Improvement of a laboratory reflective cracking test by mean of the LCPC's APT FABAC machine

S.A. Pérez,
Belgian Road Research Center, Brussels, Belgium

J.M. Balay,
Laboratoire Central des Ponts et Chaussées, Nantes, France

Ch. Petit,
Université de Limoges, France

L. Wendling
Laboratoire Régional d'Autun, Autun, France

ABSTRACT: This experimental and numerical study concerns the maintenance and reinforcement of damaged pavements by mean of bituminous overlays. Its main objective is the improvement of the techniques used for pavement rehabilitation. In this domain, one of the major problems observed is the frequent incidence of reflective cracking over the top asphalted new layer. One experiment has been adapted then to evaluate this kind of damage on a small track in a full scale test using an Accelerated Pavement Testing (APT) machine. The experience made with this APT facility (FABAC) is the next step in the way to improve a laboratory test: the so called MEFISTO. This laboratory test equipment allows the evaluation of the behaviour of bituminous layers confronted to reflective cracking damage mechanisms. In order to determine the loading protocols of this machine, the results of the full scale test are compared to numerical calculations made with the 3D FEM software of the LCPC (CESAR).

1 INTRODUCTION

1.1 *Context*

The propagation of cracking from the base layer into the surface bituminous layers is one of the main mechanisms of deterioration in semi-rigid roadways and the repaired pavement. In both situations, semi-rigid and reinforced pavement, the cracking damage mechanism has the same characteristics.

A semi-rigid pavement structure has a base layer treated with hydraulic binders covered with an asphalt concrete surface layer. This base layer is expected to crack. Cracks on this kind of material are normal and they appear because of the thermal shrinkage.

The reinforced pavement has a bituminous overlay on top of a cracked pavement. The relationship established between the bituminous layer and the cracked layer in both cases is then alike and leads into a reflective cracking deterioration. In spite of the great number of roadways concerned, there is no reliable method to predict the development of reflective cracking as a function of the traffic and to determine the minimal thickness of the bituminous overlay necessary to reinforce a given damaged pavement.

There are few records of an operational test that can quantify the effectiveness of bituminous surface layer complex in reflective crack cases. Furthermore, neither the French Guide (SETRA-LCPC, 1994), nor American Guides (NCHRP1-37A 2005, NCHRP 9-19 2005) specifically addresses tests on this matter (Zhou & Scullion 2005). Many authors agreed that there is a lack of methods and simple and rapid tests equipments to characterize reflective cracking.

Some of the latest developments on this way are the Texas Transportation Institute Overlay Tester of the Texas Department of Transportation (Zhou & Scullion 2005) and the Wheel Reflective Cracking of the Universidad Politéctnica de Madrid (Gallego & Prieto 2006). In both cases the test can be classified as a behavior-related test but a behavior-based test is still needed.

The Laboratoire Central des Ponts et Chaussées (LCPC) is developing in France a new reflective cracking laboratory test based on the already existing test equipment called MEFISTO. The dimensions of the tested samples are the same as in the precedent test (Fig. 1). The final objectives are to predict reflective cracking and quantify life time service of different layer complexes used as surface layer on semi-rigid new pavements or in reinforced cracked pavements. This quantification of life time service depends on how realistic is the strain field reproduced on the sample and how close it is to the one induced by the traffic loads in the roadways. Therefore the MEFISTO test has been improved by modifying its configuration. From a displacement controlled test it has been changed into a force controlled test by adding two vertical hydraulic jacks. Due to this modification, in order to reproduce a realistic strain field on the sample, loading protocols must be defined to simulate the passage of the wheel.

To define these protocols the LCPC has worked on two main aspects. On the one hand, the simulation of strain fields leading to reflective cracking requires validated numerical tools related to the phenomenon of multi-layer material cracking. On the other hand it also requires accurate experimental data on the behavior and the damage of materials subjected to this phenomenon in a heavy loaded roadway.

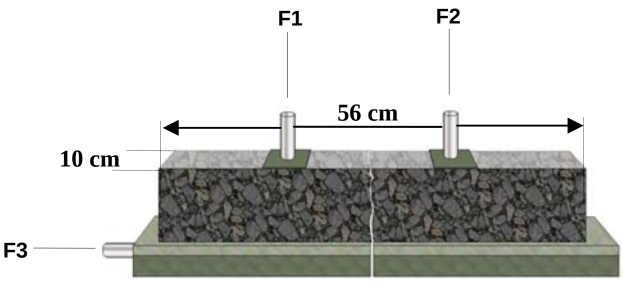

Figure 1. New laboratory test based on the equipment MEFISTO

1.2 *Objectives of the Accelerated Pavement Testing*

The experience made with the LCPC's linear APT facility (FABAC) was defined to study in a full scale test track the behavior of three complexes subjected to the reflective cracking damage. The collected data of the cracking propagation, the strains and the displacements are used to identify the good assumptions and the choice of numerical values leading to a satisfactory simulation of the reflective cracking in pavement, using the Finite Element Analysis (FEA).

