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Elaboration of an Analytical Formula for the Calculation of the Surface Temperature

Abdelhamid Mammeri [a*], Mostefa Lallam [b]

[a] *Laboratory Mechanics of Structures, University of Tahri Mohamed, Béchar 08000, Algeria.*

[b] *Laboratory of Sciences and Water Technical, University of Mustapha Stambouli, Mascara 29000, Algeria*.

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Abstract

Pavement structures are sometimes subject to repeated dimensional variations of thermal origin generating mechanical stresses that may be detrimental to their durability. Among the most frequently observed degradations, by these stress, are the transverse cracks whose frequency, depth, and variable openings reduce the ride comfort. In this context, where such solicitations are preponderant and the strong variation is noticed on the surface, an analytical approach for calculating the surface temperature of a flexible pavement has been proposed. This approach is able to deal with the transient thermal problem including the phenomenon of ambient temperature and the influx of solar flux specifically for arid regions where the sky is often clear. This approach is adopted because it proposes a simplified calculation of the surface temperature. The model was built on a database measured on the experimental pavement of the laboratory of Egletons GEMH (France), using the calculation code Eureqa formulate. Although neglected in the domain's literature, the meteorological parameters (air temperature and solar flux) are taken into consideration in the analytic function because they give good prediction. The model has practical meanings to predicting the maximum, minimum, and amplitude of the pavement surface temperature. Hence, a good surface temperature assessment provides a key factor for further thermal cracking modeling.

Keywords: Pavement; Temperature; Solar Flux; Monitoring; Analytical Model.

1. Introduction

Although pavement structures are sensitive to temperature, there are not considered as an indispensable factor in asphalt pavement design in areas with large temperature differences, which may be detrimental to their durability [1]. Cracks in pavements are commonly observed in areas that experience low temperatures and large temperature differences [2]. The sizing methods around the 45th parallel (in France in particular) neglect this type of solicitations as regard the traffic.

On the other hand, there are regions where thermal stresses are predominant [3, 4], arid regions with a desert climate are part of it [5]. Pavements structures have in common cracking mechanisms of various origins. The thermal stresses and the traffic are at the origin of these disorders [6], but the nature of these will vary according to each type of structure. This variation of daily and seasonal temperature in such regions has a peculiarity, sometimes the temperature easily exceeds 45 °C in the shade in summer [7].

The influence of temperature on pavement structures remains a subject of much research in one-dimensional studies [8], two-dimensional [9], or three-dimensional [2].The amplitude and maximum of the surface temperature of pavements

* Corresponding author: mammeri_ab@yahoo.fr

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have gained numerous studies. Numerical and empirical models have been contributed to predict the pavement temperature development and to estimate the variation of the pavement surface temperature, or the impact of the thermal effect at different positions of the pavement structure [10-12]. This distributions presented in a very simplified way, or more complete but on short sequences, less analytical formulas that measure this temperature [13-16].

Mammeri et al. (2014), has developed a finite element numerical model using software (Cast3M) where we highlighted the importance of sun rays parameters and the cooling effect at night. Radiation to the sky on the pavement surface, which is not an insignificant parameter in these regions with low cloudiness. This model has been validated experimentally on a pavement that exists on the Egletons site (France) where measurements of the surface temperature and thermal stresses were taken by means of a metrological station on the same site [17].

In this study, empirical approach has presented, that it is often neglected in the literature, in order to calibrate the curve of the equation of the surface temperature with the signal found experimentally and especially during sunny days. First, we try to deduce the function of the surface temperature with the air temperature, then the surface temperature according to solar flux was calculated, and finally, we calculate the surface temperature taking into consideration the air temperature and solar flux, using the Eureqa-Formilize calculation code.

2. Experimental Program

2.1. Presentation of the Experimental Pavement

The case study that is proposed corresponds to the experimental pavement is in the Egletons GEMH laboratory (France). This pavement is a project carried out in March 2007, in order to study the methods of diagnosis of flexible pavements and the follow-up of their evolution over time. It is 70 m long and 10 m wide, composed of three different types of structures including the one authors were dealing with. It is a so-called classical structure rather used in the case of medium traffic pavement. It consists of a supporting soil, a 30 cm thick untreated (GNT) layer, a 8 cm thick bitumen (GB) layer, and a 5 cm layer of semi-granular bituminous concrete (BBSG) [18]. The latter is used to undertake comparisons with numerical results and to validate the numerical model developed [17].

