

Temperature Distribution Through Asphalt Pavement in Tropical Zone

khalid S. Shibib
University of Technology

Dr. Qusay Abduljabbar Jawad
University of Technology

Haqi I. Gattea
University of Technology

Received on: 5/9/2011

Accepted on: 23 /10 /2012

ABSTRACT.

Temperature distribution through asphalt and the underlying layer have been obtained numerically using finite element method where a varying induced heat from sun and environment cause fluctuating temperature distribution throughout. The maximum effect of these parameters on the temperature of the asphalt is expected in summer, so the temperature distribution was studied in the summer only. Some interesting results were found; at tropical zone such as in Baghdad the asphalt surface temperature may reach (70°C) and it is reduced with depth. Due to fluctuating environment heat effect, the subsequent temperature of the asphalt and the underlying layer may fluctuate with some delay and damping depending on the layers thermal properties, these results may be used later to predict both the erosion rate of car tires and asphalt thickness, also the preserved energy using asphalt layer may be used to confine heat for further usage as in electrical generation.

Keyword: asphalt temperature, finite element method, tropical zone environmental, Solar heat gain and temperature measurements.

1. INTRODUCTION.

The temperature distribution through asphalt pavement has special importance due to its effect on the efficiency of braking in vehicles. The rate of erosion in the rubber of the tires is affected mainly by its temperature; also the temperature in asphalt is important due to its effect on the temperature of its environment such as building. The emission of heat from asphalt to the environment has a deep effect on the amount of heat received by the building and the subsequent increase in its temperature which highly affects the building thermal load.

So special attention has to be concentrated on this field. In this work the temperature distribution through a layer of asphalt was studied taking into account the influence of the environment and the heat flow through the layer of the asphalt. The benefit of determining temperature distribution through the asphalt can be extended to study the rate of erosion of the asphalt itself so the expected life of the asphalt road with good characteristics can be determined.

2. LITERATURE SURVEY.

A literature review was conducted to locate previous work done in the field of modeling temperature distributions in asphalt layers as a function of thermal environmental conditions. The more significant studies that deal with the same state are:

Pioneering research in the field of asphalt pavement temperatures was done by Barber [1]. Barber attempted to correlate pavement surface temperatures and temperatures at 3.5 inch depths with standard weather report information. The weather parameters used were wind speed, precipitation, air temperature, and solar radiation.

The research and analyses showed that when solar radiation was included in the analyses with air temperature, the sine curve approximation provided reasonable estimates of asphalt surface temperatures.

Straub, et al [2] studied asphalt pavements in the northern climate of New York. The study considered both 6- and 12-inch thick dense graded pavements at various depths. The study showed that surface temperature measurements must be made at the surface to achieve a good correlation with solar radiation received at the site. Straub stated that temperatures at various depths of an asphalt pavement are independent of the thickness of the asphalt pavement.

Demsey and Thompson [3] used an approach similar to that of Straub et al., to create a model to evaluate frost action in multilayered pavements. The inputs required for the model included the climatic properties of short-wave and long-wave back radiation, convection, and air temperature. Inputs of thermal and material properties were unit weight, moisture content, material classification, thermal conductivity, and heat capacity of the pavement material.

Williamson [4] developed a model by adapting a FORTRAN IV model developed by Schenk, Jr. (1963). This model used finite-difference techniques to predict temperatures at various depths over a short period of time, usually a day. Inputs for the model included climatic parameters as well as the thermal properties of the pavement. Results of the analyses indicated that while variations in the surface absorption coefficient had large effects on temperatures, variations in other items, such as, emissive power, convection coefficient, and thermal conductivity had more marginal effects on temperature.

