ASPHALT CONCRETE OVERLAY EFFECT ON CONCRETE PAVEMENT SLABS CURLING

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I. INTRODUCTION

At both Charles de Gaulle and Orly airports (*Aéroports de Paris*), plain concrete pavements do not always perform as well as expected in the original design. The basic reason of this failure is often the underestimation of the temperature effects on the concrete slabs behavior.

First of all, the load transfer at joints due to grain interlock is lost by the slabs contraction in case of an uniform temperature drop. Pumping at the subgrade interface and slabs stepping result in premature cracking located at corners or near by the joint. Furthermore, warping deformation due to thermal gradients inside slabs may considerably change bearing conditions, especially for very stiff subgrades. The pavement is no longer supported uniformly and warping stresses may be so high that slabs crack. In the morning, the slab is concave and cracking occurs under corner loads or edge loads. In the afternoon, the slab is convex and the critical loading is the interior load.

Runways having a lifetime of more than twenty years are presenting such distress and have to be rebuilt or overlaid. Airport congestion makes it critical that pavement repairs or reconstruction be made in a timely manner, possibly during nighttime. This is the reason why an asphalt concrete overlay is the selected rehabilitation process at Paris airports

The overlay is designed according to the structural reinforcement needed, but also taking into account the reflection cracking (see Asphalt Institute *Asphalt pavements for Air Carrier Airports*). In order to delay the reflection cracking, an additional thickness may be necessary, or other alternatives. *Aéroports de Paris* has adopted the following arrangements :

- retrofit the existing joints with load transfer systems, keys and/or dowels ;
- mill the edge surface of slabs presenting stepping ;
- place a thin strain absorbing interface made of modified asphalt sand.

Additionally, the question has been raised as to whether the bituminous overlay has a role of a thermal shield, absorbing or damping the temperature variations in the cement concrete slabs. Such a black body could markedly limit the heat reflection and therefore the morning differential contraction of slabs. Moreover it can change the slabs curling and warping, that intuitively become more severe in case of thin surface layer (increase of thermal absorption because of black surface), and less severe in case of thick surface layer (reduced heat conduction because of bituminous layer). If these effects of a bituminous surfacing of concrete pavement could be better described and modeled, they could be taken into account :

- in the design of new concrete pavements, when future reinforcement by A.C. overlay can be initially considered ;
- and also in the design of bituminous overlays for existing concrete structures.

There is no reference so far to this effect in the design methods. Since the *Aéroports de Paris* overlays, including a 6.5 cm A.C., perform pretty well after five years, it is useful to tackle the problem and to try to find an estimate of this factor. A research program due for completion by the end of 1997 has therefore been carried out.

It comprises at first an experiment on a concrete pavement at Orly airport. In two untrafficked slabs, one of them being overlaid by 12 cm A.C., temperature distribution and associated vertical displacement are continuously recorded and compared since August 1995.

Secondly, the theoretical analysis of this data is done using the finite element program César-Lcpc developed by the *Laboratoire des Ponts et Chaussées*. The pavement is represented as a 3D elastic multilayered structure, and the model includes special interface elements permitting to simulate a variable and *a priori* unknown contact area between slabs and foundation. The objective is to validate a numerical model for the prediction of the behavior of concrete slabs subject to traffic loading together with various temperature conditions, including the effect of possible bituminous surfacing.

This paper presents the experiment conditions and the first experimental and theoretical results of this research, which is still continuing today.

II. LITERATURE REVIEW

The study of thermal effects in concrete slabs has previously been the purpose of various theoretical and experimental works.

The first rigorous analytical model was proposed by Westergaard [1] in 1926. The slab is likened to a thin elastic plate carried by a Winkler's (dense liquid) foundation without possible separation between the slab and the subgrade (full contact area). Westergaard developed formulas of deflections and stresses for a slab subject to a linear temperature profile through its thickness, for three cases : 1, slab infinite in both directions; 2, semi-infinite slab with two edges and 3, infinite strip of finite width.

Bradbury [2] extended Westergaard's model in 1938 to the case of a finite size slab and proposed a formula for thermal stresses at the edge and at the interior of the slab.

Harr and Leonards [3] in their turn extended this model in 1959 by introducing the possibility of separation between the slab and the subgrade (partial contact area).

In the sixties, Eisenmann [4] studied the behavior of a beam and a slab subject to a positive difference of temperatures between top and bottom. He specifically introduced the notion of critical length, that is the slab length from which the central deflection due to self-weight makes up for the expansion due to thermal effect : the slab lies on its foundation not only on its corners, but also on its center. There, the thermal tensile stress at the slab bottom reaches its maximum value. Eisenmann later extended his model to take into account the reaction of the subbase under the edges of a beam. He substituted the beam length with an effective span length, and modeled the reaction foundation by a vertical triangular distributed load proportional to displacement.

Silfwerbrand [5] was inspired more recently by Eisenmann's process to take into consideration the foundation effect on the behavior of a square slab under a positive temperature difference. He modeled the soil action by a vertical pyramidal load, the base of which is an isosceles right-angle triangle and which is proportional to displacement. The slab is characterized by its effective length which takes into account the bearing surface at the corners. Silfwerbrand perfected an iterative method to determine the bearing surface at the slab corners and the maximum thermal tensile stress.

The finite element method has naturally been applied to the study of thermal effects in concrete pavement. In two-dimensional subgrade reaction modulus models (Wesliq [6], Weslayer [6], Risc [7], J-slab [8], Feacons [9]), the slab is modeled as a thin plate on a dense-liquid foundation. The difference of temperatures between top and bottom of the slab is globally simulated either by imposing a spherical deformed shape ([6], [7]), or by applying a bending moment at the slab edges ([8], [9]). In three-dimensional multilayer elastic models (Abaqus [10], César-Lcpc [11]), the slab and its foundation are constituted with massive elements and thermal effects are locally represented by initial thermal stresses, complying with the vertical temperature profiles, possibly not linear.