2.2. Implementation of Instrumentation

During construction, this structure was instrumented using a surface sensor (T0), a sensor on each interface (T2, T3, T4), an intermediate sensor in the BBSG layer thickness (T1), and a depth sensor in the soil layer (T5), see Figure 1.

Figure 1. Location of thermal sensors

Figure 2 also shows the cell and more particularly the positioning of the instruments measuring the conditions at the outer limits. The main site meteorological variables are: ambient temperature, relative humidity (thermo hygrometer), global solar radiation incident on a horizontal surface, and wind speed. They are measured and recorded every 15 minutes thanks to the meteorological station located on the experimental site.

Figure 2. The weather station

3. Development of Analytical Model

In this part, the Eureqa-formulize calculation Code 1.24.0 was used for the development of the analytical function model. Eureqa is a scientific data mining software that searches for hidden mathematical models in data. The program combines many of the above discussion points. First, the program uses the genetic algorithms to select variables and develop equations. Second, in addition to simply being able to select predictor variables; it can also investigate many different data operators such as trigonometric functions, power, square root, Boolean and many others as applied to the predictor variables; and, last, it can easily combine different operators in the same equation [19]. The formulation steps can be presented under a following flowchart.

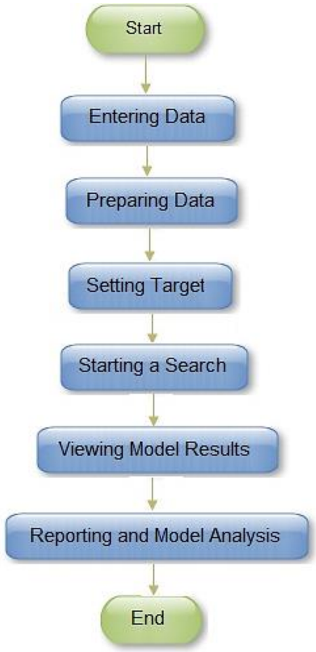

Figure 3. The analytical model development flowchart

Eureqa's user interface is organized as a set of six tabs that correspond to the normal workflow through the program. It is capable of testing a wide variety of mathematical functions, and combinations thereof, to find relationships between data. Functions include the standard functions used in multi-linear regression (MLR; +, −, /, *, k) plus others, such as exponentials, roots, trigonometric etc, and this software is organized around those tabs. The six main pages linked to below explain the most important features and options available on each tab, and they are presented in the following sections [20]:

1. Enter Data

This spreadsheet-like view (Figure 4) is the place to enter, edit, and inspect our data. We can paste in data from Excel, from Matlab's array editor, or from just about any other source of tabular data, including plain-text files with tab-separated values.

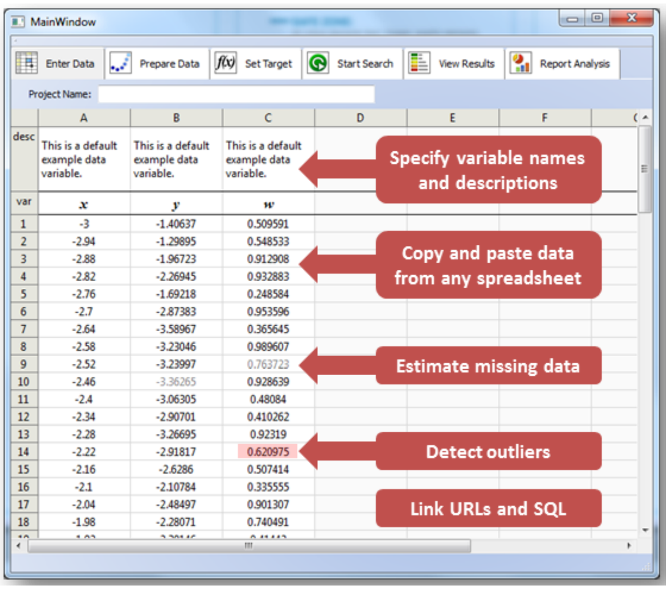

Figure 4. Interface entering data tab

2. Prepare Data

Figure 5 shows the data preprocessing options: it is possible to smooth the data, handle missing values, remove outliers, normalize scale and offset, and apply a filter. These processes can be applied to a single variable or simultaneously to any combination of variables. To select a variable for processing, by clicking on this variable in the "Variables" window in the upper left.

