

Impact of Short-Wave Solar Absorptivity on Jointed Plain Concrete Pavement Response

Jacob E. Hiller, Ph.D.¹ and Yinghong Qin, Ph.D.²

Abstract

This study investigates the impact of the pavement's short-wave solar absorptivity (SA) on the temperature profile and subsequent thermal-stress distribution through rigid pavement slabs. A one-dimensional heat transfer model is proposed to simulate the pavement temperature using a modified Blasius solution to estimate the heat convection coefficient at the pavement surface. In-service slab temperatures are used to verify the feasibility of the proposed model. It was found that an increase in SA amplifies both the magnitude and non-linearity of the temperature gradients in the slab, thus raising the linear bending stress and self-equilibrating stresses through the slab. Concrete surface materials must be properly characterized in order to accurately assess the thermal-induced stress development in concrete pavement structures and to better estimate the longevity of its service life.

Introduction

Temperature distributions through in-service pavement slabs depend on the amount of the absorbed solar radiation, which is determined by the concrete's short-wave surface absorptivity (SA). The SA of a concrete pavement slab evolves during its service life, starting at a lower value and increasing over time. The SA of concrete is typically around 0.6-0.65 for new concrete, but can be as low as 0.5 using "cool" materials such as tan beach sands and plagioclase as aggregates (Levinson and Akbari 2002). This SA factor is highly dependent on the texture, color, and condition of the pavement surface. Conversely, the SA of an asphalt material starts at a very high value (typically 0.9-0.95) and reduces over time as the asphalt concrete oxidizes and becomes more reflective. The impact of the solar radiation absorption on the pavement temperature distribution thus merits investigation.

Impacts of the SA on the temperature distribution and the thermal-stress distribution across a slab have been well studied (Solaimanian and Bolzan 1993; Solaimanian and Kennedy 1993; Ongel and Harvey 2004). It has been found that small differences in SA cause a significant change in pavement temperature profiles. Solaimanian and Bolzan (1993) found that a rise in SA by 0.1 can increase the temperature at any depth by approximately 2.8°C. The Solaimanian and Bolzan study centered on the uniform temperature rise rather than on the temperature distribution through a slab. It thus, to a great degree, failed to characterize the impact of SA on the developed thermal stresses and subsequent performance of a pavement slab. Recently, the developed thermal stresses and their impacts on rigid pavement performance were reported in Kannekanti and Harvey's work (2006). It was found that transverse cracking

¹ ISCP Director, Assistant Professor, Michigan Technological University, 1400 Townsend Drive, Houghton, Michigan, USA, 49931, jhiller@mtu.edu, phone: 906-487-3053, fax: 906-487-1620

² ISCP Student Member, Faculty of Engineering, China University of Geosciences, Wuhan, China 430074

development was sensitive to SA, climate zone, as well as other factors. An investigation on the role of SA on a rigid pavement's performance thereby has to consider both the increase in SA with time and traffic as well as the availability of solar radiation at a particular site.

This study investigates the change in SA on the temperature and stress distributions within rigid pavement slabs. A one-dimensional heat transfer model is proposed to predict the temperature profile through a slab's depth. It simulates both temperature distribution and thermal-stress distribution of a JPCP (Jointed Plain Concrete Pavement) slab under different weather conditions (sunny and cloudy) in order to study whether the available solar radiation amplifies the influence of SA.

Numerical model

One-dimensional heat transfer model. Pavement temperatures are mainly controlled by the heat flux at the surface as the width and length of a pavement slab is far greater than the thickness. A one-dimensional heat transfer model is thus adequate to predict the temperature distribution of a slab and its underlying layers. Since the water and vapor migration (if any) in the ground is relatively stagnant, the Peclet Number of this migration is close to, or even, zero such that heat convection in the ground and pavement is negligible. Temperature T ($^{\circ}\text{C}$) of the mediums (the pavement slab and the underlying layers) can be described by the Fourier Equation:

$$\rho c \frac{\partial T}{\partial t} = \text{div}(k \cdot \text{grad}T) + q \quad (1)$$

Where k ($\text{W}/\text{m}^{\circ}\text{C}^{-1}$) is the thermal conductivity of mediums; ρ (kg/m^3) and c ($\text{J}/\text{kg}^{\circ}\text{C}^{-1}$) are the density and the heat capacity of mediums, respectively; q (W/m^2) is the internal heat generation rate, for hardened concrete, $q = 0$. The thermal capacity, density, and thermal conductivity of concrete have been well documented (Chung and Shin 2008; Kim et al. 2003; Khan 2002). These properties are a function of concrete mixture characteristics, e.g., water-to-cement ratio, aggregate volume, and porosity of the concrete. Detailed values for these parameters are site-specific and reasonably controllable parameters. Typical ranges and the specific thermal property values used in this paper are shown in Table 1.

Table 1. Thermal parameters of the pavement and underlying layers.

Stratum	c ($\text{W} \cdot \text{K}^{-1} \cdot \text{m}^{-1}$)	k ($\text{KJ} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$)	ρ (kg/m^3)
Slab ^a	2.5 (1.5-3.5)	1.0 (0.84-1.17)	2350 (2200-2400)
Asphalt base ^b	1.8 (1.5-2.0)	0.9 (0.9-1.3)	2210 (2297-2425)
Gravel subbase ^c	1.8 (1.5-1.8)	0.9 (0.7-0.9)	2210 (1792-2405)
Subgrade ^d	1.5 (0.5-2.0)	0.86 (0.8-0.9)	1560 (1380-1600)

Note: The values within the bracket are a rough range of the medium's thermal properties; the exact value is site-specific. ^a(Morabito 2001); ^b(Luca and Mrawira 2005); ^c(Jean and Jean-Marie 2005); ^d(Lu et al. 2006); Density for sub-base is dry density.