Other experimental studies aim at characterizing thermal distribution in slabs. From the experimental results of the Arlington Road tests, Teller and Sutherland [12] showed in the thirties that temperature distributions through slab thickness were mostly non-linear. They suggested at this time that the hypothesis of linearity was safety, since it resulted in increasing the calculated bending stresses. Nevertheless, Lang [13] underlined at the same

period that the gap between the real temperature distribution and a straight-line relationship was small enough to neglect the non-linearity effect on thermal stresses. Using the FEM program Feacons and their model of temperature distribution introduced later, Choubane and Tia [14] showed that linear temperature profiles lead to overestimating stresses for positive thermal gradients and to underestimating stresses for negative gradients.

The prediction of temperature profiles in slabs was the purpose of Thomlinson's works [15]. He modified Westergaard's approach by supposing a simple harmonic temperature variation at the slab top surface in combination with the heat flow laws. He ended in the same types of temperature profiles as those obtained by Teller and Sutherland. Hsieh et al. [16] proposed a three-dimensional model based on the coupled theories of heat-moisture conduction through a semi-infinite, isotropic and homogeneous porous medium; the inputs required for the calculus are weather conditions and concrete and soil properties. Choubane and Tia [17] analyzed experimental temperature data measured on a concrete pavement built at the Florida Department of Transportation. They achieved a comparative study of the existing models for the prediction of temperature distribution and proposed to represent temperature in terms of depth by a quadratic equation. Kuo [18] corroborated this result by conducting finite element simulations of thermal conduction through concrete slabs experiencing temperature variations. His results showed that temperature distributions fit parabolic curves with 99 per cent correlation.

The conclusion of the present review is that models for the prediction of temperature distribution have been widely validated by experiments. But on the other hand, the models for evaluating the effects of temperatures gradients on displacements and stresses in slabs are short of experimental data for their validation. The experiment presented below provides such results.

III. PRESENTATION OF THE EXPERIMENT

The experimental site is located at Orly airport in a waiting area built in the mid sixties, and used to channel the traffic of taxiing planes before take off.

The experimented plain concrete pavement (see figure 1) consists of square slabs 7.5 meters long, 0.4 meter thick, made of crushed hard calco-silicate aggregates (30 500 MPa Young modulus). It rests on a 0.15 meter thick layer of cement bound graded aggregate subbase (0-31.5 mm grading, 20 000 MPa Young modulus). The subgrade consists of silty soils, with a mean CBR value of 6. The construction joints are keyed untied and the contraction joints are not doweled.

In order to evaluate the effects of a bituminous surface layer on the behavior of the pavement, two slabs named slab A and slab B were selected. A six-month preliminary phase was used to verify that the two slabs exhibit a similar behavior, by monitoring and comparing the internal temperatures and the curling and warping deformations. Then slab B was overlaid with 0.15 meter thick asphalt concrete (0-12 mm grading), spread in two layers on the surface previously cleaned and tack coated.

The experiment consists in continuously measuring the temperatures within the two slabs and the vertical displacements caused by thermal gradients. The environmental constraints such as site remoteness require the use of heavy-duty equipment consuming little power, if not self-powered. Moreover, the wing of the plane taxiing close to the experimental site requires that the height of instruments must be less than 0.25 meter which is the height of the beacons marking out the site. Finally, as usual at airport sites, Radar, Information Landing System and other hertzian connection systems which can affect the measurement quality must be dealt with.

Temperature measures are easily performed through 8 gauges placed on a vertical profile in slab A, and 10 gauges in slab B. All gauges are connected to a data logging device. The measurement of the vertical displacements is more tricky on one hand by lack of a reference basis, and on the other hand because of the climatic conditions affecting instruments (temperatures range from -20°C to +60°C at the slabs surface). Laser leveling coupled with inclinometer recording was used through manual readings during the first observation stage, before slab B was overlaid.

After overlaying slab B, both slabs A and B were fitted with eight high precision inclinometric sensors along half a diagonal, connected to the data logger (figure 1). The differential vertical displacements of slabs between their center and their corner are then calculated by integrating the inclinometric

measures. Inductance displacement transdu-cers were also placed at both the center and corner of another non-overlaid slab, in order to measure the contact opening between the concrete slab and the subbase.

Parallel to the previous continuous measurement, absolute vertical displacements are performed on slab A during short periods, by classical topographic measurement using digital equipment.

IV. EXPERIMENTAL RESULTS

The measurement on slabs A and B began in August 1995 and in November 1996. Continuous recording of temperatures and rotations are available from then through the present.

Examples of temperature results

Figure 2 represents the temperatures measured in the two slabs at different hours during a sunny day in April 1996. Accordingly to Choubane and Tia, the temperature distribution through the thickness of the slabs is strongly non-linear : it can be satisfactorily approximated by a parabolic curve in both slabs. Nevertheless, the non-linearity effect is less marked in the overlaid slab B.

The bituminous concrete does not exhibit any black body effect, insofar as temperatures are not more attenuated under ten centimeters of bituminous concrete than under ten centimeters of cement concrete. The daily amplitude of temperatures noticeably decreases with depth and it is strongly reduced by the bituminous overlay.

Figure 3 shows, for the 2 slabs, the mean thermal gradient overall the thickness of the slabs during a warm 2-day period of June 1996, corresponding with the more important recorded gradients :

- the variations are much lower in the overlaid slab B : they are comprised between -0.06 and +0.28°C/cm in this slab, and between -0.15 and +0.49°C/cm in the non-overlaid slab ;
- the thermal gradients are phase-delayed by 2 to 3 hours between the non-overlaid slab A and the overlaid slab B.

Synthesis of temperature measures

Figure 4 gives the distribution in percentage, during the 375 days of measurements, of the maximum and minimum daily temperatures at the surfaces of cement concrete of the 2 slabs :

- in the cement concrete of the non-overlaid slab A, the maximum daily temperatures are comprised between -5°C and +50°C and the minimum daily temperatures between -10°C and +50°C ;
- in the cement concrete of the overlaid slab B, the maximum daily temperatures are comprised between 0°C and +45°C, and the minimum daily temperatures between -5°C and +35°C.

The temporal distribution of temperatures at the bituminous concrete surface of slab B, not shown in this paper, is found to be roughly similar to the temporal distribution of the temperatures at the cement concrete surface in the non-overlaid slab A.