3. MATHEMATICAL FORMULATION AND BOUNDARY CONDITIONS.

Usually the depth of asphalt layer in the roads is much smaller than its width then the one dimension modeling of the heat transfer equation is reasonable. So the governing partial differential equation that covers this case is the one dimensional heat flow known as Fourier equation for heat flow [5]

$$\rho C_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} \quad (1)$$

And the possible boundary conditions are

a) Solar heat gain

Solar radiant heat gain is the net solar radiation absorbed by the asphalt .It is assumed that all solar radiation incident on the asphalt surface becomes heat gain except for the portion reflected at the surface .The absorptivity of the asphalt is taken 0.9 [6]. To determine the reflected and absorbed portion of solar energy

$$I_{ind} = \alpha_s (I_{DN} \cos \theta + I_d) \quad (2)$$

Where

$$I_{DN} = A e^{\frac{-B}{\sin \beta}} \quad (2a)$$

$$\cos \theta = \cos \beta \text{ for horizontal surface} \quad (2b)$$

$$I_d = I_{DN} C \quad (2c)$$

A, B, C can be found in many references such as is ASHRAE hand book see [7], there a well established criteria of calculating angle of sun β is established. A computer program was developed to calculate this angles at each hours of a day for June, July and August in order to obtain the part of solar energy induced to asphalt surface at each hour of a day, the calculation will determine the solar energy that strike the asphalt surface for the three months at latitudes of 32.2° (i.e. at Baghdad)

b) Thermal radiant heat transfer

A well defined linearized radiation coefficient is [4]

$$h_r = 4\epsilon_{low} \sigma \left(\frac{T_s + T_{sky}}{2} \right)^3 \quad (3)$$

Here T_{sky}, T_s are in $^\circ K$, and $\epsilon_{low} = 0.9$

The value of T_{sky} can be obtained from many references [1] where the average weather condition is shown in tab.1.

$$T_{sky} = T_a [0.71 + .0056T_{dp} + 7.3 \times 10^{-5} T_{dp}^2 + 0.013 \cos(2\pi t / 24)]^{0.25} \quad (3a)$$

A dew point temperature can easily be obtained depending on weather condition [7]
Then

$$q_{rerad} = h_r (T_{sky} - T_s) \quad (4)$$

c) Convective heat transfer

Heat transfer coefficient is defined by many references [5] and heat transfer by convection to or from the Asphalt can be defined as

$$q_{co} = h_{co} (T_{inf} - T_s) \quad (5)$$

Nussult number is used here to determine the turbulent heat transfer coefficient.

$$Nu_x = 0.0296 Re_x^{4/5} Pr^{1/3} \quad (6)$$

And by integration through the width of the asphalt one can obtain the average value:

$$Nu_{av} = 0.037 Re_L^{4/5} Pr^{1/3} \quad (7)$$

Where air properties are found at film temperature and L is the width of asphalt =5m

d) Daily temperature variation

Daily temperature variation program is published by Parton [9] and is used in this work, it need some local assumption depend on the location, the hour after noon of the sun to reach the maximum temperature which is measured in Baghdad to be 3 hours after the noon of the sun and the time in hours after sunrise to reach the minimum temperature which is chosen to be zero.

3.1. Surface Boundary Condition.

The surface equation of heat transfer can be summarized as

$$q_s = I_{ind} \mp q_{co} - q_{rerad} \quad (8)$$

3.2. Asphalt Properties.

The thermal properties of asphalt and the ground are [6]

Asphalt	Ground
Thickness=20cm	Thickness=2.8m
$k = 0.43 \text{ W. m}^{-1} \cdot \text{K}^{-1}$	$k = 8.65 \text{ W. m}^{-1} \cdot \text{K}^{-1}$
$\rho = 1200 \text{ kg. m}^{-3}$	$\rho = 1885 \text{ kg. m}^{-3}$
$C_p = 1080 \text{ J. kg}^{-1} \cdot \text{K}^{-1}$	$C_p = 796 \text{ J. kg}^{-1} \cdot \text{K}^{-1}$

The unaffected depth is tested to be 3 m ,there an adiabatic boundary condition can be assumed

