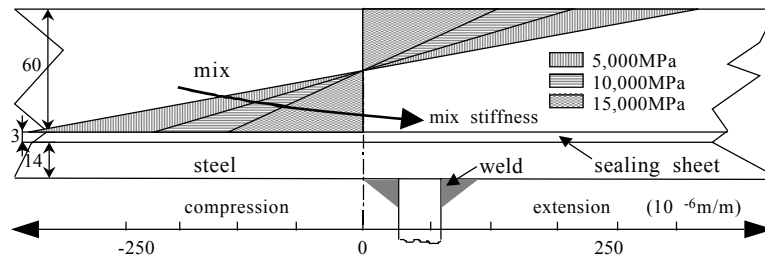Figure 9: Horizontal strains in the mix layer (12mm thick deck plate).

Figure 10: Horizontal strains in the surfacing for a 14mm thick plate and for different mix stiffness.

Table 4. Maximum horizontal tensile strain and stress in the mix (14mm thick plate).

E_{mix} (MPa)	ε_{xx} (µm/m)	σ_{xx} (MPa)
1,000	1250	1.5
5,000	400	2.3
10,000	185	2.4
15,000	130	2.5

6 APPLICATION OF THE MILLAU VIADUCT SURFACING

Before laying the bituminous mix, the sealing was carried out on the whole structure since April until September 2004. After that, application of Orthochape[®] lasted only four days (September 21-24). During the execution of this surfacing complex, the workmanship and materials were controlled closely (Courtehoux et al. 2004, Onfield 2004) so that 10 laboratory technicians were on the site. Conventional control tests were carried out for aggregates and binders at the two used mixing plants and at the tarping platform. During application of Orthochape[®], its temperature was measured on the paver screw and behind the paver screed. After the application, measurements of thickness, density, evenness and sand patch depth were done every day. Besides, it is noteworthy that two prior full scale suitability tests were carried out beforehand in Rivesaltes (on a plate of the same type with reduced dimensions) and in Millau (on the viaduct itself) with an eye to prepare this unusual roadwork. These two suitability tests made it possible to validate the technical choices, the manufacturing and control methods before applying the surfacing on the Millau Viaduct steel deck.

Figure 10: Laying Orthochape[®] on the Millau Viaduct.

7   CONCLUSIONS

The technical studies led in parallel to the construction of the Millau Viaduct (France) have provided the opportunity of new progress and have already made it possible to obtain the following achievements :

- development of a laboratory device reproducing the stresses undergone by a bituminous mix on an orthotropic plate. Other test conditions, with or without rest periods, can be used. Healing phenomenon will be studied in a complementary work,
- design of a highly polymer modified asphalt, called Orthochape$^{®}$, resistant to rutting, fatigue and thermal cracking, the applications of which can be numerous,
- some additional information relating to some PMB's, exceeding the only framework of orthotropic plates, and thus beyond the scope of this paper.

Improvements of the 5-point bending fatigue test are under consideration (*e.g.* follow-up of the macrocrack onset and propagation within the bituminous mix, *etc.*).

As regards the FE analysis, three main improvements are being considered :

- 3D FE analysis to check the relevancy of the 5-point bending fatigue test in comparison with a more realistic 3D geometry of the orthotropic bridge,
- taking into account the non-linearities of the material and even, if possible, the viscous effects under cyclic loading of traveling vehicles,
- fatigue law equations proposed by Bodin et al. (2002-04) can be easily implemented into CASTEM 2000. This point needs further investigation.

Eventually, as regards the realization of this exceptional work, the bringing into play of considerable resources made APPIA succeed in delivering within the deadlines a surfacing of the highest standard for the Millau Viaduct.

ACKNOWLEDGEMENTS

REFERENCES

Airey, G.D., Rahimzadeh, B., Collop, A.C., 2002. *Evaluation of the linear and non-linear viscoelastic behaviour of bituminous binders and asphalt mixtures.* Proceedings of the Sixth International Conference on the Bearing Capacity of Roads, Railways, and Airfields, Lisbon, Portugal.