Boundary conditions. Temperature distributions through the pavement and the ground are controlled by the heat flux from the deep ground as well as the pavement surface.

The lower boundary is mainly affected by the heat flux from the interior of the earth and therefore exhibits less variation. The depth of zero annual temperature amplitude approximately ranges from 10 to 20m below the ground surface (Andersland and Ladanyi 1994). To accurately predict the ground temperature for different site-specific conditions, this study selects the lower boundary as 20m beneath the bottom of the pavement's base layer (Figure 1). This depth and its temperature are site-specific and thus are difficult to determine. Usually, the geothermal gradient in the subgrade layer is $0.03^{\circ}\text{C}/\text{m}$ (Goering and Kumar 1996), as shown in Figure 1b. This geothermal gradient adds another heat component to the underlying layers and keeps the deep ground thermal gradient, not the temperature magnitude, a constant.

The upper boundary condition depends on the local weather conditions (Figure 1a). The magnitude of the heat flux is again a site-specific, but less controllable, parameter. Estimation of the heat flux at the pavement surface has to consider the solar radiation, thermal irradiation, and heat convection, respectively.

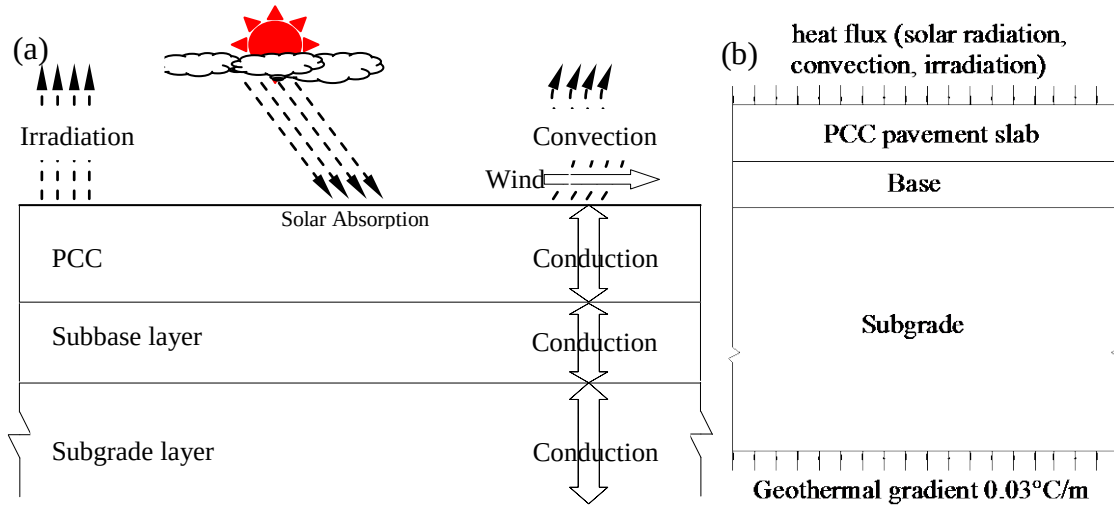


Figure 1. Heat transfer model; a) Schematic for heat transfer model, b) boundary conditions.

Solar Radiation. Solar radiation propagates energy as a short wave arriving at the ground surface. The energy absorbed by the earth surface depends on the medium's thermal properties and on the color of the surface. The following formula has been widely used to compute the short-wave absorption of solar radiation q_{abs} (W/m^2):

$$q_{abs} = \gamma_{abs} \times I_f \times q_{solar} \quad (2)$$

Where γ_{abs} is the solar absorptivity of the pavement surface; I_f is the intensity factor counting for the sun's angle during a 24-hour day; and q_{solar} is the daily peak value of solar radiation. The solar absorptivity γ_{abs} relies on the ground surface color. For concrete pavement, γ_{abs} ranges from 0.5 to 0.85 for new and older concrete, respectively. Considering a rigid pavement slab becomes darkened after opening to traffic, this paper uses $\gamma_{abs} = 0.8$. The solar radiation intensity I_f strongly depends on the atmospheric conditions, time of day, and incident angle of the sun's ray on the ground surface. During nighttime conditions, the solar radiation is negligible. During the daytime, I_f is assumed to follow a sinusoid function (Bentz 2000; Ge 2005). It varies with the time

of day and ranges from zero at both sunrise and sunset to a peak value at midday. Solar radiation q_{solar} depends on the sky conditions, e.g., cloud cover. According to McCullough and Rasmussen (1999), q_{solar} is 1000 W/m² on sunny days, 700 W/m² on partly sunny days, and 300 W/m² on cloudy days.

Thermal irradiation. Thermal irradiation emits long-wave energy between the natural ground surfaces and the sky. The emitted flux, q_{irr} (W/m²), follows the Stefan-Boltzmann law and can be expressed as:

$$q_{irr} = \varsigma \times \varepsilon \times (T_{sky}^4 - T_s^4) \quad (3)$$

Where T_s is slab's surface temperature, (°K). ς (Wm⁻²K⁻⁴) is the Stefan-Boltzmann constant, $\varsigma = 5.669 \times 10^{-8}$, T_{sky} (°K) is the effective sky temperature (effective sky temperature is the temperature of blackbody radiation having the same flux as the downward atmospheric radiation and is not equal to air temperature), and ε is the ground surface's emissivity. $\varepsilon = 0.90$ is used in this study and others (Kapila et al. 1997; Rohsenow et al. 1998) when evaluating pavement temperatures. Walton (1985) used the following formula to predict T_{sky} :

$$T_{sky} = \varepsilon_{sky}^{0.25} \times T_a \quad (4)$$

Where T_a (°K) is air temperature; ε_{sky} , the sky emissivity, is given by (Tang et al. 2004):

$$\varepsilon_{sky} = 0.754 + 0.0044T_{dp} \quad (5)$$

Where T_{dp} (°C) is the local dew point, which is available from the National Oceanic and Atmospheric Administration (NOAA) database for sites within the United States.