3.3. Finite Element Formulation.

The space wise discretization of Fourier equation subject to the above boundary condition can be accomplished using Galerkin method .The region of interest Ω is divided into a number of elements, Ω^e , with usual shape function N_i associated with each node, the unknown function T is approximated through the solution domain at any time by:

$$T = \sum N_i(x, t) T_i(t) \quad (9)$$

Where $T_i(t)$ represent the nodal parameters. Substitution of the above equation into Fourier equation (i.e. equation 1) and the application of Galerkin method results in a system of ordinary differential equations of the form [10]

$$[C] \dot{T} + [K] T + [F] = 0 \quad (10)$$

Where $\dot{T} = \begin{Bmatrix} \frac{\partial T_1}{\partial t} \\ \frac{\partial T_2}{\partial t} \\ \dots \\ \frac{\partial T_p}{\partial t} \end{Bmatrix}$, $T = \begin{Bmatrix} T_1 \\ T_2 \\ \dots \\ T_p \end{Bmatrix}$ and $[F] = \begin{Bmatrix} F_1 \\ F_2 \\ \dots \\ F_p \end{Bmatrix}$ where p is the total no. of node

And the typical matrix elements are

$$K_{ij} = \sum \int_{\Omega^e} k \left(\frac{\partial N_i}{\partial x} \frac{\partial N_j}{\partial x} \right) d\Omega \quad (11)$$

$$C_{ij} = \sum \int_{\Omega^e} \rho C_p N_i N_j d\Omega \quad (12)$$

$$F_i = -\sum_{\Gamma^e} \int q_s d\Gamma \quad (13)$$

In the above, the summation are taken over the contribution of each element, Ω^e , in the element region and Γ^e refers only to the element with external boundary on which surface condition is applied, using linear shape function which normalize to time interval Δt , the result is in standard linear shape function, then the application of weighted residual theory to equation 9 with linear shape function than the result in matrix form will be:

$$\left(\frac{[C]}{\Delta t} + \Theta[K] \right) \bar{T}_{n+1} + \left(\frac{-[C]}{\Delta t} + (1 - \Theta)[K] \right) \bar{T}_n + \bar{F} = 0 \quad (14)$$

Where

$$\bar{F} = \bar{F}_{n+1} \Theta + \bar{F}_n (1 - \Theta) \quad (14a)$$

And Θ can have different value. In this solution a forward difference has been chosen due to its simplicity (i.e. $\Theta = 0$) an iteration solution has been used at each time step to insure an accurate results. A time step of 1/4 hour is chosen and a starting time at 1st of April with initial condition asphalt temperature of 22° C and the calculation will be stopped at 22 August. Assume 20 cm thickness of asphalt and the temperature variation is vanished at 3m.

4. RESULT AND DISCUSSION.

The Environment temperature for daily variation of temperature is shown in **Fig.(1)**. It was assumed that the maximum temperature occurs 3 hours after the noon of the sun and the minimum temperature occurs at sunrise. Assume the modulation used to determine the variation of daily temperature as suggested by Parton [9]. The solar radiation that strikes the surface of the asphalt is shown in **Fig.(2)**, as calculated by the program developed to determine induced energy to asphalt. It includes horizontal component of direct normal radiation and the diffused solar radiation at 21 June, 21 July, 21 August. Clearly at this altitude the maximum solar energy occurs at 21 June.

The localized heat transfer coefficient of heat transfer between air and asphalt is obtained using eq.(7) where the wind velocity is equals to 4 m/sec which is the common wind velocity in Iraq. The surface temperature of asphalt for this wind velocity is shown in **Fig.(3)** for 21 June, 21 July, and 21 August.

Because the combination effect of solar radiation and thermal environment load dominate in July then the surface temperature of asphalt will be maximum at this month see **Figs.(2 ,3)**. The in-depth temperature distribution with asphalt thickness of 20 cm will fluctuate, this is due to fluctuating in environment conditions (i.e solar heat flux and ambient condition), See **Fig.(4)**. The inside temperature distribution is shown in **Fig.(4)** for 21 June where the transient fluctuating is damped as thickness increased this is due to influence of layers thermal properties.

Good agreement can be observed between theoretical and experimental data which may verifies the mathematical model.

5. CONCLUSIONS.

1. The finite element method describes well temperature distribution through asphalt pavement and good agreement is found comparing with experimental data.