The bituminous overlay seems to attenuate extreme temperatures in cement concrete : it decreases maximum temperatures (maximum temperatures in the range [+40°C;+45°C] during 0.3% of the time in the slab B and in the range [+45°C;+50°C] during 1.9% of the time in the slab A) and increases minimum temperatures (minimum temperatures in the range [-5°C;0°C] during 4.8% of the time in the slab B and in the range [-10°C; -5°C] during 1.1% of the time in the slab A).
Figure 5 shows the temporal distribution in percentage, during the 375 days of measures, of the mean extreme thermal gradients. The bituminous overlay distinctly reduces extreme values of mean gradients : they are comprised between -0.3 and +0.5°C/cm for the non-overlaid slab A, and between -0.2 and +0.4°C/cm for the overlaid slab B.

In the non-overlaid slab A and in the overlaid slab B respectively, the mean thermal gradient :

- daily equals zero during two periods : 8h-12h, 18h-22h and 10h-14h, 20h-24 h ;
- reaches positive maximum between 12h and 15h and between 15h and 18h ;
- reaches negative minimum between 4h and 8h and between 6h and 10h.

Vertical displacements

The integration of inclinometers measu-rements along the diagonal of each slab leads to relative displacements between the corner and the center of the 2 slabs. Figure 6 illustrates the evolution of these displacements over the same previous 2-day period for the 2 slabs. Displacements in the overlaid slab B are reduced by 70% with respect to displacements in the non-overlaid slab A.

The evolution of the absolute vertical displacement of the non-overlaid slab A corner is shown in figure 6 ; its amplitude between a cold period and a hot period reaches 4.2 mm during the considered two days. On the other hand, the two other displacements measurements (topographic measurements and differential displacement) imply that the absolute vertical displacement of the slab center is extremely low : the daily amplitude is less than 1.5 mm. This observation is surprising and can only be explained through the hypothesis of an initial curling deformation of the slabs caused by temperature and moisture gradients during drying of concrete, as observed by Al-Nasra and Wang [19]. The resulting differential shrinkage could explain that the slabs edges curl upward in absence of thermal gradient, limiting the warping induced by a positive thermal gradient. This hypothesis about initial deformation of slabs will be dealt with in a particular theoretical FEM calculation, as presented below.

V. THEORETICAL INTERPRETATION

Analysis of temperature regimes

The prediction of the temperature regime within multilayered pavements can be performed in good conditions, using the thermal properties of materials and readily available meteorological data, as illustrated by Christison et al. [20]. But at present, the analysis by such a complete heat transfer model of temperature recorded on Orly's slabs has not yet been realized, since the experiment is still continuing, and all environmental data required are not yet available.

Nevertheless, a simplified theoretical analysis of the recorded thermal distributions has been achieved, by considering the changes in temperature at the pavement surface with respect to time as a known boundary condition, instead of setting a relationship between surface temperatures and the climatological factors of the site. The one-dimensional heat dissipation model in an homogeneous layer is naturally used. The governing heat conduction equation is :

$$c\frac{\partial T(z,t)}{\partial t} - k\frac{\partial^2 T(z,t)}{\partial z^2} = 0$$

where :

- T(z,t) = temperature at specific depth z and time t ;
- c = volumetric heat capacity ;
- k = thermal conductivity.

Because of complex boundary conditions and non-homogeneity of the structure, the heat conduction equation cannot be solved analytically. So the comparison between recorded and predicted temperature is made with the finite difference program Gel1d-Lcpc [21], which is generally used in France to determine frost line in pavement structures. The volumetric heat capacity and the thermal conductivity of pavement materials used as data for calculations are estimated using the values generally employed for thermal problems in roads mechanics, and found in literature. They are respectively :

- for asphalt concrete : $c = 1.96\ 10^6\ J/m^3/°C$ $k = 2.0\ W/m/°K$
- for cement concrete : $c = 1.70\ 10^6\ J/m^3/°C$ $k = 1.7\ W/m/°K$
- for cement bound gravel : $c = 1.75\ 10^6\ J/m^3/°C$ $k = 1.8\ W/m/°K$
- for soil : $c = 1.38\ 10^6\ J/m^3/°C$ $k = 1.1\ W/m/°K$

An example of the comparison between calculated and recorded temperatures for a selected hot summer day is presented in figure 7. Excellent agreement between calculation and measurement during all the temperature cycle for both slabs A and B is evident. This good agreement has also been obtained when simulating various periods distributed during all the experimentation. This suggests that temperature in concrete slabs covered or not by a bituminous layer can be predicted precisely enough by the one dimensional heat conduction model.

3D FEM modeling with César-Lcpc

Presentation of the model

The theoretical analysis of the experiment is made with the FEM program César-Lcpc [22]. The modeling of the structures is three-dimensional : each part of the structure (bituminous overlay, slab, foundation and soil-support) is discretized with one or several layers of hexahedral isoparametric elements with 20 nodes. All the materials are considered in the modeling as linear elastic. The possibility for the slabs to separate from their foundation under temperature variations is taken into account by integrating between slabs and foundation special hexahedral contact elements with 16 nodes. The program Cesar-Lcpc permits to resolve 2D and 3D contact problems and leads to the determination of the contact area at the slab-foundation interface, in addition to stresses and displacements. The algorithm is iterative and is based on the verification of 3 criteria :

- a non-interpenetrating criterion, which consists in verifying that slabs and foundations do not interpenetrate;
- a sliding criterion, which verifies the considered sliding law (in the circumstances, sliding law with Coulomb friction);
- and a separation criterion, which is triggered by the separation between slab and foundation, when normal stress at the interface becomes greater than the interface tensile strength.

The slab-foundation interface is assumed to be perfectly sliding, according to the interface state observed in a core sample cut out in-situ.

Contrary to 2D FEM thin-plate models in which only a uniform thermal gradient can be considered, the 3D Cesar-Lcpc model allows consideration of non-linear temperature profiles. The slabs response under various typical thermal conditions has been calculated by introducing temperatures measured at different depths. Figure 8 shows the non-overlaid slab A shape under a positive and a negative thermal gradients respectively. Note that only a quarter of the structure is represented in the FEM mesh, due to the double symmetry of the structure and of the load.

Comparison with experimental results

The comparisons between numerical and experimental results are first analyzed in reference to the relative vertical displacements between the corner and the center of the slab Δw. The experimental values of Δw result from integration of inclinometers measurements. Figure 9 compares, for the two slabs A and B, the variations of Δw, obtained experimentally and numerically, in terms of the thermal gradient between the top and the bottom of the slabs. The theoretical and experimental variations show reasonably good agreement for the two slabs. This

conclusion implies the proposed numerical model is very well suited to simulate thermal effects in concrete structures, both with regard to mechanical side and to the choice of physical coefficients values.