The FEA numerical simulations are made with the software CESAR-LCPC (CESAR-LCPC 2001). The module used in this study is TACT – TACT stands for conTACT – which introduces different boundary conditions at the interface between the two top layers of the pavement. In the present work, after describing the APT experience, focus is made only on the results concerning reflective cracking initiation and its relevance for the model validation.

A successful validation of the model will allow its use into further numerical calculations of reflective cracking damages in other pavement structures. The next modeling steps are the evaluation of reflective cracking into a real pavement geometry and then into a sample laboratory test geometry. This final modeling will allow the definition of the loading protocols of the new laboratory equipment, reproducing a realistic strain field on the sample, leading into reflective cracking damages.

2 EXPERIENCE WITH THE APT FACILITY

2.1 *Equipment characteristics*

The LCPC has two FABAC machines. They are small heavy traffic simulators built in 1995. Theirs characteristics make them optimal for structural pavement researches. The main advantage of the LCPC facility is the possibility to apply the equivalent of 10 to 20 years (according to the real traffic intensity) of heavy loadings on a full scale pavement structure in less than two months.

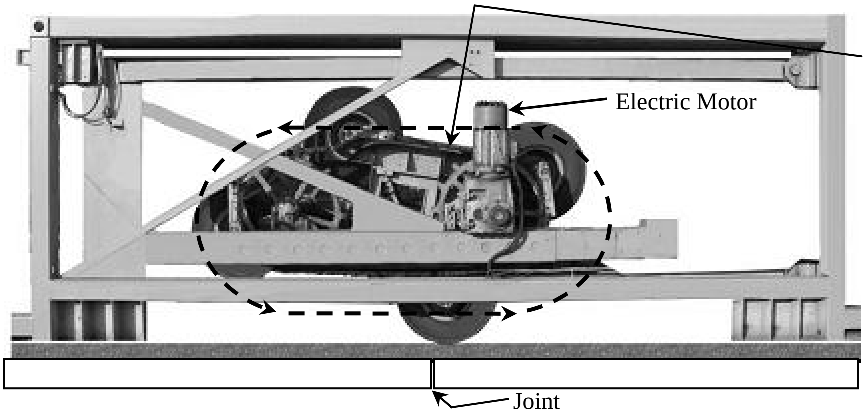

Figure 2. APT equipment used for reflective cracking test on full scale pavement structures at the LCPC.

The load applied by the twin wheel of this equipment is 65 kN, namely one half of the reference load of 13 tons on one single axle. Each machine has 4 twin wheels which are carried by a chain to apply the load in 2 meters of the test track (Fig. 2). Two experiences can be done at the same time but the size of the machines imposes a particular disposition of the surface layers.

2.2 *Test track configuration*

The pavement structure was specially adapted for reflective cracking testing. There were 3 main particular improvements implemented on the track for the present test. Those improvements concern the pavement structure, the transversal cross section and the instrumentation.

2.2.1 *The pavement structure.*

The test is performed on a 30 meters long track with eight discontinuities on the base layers. The pavement base is composed of three layers. The one at the bottom is a sand concrete cemented ribbon, over this one there is a granular asphalted layer and on top a concrete ribbon. This 2 meters width concrete ribbon is composed of nine adjacent slabs. The eight joints between them pass through all the base layer thickness simulating the crack in the pavement base layer. Their role is to avoid transfer displacements as cracks in semi-rigid base layer or in an old damaged pavement do.

Three different overlays have been placed over the pre-existing concrete pavement, constructed for a previous research (Pouteau 2004). The distribution of the different types of overlay over the total length of the concrete ribbon was determined taking into account the fact that the two machines had to run simultaneously on the two locations chosen for a given test, avoiding any obstruction between them.

Four of the structures have a surface layer composed of 6 cm of standard bituminous layer without any additional material (joints J3, J4, J5 and J8). These structures are set as the reference ones (referred to here as BBC). Two joints, J1 and J2, are covered with a composite layer made of 2 cm of sand bituminous mixed layer and 4 cm of regular bituminous layer (referred to here as SB+BBC). Finally the last two structures have 1 cm of a bituminous layer added with a Metallic Grid and 5 cm of regular bituminous layer (referred to here as MG+BBC).

