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Accelerated pavement cracking testing. Experimental and finite element analysis

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ABSTRACT: In the domain of pavement reinforcement one of the major problems is the frequent incidence of reflective cracking over the top asphalt new layer. One experiment has been done to evaluate this kind of damage in a full scale test using an Accelerated Pavement Testing (APT) facility to improve the methods evaluating reparation quality. The experiment was performed on a 30 m track where 8 transversal joints were established by sawing the sub-bases in order to ensure a reflective cracking in the bituminous layer after applying traffic heavy loads. The width and the thickness of the bituminous layer were optimized and a number of sensors measuring deformations, temperature, vertical displacements and crack evolution were used. The experimental data has been compared with numerical computation results made with the CESAR-LCPC's FEA software. This comparison had lead to a validation of the calculation hypothesis and a better understanding of the reflective cracking failure mechanism.

1 INTRODUCTION

1.1 *Context*

One of the main mechanism of deterioration in semi-rigid roadways and the repaired pavement is bottom-top propagation cracking into the surface bituminous layers of the base layer's cracks. 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 and 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 is 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 Politécnica 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.

Two main approaches to predict reflective cracking can theoretically be used. The first one is to improve mathematical models of the cracking initiation and propagation phenomenon. The second one is to develop a laboratory method associated to a particular innovative reflective cracking test. In both cases pertinent precise data will be required to validate and/or calibrate the calculations or the procedures. In the “Laboratoire Central des Ponts et Chaussées” (LCPC) the second approach is being developed over the last years.

Different investigations were undertaken on this subject and today the objective is to set a new laboratory test – MEFISTO2 – to predict reflective cracking (Fig. 1). Most precisely, this test equipment is to be created based on the equipment MEFISTO and it will be able to quantify life time service of bituminous layer complex used on top of semi-rigid pavements or in reinforced cracked pavements supporting heavy load traffic. The dimensions of the tested samples are the same as in the precedent test (560mm x 110mm x 95mm), but with the new adjustment the definition and the reproduction, on the sample laboratory test, of a realistic strain field will be possible. This strain field of cracked pavements under real loading conditions, needs validated numerical tools.

To respond to this necessity the LCPC has worked on two main aspects. On the one hand, the simulation of reflective cracking requires numerical models 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.

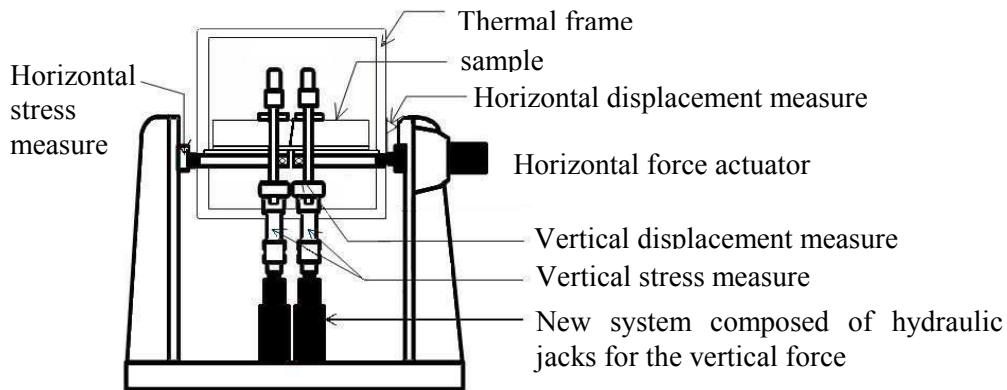


Figure 1. New laboratory test based on the equipment MEFISTO

1.2 Objectives of the Accelerated Pavement Testing

The experience made with this APT facility (FABAC) is the next step in the development of a new laboratory equipment to evaluate the behaviour of bituminous layers confronted to reflective cracking mechanism.

The data of cracking, strains and displacements obtained on the test track with the APT facility 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 concerning reflective cracking. 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 define the loading protocols to reproduce reflective cracking conditions when testing the sample with the new laboratory equipment MEFISTO2.

2 EXPERIENCE WITH THE APT FACILITY

2.1 Equipment characteristics

The two FABAC machines are small heavy traffic simulators built in 1995. APT characteristics make it optimal for structural pavement researches. In this particular case the main advantage of the LCPC facility is the ability to apply the equivalent of 10 to 20 years (according to the real traffic intensity) of heavy loadings on a full scale pavements structure less than two months.