Nevertheless, some discrepancy is observed between the absolute vertical displacements calculated and measured : under a positive thermal gradient, experimental results reveal a very small vertical displacement of the slab center, whereas calculations lead to a consistent vertical displacement : for example, under a thermal gradient of 0.49°C/cm, the vertical displacement of the slab center obtained experimentally is less than 1 mm, whereas it is 3.2 mm when calculated.

This result can be explained by an initial partial contact between the slab and its foundation due to temperature and moisture gradients during drying, as underlined before (see *Experimental results)* and studied by Al-Nasra [19]. In order to verify the effect of an initial partial contact area, another calculation has been performed by simulating an initial separation between the slab and its foundation on about 2 m along its whole periphery. The results lead to a much smaller rising of the slab center : under the thermal gradient of 0.49°C/cm, the vertical displacement of the slab center is reduced to 1.2 mm, whereas it is 3.2 mm when the initial contact is complete.

VI. CONCLUSION

Despite difficult metrological and environmental conditions, the Orly instrumentation proved suitable for following accurately the temperature in the two instrumented slabs, together with the associated warping displacements. Continuous data recorded for 375 days have been analyzed from several points of view :

1. The comparison between the observed behavior of the two slabs shows that the effect of heat conduction across the thickness of the bituminous concrete prevails over the increase of the thermal absorption created by the black surface. Consequently, warping effects in slabs overlaid by medium asphalt concrete thickness (12 cm or more) should be significantly attenuated compared with non-overlaid slabs.

2. The response behavior of the slabs also gives indirect information about their initial contact area with their foundation (in absence of thermal gradient). Slabs edges and corners appear to be curled upwards without contact with the subbase. These initial conditions minimize the absolute vertical movement of the pavement under positive thermal gradients, probably leading to some significative attenuation of bending stresses in concrete. This curling, caused by temperature and moisture gradients during concrete curing, has to be taken into account both in back analysis of pavement behavior and probably also in design.

3. The theoretical analysis of the recorded thermal regime has shown that temperature variations can be accurately described by the classical one dimensional heat convection model. This confirms the interest of this simple theoretical model, which will subsequently permit to extend the results on the heat shield effect obtained in the present study, for instance by calculating temperature regimes and gradients in concrete for other thicknesses of bituminous overlay. But the possibilities of connecting surface temperature with environmental and meteorological conditions still requires investigation.

4. The analysis of the mechanical behavior (mainly the vertical displacements caused by thermal gradients) has shown that the 3D Cesar-Lcpc finite element model is in good agreement with the experimental results, providing that actual initial contact area between slabs and foundation is realistically described. Therefore in the next step of this research, this numerical model will be used to determine the combined effects of temperature and traffic load. But before examining consequences of bituminous overlay on the practical design of concrete pavements, theoretical results obtained for combined loading will have to be compared with experimental data, in order to thoroughly validate the process. So, it is planned to carry out during 1997 tests with traffic loads on the instrumented Orly slabs.

FIGURE 1 : Details of the instrumentation, slabs A and B

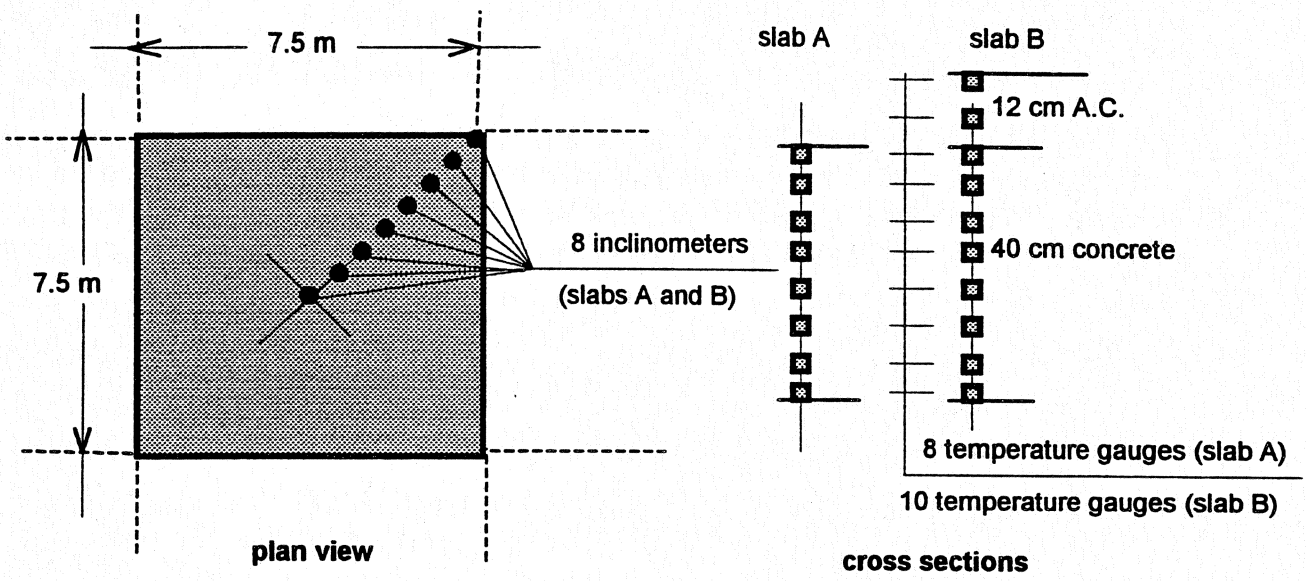


FIGURE 2 : Vertical temperature profiles at different hours of a day in the non-overlaid slab (a) and in the overlaid slab (b)