The characteristics of all the materials were determined with classical laboratory tests made in the LCPC. The summary of the characteristics used on the FEA numerical simulations are shown in Table 1: the Young modulus in MPa (E), the Poisson ratio (ν) and the layer thickness in cm. The Young modulus of these materials was determined with the complex modulus laboratory test which defines the Young Modulus as a function of the temperature and the frequency of loadings. The first modulus value shown in the table 1 is the modulus of the bituminous layer for 20°C and 0.5 Hz. This frequency is defined by the velocity of passage of the wheels (1 m/s) and the longitude of the tested surface (2 m). To extrapolate calculations to real weather conditions, the Young modulus was also used in 10° and 0°C simulations (also shown in table 1).

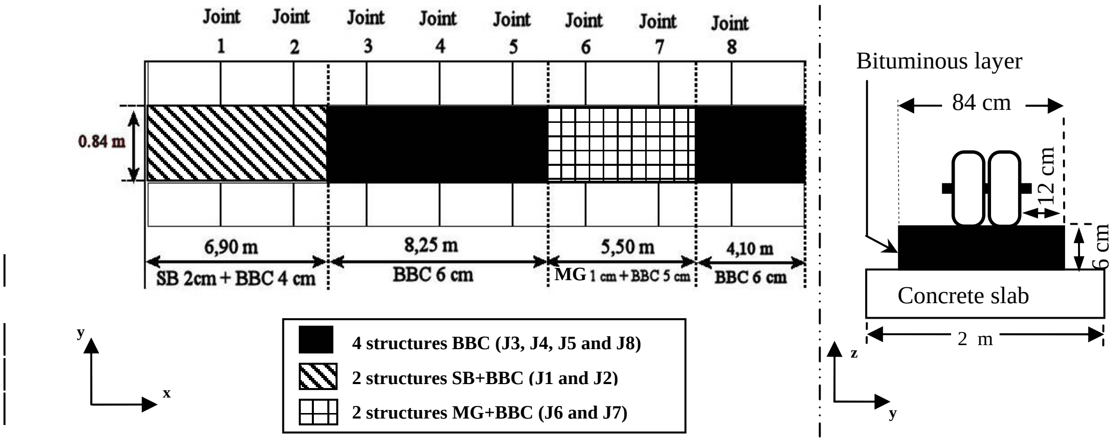

Figure 3. Position of the different surface layers on the tested track

Table 1. Characteristics of all the layer materials

Pavement layer	Young Modulus E (MPa) Temperature 20°C	10°C	0°C	Poisson Ratio ν	Thickness e (cm)
Bituminous layer	2000	8000	12,000	0.35	6
Concrete Slab	35,000	35,000	35,000	0.25	8
Granular bituminous layer	5000	10,000	17,000	0.35	10
Sand concrete cemented layer	2000	2000	2000	0.25	15
Soil	110	110	110	0.35	--

2.2.2 *The transversal cross section.*

Before setting the instrumentation, one improvement has been made to the track concerning its geometry. The best way to get information of the propagation of the crack under the loading application zone is the observation of the lateral faces of the track.

In order to obtain reliable data of the reflective cracking the track's width was reduced. The precise length over the twin wheel width was defined as the double of the thickness of the layer (Fig. 3). This reduction was optimized not only to facilitate the observation of the crack propagation, but also to avoid any creep of the material.

2.2.3 *The instrumentation of the test track.*

The main objective of the APT is to obtain accurate data to understand the structure behavior under rolling load making a parametrical study and validate the model in FEA numerical simulations. To ensure the correct and detailed acquisition of data associated to stress fields, vertical displacements, cracking propagation and thermal conditions, a large amount of sensors has been placed in the bituminous overlay. Four main types of sensors have been placed on the test track: strain gages for the transversal and longitudinal strains in the surface layer, LVDT for vertical displacement of the surface bituminous layer and the concrete slabs, lateral cracking evolution sensors for the propagation of the crack in the surface layer and thermocouples for the temperature inside and outside the pavement layers. The figure 4 shows the position of these sensors on each joint.

The strain gages at top of the surface layer are placed between the twin wheels without any cover material. The ones at the bottom of the surface layer are the so called H-shaped sensors consisting of horizontal stain gages protected by a resin coating. Two aluminum bars are attached to the extremity of the gage in order to ensure that the sensor is properly anchored to the material in which it is embedded. The LVDT sensors for measuring vertical displacement are fixed on a metallic beam. The cracking sensors consist of a horizontal net of silver paint made on the lateral face of the surface bituminous layer to detect the crack propagation. The acquisitions of those three types of measurement were realized two times per day during 40 loading cycles. The measurement of the temperature was made each 15 minutes.