Convection. The heat flux q_{conv} (W/m²) due to the convection at the pavement surface is given by:

$$q_{conv} = h_{conv}(T_a - T_s) \quad (6)$$

Where h_{conv} is the convection coefficient, W/m²°C⁻¹. The magnitude of h_{conv} is a function of the local Reynolds number Re , the thermal conductivity of the air K_{air} (W·K⁻¹·m⁻¹), the air's Prandtl number Pr , and the characteristic length of the medium where wind blows upon. According to traditional heat transfer theory (Jiji 2009; Rohsenow et al. 1998), h_{conv} consists of two parts: free and forced convections. The heat convection coefficient of free air convection on a flat plane is approximately 5.6 W/m²°C⁻¹ (Jiji 2009). According to the Blasius solution (Jiji 2009), the coefficient of a forced convection on a flat plane is $0.332Re^{0.5} Pr^{1/3} K_{air}/L$ if the airflow is less than 6m/s. This study modifies the Blasius solution by combining the heat convection coefficients at free and forced convections. Therefore, the heat convection is expressed as:

$$h_{conv} = 5.6 + 0.332Re^{0.5} Pr^{1/3} K_{air}/L \quad (7)$$

Where for the air, $K_{air} = 0.027$, $Pr = 0.7$. For the airflow upon an infinite flat plate, $L = 0.15$ m. The Reynolds number Re is:

$$Re = \nu L/\nu \quad (8)$$

Where v is the local wind velocity, ν (m^2s^{-1}) is the air's kinematic viscosity (16×10^{-6}).

Therefore, the total heat flux at the pavement surface can be calculated as:

$$q_{total} = q_{conv} + q_{abs} + q_{irr} \quad (9)$$

Simulation verification

To simulate thermal effects for a concrete pavement, the computational domain in this 1-D finite element model is discretized by 23 quadratic elements, with 10 elements for the slab, 3 elements for base, and 10 elements for the subgrade. The base is assumed to be 10cm thick asphalt concrete. The time step is 6 minutes to ensure the convergence of the simulation in realistic time. The initial temperature for both pavement structure and underlying layer is obtained by use of the ground temperature profile from the preceding date. This date's temperature profile is gained by utilizing the local air annual mean temperature to simulate the ground temperature to a degree such that the temperature profile difference between this date and the same date in the previous year is less than 0.01°C . The Crank-Nicolson method is used to implicitly solve the differential Eq.(1).

The reliability of the proposed one-dimensional heat transfer model is partially verified by the documented data in (Yu et al. 1998). The verification uses climatic conditions obtained from the NOAA database as input parameters for the model. The thermal properties of the slab, base, and subgrade utilized in this study are listed outside the brackets in Table 1. Numerical results computed from the proposed model visually and statistically coincide with the in-situ observed data of temperatures through the slab depth (Figure 2). The maximum temperature difference between predicted results and the observations is 2.5°C . The mean error and standard error are -0.17°C and 1.24°C , respectively.

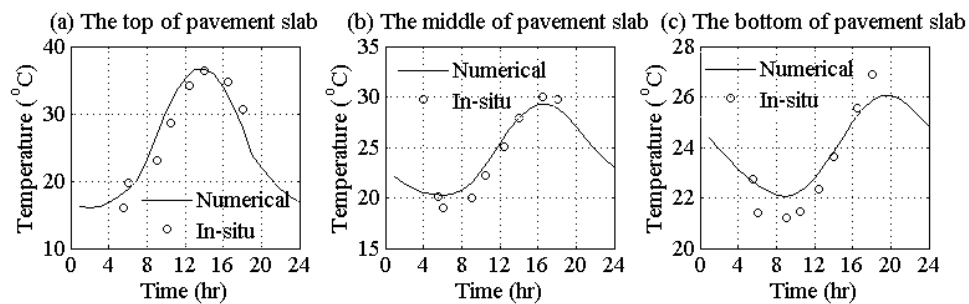


Figure 2. Predicted numerical results from 1-D thermal model versus the in-situ observed temperatures (dotted data reproduced from (Yu et al. 1998)).

Results and discussion

This study estimates the temperature distribution and thermal-stresses distribution through a JPCP in Reno, Nevada, USA. It models the pavement's temperature regime for July 12, 2010, in order to assess the maximum stress effect during summer conditions. The thermal parameters of the subgrade under I-80 at Rainbow Ridge Park (in Reno) are obtained from United States Department of Agriculture (USDA). The slab's thickness is assumed to be 25cm. The local air temperature, wind speed, and dew point are obtained from NOAA and plotted in Figure 3.