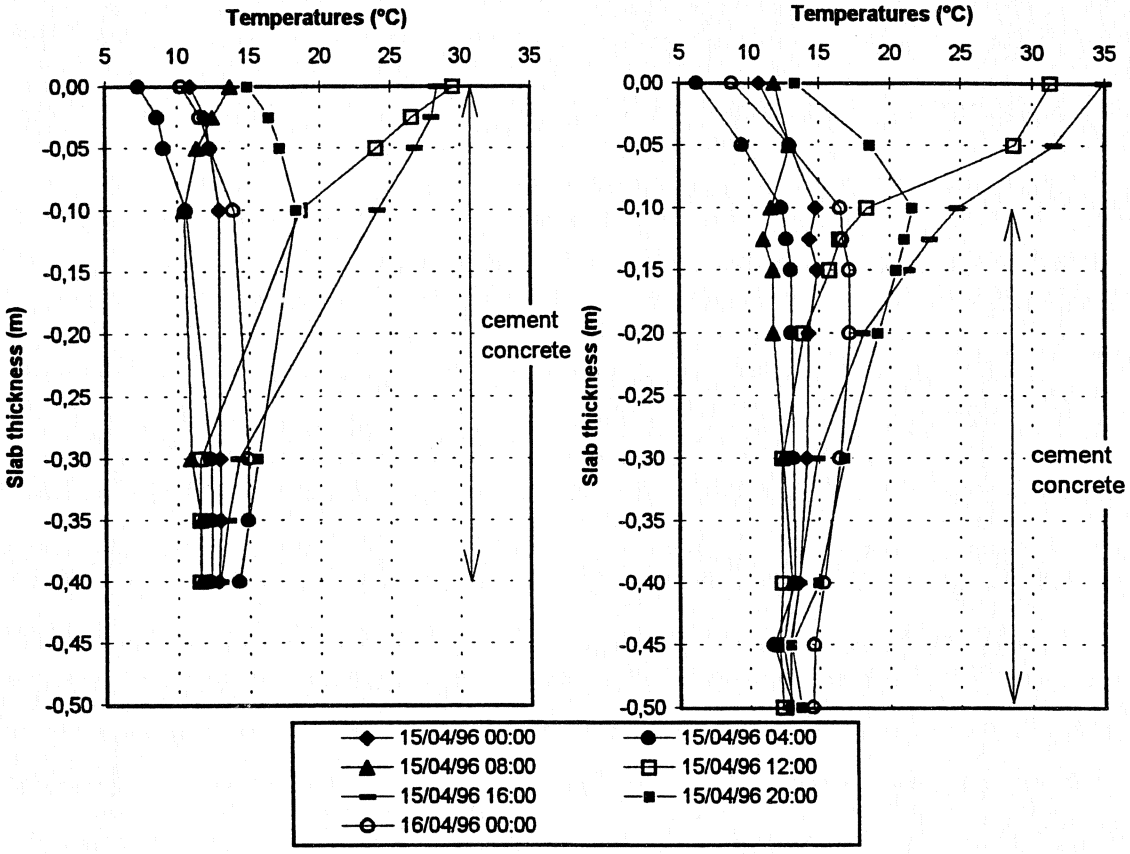


Figure 2a : Non-overlaid slab

Figure 2b : Overlaid slab

FIGURE 3 : Thermal gradients in the two slabs during two days

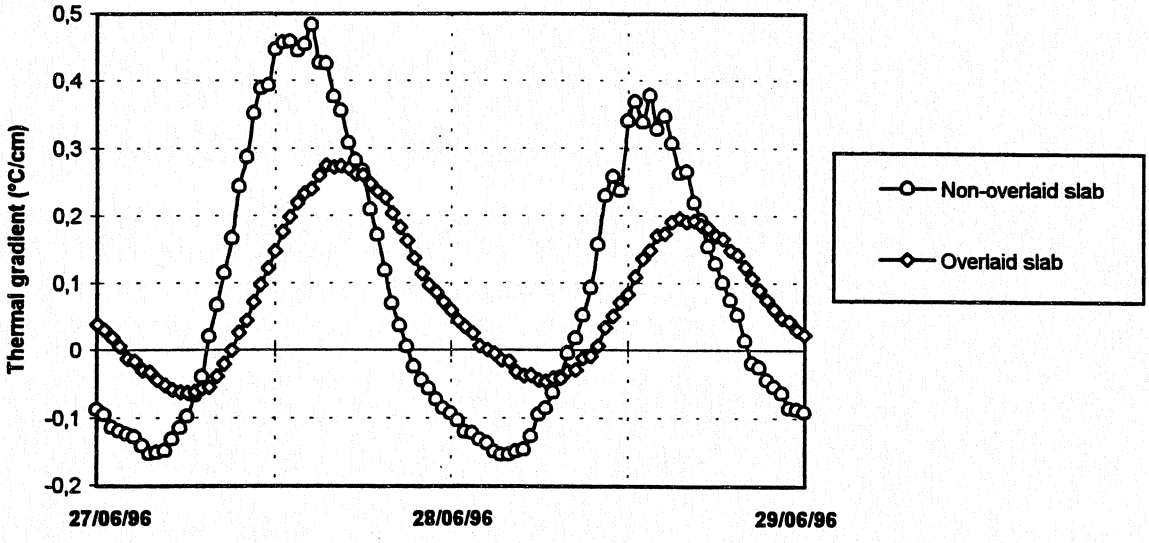


FIGURE 4 : Temporal distributions of maximum (a) and minimum (b) top cement concrete temperatures in the two slabs