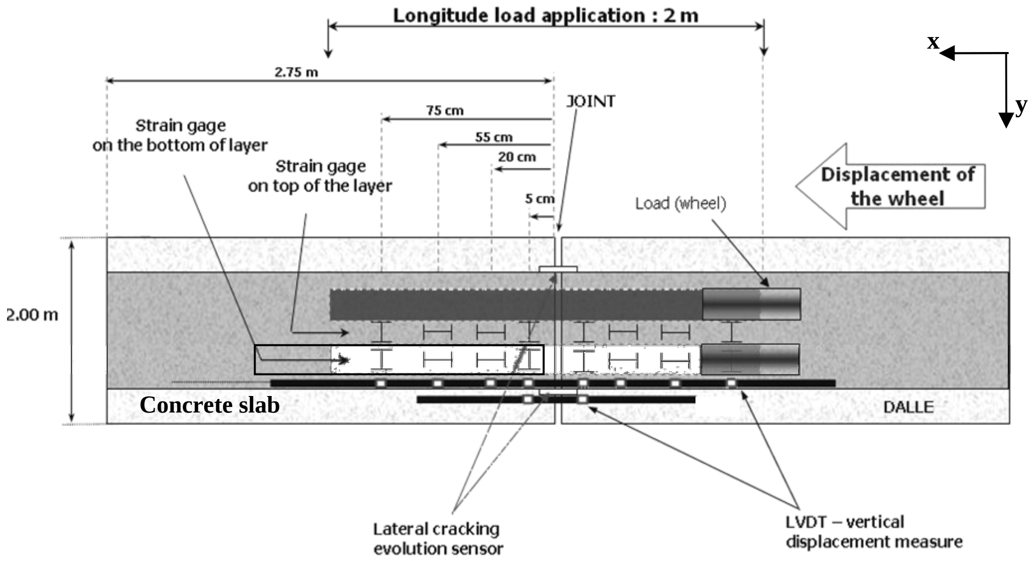

Figure 4. Instrumentation placed on each tested joint

2.3 *Test procedure and reflective cracking with APT facility*

Three series of tests have been performed until now. The principal restrictions to carry out the APT experiences are high temperatures. To avoid rutting and creep of the bituminous material, to be representative of the whole thermal condition over the total life duration of the real pavement, and also because high temperature considerably reduces reflective cracking, the tests have to be made in the cold periods of the year.

Schedule and final number of passages for the different experiences were different for each one of the series of tests:

- The joints n° 3 and n° 7 were tested between March and April 2005. The experience was stopped after 600,000 loading.
- The joints n° 2 and n° 6 were tested between end September and beginning of November 2005. The experience was stopped after 1,000,000 loading.
- The joints n° 1 and n° 5 were tested between January and February 2006 and between May and June. The last part of the third series was made at nightly to avoid high temperatures. A breakdown of an APT machine had stopped the experience for two months. The experience was stopped after 1,000,000 loading.

After each test, bonding properties between surface layer and concrete slab were studied near the joint by sawing and extracting the entire tested bituminous surface layer in small samples. For each sample the bonding condition was qualitatively defined as debonded, intermediate bonded or well bonded. From the observed interface and the collected samples, it is possible to conclude that three general bonding conditions were present:

- In some joints the contact between base layers and the surface layer presents large debonded zones. All strain gages related to the joint are in the debonded zone or at least in a transitional debonded zone. The joints concerned by this kind of debonding conditions are J3, J6 and J7. The two MG structures belong to this description. Those structures have been reinforced with a metal grid but they both cracked as fast as one of the baseline structures. Bonding interface properties had proved bigger influence on reflective cracks development than reinforcement of the layer.
- In one of the structures (J5 baseline structure) the debonded zone existed in a relatively short distance near to the joint. Half of the strain gages placed near to the joint were in a debonded zone and the other half in a well bonded zone or in a intermediate bonded zone (Fig. 5). Because of the big temperature variations during the third test series, the comparison between baselines structures J3 and J5 cannot be made without further analysis.
- One joint presented better bond conditions. Only very near to the Joint n° 1 the interface had intermediate or bad bonding properties but the rest of the interface presented good bonding properties. The sand bituminous structure is already used as a reflective cracking retarding.

This type of layer has a high thermal susceptibility and sometimes it can present other type of damages like creeping or rutting. After one millions of cycles the Joint n°1 didn't present any crack.