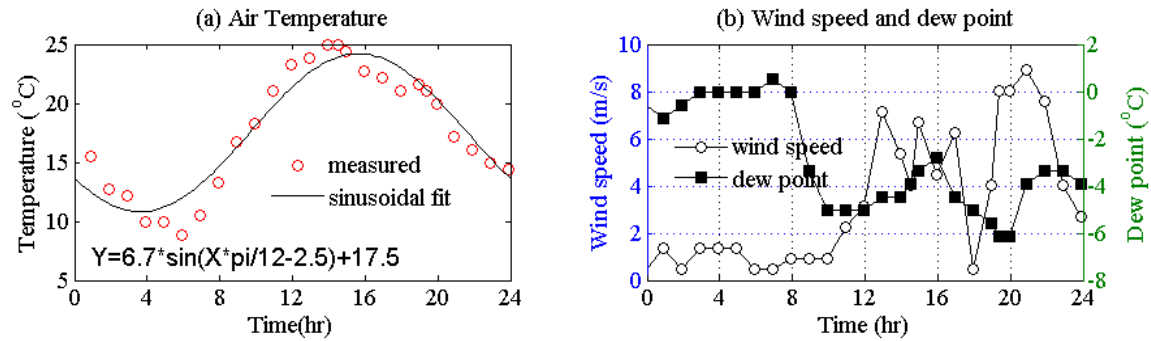


Figure 3. Air temperatures, wind speed, dew point on July 12, 2010, in Reno, Nevada, USA.

Effect of SA on temperature regime in the slab. The temperature across the slab increases with the SA, especially on a sunny day. An increase in SA allows the slab surface to absorb more solar radiation and, consequently, increases the entire slab's temperatures. If the SA grows from 0.5 to 0.86, temperatures within the slab rise by approximately 2 to 4°C (depending on depth) during a cloudy day and elevate by 4 to 12°C during a sunny day (Figure 4a and b). This temperature increase through the slab intensifies during the daytime as the rise of the SA directly amplifies the amount of heat the sub-surface mediums absorb during the daytime. These temperatures wane during the nighttime since the inheritance of the absorbed heat during the day hours maintains the entire slab depth at a relatively warmer state.

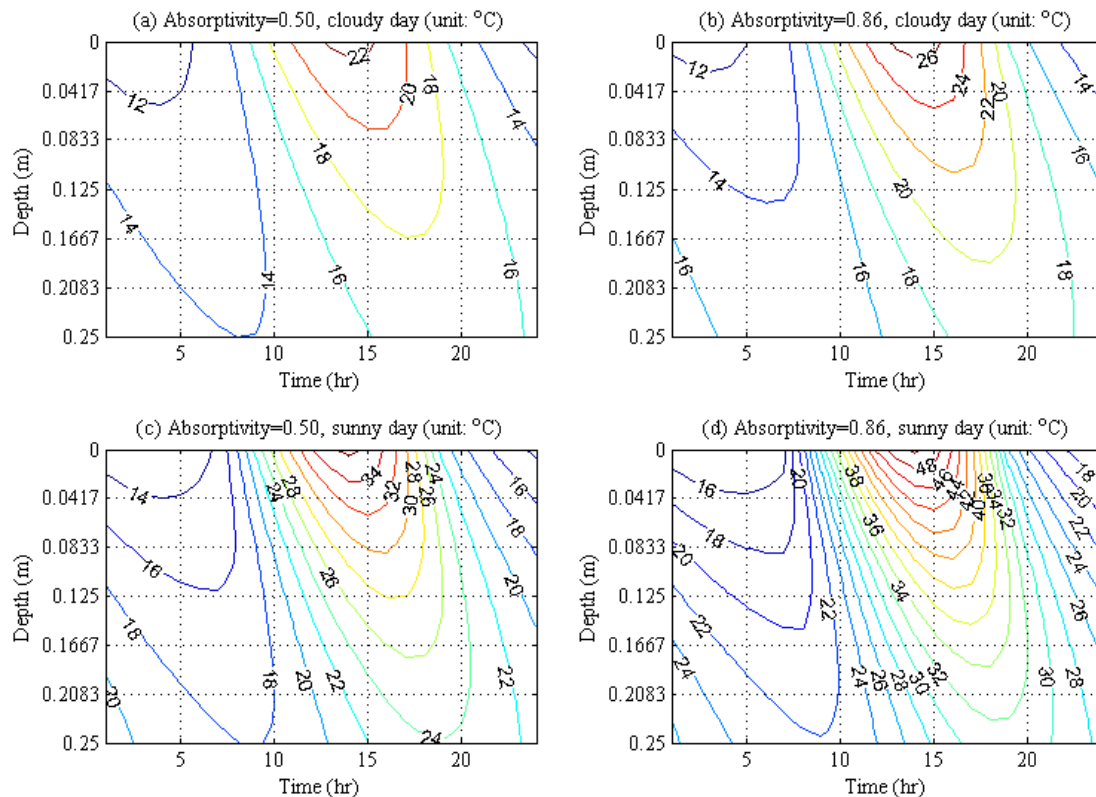


Figure 4. Temperature contours of a slab with different SA.

Increase of the SA also induces nonlinearity within the temperature profiles across the slab depth. The rise of temperature gradients is reflected in the difference, ΔT , between the temperatures at the top and bottom of the slab. During a sunny day at noon, the ΔT of slabs with 0.5 and 0.86 SAs are approximately 12 and 20°C, respectively. The rise of slab temperature gradients is also represented by the temperature contours. Both on cloudy and sunny days, the contours of the slab with SA=0.86 are spaced closer together than with concrete at SA=0.5. This rise is especially pronounced during mid-day under higher SA and sunny conditions (Figure 4d). This increase in the temperature gradient through the slab will induce larger thermal stresses in the slab.

