NONDESTRUCTIVE THERMAL CHARACTERIZATION OF THE SPHERICAL DEFECTS IN THE ROADWAYS

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Abstract
In this work, we present numerical simulations, in 3D, which aim at studying the aptitude of the thermal non-destructive testing to detect the defects of spherical form in a semi-rigid roadway structure. We will study the influence of the geometrical and thermophysical parameter of such defects on the simulated surface temperature evolution and the thermographical image of surface. For that, we will consider a parallelepipedic structure of semi-rigid roadway, containing defects of spherical form and excited by a heat flux on the surface. The opposite face being maintained at a constant temperature and other surfaces are thermically isolated. Once steady operation is established, we will take and study the thermographical image on the surface. This study is made using numerical commercial computation software, based on the finite element method.

Keywords: thermal non-destructive testing; infrared thermography; numerical simulation; finite element; roadway; semi-rigid; spherical defect; heat flow; asphaltic concrete; base layer.

1. Introduction

The defects in the roadways are of a harmful influence over the lifespan of such structures. These defects come either from defects to the implementation or from the difficulty of obtaining a good joining between materials, in particular, between bituminous and hydraulic layers. The detection of these defects is thus of primary importance in order to identify the problematic zones and to develop thereafter remedies to attenuate the negative impacts and to lengthen the lifespan of the roadways [1]. The ideal scenario in the detection of the defects is based on non-destructive approaches to prevent to obstruct the vehicular traffic. During the last years, infrared thermography has proven to be one of the best suited non-destructive testing methods to detect defects in the structures [2]. The only precondition for detection is that these defects lead to a sufficient variation of thermal properties compared to the bulk material.
In this article, we will model numerically a method of non-destructive testing based on the infrared technique in order to study the roadway response, containing defects of spherical form, to a thermal wave and the influence of such defect on the simulated thermographical image on the road surface.
The adopted approach is a numerical approach based on the finite element method and concretised by a commercial.

2. Description of the model

In this study, we considered a semi rigid structure of roadway, having a length L=10000 mm, a width l=4000 mm and a thickness e=420mm (fig. 1).
This structure is composed of a single layer of gravel, treated with the hydraulic binders, of height h_2=340mm, covered by a layer of surface having a height h1=80mm, (asphaltic concrete of connection and thin asphaltic concrete) (Fig. 1); the whole rests on a platform.

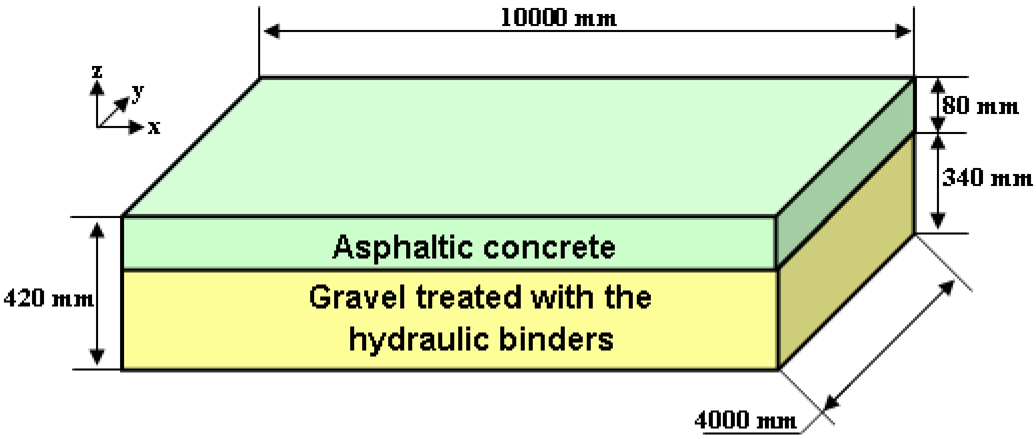

Figure 1 : Geometry in 3D of the studied structure

3. Mathematical model

Let us consider the following thermal equation:

$$\rho . c_P \dot{T} - div(\overline{\overline{\lambda}}.\overrightarrow{gradT}) - q = 0 \qquad (1)$$

Where:

ρ : the material density

c_P : the calorific capacity

$\overline{\overline{\lambda}}$: the thermal tensor conductivity;

q : Voluminal source of heat;