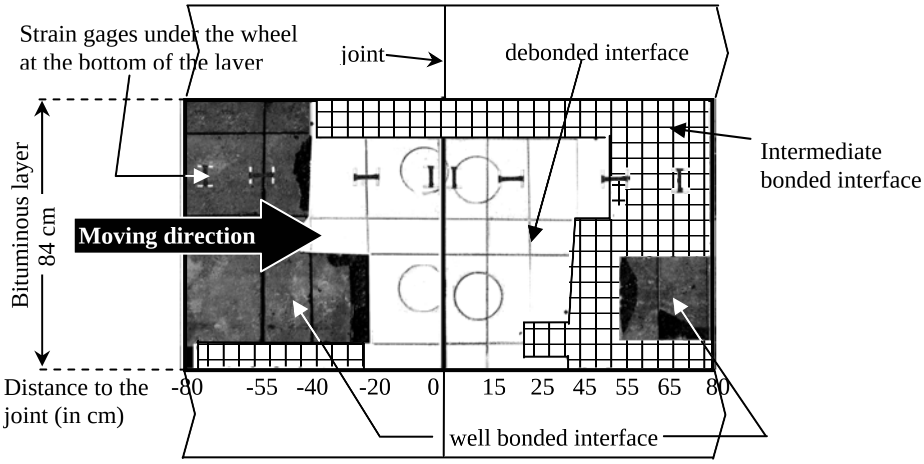

Figure 5. Example of collected data of the bonding properties of the interface (joint n° 5)

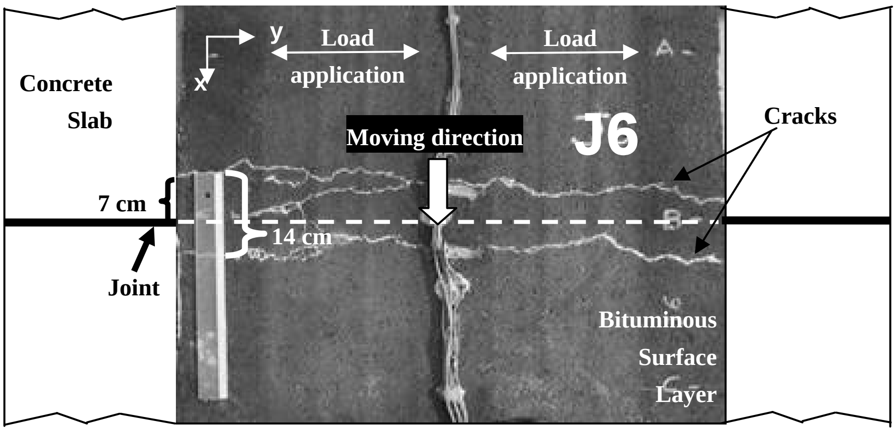

Figure 6. Top view of double reflective cracking over the tested joint n° 6

Table 3. Summary of the characteristics of the tested joints

Series	Joint	Type of structure	Average Temperature	Visual observation of Reflective Cracking (Cycle number)
1	J3	Bituminous baseline structure (BBC)	12°C	450,000
	J7	Metallic Grid (MG)		450,000
2	J2	Sand bituminous mixed layer (SB+BBC)	16°C	Creep
	J6	Metallic Grid (MG)		450,000
3	J1	Sand bituminous mixed layer (SB+BBC)	7°C and 21°C	No crack
	J5	Bituminous baseline structure (BBC)		500,000

The expected reflective cracking in thin asphalt overlay over existing Portland cement concrete is a double reflective cracking (Zhou & Sun 2002, Zhou & Scullion 2005). This cracking occurs only at joints with significant vertical movement, like in the cases of the joints n° 3, n° 6 and n° 7. The magnitudes of verticals movements are also related to the bonding interface characteristics. As in joint n° 5, a better bonded surface layer reduced them and the structure presented only one reflective crack. The double reflective cracking can be appreciated in figure 6.

The table 3 shows a summary of some of the results of the different tests. The temperature of the bituminous layer is calculated as the average of the temperature given by the two thermocouples in this layer. The average temperature shown in the table was calculated as the average of the temperature in the bituminous layer during the whole experiment.

3 NUMERICAL FINITE ELEMENT ANALYSIS OF THE APT EXPERIENCE

3.1 *CESAR FEA and its TACT module for contact calculations*

CESAR-LCPC is a finite element software, developed at the LCPC since 1981 (CESAR LCPC 2001), particularly adapted to the resolution of Civil Engineer problems (soil mechanics, structures calculations, etc). This program is composed of modules of data management and modules of execution. The module which is used here to solve contact calculation between two elastic layers is the module TACT.

The standard mesh for 3D calculations of CESAR-LCPC's finite elements code is made up mainly with parallepipedic isoparametric elements with 20 nodes. Those elements easily support automatic generation of volumes and definition of uniform multi-layer solids. The final 3D mesh made with this kind of elements also allows the use of flat contact element with 16 nodes. These elements were used to simulate the interface behavior. The module TACT is based on the method of penalization, which was particularly developed in CESAR software for contact element approach. The method of penalization introduces a very specific and variable rigidity matrix at the level of the interface. The reason of its variability is because the matrix depends on the state of the interface on each iteration (Salasca 1998).