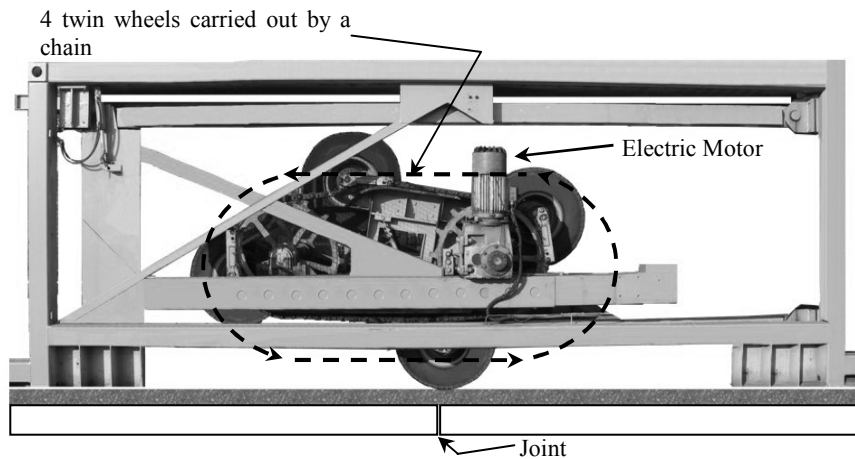


Figure 2. LCPC APT equipment and track structure pavement for reflective cracking test.

The load applied by FABAC's twin wheel 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 8 discontinuities on the base layers. The pavement base is composed of 3 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 9 adjacent slabs. The 8 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 2 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.

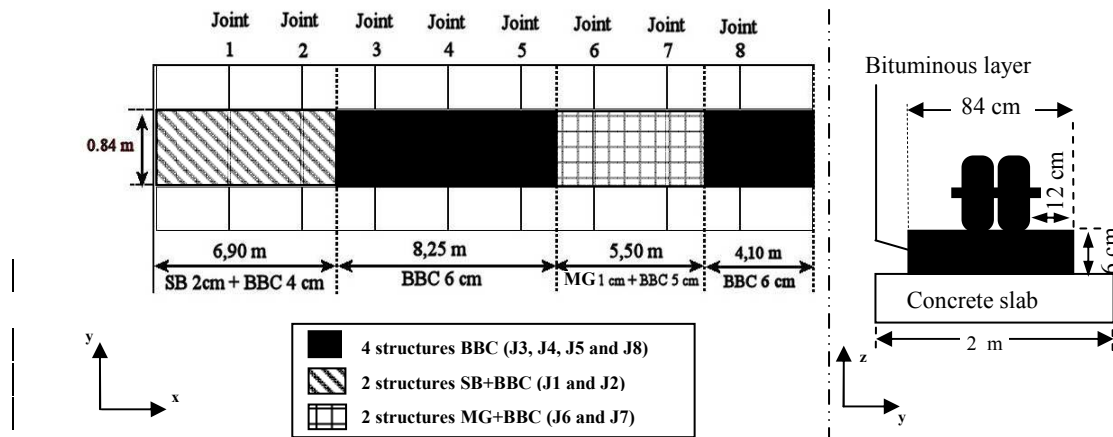


Figure 3. Position of the different surface layers on the tested track

Bituminous layers are thermally susceptible. 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 table 1 corresponds to the temperature of 20°C and a frequency of 0.5 Hz, which corresponds to the velocity of the experiment. To extrapolate calculations to real weather conditions, the Young modulus was also used in 10° and 0°C simulations (also shown in table 1).

Table 1. Characteristics of all the layer materials

Pavement layer	Young Modulus E (MPa)			Poisson Ratio ν	Thickness e (cm)
	Temperature				
	20°C	10°C	0°C		
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. As it is shown in Figure 4, four main types of sensors have been placed on the test track: strain gages for the transversal and longitudinal strains, LVDT for vertical displacement, lateral cracking evolution sensors for the propagation of the crack and thermocouples for the temperature inside and outside the pavement layers.

As it was noted before in the present work only results of initial conditions causing reflective cracking are presented. Therefore the model results presented later on will take into account mostly:

- The data obtained from the strain gages placed at the bottom of the surface layer under one of the loading twin wheels.
- The thermocouples data results.