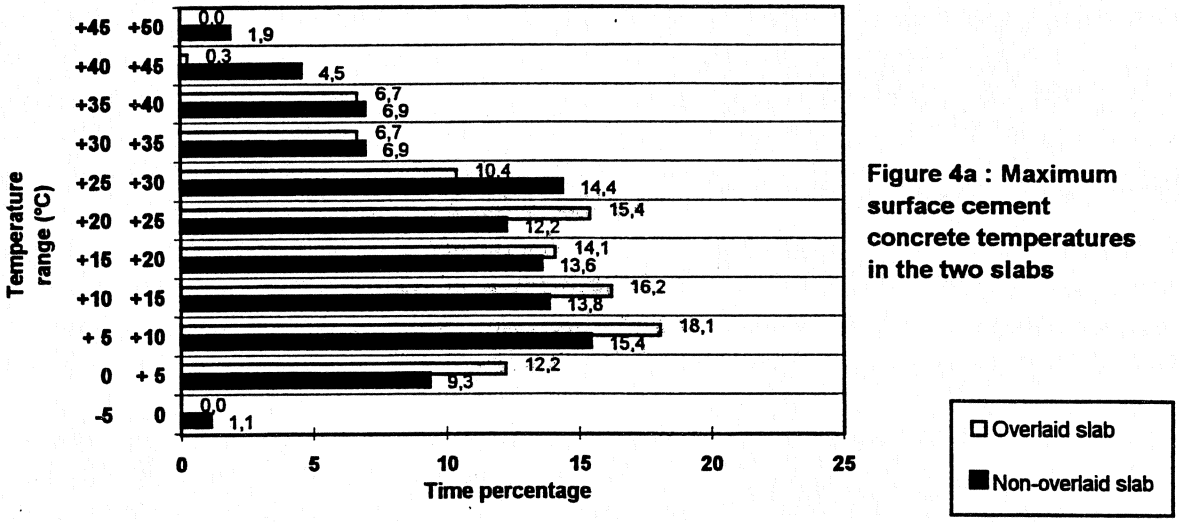


Figure 4a : Maximum surface cement concrete temperatures in the two slabs

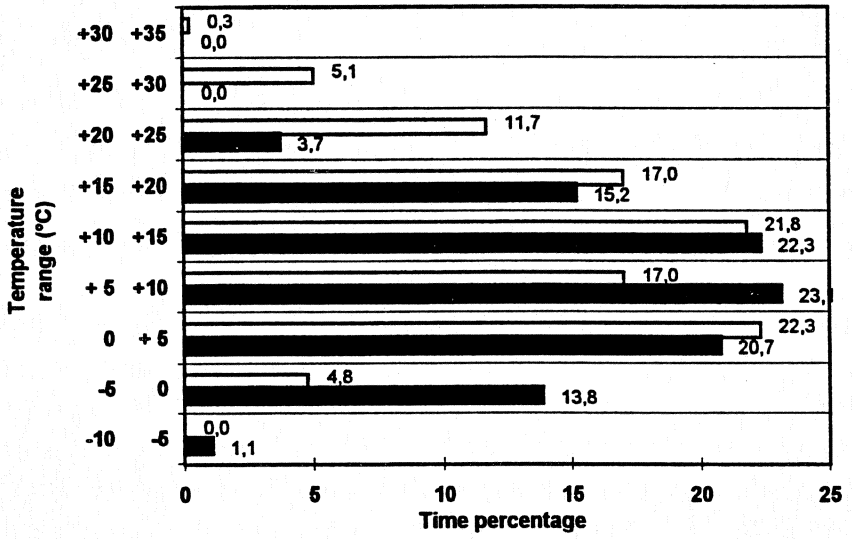


Figure 4b : Minimum surface cement concrete temperatures in the two slabs

FIGURE 5 : Temporal distributions of maximum positive (a) and minimum negative (b) therm gradients in the two slabs

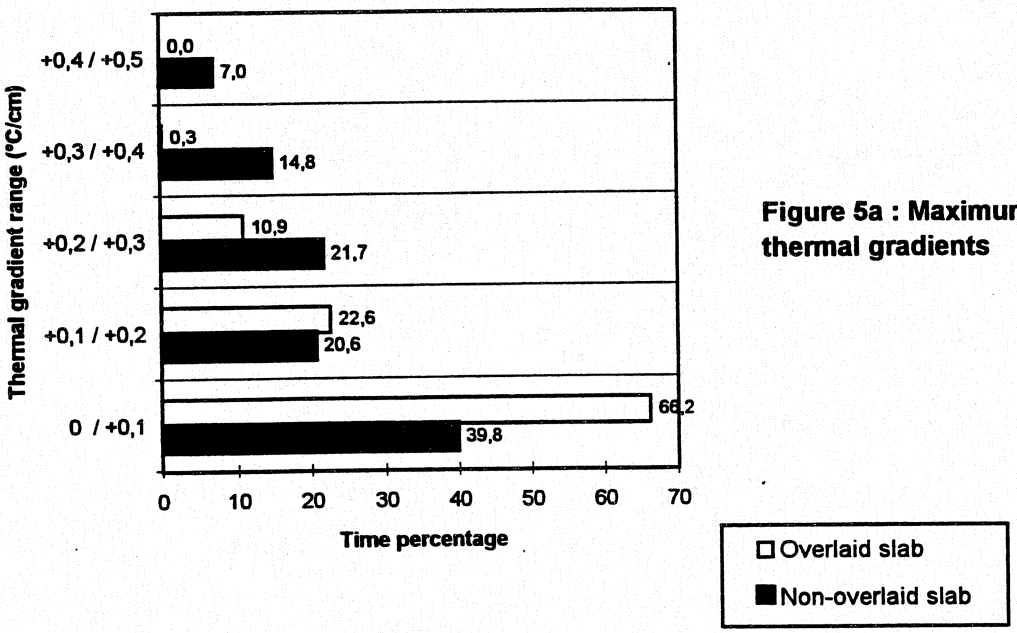


Figure 5a : Maximum positive thermal gradients

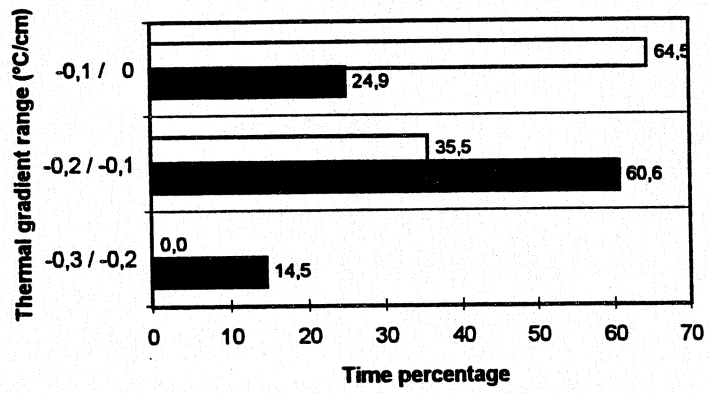


Figure 5b : Minimum negative thermal gradients

FIGURE 6 : Relative center-corner displacements and absolute corner displacements during two days