3.2 *Numerical simulation parameters and series of calculations*

3.2.1 *Load characteristics*

A static vertical load is placed on the surface elements to calculate the strain and stress fields caused by the wheel on a particular position. To simulate the passage of the wheel, the load is placed on 9 different positions. The wheel shape is associated to a rectangle of 0.3 m x 0.2 m and the uniform pressure is 0.541 MN/m2.

3.2.2 *Bonded and debonded zones for calculations*

In the APT experiences it was found that the bonding interface properties between the surface layer and the concrete slab ribbon were particularly determinant in the reflective cracking. For the numerical simulations with CESAR software this parameter can be taken into account using the TACT module. This module permits to introduce double bar elements which can simulate two main bonding conditions. In the perfect bonded condition the continuity of the whole stress field is assured. In the perfect debonded condition the elements introduced assure the normal and tangential displacements and two tests are made: the first one to avoid interpenetration of the materials and the second to verify the normal stress value (which must be superior or equal to 0).

To define bonded and debonded zones the interface was divided in 6 zones on each side of the joint. The contact elements placed in these zones allow setting bonding interface properties in a chosen distance on each side of the joint. Calculations were made with the whole bonded interface and with different debonded distances from the joint: 0.05 m, 0.25 m, 0.45 m, 1.75 m. Combinations of symmetrical and non symmetrical debonded areas were calculated using these distances.

3.2.3 *Number of load positions for calculations*

To simulate the passage of the wheel over the joint, 9 positions of the load were define for symmetrical debonded calculations and 17 positions were defined for non symmetrical calculations. Some of the load positions correspond also to a sensor position.

3.2.4 *Materials and mesh characteristics*

For each position of the load one mesh must be established. In order to optimize the software capacity only the pavement under the load and near the joint had a very dense mesh. To simplify calculations only one half of the track was considered in the modeling by using the existing symmetry to the xz plane. This means that only one wheel of FABAC's twin wheel was modeled. To take into account the effect of the other adjacent discontinuities, 3 concrete slabs were set in the calculation meshes. The discontinuities were set geometrically by defining a void at the position of the joint. The properties of the materials are the ones defined before in table 1. Three different calculations changing the Young Modulus for temperatures of 0°C, 10°C and 20°C were made for each position of the load for each combination of debonded zone.

3.2.5 *Summary of the combination made of calculations*

Each data acquisition taken during the test has a specific temperature and bonded area, so a vast number of calculations should be made. These parameters were then combined to guarantee a complete analyze of the accelerated pavement test. At least four symmetrical debonded calculations were made for three temperatures (243 FEM individual calculations) and two non symmetrical debonded calculations for the same three temperatures (102 FEM calculations).

3.3 *Validations results*

The number of measures realized for each test was about 100 data acquisitions. In each data acquisition, 20 passages of Fabac wheels were stored for the 31 sensors placed in the test track (strain gages, LVDTs, thermocouples, cracking sensors).

The thermocouples information will be always implicitly linked to the other sensor's data. In the initial phase, before cracking reflection, the vertical displacement data is used only to pre-calibrate the model.

To study the initial strain/stress conditions leading to the reflective crack initiation the strain gages measurements at the bottom of the surface layer were used. These sensors were able to record small changes and their behavior can be associated to the bond interface evolution properties.

First calculations were compared to single position response of the sensor on the track (Fig. 8). The strain values of the joints presenting debonded interfaces during the test were coherent with the CESAR's calculations debonded case.

In figure 8, results present the existing static strain field in the entire section for a position of the load on each case. The CESAR curves represent limit control values of the calculations since one of the curves is issued from the 0°C calculation and the other one from the 20°C calculation. For this particular measure of the strain in the test track, the temperature was 17.5°C. The strain gages placed on the bottom of the surface layer were placed at 75 cm and 5 cm after the joint. As it is shown in the figure 8 strain gages data results are mostly placed in between the two limits established by the FEA calculations.

The next step to completely define the initial strain field on the test track is to make, for the whole passage of the load, FEA calculations and confront them to the whole sensor's response. An example of this comparison is shown in figure 9. In this figure the curve represents the response of the strain gage placed 75 cm before the joint as the wheel passes over the slabs and the joint n° 2 and n° 6. The temperature of APT Joint n° 2 and n° 6 data is 17.5 °C and the calculations temperatures are 10°C and 20°C. The test results are correctly placed between 10°C and 20°C validating calculation hypothesis concerning the bonding properties of the layers and the material properties.

For all the initial strain fields in all the tested joints the same exercise was done and the same good correlation between observed bonding conditions and bonding calculation hypothesis were obtained.