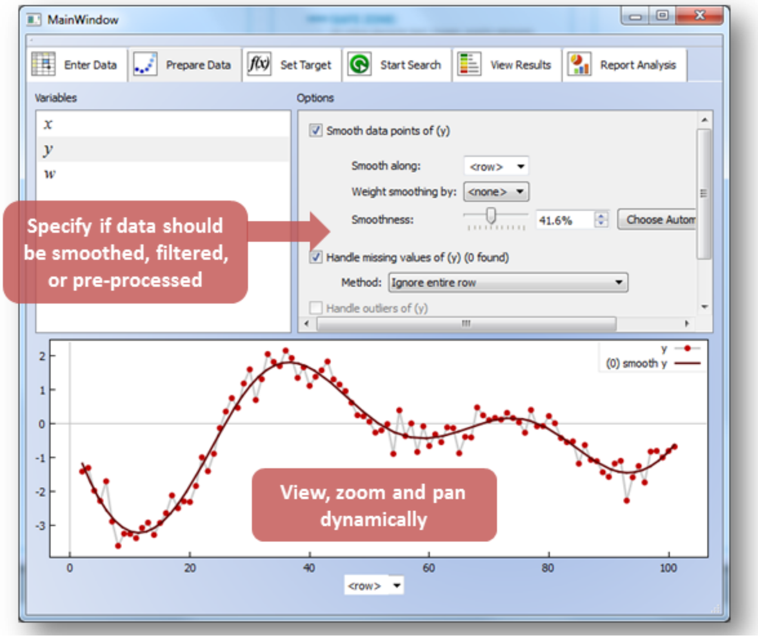

Figure 5. Prepare data tab

3. Set Target

In this step, the edition of the form of the equation is introduced according to different variables, as shown in the following figure. For example, if someone want to model the variable (y) as a function of (x), and (w), he/she can introduce y = f (x, w), on the other hand, if he/she wants to ignore the variable (w), he/she can simply enter y = f (x). This flexibility in specifying the form of the target solution gives you a lot of power to search for complex relationships.

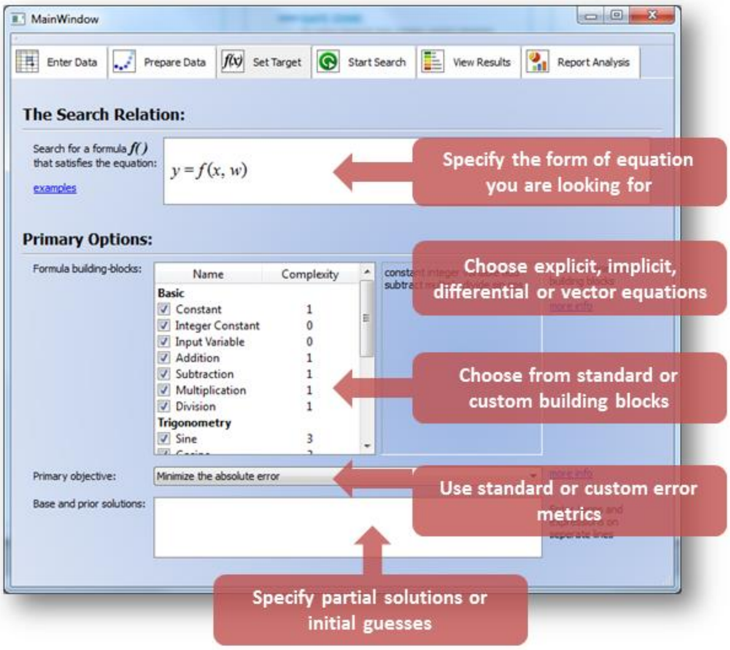

Figure 6. Setting the interface of the target tab.

4. Start Search

It is possible to start and stop the formula search here. Also monitor various aspects of the performance and progress of the ongoing search. These option control the formula search (Figure 7).