Effect of SA on stress distribution in concrete slab. Temperature profiles in a pavement lead to thermal stress development in the slab in multiple ways. The thermal stresses developed can be decomposed into linear stress and nonlinear stress components as shown in Figure 5. The linear temperature difference between the top and the bottom creates a bending moment and leads to the bending stress through a slab. The nonlinearity of a temperature profile results in an internal restraint between the slab's elements in order to satisfy the continuum of the slab. This stress induced by the internal force is referred to as the self-equilibrating stress. Assuming negligible uniform temperature effects (Hiller and Roesler 2008; Hiller and Roesler 2010), the combination of these two stresses is referred to as the total thermal stress. Detailed information concerning the calculation of these thermal stresses across the concrete pavement slab can be found in (Mohamed and Hansen 1996; Mohamed and Hansen 1997).

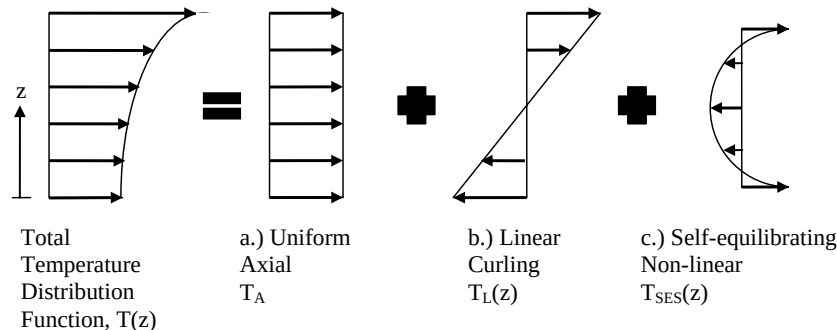


Figure 5. Components of the total temperature-induced stresses.

This study computes the thermal stress using the following parameters:

PCC slab

- Coefficient of thermal expansion $\alpha = 9\mu\epsilon/^{\circ}\text{C}$
- Young modulus $E = 20\text{GPa}$
- Poisson ratio $\mu = 0.15$
- Slab dimensions: X=3.6m (transverse); Y=6.0m (longitudinal);

Subgrade

- Modulus of sub-grade reaction, $k = 50\text{ MPa/m}$

By using these parameters, the stress correction factor for the PCC slab width and length are $C_x = 0.62$ and $C_y = 1.01$, respectively (Bradbury 1938; Westergaard 1927). The stresses plotted and discussed in the following section are the longitudinal stresses, which are greater than the transverse stresses since $C_y > C_x$.

Stress profiles. A rise in the concrete's SA increases the linear stress developed through the slab (Figure 6). During the daytime, an increase of the SA directly raises the near-surface temperature and, subsequently, the temperature difference ΔT in the slab. It therefore increases the bending moment and the subsequent linear stress developed in the slab as well (Figure 6a and c). During the nighttime, a slab with higher SA experiences a warmer thermal state at the slab bottom as it inherits more heat from the solar radiation experienced during the day hours. It thereby develops a greater negative temperature gradient and is subjected to a higher linear bending stress.

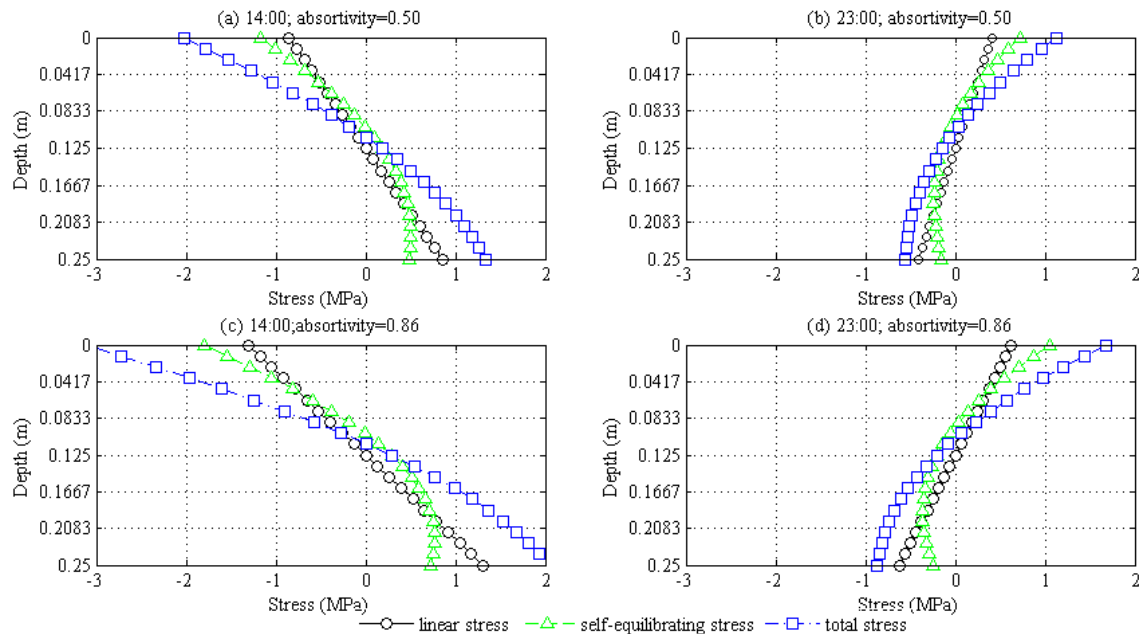


Figure 6. Predicted thermal stress in slab in a sunny day (Note: positive=tension).