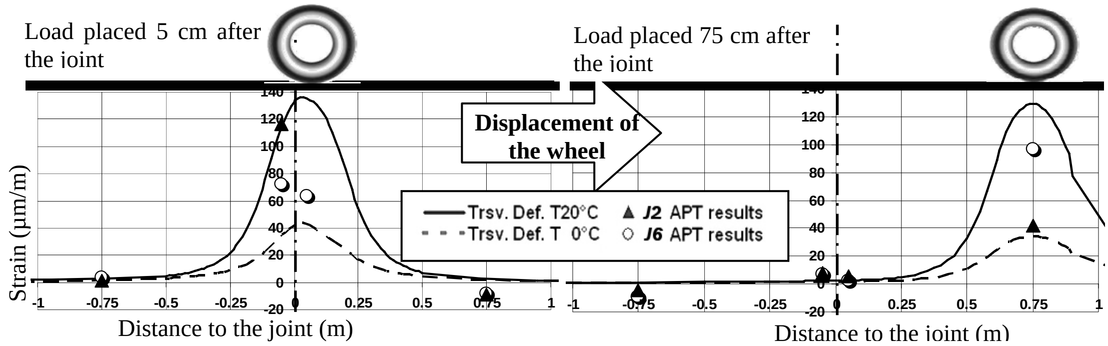

Figure 8. CESAR calculations for 2 positions of the load compared to punctual values obtained with the strain gages at 75 and 5 cm before the joint. Temperature of the acquisition: 17.5 °C

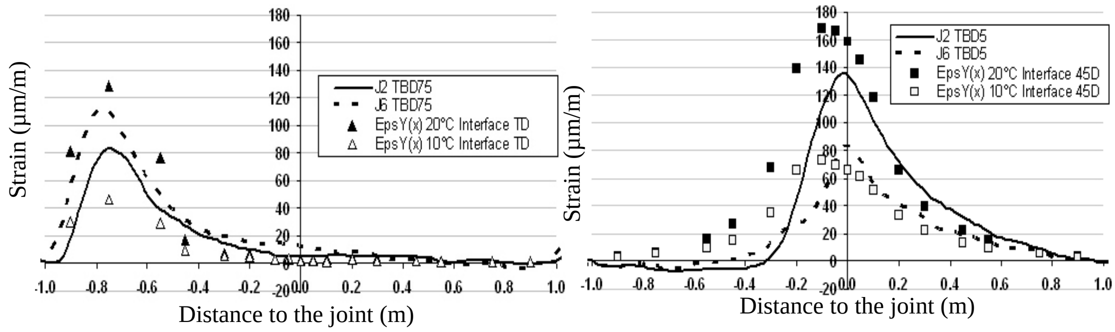

Figure 9. Comparison between an APT strain gage acquisition data placed 75 cm and 5 cm before the joint for one passage of the load (Temperature 17.5°C) and CESAR results for 10°C and 20°C.

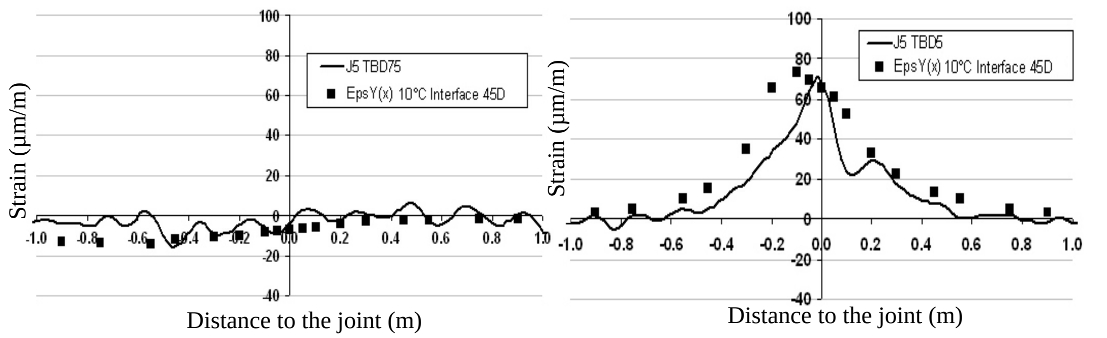

Figure 10. Comparison between an APT strain gage acquisition data placed 75 cm and 5 cm before the joint for one passage of the load (temperature 11°C) and CESAR calculations results for 10°C.