With the boundary conditions:

$$\begin{cases} T = T_P \ on S_T \\ \vec{n}.\overline{\overline{\lambda}}.\overrightarrow{gradT} = \varphi_S + \underbrace{h(T_f - T)}_{convection} + \underbrace{\varepsilon.\sigma(T_\infty^4 - T^4) on S\varphi}_{radiation} \\ S = S_T \cup S_\varphi, S_T \cap S_\varphi = \Phi \end{cases} \qquad (2)$$

Where:

T_P : the imposed temperature on a surface S_T;

φ_S : the imposed flow on a surface Sφ ;

S : the surface of the solid ;

$\vec{n}$: the unit vector perpendicular to S and directed towards outside.

And the initial condition:

$$T(x, y, z, t_0) = T_0(x, y, z) \qquad (3)$$

The analytical resolution of the equation (1) is in general inaccessible. One is thus led to seek a solution approached by the finite element method [4].
The method consists in using an approximation by finite elements of the unknown functions T to discretize the variational form of the equation (1) and to transform it into system of algebraic equations of the form:

$$[A]T = F \qquad (3)$$

Where:

A : is a square matrix of dimension [Nh, Nh];

F : is a vector of Nh components;

T : is the vector of the temperatures to be calculated;

We start by building the variation form of the equation (1). We carry out a spatial discretization which consists in calculating the elementary integrals by using the finite element and a temporal discretization.
There are many specialized software which make it possible to implement the method of resolution of problems by finite elements in a more or less simple and convivial way. They take care in particular of the grid of the studied object, of the automatic numbering of the elements and the nodes, of the calculation of a solution then of the chart of the results.
In this study, we used commercial software based on the finite element method and which makes it possible to calculate the evolution of temperature at any moment and in any point of material. The material is considered isotropic.
The calculation of the thermal response is made in the case of a portion of roadway subjected to a step of flow on the front face, continuous and extended of density Q=100 W/m^2. The temperature of the back face, which is in contact with the ground, does not change considerably, for that, we consider that it is maintained at a constant temperature Ta = 25°C. The others faces are insulated (Q=0). It is supposed that the thermal excitation is applied in a uniform way to considered surface and the initial temperature is T0=25 °C (fig. 2).

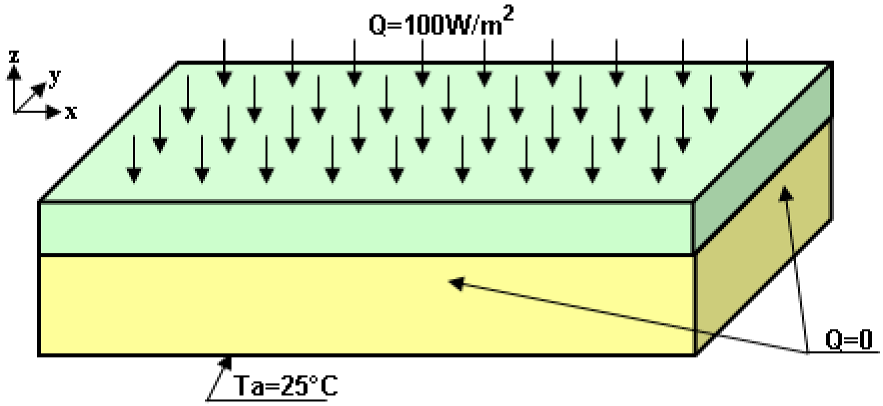

Figure 2: boundary conditions

4. Results of simulations

The computation results of the thermal response of excited structure are presented in the case of a roadway containing [5]:

- Asphaltic concrete wearing layer characterized by λ = 1.5 W/m.K (thermal conductivity), ρ = 2400 Kg/m^3 (density) and C = 907 J/Kg.K (specific heat).
- A base layer in treaty gravel characterized by λ =0.95 W/m.K (thermal conductivity), ρ=2350 Kg/m^3 (density) and C = 886 J/Kg.K (specific heat).