2. In hot region at summer the maximum temperature of asphalt may reach 70 °C with wind speed of 4 m/sec at 21 July which is the maximum temperature that may occur since the combination of maximum solar radiation and thermal environment load is maximum.
3. The inside temperature distribution at a depth of 20 cm of asphalt will fluctuate reaching its max of 48C, 6 hour after the max temperature of the environment and its minimum temperature is 42 °C, occurs three hour before the max temperature of the environment this may vary depending on the thickness of asphalt layer.

6. REFERENCES.

- [1] Barber, E.S., "Calculation of Maximum Pavement Temperatures From Weather reports. Highway Research Board Bulletin", 1957, 168: 1-8.
- [2] Straub, A.L., H.N. Schenck Jr., F.E. Przybycien, "Bituminous Pavement Temperature Related to Climate". Highway Research Record, 1968, 256: 53-77.
- [3] Dempsey, B.J., H. Hill, et al. 1987. "Characterizing Temperature Effects for Pavement Analysis and Design". Transportation Research Record, 1121: 14-22.
- [4] Williamson, R.H. 1972. "Effects of Environment on Pavement Temperatures". International Conference on Structural Design Proceedings: 144-158.
- [5] Faye C. Mcquistion, Jerald D. Parker, and Jeffrey D. Spitler . Heating, Ventilating, and Air conditioning, John Wiley and Sons Inc. 5th edition, New York, USA, 2000.
- [6] V.P. Isachenko, et al., Heat Transfer, Mir Publishers, Moscow, 1977.
- [7] ASHRAE 1997 & 1999 *ASHRAE Handbook-CD, 1997-1999*.
- [8] Chiasson, A.D., J.D. Spitler, S.J. Rees, M.D. Smith.. A Model For Simulating The Performance Of A Shallow Pond As A Supplemental Heat Rejecter With Closed-Loop Ground-Source Heat Pump Systems. ASHRAE Transactions. 106(2000), 2, pp. 107-121
- [9] Parton W.J. And J.A. Logan . A Model for Diurnal Variation in Soil and Air Temperature. Agricultural Metrology 23(1981), pp.205-216
- [10] R.W. Lewis, et al., The Finite Element Method In Heat Transfer. , John Wiley & Sons LTd , Chi-chester, UK, 1996

Nomenclature.

A- apparent solar radiation at air mass=0 [W. m⁻²]

B- atmospheric extinction coefficient

C- diffused coefficient

C_p - specific heat [J .kg⁻¹ .K⁻¹]

h -coefficient of heat transfer by convection [w. m⁻² .K⁻¹]

I -solar flux [w. m⁻²]

k -thermal conductivity [w. m⁻¹ .K⁻¹]

N_i - shape function

q - heat flux [w. m⁻²]

T -temperature [°C or °K]

t-time [s or hr]

[C],[K],[F] -matrices

Greek letters.

α -absorptivity

β -solar altitude with horizontal

ε -emissivity

γ - solar surface angle (from south)

Ω -region

ρ - density [$\text{kg} \cdot \text{m}^{-3}$]

σ - Stefan Boltzmann constant= $5.669 \times 10^{-8} [\text{w} \cdot \text{m}^{-2} \cdot \text{K}^{-4}]$

θ - angle of incidence between the direct solar beam and the normal to surface

Γ - surface

Subscripts or Superscripts.

av-average

a-air

d-diffused

DN –direct normal

dp-dew point

co- convection at outside

e-element

ind-induced

low-low temperature radiation

r-radiation

s-surface

rerad- reradiation

Affiliations.

1 -Baghdad - University of Technology –Department of Laser and optoelectronics Engineering, P.O Box 35010 , E-mail: Assprofkh@yahoo.com

2-Baghdad-University of Technology-Energy and fuel research center P.O Box 35010, E-mail: qaj_2010j@yahoo.com

Table (1): Summer environment weather condition in Baghdad.