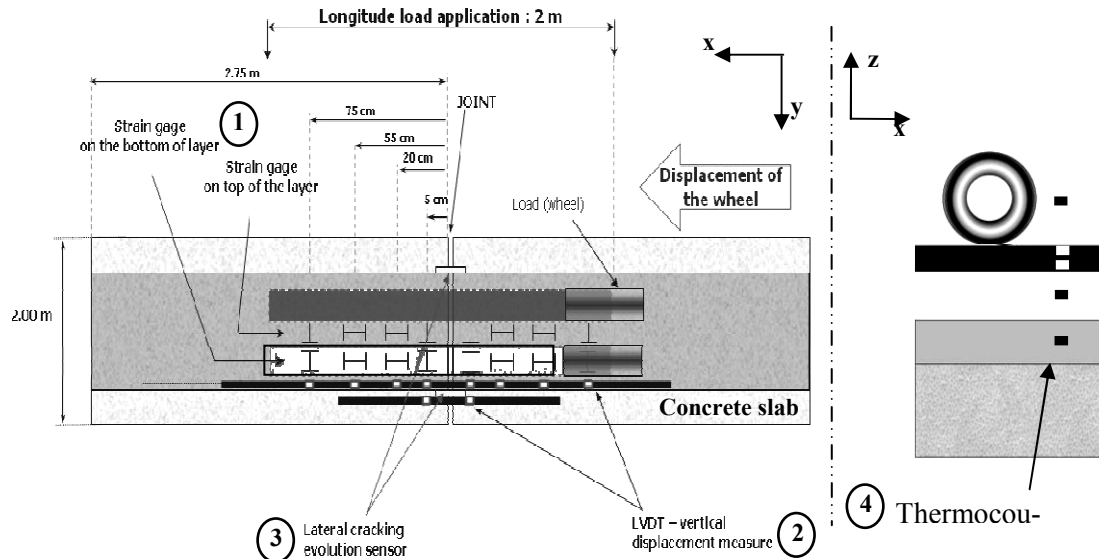


Figure 4. Instrumentation placed on each tested joint

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 night 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. From the observed interface and the collected samples, it is possible to conclude that three 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. 6). 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.

- Only 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.

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.

Table 2. Summary of the characteristics of the tested joints

Series	Joint	Type of structure	Average Temperature	Visual observation of Reflective Cracking
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)	4°C and 18°C	No crack
	J5	Bituminous baseline structure (BBC)		500,000

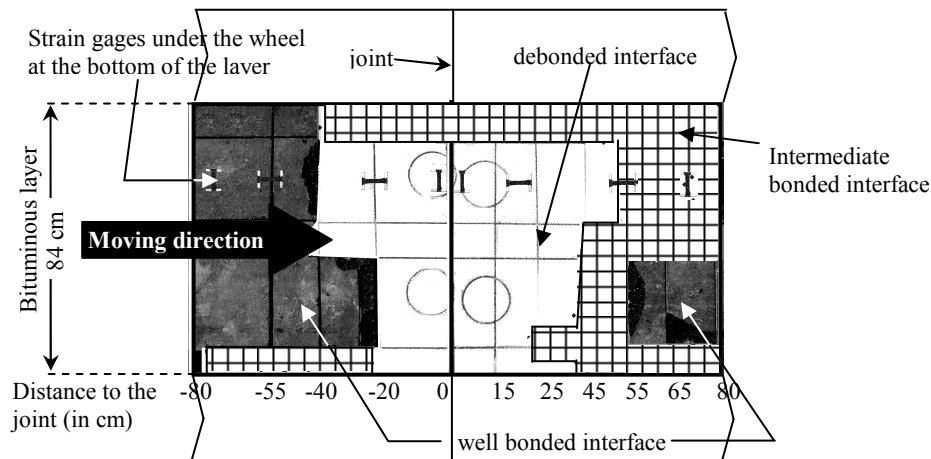


Figure 6. Example of collected data of the bonding properties of the interface (joint n° 5)