By exploiting the equation of heat, knowing the thermophysical characteristics of the roadway and by using a commercial numerical computation software based on the finite element method, we can determine the distribution of temperature in any point of the structure, the assumptions calculation are as follows:

- the temperature in bottom of structure (base of the platform) is constant;
- there is not discontinuity between the various layers of materials;
- to highlight the influence of the geometrical parameter, we chose defects of the delamination type characterized by λ = 0.0272 W/m.K (thermal conductivity), ρ = 1,057kg/m^3 (density) and C = 717,8J/kg.K (specific heat).
- to illustrate the influence of the thermophysical parameter, we considered defects of spherical form out of steel, copper, PVC, and in air.

The results of simulation are given thereafter in the form of thermal images representing the distribution of the apparent temperature, in degree Celsius (°C), on the upper surface of the roadway. The scale of temperature chosen to describe the variation in the temperature on the surface is a scale of color which associates the highest temperatures of surface the red color and the lowest temperatures the blue color.

4.1 Effect of the geometrical parameters

In this part, a portion of semi rigid roadway, in which we inserted twelve defects (fig. 3) of a spherical form, having respectively a diameter d of 60mm, 80mm, 120mm and 200mm (fig. 4) and located at 90mm, 130mm and 170mm of the road surface (fig. 5) is considered.

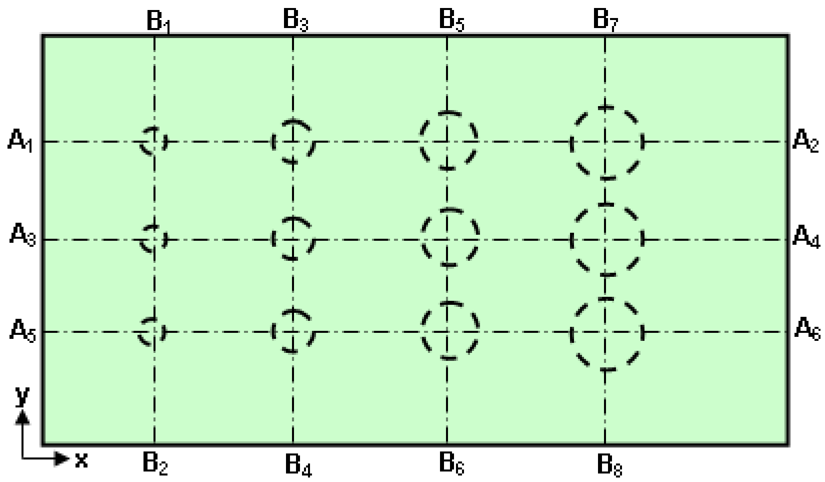

Figure 3: front view of the studied structure

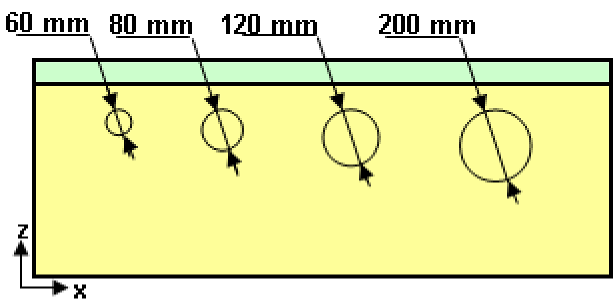

Figure 4: cross according to the (xoz) plan of the structure

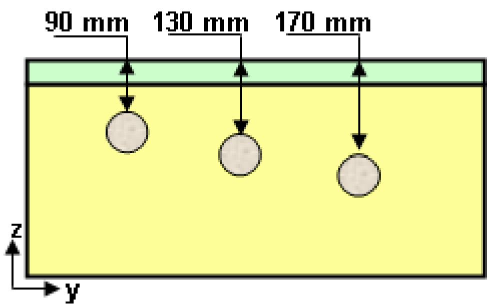

Figure 5: cross according to the (yoz) plan of the structure

a. Effect of the defect size

Figures 6 represents the profiles of temperature distribution on the road surface. It shows a hotter thermal tasks on the level of the problematic zones than those of the healthy zones. Indeed, the defect of the spherical form, being resistive, deviates the heat flow and produces hotter tasks of the temperature on the surface.