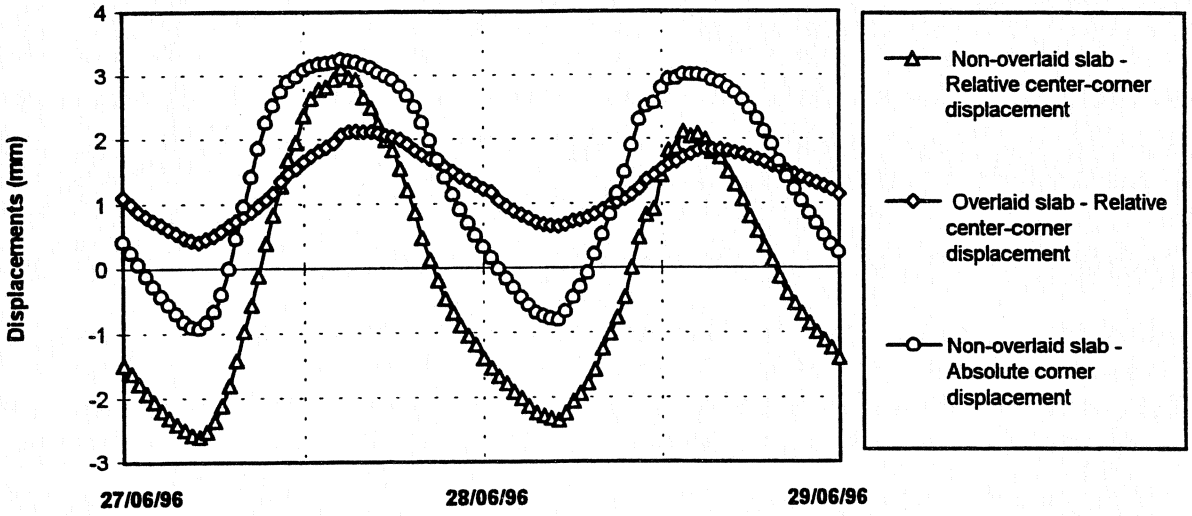


FIGURE 7 : Comparison between calculated and measured temperature distributions in the non-overlaid slab (a) and in the overlaid slab (b)

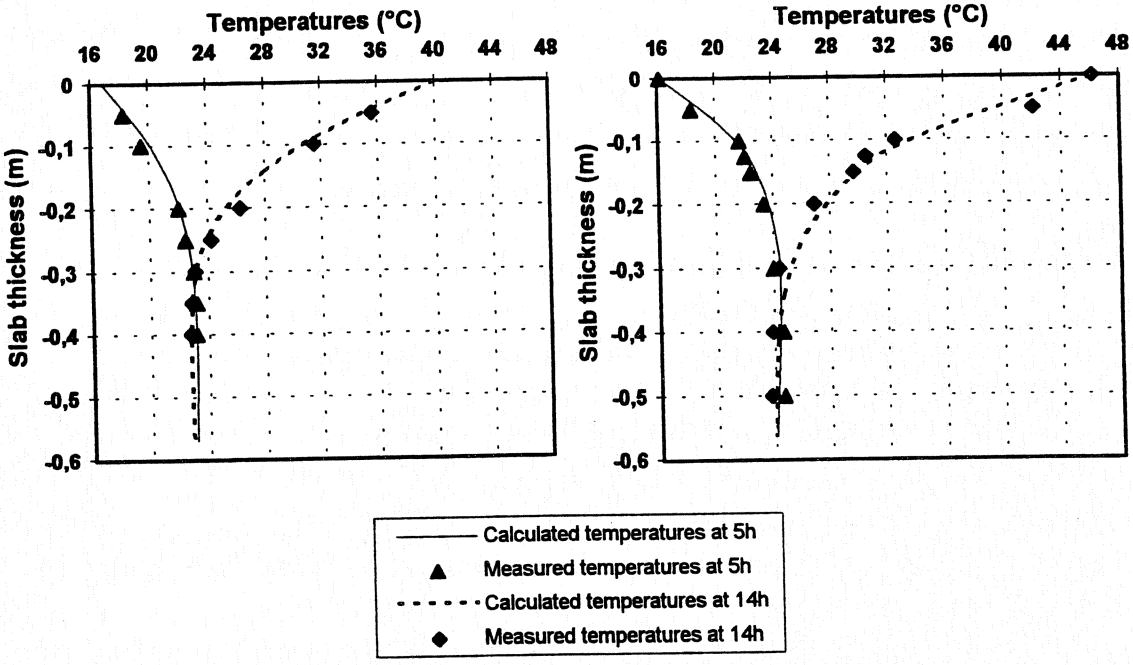
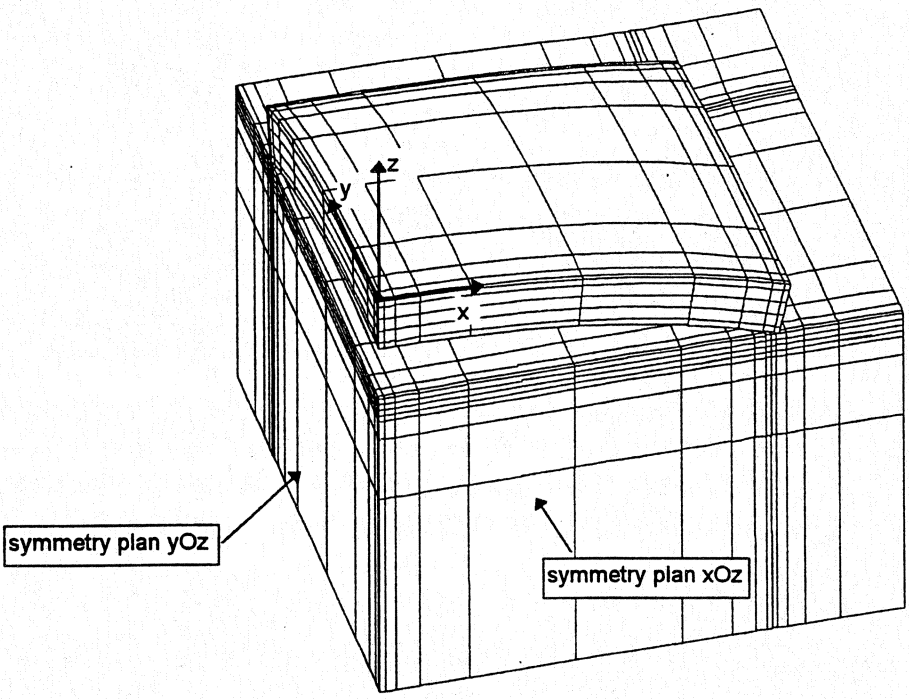