A rise in the concrete's SA also increases the self-equilibrating stress through the slab as the temperature profile becomes highly non-linear near the top of the slab. During the daytime, the incoming solar radiation dominates the heat flux at the pavement surface. An increase in SA enhances this dominance and increases the pavement surface temperature; whereas the remaining part of the slab is still of relatively lower temperature. During the nighttime, top of the slab is rapidly cooled whereas the heat inheritance during the daytime hours causes the remaining portion of the slab to become relatively warmer. That is, the top of the slab generally experiences a steeper temperature gradient than the near the bottom of the slab, thereby increasing significance of the self-equilibrating stresses in concrete pavements.

The total thermal stresses developed for this site are lower than the slab designed strengths. Normal portland concrete strengths are about 4.6 and 40MPa for tensile and compressive bending strengths, respectively. The predicted thermal-induced compressive stresses are one order of magnitude lower than the designed strength (Figure 6). At the

bottom of the slab, the maximum tensile stress (total stress) of approximately 2MPa is roughly half of the tensile strength of the slab. Although this is lower than the designed tensile strength, the influence of these stresses can be magnified when combined with the other loadings, e.g., shrinkage-induced stress and traffic loadings, as well as through repeated fatigue effects.

Stress contours. A somewhat unexpected result is that the bottom of the slab suffers from more tensile stress than the top (Figure 7) for this scenario. An increase in the SA augments this difference. For instance, when the SA is 0.5 during a sunny day, the maximum tensile stress at the bottom (1.2MPa) and top of the slab (1.1MPa) are quite similar. When increasing the SA to 0.86, this maximum tensile stress is 2.1MPa at the bottom during the daytime, but only 1.6MPa at the top during nighttime hours. This influence of SA greatly affects the bending stress of a slab during the day hours and therefore increases the total stress at the bottom of the slab at this time.

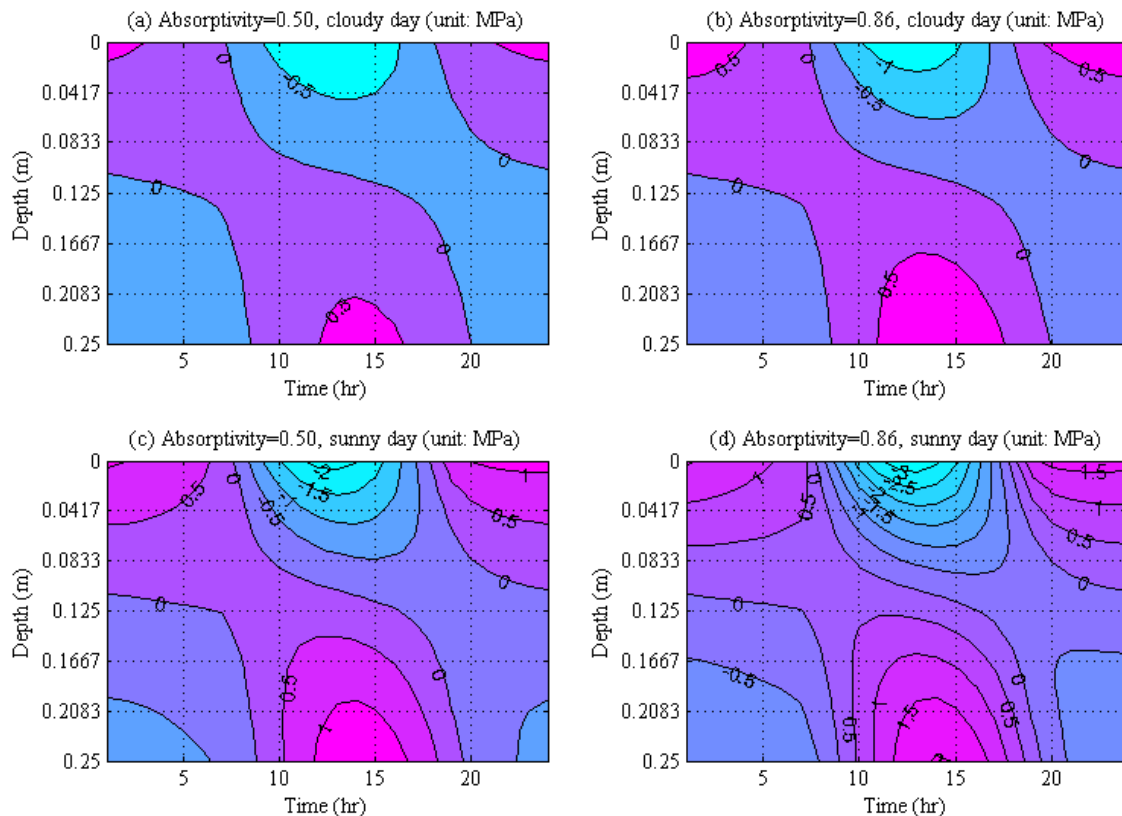


**Figure 7. Predicted total thermal stress distribution in the concrete slab
(Note: positive=tension).**

Compared to the thermal stresses of a concrete slab with lower SA, a slab with higher SA suffers from a higher cyclic stress. An increase of SA from 0.5 to 0.86 considerably intensifies the thermal stresses at the top and bottom of the slab, but has less effect on stresses at mid-depth. This increase is reflected in the heightened magnitude of thermal stresses through the slab and in the increased stress gradient near the top and the bottom of the slab. For example, on a sunny day, the loading cycles at the top of a slab with 0.50 and 0.86 SA are roughly 3.0 and 4.5MPa, respectively.