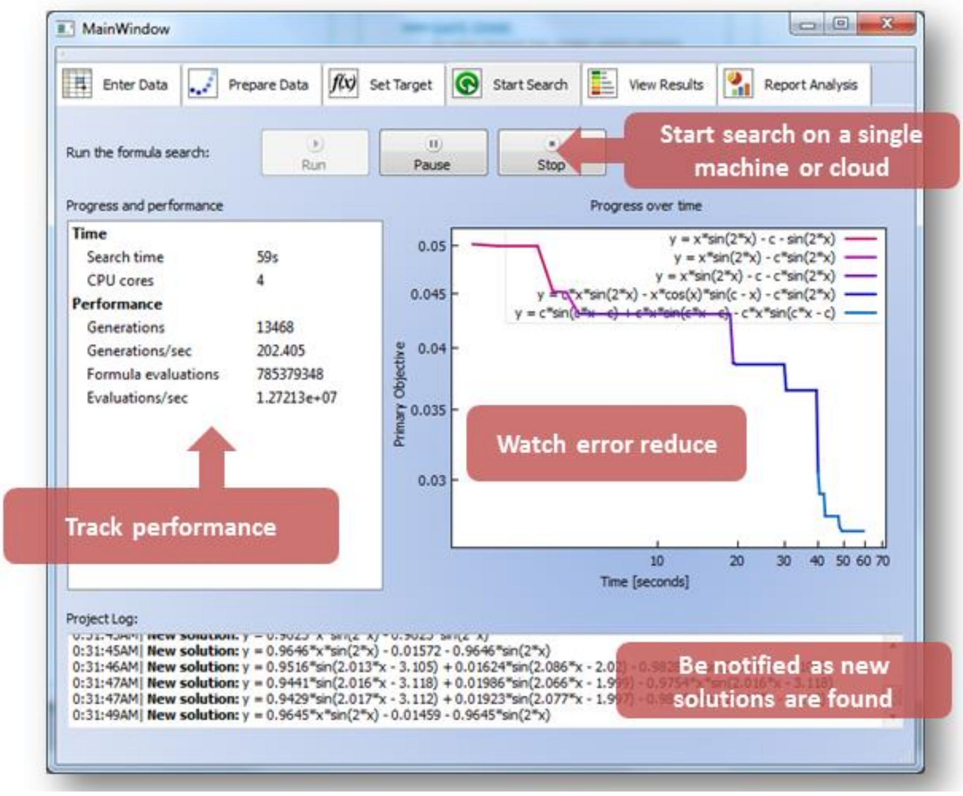

Figure 7. Star search tab

5. View results

Figure 8 shows the best solutions Eureqa has found so far. The best solutions are determined by two factors: their complexity and their accuracy on the validation data. Both training and validation data are shown.

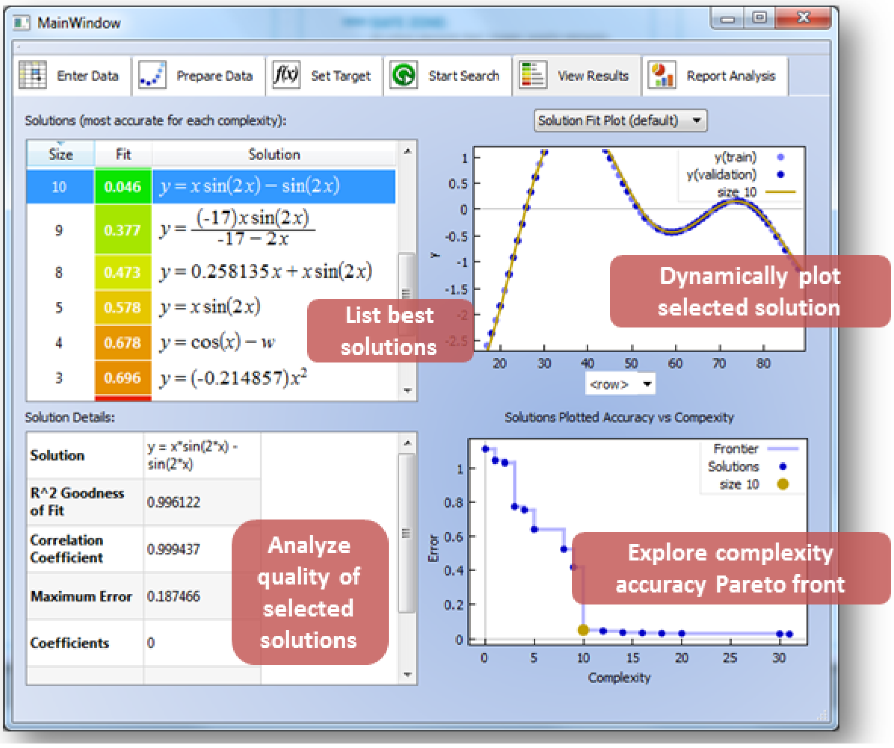

Figure 8. View result interface

6. Report analysis

This report gives general information about the search and about the most accurate formula at each level of complexity, as like given by the Figure 9. Also, for each formula there's a solution plot and a plot showing where that formula sits in comparison to other formulas with respect to accuracy and complexity.