Figures 7 shows the temperature evolution on the surface of considered structure, along the axes A_1A_2, A_3A_4 and A_5A_6 (Fig. 3), passing respectively by the pairs of points [(0,1,0.42); (10,1,0.42)], [(0,2,0.42); (10,2,0.42)] and [(0,3,0.42); (10,3,0.42)]. These defects are located respectively at 90mm, 130mm and 170mm for these axes. This figure highlights the influence of the defect size on the surface temperature distribution; thus, the smaller the diameter is, the more the intensity of the peak reflecting the presence of defect is low and conversely. Of such intensity allows to determine the necessary sensitivity of the material of non-destructive testing to use. Also, it is noted that as the width of the defect decreases, one tends towards a limit of detectability, which is of course unfavourable for the non-destructive testing.

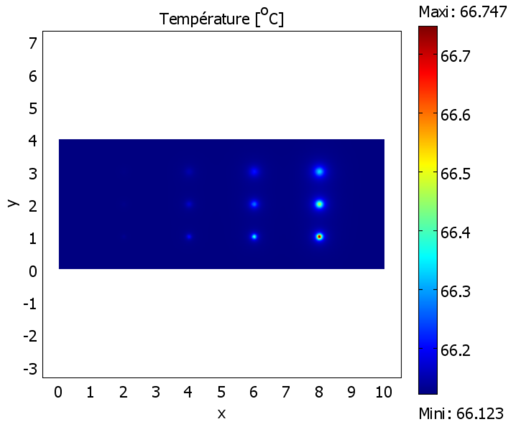

Figure 6 : thermographical image of the entry face

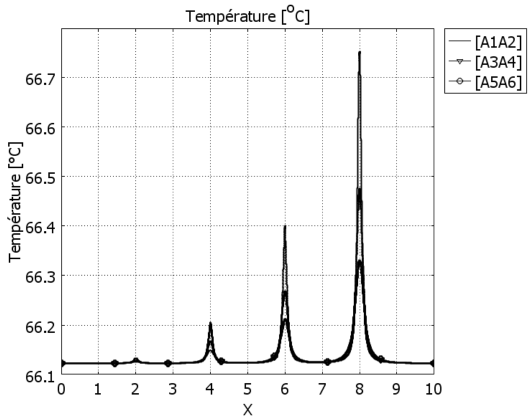

Figure 7 : Temperature evolution along the axes: A_1A_2, A_3A_4 and A_5A_6

b. Effect of the defect position

In this part, to illustrate the position influence of defect, we represented the temperature evolution along the axes B_1B_2, B_3B_4, B_5B_6 and B_7B_8 (fig. 3), passing respectively by the points: [(8,0,0.42); (8,4,0.42)], [(6,0,0.42); (6,4,0.42)] ; [(4,0,0.42); (4,4,0.42)] and [(2,0,0.42); (2,4,0.42)].

The figure 8 represents the temperature evolution along such axes. The effect of the position defect on the surface temperature distribution is remarkable. In fact, for defects of the same diameter, more one moves away from surface, more the temperature peak associated with the defect becomes weak and the limit of detectability of such defects will depend on the resolution of the equipment used in control.

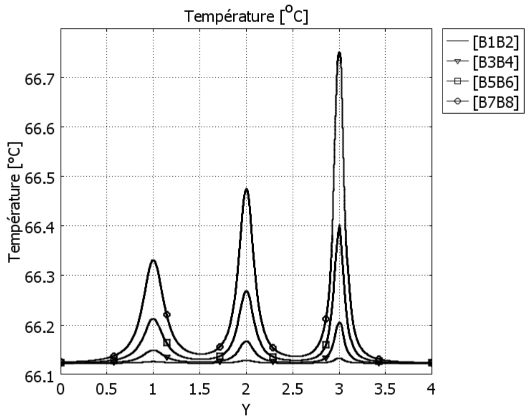

Figure 8: Temperature evolution along the axes: B_1B_2, B_3B_4, B_5B_6 and B_7B_8

4.2 Effect of the thermophysical parameter

In order to illustrate the influence of the defect thermophysical parameters, we considered the same structure of roadway which contains four spherical defects, having 40mm as ray, of different materials (fig. 9). The following materials are considered (table 1). These various defects are located at the same position (90 mm) compared to the road surface.