Thermal stresses and SA. The maximum tensile stresses developed in a concrete slab linearly increases with the SA. An analysis for the stress series at the bottom and top of the slab showed that the maximum tensile stress at the top appeared at 23:00 (11 pm) while the maximum tensile stress at the slab bottom occurred at 14:00 (2 pm). For both cloudy and sunny days, the maximum tensile stresses across a concrete slab section linearly increased with the rise in the SA (Figure 8). The increasing rates of these stresses on a sunny day are approximately 3 times of those on a cloudy day (Figure 8a and b). However, both the maximum tensile stress and its increasing rate at the bottom of the slab are consistently larger than those at the top, regardless of a sunny or cloudy day.

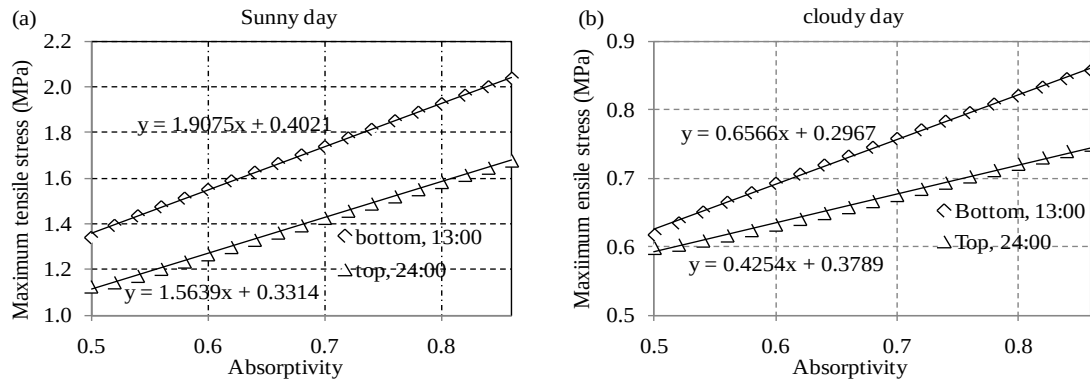


Figure 8. Effect of SA on the maximum thermal tensile stress developed (Note: positive=tension).

Discussion

The predicted performances of a rigid pavement design are sensitive to the concrete's SA. Although the developed thermal stresses of a JPCP slab are lower than the designed tensile strength, the influence of these stresses can be magnified when combined with other loading mechanisms. As shown in Figure 8, a SA's growth from 0.5 to 0.86 will increase the maximum developed tensile stress approximately 0.7MPa. Therefore, the thermal-induced tensile stress resulting from the increase of the SA is of extreme importance to assure a pavement slab can withstand fatigue for its design life.

The Enhanced Integrated Climatic Model (EICM), version 3.4, of the Mechanistic-Empirical Pavement Design Guide (MEPDG) may overestimate the fatigue damage of a JPCP slab as it assumes a constant default value for SA of 0.85 throughout the life of a pavement. The thermal stress developed in a concrete slab is possibly overestimated in the early service periods of a pavement as a young concrete slab will possess a SA significantly less than 0.85. The SA of young concrete slab typically ranges from 0.6 to 0.65, but can possibly be even lower (Levinson and Akbari 2002). Based on the thermal profiles and subsequent stress development results presented in this paper, the MEPDG model possibly overestimates the predicted thermal stresses through a slab and thus over predicts the damage induced by the thermal stresses. This is particularly the case for the damage at the bottom of the slab as this study indicated that the slab bottom normally suffers from higher thermal tensile stress than the top and that an increase of SA enlarges this difference.

An evolvable, variable SA in the EICM or comparable model may be an alternative to better predict the thermal stress development and, ultimately, the

performance of a rigid pavement. The matured SA of an unexposed, abraded concrete slab depends on the albedos ($1 - SA$) of the concrete's components including sand, cement, etc. A flexible input of the SA will help materials and pavement designers to better estimate the fatigue cracking performance of a rigid pavement according to the field observed SA evolutions.

The manner of the evolution of a slab's SA from a lower to a higher value needs further investigation. Although the correlation between the SA and maximum tensile stress follows a linear relation (Figure 8), the time required to increase the SA from 0.5 to 0.7, or even 0.85 remains unknown and is site, traffic, and material-specific.

In addition to the decrease in fatigue life from an increased SA, there also exists an increase in the urban heat island (UHI) effect. Due to the increase in solar radiation absorbed by the pavement material, the surrounding environment is also affected through increased ambient temperatures and higher energy costs to cool nearby buildings. Therefore, the use of concrete that minimizes the SA long-term is beneficial to reduce UHI effects. The use of slag as cement replacement has been shown to decrease the SA significantly, while meeting all the long-term strength and durability concerns that a highway concrete requires (Boriboonsomsin and Reza 2007). These factors should be considered during material selection as well as during the pavement design process as their interaction can help promote long-term sustainable transportation infrastructure solutions for the pavement and environment.

Conclusions

An increase in a concrete pavement's short-wave solar absorptivity (SA) increases the slab temperature at all depths as this allows for heat transfer between the environment and the concrete slab. This increase in SA also raises the temperature gradient and level of non-linearity developed through the slab, thereby increasing the thermal stresses developed through the slab. The amount of the increased thermal stress strongly depends on the available solar radiation from a particular site and day.

The bottom of the slab usually suffers from higher thermal tensile stresses than the top. An increase of the concrete's SA enlarges this difference. While the maximum tensile stress developed through a slab are typically not higher than the bending strength of normal portland cement concrete, these thermal stresses may accelerate the fatigue damages of the slab when combined with other stress-inducing effects from traffic, drying shrinkage, and moisture warping.