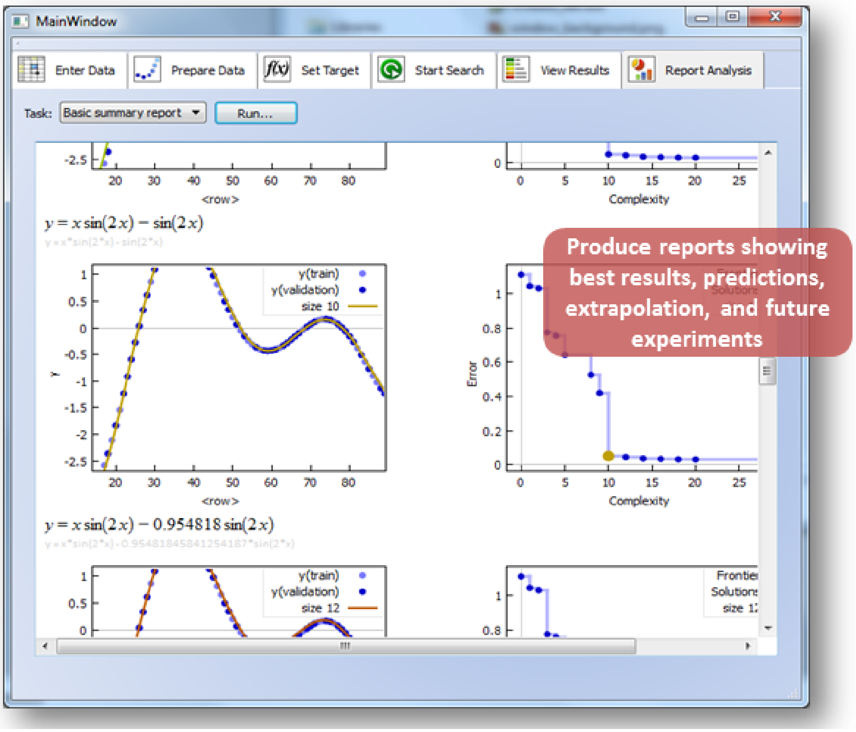

Figure 9. Report analysis tab

4. Results and Discussion

4.1. Experimental Results

The acquisition of experimental data is done with a time lap of 15 minutes. The data recorded by the sensors are directly displayed on the laboratory computer via a connection with the AMR Control software. Here the surface temperature, air temperature and solar flux has been measured.

A sequence of experimental measurements was carried out on the experimental pavement of Egletons (France) during the summer period in order to have a clear sky from 10/07/2012 to 30/07/2012. We present in the Figure10 the experimental results of two days of good weather, 25 and 26 July, 2012 (clear sky).