Month	Max. temp. °C	Min. temp. °C	Relative Humidity%	
			P.M	A.M
June	41	23	13	34
July	43	24	13	32
August	43	24	13	33

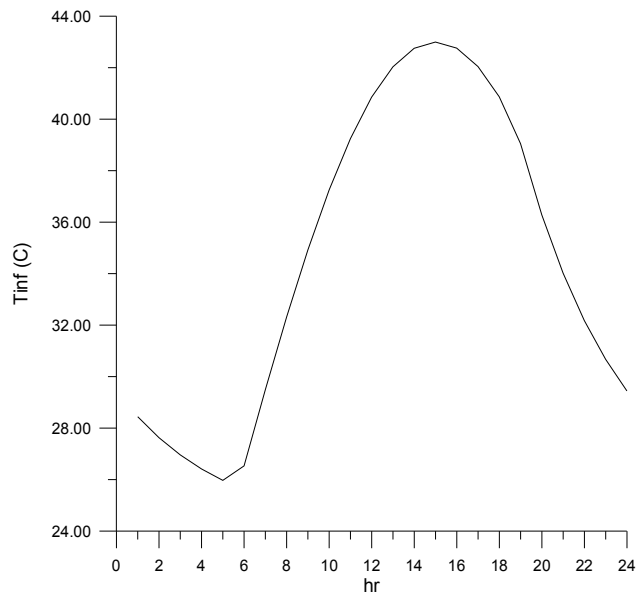
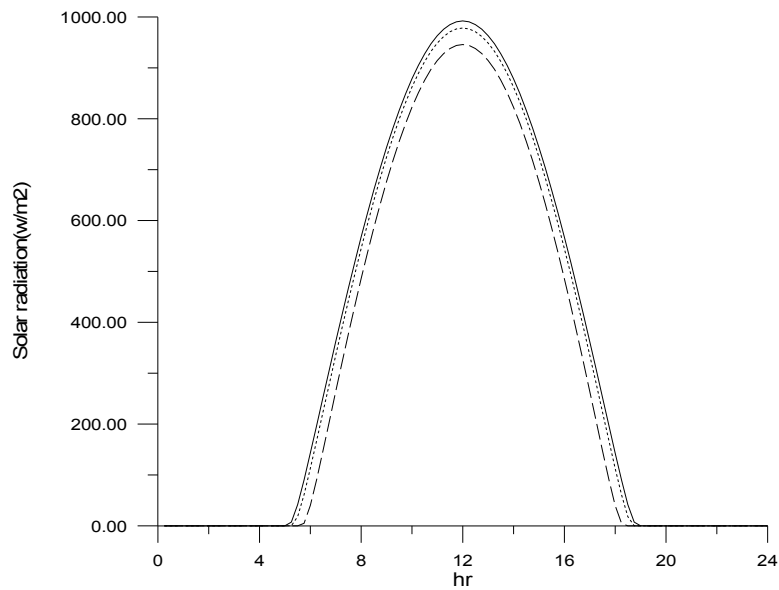


Figure (1): Daily variation of environmental dry-bulb temperature at July.



Figure(2): Solar radiation at different months, solid line for 21 June, small dashed for 21 July, long dashed for 21 August.

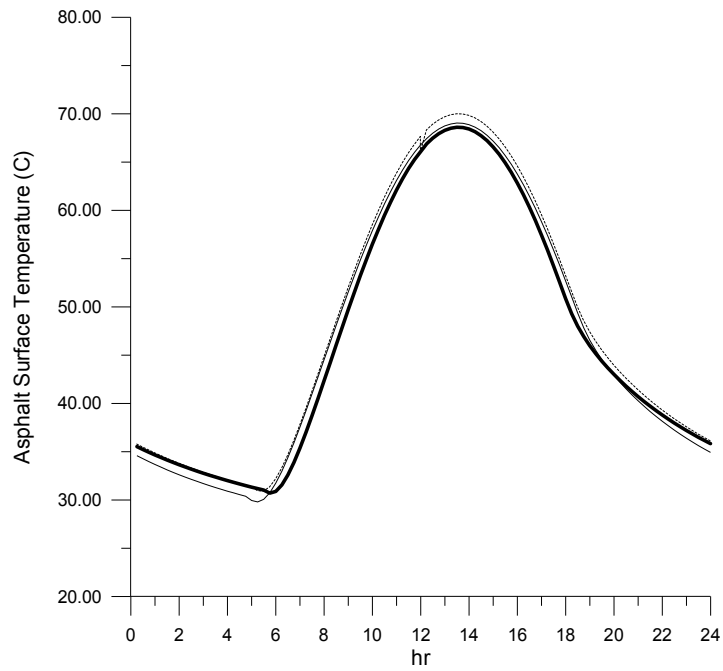


Figure (3): Daily temperature variations through different months, bold line for 21 August, dashed line for 21 July, thin line for 21 June.