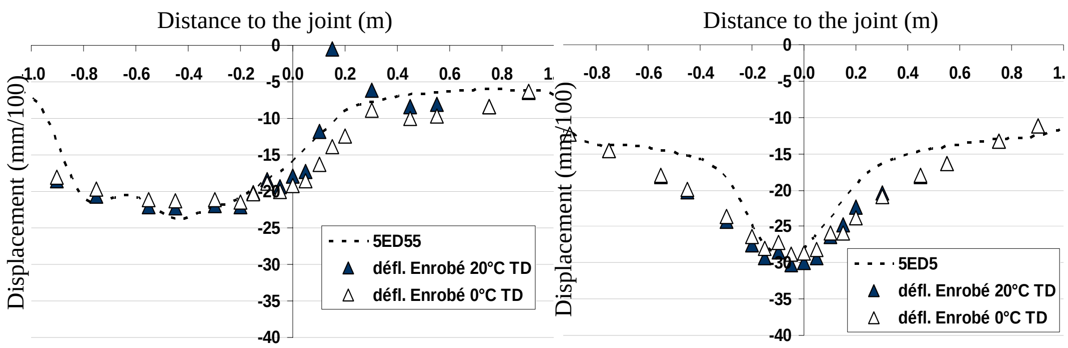

Figure 11. Comparison between an APT deflection acquisition data placed 55 cm and 5 cm before the joint for one passage of the load (temperature 11°C) and CESAR calculations results for 10°C and 20°C.

As an example, figures 10 and 11 show the case of a partially debonded joint (§2.3 and Fig. 5). In this case, bad bonding properties were observed only very near of the joint. Here the temperature test was 11°C. In this case, the measured data fits very well with the 10°C CESAR calculation for a partially debonded condition of the interface (only 45 cm debonded interface on both sides of the joint). All the other strain gages under the twin wheel present similar good correlations between experience and calculation when bonding properties are correctly defined.

4 CONCLUSIONS AND PROSPECTS

The large amount of precise and accurate experimental data has demonstrated the utility of the Accelerated Pavement Testing in the reflective cracking simulations. There is no record of an APT reflective cracking test using neither the kind nor the amount of instrumentation used for the present test.

For the first time it was possible to record and to visualize cinematically, in a full scale pavement structure, the reflective cracking propagation, using very simple instrumentation by optimizing its position on the pavement structure. The advantage to be able to put the instrumentation very close to the loaded road is an advantage only given by the APT facility and it wouldn’t be probably possible in a real pavement. Also, concerning the acquisition of strain data, the test presents some new punctual data values of the strain field occurring on a full scale pavement. With this data the initial strain and stress field could be deduced.

Conclusions of the impact of bonding interface properties in the reflective cracking evolution were then confirmed using the FEM code of calculation CESAR and its contact module (TACT) simulating the structure test pavement including the bonding interface properties.

The calculations results match particularly well to the strain data obtained from the test. Further more, theoretical types of cracking evolutions depending on bonding interface conditions were also confirmed by crossing experimental failure data (test recorded data and failure observation conclusions) and strain field calculation data. Namely when single or double reflective cracking occurs, the specific causes are detected and their relationship is coherent in the experiment and the numerical simulations.

Finally, since the FEA software is validated for the reflective cracking Accelerated Pavement Test, further simulations have been made to reproduce on the MEFISTO sample, the results from this APT reflective cracking experience. The next step is to optimize the position of the vertical hydraulic jacks and the magnitude of the forces that must be applied on the laboratory test sample to simulate the loading leading to reflective cracking.

5 REFERENCES

CESAR-LCPC 3.3 2001. Le code de calcul CESAR. 2e édition – Mode d’emploi.

Gallego J. and Prieto J. N., 2006. New Laboratory Equipment for Study of Reflective Cracking in Asphalt Overlays. 2006 Annual Meeting of the Transportation Research Board of the National Academies. ISSN 0361-1981. Issue Volume 1970 / 2006. DOI 10.3141/1970-25. Pages 215-222.

NCHRP 1-37A, 2005. Development of the 2002 Guide for the Design of New and Rehabilitated Pavement Structures: Phase II. College Station, Texas, Mar. 1, 2005.

NCHRP 9-19, 2005. Superpave Support and Performance Models Management. College Station, Texas, Mar. 1, 2005.

Pouteau, B. 2004, Durabilité mécanique du collage blanc sur noir dans les chaussées. Thèse de Doctorat. Ecole Central de Nantes, Université de Nantes. France.

Salasca, S. 1998; Phénomènes de contact dans les chaussées en béton : modélisation théorique et validation expérimentale. Thèse de Doctorat. Ecole Central de Nantes, Université de Nantes. France.

SETRA-LCPC, 1994. Conception et dimensionnement des structures de chaussée. Guide Technique. Ministère de l’équipement des Transport et du Tourisme. Paris, France.

Zhou, F. & Sun, L. 2002. Reflection Cracking in Asphalt Overlay on Existing PCC, Proceedings of the 9th International Conference on Asphalt Pavements, Copenhagen.

Zhou, F. & Scullion, T. 2005. Overlay tester: a rapid performance related crack resistance test. Texas Transportation Institute & The Texas A&M University System, USA.