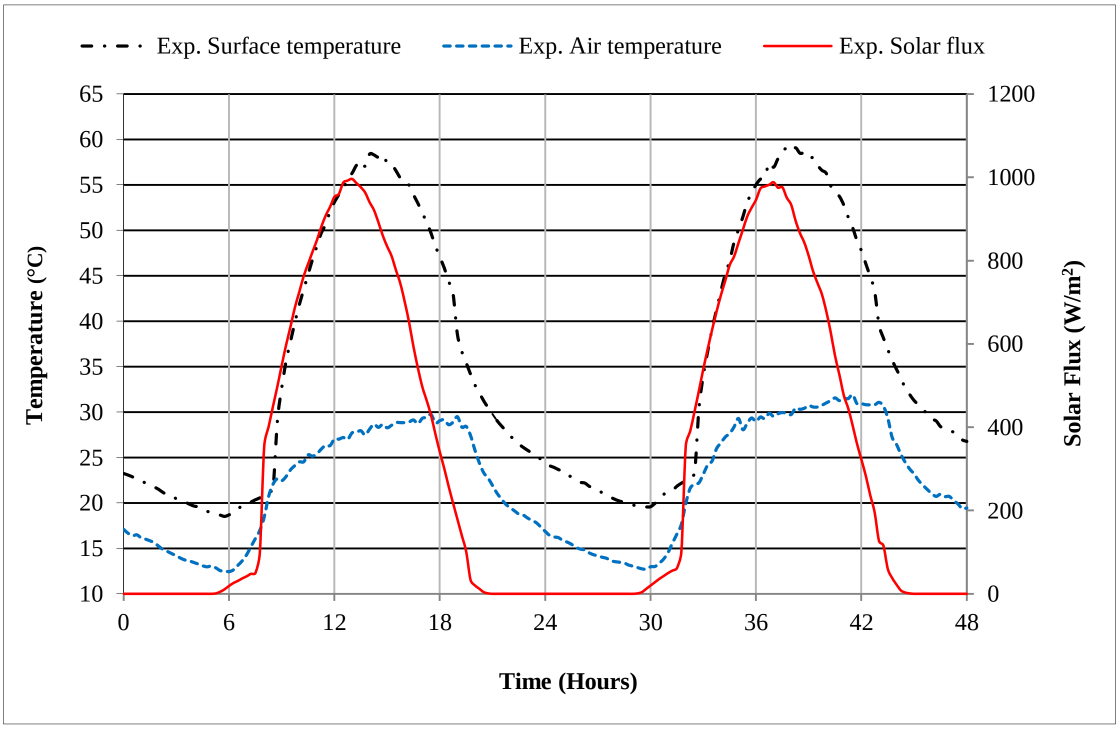

Figure 10. Experimental results for two days of good weather (25 and 26 July 2012)

In this figure, maximum surface temperature that reaches 60 °C in surface for these two days can be obsurved. In parallel, we demonstrate from this figure also that the hypothesis proposed by other researchers, for example [21], which supposes the surface temperature to correspond practically to the air temperature, whereas this hypothesis is not valid. We also present the measurements obtained for the solar flux, for these two days, the sky is clear and the global solar radiation is close to 1100 W/m^2.

4.2. Model Results and Discussions

Authors followed the same steps mentioned in section 3 in order to get out the analytical functions that allows us to deduce the surface temperature profile, knowing these two parameters separately (ambient temperature, solar flux) or both at the same time. The input values used in the development of our model are 192 values of air temperature, solar flux, and surface temperature. For the three case studies, the calculations were left after 30 minutes, an 8 core CPU and a convergence percentage of 100%.

4.2.1. Deduction of the Surface Temperature according to the Air Temperature (Analytical Approach N°01):

In Figure 11, the variation of the surface temperature as a function of the air temperature compared with the experimental results, to bring out the analytical formula. We notice after confrontation of the results that the two curves are a little distant, and the correlation coefficient is of the order 94.29%. The analytical approach in this case is:

$$T_{surf} = 2.327\,T_{air} + 0.159\,T_{air}\mathrm{Cos}\left(-0.0002\,T_{air}^{3}\right) - 15.374 - 3.058\,\mathrm{Cos}\left[-1.366\,T_{air} - 6.916\cos\left(-0.0051\,T_{air}^{2}\right)\right] \quad (1)$$

Where: T_{surf} is the surface temperature, and T_{air} is the air temperature.