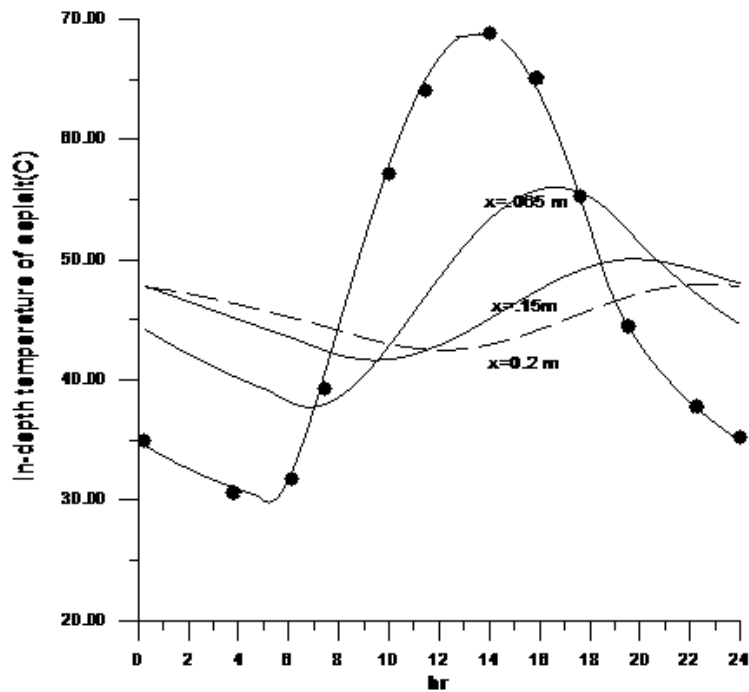


Figure (4): Temperature distribution at different depths, the line combined with dot point indicates experimental data(dot) and theoretical result (line) at the surface.

توزيع درجات الحرارة خلال التبليط الأسفلتي في المناطق الاستوائية

م.م.حقي إسماعيل كاطع
هندسة كهروميكانيك

م.د.قصي عبد الجبار جواد
مركز تكنولوجيا الطاقة والطاقات المتجددة

م.م.خالد سالم شبيب
هندسة الليزر والبصريات

الخلاصة.

تم استنباط توزيع درجات الحرارة خلال الإسفلت والطبقة السفلية له عددياً باستخدام طريقة العناصر المحددة حيث أن التغيير في الحرارة المحتثة من الشمس والظروف المحيطة تسبب تذبذباً في درجات الحرارة . ان التأثير الأقصى تم توقعه لأن يكون في فصل الصيف الحارة وعليه فقط تم دراسة توزيع درجات الحرارة في هذا الفصل فقط وفي المناطق الحرة كبغداد فان درجة حرارة سطح الإسفلت تصل إلى 70 درجة مئوية وتقل مع العمق . نتيجة تذبذب الظروف المحيطة فان درجة حرارة الإسفلت والطبقة السفلية ستذبذب أيضاً مع بعض التأخير في الزمن اعتماداً على المواصفات الحرارية للإسفلت والطبقة السطحية. من الممكن الاستفادة من هذه النتائج لاستنباط الاهتراء في عجلات السيارات وطبقة الإسفلت نفسها كذلك من الممكن الاستفادة من النتائج لمعرفة كمية الحرارة المخزونة في وتحت طبقة الإسفلت لاستخدامها لاحقاً في محطات توليد الطاقة الكهربائية.

الكلمات الرئيسية: حرارة الإسفلت، طريقة العناصر المحددة، المنطقة المدارية، الكسب الحراري الشمسي وقياسات درجة الحرارة.