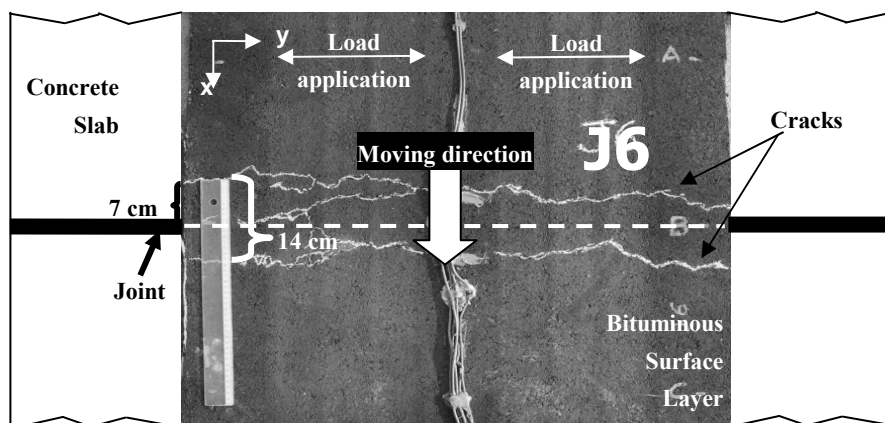


Figure 7. Top view of double reflective cracking over the tested joint n° 6

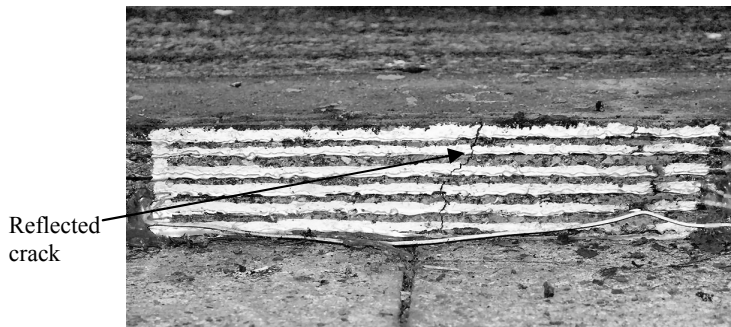


Figure 8. Lateral view of single reflective cracking over the tested joint n° 5

The difference between both types of reflective cracking can be appreciated in figures 7 and 8. In figure 7 the reflection of the discontinuity in the bottom layer had developed a double cracking while in figure 8 the joint n° 5 has only one.

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 parallelepipedic 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. 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 defined for symmetrical debonded calculations and 17 positions were defined for non symmetrical calculations. Some of the load positions correspond also to a captor 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 other adjacent discontinuities, 3 slabs were set in the calculation meshes. 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 captors placed in the test track (strain gages, LVDTs, thermocouples, cracking sensors).

The thermocouples information will be always implicitly linked to the other captor'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 captors 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 captor on the track (Fig. 9). The strain values of the joints presenting debonded interfaces during the test were coherent with the CESAR's calculations debonded case.

In figure 9, 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 9 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 captor's response. An example of this comparison is shown in figure 10. 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. As an example, figure 11 shows the case of a partially debonded joint (§2.3 Joint n°5 and Fig. 6). 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 strain gages under the twin wheel (transversal and longitudinal, distances to the joint 75 cm, 55 cm, 20 cm, 5 cm, on each side of the joint) present similar good correlations between experience and calculation when bonding properties are correctly defined using the bonding test information.

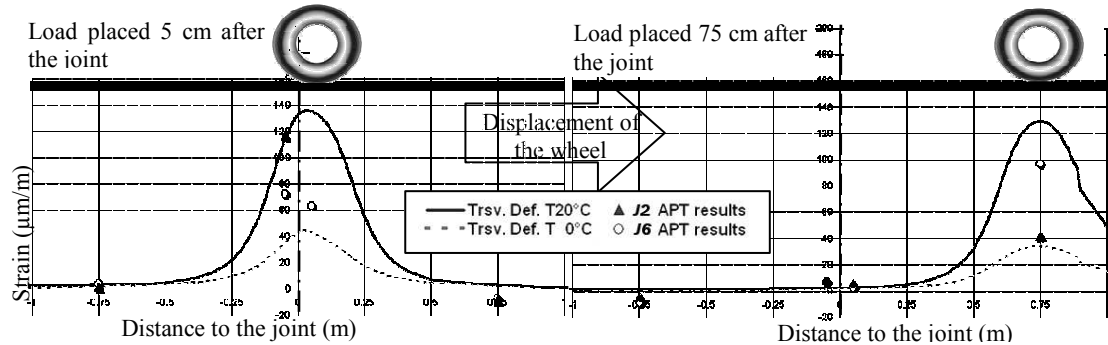


Figure 9. CESAR calculations for 2 positions of the load compared to punctual values obtained with the strain gages at 75 and 5 cm before the joint. Temperature of the acquisition: 17.5 °C