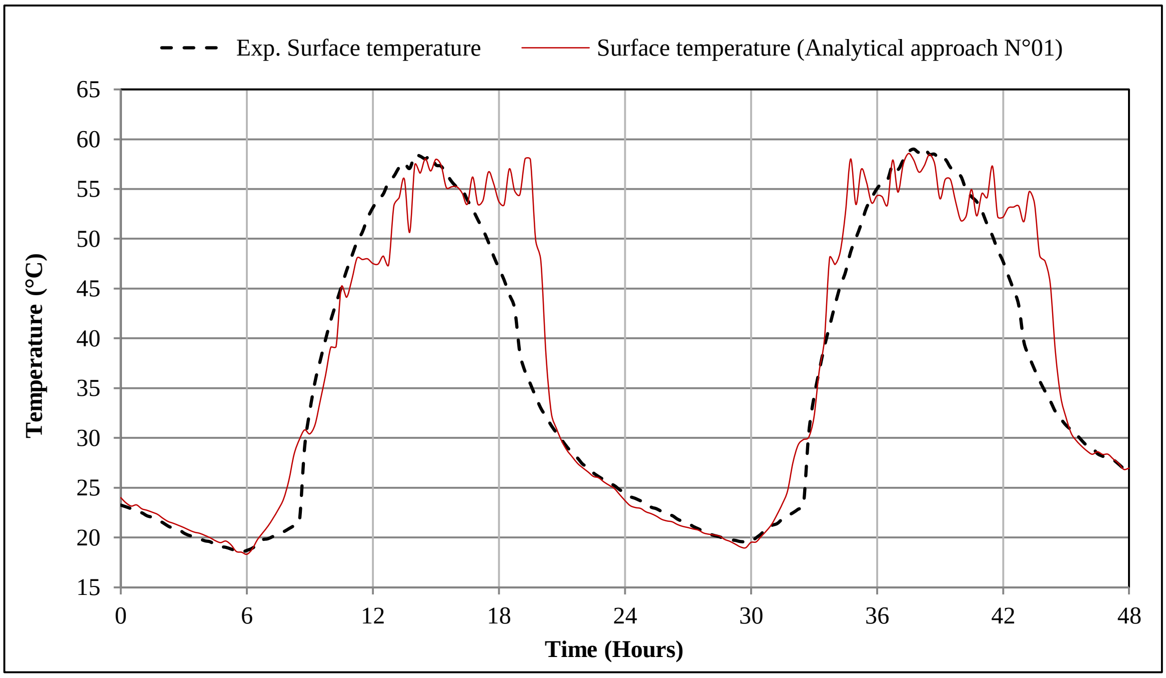

Figure 11. Allure of the analytical function of surface temperature as a function of air temperature compared to the experimental results

4.2.2. Deduction of the Surface Temperature according to the Solar Flux (Analytical approach N°02):

In Figure 12, the same comparison with that of Figure 11 is presented, but this time as a function of solar flux. The surface temperature curve almost the same as the solar flux curve. The result remains the same with a decrease in the correlation coefficient, and the correlation coefficient is 89.32%. The equation taken from this curve is:

$$T_{surf} = 25.41 + 0.0327\,\mathrm{Flux} + 9.557\,\mathrm{Sin}(0.399 + \mathrm{Flux}) + 7.291\,\mathrm{Sin}(5.23 - 7.291\,\mathrm{Flux})$$
$$2.658\,\mathrm{Sin}(2.658\,\mathrm{Sin}(9.549\,\mathrm{Flux})) - 0.00149\,\mathrm{Flux}\,\mathrm{Sin}(\mathrm{Flux}) \quad (2)$$

Where, Flux represents the of solar flux values.

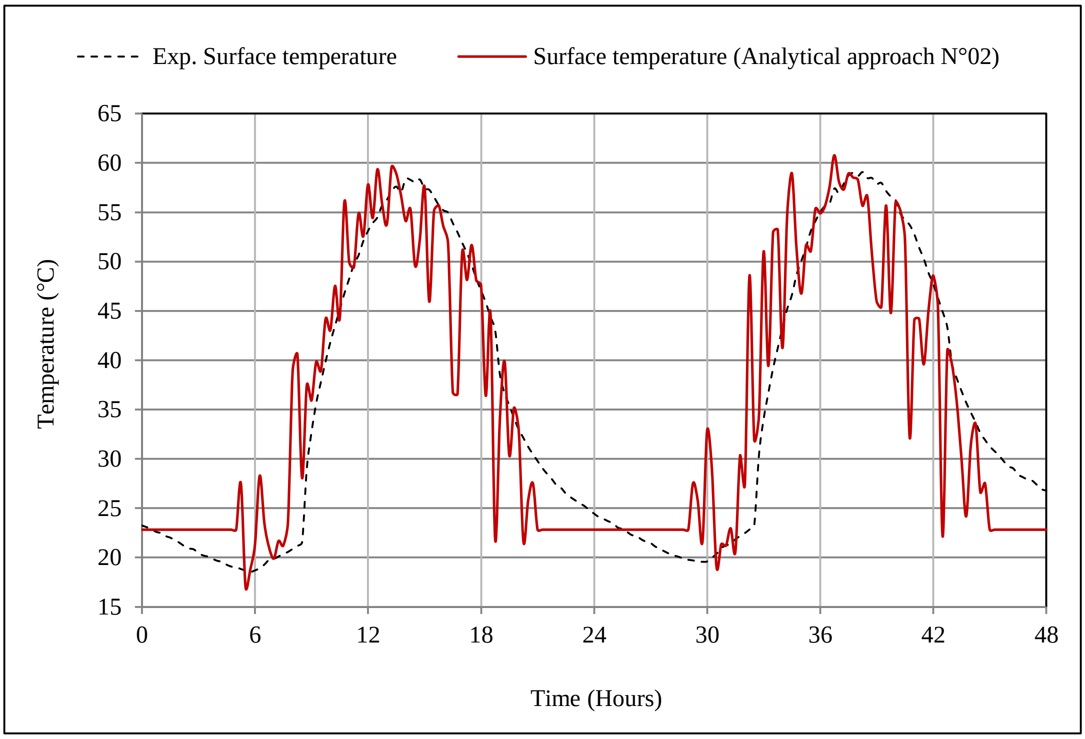

Figure 12. Allure of the surface temperature analytic function as a function of solar flux compared to the experimental results