Bodin, D., de La Roche, C., Piau, J-M., Pijaudier-Cabot, G., 2002. *A damage approach for asphalt mixture fatigue tests.* 9th International Conference on Asphalt Pavements.

Bodin, D., Belzung, F., De la Roche, C., Chabot, A. 2004. *Thermomechanical modelling for fatigue damage of bituminous materials.* Proceedings of the Fifth International RILEM Conference "Cracking in Pavements", Limoges, France.

Cadic, R., 1999. *Mesure de la résistance à la fatigue des revêtements de chaussée destinés à revêtir les tabliers métalliques d'ouvrages d'art. Essai de tenue à la déformation du support au droit d'un raidisseur.* Méthode d'essai L.P.C.

Courtehoux, M., Krafft, S., Héritier, B. 2004. *Réalisation des chaussées du Viaduc de Millau.* Revue Générale des Routes et des Aérodromes, N°834.

Doubbaneh, E., 1995. *Comportement mécanique des enrobés bitumineux en "petites" et "moyennes" déformations.* Thèse de Doctorat ENTPE-INSA.

Edwards, Y., Westergren, P., 2001. *Polymer modified waterproofing and pavement system for the High Coast bridge in Sweden*, VTI rapport 430A, Swedish National Road and Transport Research Institute.

Hameau, G., Puch, C., Ajour, A-M., 1981. *Comportement à la fatigue en flexion sous moment négatif.* Bull. de liaison des Laboratoires des Ponts et Chaussées, N°111.

Héritier, B., Olard, F., Loup, F., Krafft, S., 2005. *Design of a specific bituminous surfacing for the highest orthotropic steel deck bridge in the world : the Millau Viaduct.* Presentation at the Transportation Research Board annual meeting and Publication in the Transportation Research Record.

Héritier, B., Olard, F., Saubot, M., Courtehoux, M., Krafft, S., 2005. *Orthochape® : outstanding technical solution for the Millau Viaduct surfacing.* European Roads review, N°5.

Hicks, R.G., Dussek, I.J., Seim, C. 2000. *Asphalt Surfaces on Steel Bridge Decks.* Transportation Research Record, N°1740, Paper N° 00-0389.

Hulsey, J.L., Yang, L., Raad, L., 1999. *Wearing surfaces for orthotropic steel bridge decks.* Transportation Research Record, N°1654, Paper N° 99-1049.

Huurman, M., Medani, T.O., Scarpas, A., Kasbergen, C., 2003. *Development of a 3D-FEM for Surfacings on Steel Deck Bridges.* International Conference on Computational & Experimental Engineering.

Kolstein, M.H., Dijkink, J.H., 1989. *Behaviour of modified bituminous surfacing on orthotropic steel bridge decks.* 4th Eurobitume Symposium.

Lau, M-Y., 1978. *Ponts à dalle orthotrope. Principaux résultats des études effectuées au LCPC.* Bull. de liaison des Laboratoires des Ponts et Chaussées, N°94.

Méhue, P., 1981. *Platelages métalliques et revêtements de chaussées.* Bull. de liaison des Laboratoires des Ponts et Chaussées, N°111.

Nishizawa, T., Himeno, K., Uchida, K., Nomura, K, Higashi, S., 2004. *Longitudinal surface cracking in asphalt pavements on steel bridge decks.* Proceedings of the Fifth International RILEM Conference "Cracking in Pavements", Limoges, France.

Olard, F., Héritier, B., Loup, F., Krafft, S., 2005. *Design of a specific bituminous surfacing for orthotropic steel bridge deck.* Submitted to the International Journal of Road Materials and Pavement Design.

Onfield, J-N. 2004. *Millau viaduct. Wearing course applied.* Road News, N°138.

Saubot, M., Loup, F., 2004. *Settling of a bituminous coat on an orthotropic plate.* 3rd Eurobitume and Eurasphalt Congress.

Wøhlk, C.J., 1985. *Surfacing of steel bridge decks exemplified by the Faroe bridges.* 3rd Eurobitume Symposium.

Wolchuk, R., 2002. *Structural behaviour of surfacings on steel orthotropic decks and considerations for practical design.* Structural Engineering International, Vol. 12, N°2.