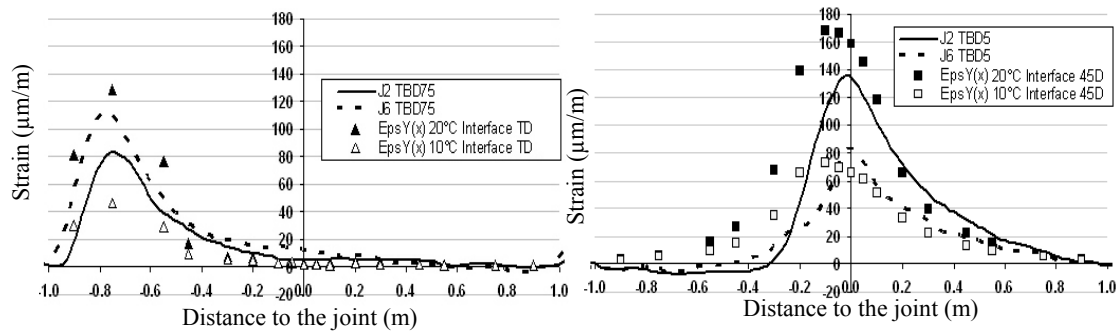


Figure 10. Comparison between an APT strain gage acquisition data placed 75 cm and 5 cm before the joint for one passage of the load (Temperature 17.5°C) and CESAR results for 10°C and 20°C.

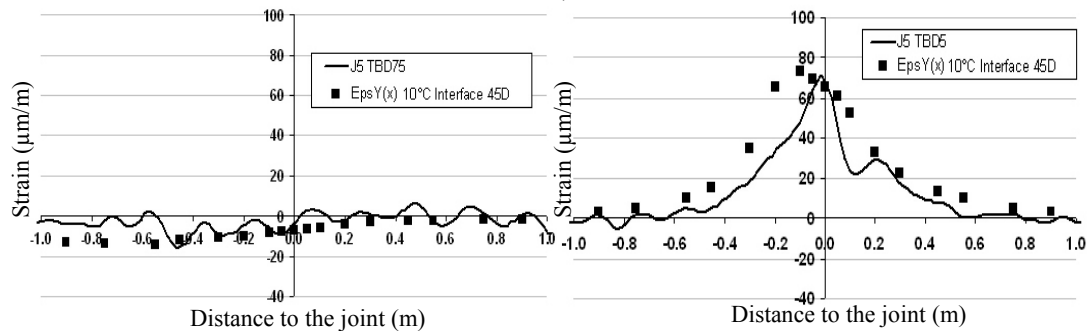


Figure 11. Comparison between an APT strain gage acquisition data placed 75 cm and 5 cm before the joint for one passage of the load (temperature 11°C) and CESAR calculations results for 10°C.

4 CONCLUSIONS AND PROSPECTS

The present Accelerated Pavement Testing used for reflective cracking simulation has demonstrated its utility by furnishing a large amount of precise and accurate experimental data useful in the study of this degradation phenomenon. 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. Furthermore, 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.

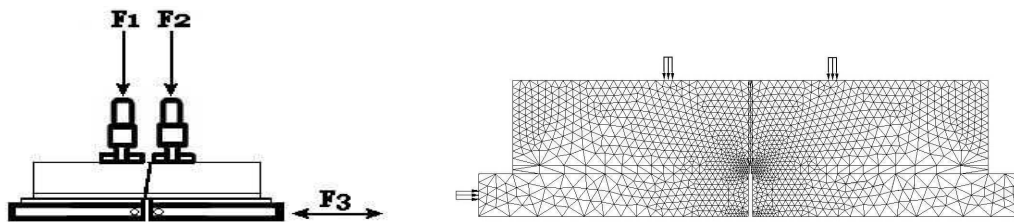


Figure 12. MEFISTO2 sample and FEA modeling mesh

Finally, since the FEA software is validated for the reflective cracking Accelerated Pavement Test, further simulations have been made to reproduce on MEFISTO2 sample, the results from this APT reflective cracking experience (Fig. 12 shows the mesh used). 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 MEFISTO2 sample to simulate the loading leading to reflective cracking.

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