4.2.3. Deduction of the Surface Temperature according to the Air Temperature and Solar Flux: (Analytical Approach N°03)

In order to improve our results we have processes to cumulate the two parameters mentioned above (air temperature and solar flux) to calculate the surface temperature. We observe that this approach is the best and has given a good correlation compared to the experimental results (Figure 13).The result improved considerably with a correlation coefficient of 99.36%, comparing with the two previous cases. The analytical approach is given by the following formula:

$$T_{surf} = 5.015 + 1.111 T_{air} + 0.000245 \, Flux^2 + 2.98710^{-12} T_{air} e^{T_{air}} + 0.00041 \, Flux \, T_{air}^2 - 9.07610^{-11} e^{T_{air}} - 0.00908 T_{air} \, Flux - 1.00910^{-5} T_{air} \, Flux^2 \quad (3)$$

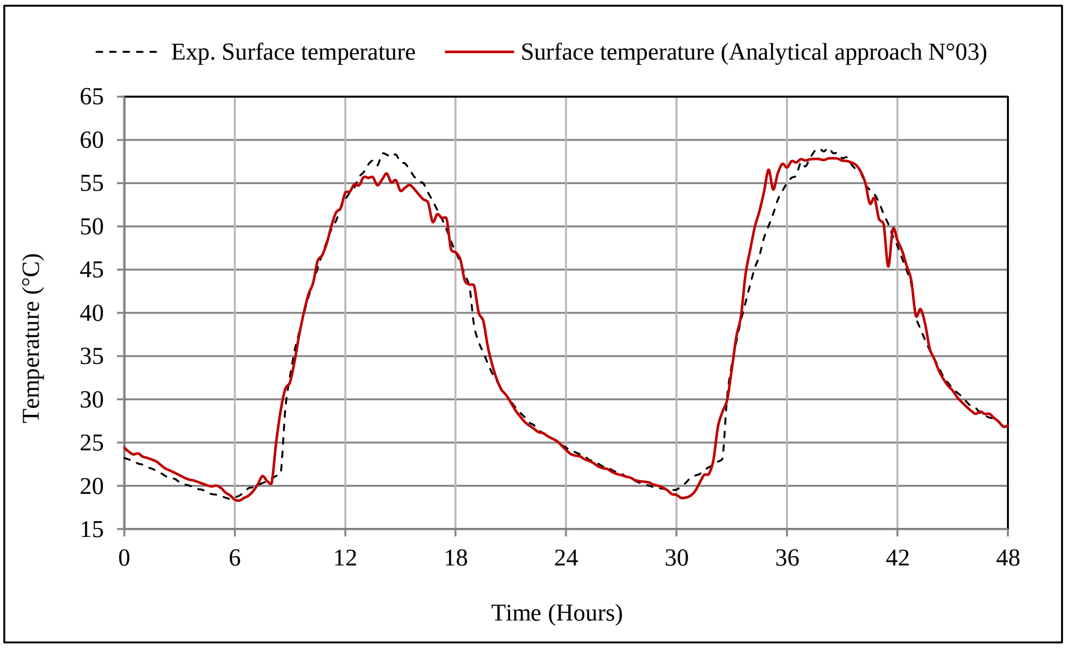

Figure 13. Allure of the analytical function of surface temperature as a function of air temperature and solar flux compared to experimental results

From this results it is possible to calculate the surface temperature profile of a flexible pavement knowing only and at the same time these two meteorological data. Know the daily surface temperature amplitudes in a pavement structures is able to determine their degradation conditions in time.

5. Conclusion

In arid regions, where often the climate is characterized by a clear sky, pavement structures are particularly sensitive to thermal effects. The change of this gradient, and especially in episodes of intense heat, has a great influence on their behavior. The objective of this work is to estimate the surface temperature, according to the air temperature and the solar flux, which remains an important parameter in the determination of the physical characteristics of the material, namely the asphaltic concrete.

The comparison of the results of the model developed, with the consideration of the two metrological parameters at the same time, with the experimental results was satisfactory and very encouraging. It confirms, on the one hand, the validity of the analytical approach elaborated, and on the other hand that a good choice of model in transient thermal calculation, and the thermo mechanical behavior of the flexible pavement structure under thermal loads in these regions.

This research may by extended in the future according to the following aspects:

- Prediction of pavement temperature at any instant of time at various of layers become accessible knowing the surface temperature, and thermal properties materials.
- In the desert climate regions, where the humidity level is too high, it is necessary to introduce the relative humidity parameter in the calculation of the surface temperature.

6. Acknowledgement

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7. Conflicts of Interest

The authors declare no conflict of interest.

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