Table 1: thermophysical parameter of the used materiels

Material	Thermal conductivity W/m.K	Density Kg/m^3	Specific heat J/Kg.K
copper	389	8940	0.38
Steel	58	7800	460
PVC	0.18	1380	1000
Air	0.0272	1.057	1005

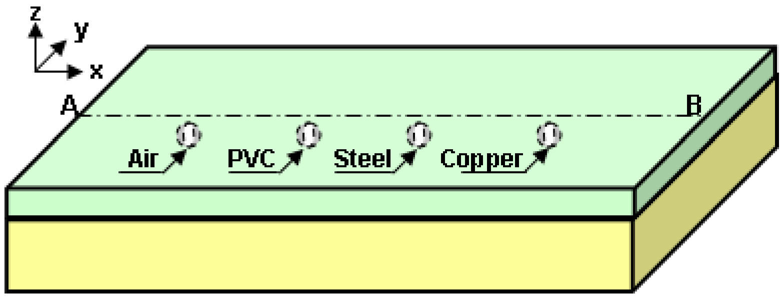

Figure 9: The considered structure for the study of the thermophysical parameters influence

Figure 10 represents the simulated thermographical image on the road surface and figure 11 shows the temperature evolution according to (AB) axis passing by the points: (0,2,0.42) and (10,2,0.42) (Fig 9). These images illustrate the influence of the defect thermophysical parameters; indeed, when the defect is resistive (air, PVC) comparatively to the structure, the heat flow crosses the structure by avoiding the anomaly (defect) and a storage of heat occurs at the entry of the defect, which generates, consequently, a rise in temperature compared to the vicinity. In the case where the defect is capacitive (steel, copper), the heat flow is absorbed by the defect what involves a fall of temperature at its entry compared to its vicinity.

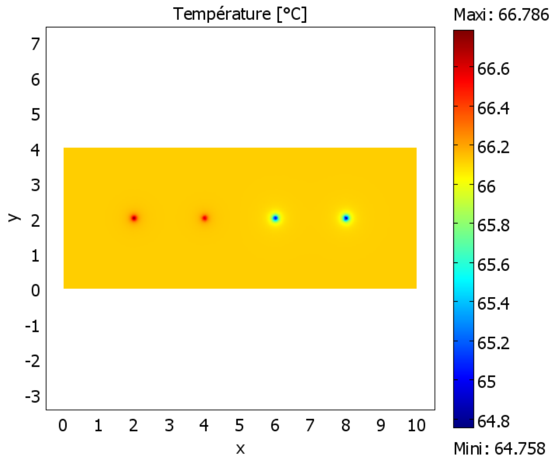

Figure 10 : thermographical image of the entry face

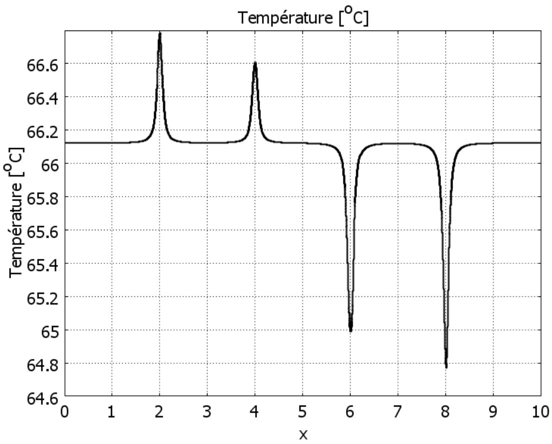

Figure 11 : Temperature evolution along the axis: AB

5. Conclusion

In this work, we studied the influence of the geometrical and thermophysical parameters of a spherical defect on the response of semi rigid roadway structure to thermal excitation. One can conclude that theoretically, as in other work already completed [3, 6] and who approached other types of defects, spherical defect can be detected by thermography, on condition that the temperature variation between the healthy zones and the problematic one is sufficient so that it may be detectable by the used thermal material of non-destructive testing. On the other hand, it is differently in practice. Indeed, we considered a structure on plane surface, which is not the case in reality because the roadways generally present defects of surface; these defects can influence the temperature distribution on the level of the thermographical image which one can take on the surface. This phenomenon which is very often observed during measurements makes it very difficult to detect the defects of low dimensions. Although the thermophysical characteristics of the roadways change from one roadway to another [5], because thermal conductivity depends strongly on granulated and granulometry, our contribution highlighted clearly the influence of the geometrical and thermophysical parameters of the spherical defects and permit to better interpret the results of measurement on roadways with defects of this type.

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