The EICM model may overestimate the fatigue damage of a JPCP slab in the MPEDG as it utilizes a constant default SA value of 0.85, which is typically greater than the SA of a young concrete slab. Allowing an evolvable SA function as an input to a thermal prediction model would be an alternative to accommodate the SA evolution over time and, ultimately, allow for better prediction of fatigue cracking performance in rigid pavements.

References

- Andersland OB, Ladanyi B (1994) *An Introduction to Frozen Ground Engineering*. Chapman&Hall, New York, USA, pp342

- Bentz DP (2000) A computer model to predict the surface temperature and time-of-wetness of concrete pavements and bridge decks. National Institute of standards and technology, NISTIR 6551,
- Bradbury RD (1938) Reinforced concrete pavement. Wire Reinforcedment Institute, Washington D.C.
- Chung Y, Shin H-C Characteristics of coefficient of thermal expansion of PCC pavement. In: Transportation Research Record 2009 Annual meeting CD-ROM, Washington D.C., 2008. National Academy Council, pp 1-18
- Ge Z (2005) Predicting temperature and strength development of field concrete. Iowa State University, Ames, Iowa
- Goering DJ, Kumar P (1996) Winter-time convection in open-graded embankments. Cold Regions Science and Technology 24 (1):57-74
- Hiller JE, Roesler JR Accounting for Self-Equilibrating Stresses Due to Non-Linear Temperature Profiles in Rigid Pavements. In, Minneapolis, Minnesota, 2008. ASCE, pp 48-55
- Hiller JE, Roesler JR (2010) Simplified nonlinear temperature curling analysis for Jointed concrete pavement. Journal of Transportation Engineering 131 (8):654-663. doi:doi:10.1061/(ASCE)TE.1943-5436.0000130
- Jean C, Jean-Marie K (2005) Thermal conductivity of base-course materials. Canadian Geotechnical Journal 42 (1):61-78
- Jiji LM (2009) Heat Convection (Second Edition). 2 edn. Springer, Berlin Heidelberg. doi:DOI 10.1007/978-3-642-02971-4
- Kannekanti V, Harvey J (2006) Sensitivity Analysis of 2002 Design Guide Distress Prediction Models for Jointed Plain Concrete Pavement. Transportation Research Record: Journal of the Transportation Research Board 1947 (-1):91-100
- Kapila D, Falkowsky J, Plawsky JL (1997) Thermal effects during the curling of concrete pavement. ACI Materials Journal 94 (2):119-127
- Khan MI (2002) Factors affecting the thermal properties of concrete and applicability of its prediction models. Building and Environment 37 (6):607-614
- Kim K-H, Jeon S-E, Kim J-K, Yang S (2003) An experimental study on thermal conductivity of concrete. Cement and Concrete Research 33 (3):363-371
- Levinson R, Akbari H (2002) Effects of composition and exposure on the solar reflectance of portland cement concrete. Cement and Concrete Research 32 (11):1679-1698
- Lu S, Ren T, Rong Y, Horton R (2006) An improved model for predicting soil thermal conductivity from water content at room temperature. Soil Science Society of America Journal 71 (1):8-14
- Luca J, Mrawira D (2005) New Measurement of Thermal Properties of Superpave Asphalt Concrete. Journal of Materials in Civil Engineering 17 (1):72-79
- McCullough BF, Rasmussen RO (1999) Fast track paving, Concrete temperature control and traffic opening criteria for bonded concrete overlays, . Task G. Final report, FHWA. U.S Department of Transportation,
- Mohamed A, Hansen W (1997) Effect of Nonlinear Temperature Gradient on Curling Stress in Concrete Pavements. Transportation Research Record: Journal of the Transportation Research Board 1568:65-71

- Mohamed AR, Hansen W (1996) Prediction of stresses in concrete pavements subjected to non-linear gradients. *Cement and Concrete Composites* 18 (6):381-387
- Morabito P (2001) Thermal properties of concrete variation with temperature and during the hydration phase. Report number 2001-18-4. Department of Civil & Mining Engineering & Division of Structural Engineering, Milan, Italy
- Ongel A, Harvey J (2004) Analysis of 30 Years of Pavement Temperatures using the Enhanced Integrated Climate Model (EICM) (Draft). Report for Caltrans. Pavement Research Center, Institute of Transportation Studies, University of California, Berkeley, University of California, Davis, Berkeley
- Rohsenow WM, Hartnett JP, Cho YI (1998) *Handbook of Heat Transfer*. McGraw-Hill, New York
- Solaimanian M, Bolzan P (1993) Analysis of the integrated model of climatic effects on pavements. Strategic Highway Research Program, U.S. Federal Highway Administration; Research Rep. No. SHRP-A-637. Washington D.C.
- Solaimanian M, Kennedy TW (1993) Predicting maximum pavement surface temperature using maximum air temperature and hourly solar radiation. *Transportation Research Record: Journal of the Transportation Research Board* 1417:1-11
- Tang R, Etzion Y, Meir IA (2004) Estimates of clear night sky emissivity in the Negev Highlands, Israel. *Energy Conversion and Management* 45 (11-12):1831-1843
- Walton GN (1985) Thermal Analysis Research Program--Reference Manual--INBSIR 83-2655. U.S. Department of Commerce, New York
- Westergaard HM (1927) Analysis of stresses in concrete roads caused by variations of temperature. *Public Roads* 8 (3):54-60
- Yu HT, Khazanovich L, Darter MI, Ardani A (1998) Analysis of Concrete Pavement Responses to Temperature and Wheel Loads Measured from Instrumented Slabs. *Transportation Research Record: Journal of the Transportation Research Board* 1639:94-101