Figure 7a : Non-overlaid slab

Figure 7b : Overlaid slab

FIGURE 8 : Deformed shape of the non-overlaid slab under a positive thermal gradient (a) and a negative thermal gradient (b)



$E_{cement\ concrete}$ = 31000 MPa
$\nu_{cement\ concrete}$ = 0.25
$\alpha_{cement\ concrete}$ = 1.2 10^{-5} /°C

$E_{bitum.\ concrete}$ = 5400 MPa at 15°C
$\nu_{bitum.\ concrete}$ = 0.35
$\alpha_{bitum.\ concrete}$ = 2 10^{-5} /°C

$E_{foundation}$ = 20000 MPa
$\nu_{foundation}$ = 0.25

E_{soil} = 50 MPa
ν_{soil} = 0.35

Figure 8a : Positive thermal gradient

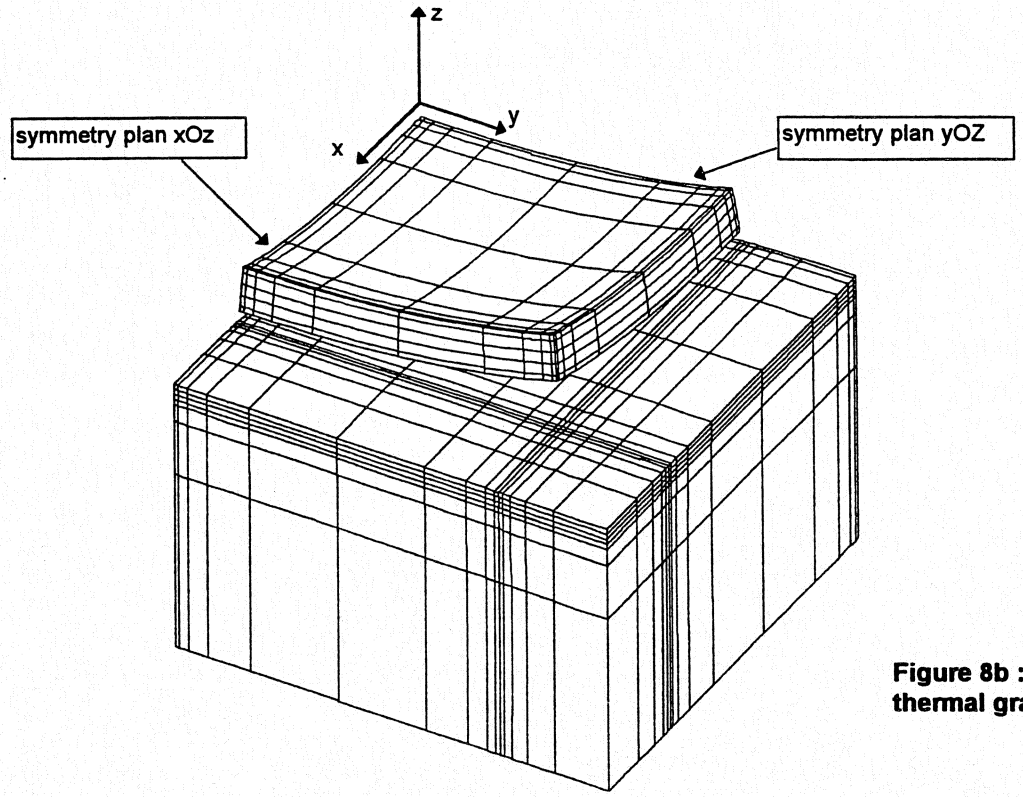


Figure 8b : Negative thermal gradient

FIGURE 9 : Comparison between relative center-corner displacements obtained numerically and experimentally for the non-overlaid slab (a) and for the overlaid slab (b)

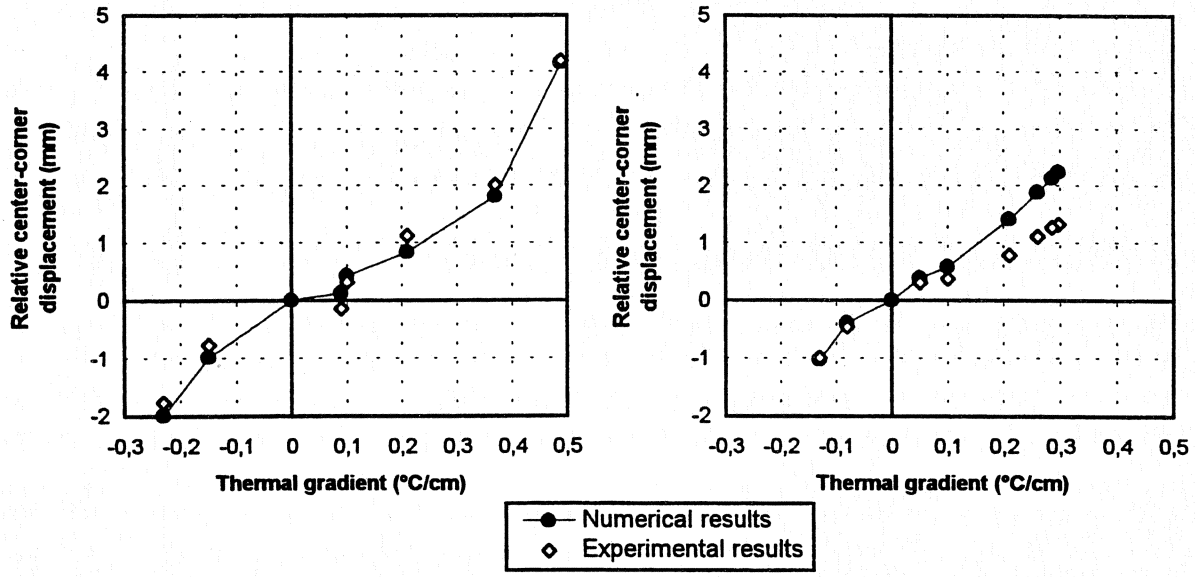


Figure 9a : Non-overlaid slab

Figure 9b : Overlaid slab

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