Hot Weather Comparative Heat Balances in Pervious Concrete and Impervious Concrete Pavement Systems

John T. Kevern, University of Missouri-Kansas City, Kansas City, MO, USA*
Liv Haselbach, Washington State University, Pullman, WA, USA
Vernon R. Schaefer, Iowa State University, Ames, IA, USA
**Corresponding author email: kevernj@umkc.edu*

ABSTRACT

Many pavements contribute to the urban heat island (UHI) effect due to their bulk mass and heat absorption capacities. Granular ground surfaces composed of soils or sands do not contribute to the UHI effect in a similar manner. Their porous nature may lessen the effect both with an increased insulating capacity and with an enhanced mechanism for evaporative cooling from absorbed water.

Pervious concrete is a novel pavement which is being developed to aid in preventing stormwater related environmental problems. Pervious concrete has a network of interconnected voids which allow water exfiltration to the subbase below. Limited studies on pervious concrete indicate that the pervious concrete surface can have elevated temperatures as compared to similar traditional impervious pavements, but that temperatures are lower under the pavements.

This study focuses on a site in Iowa where both a pervious concrete and a traditional concrete paving system have been installed and temperatures recorded within the systems for extended time periods. The analyses cover days with negligible antecedent precipitation and high air temperatures, extreme conditions for UHI impacts. This paper compares the increase in overall heat stored during several diurnal heating cycles in both of these systems. These analyses include not only the temperatures at various depths, but also the heat stored based on the bulk mass of the various layers in each system and below grade. Results suggest that pervious concrete pavement systems store less energy than traditional systems and can help mitigate the urban heat island. (246 words)

Introduction

The urban heat island (UHI) effect has been studied in many cities and the contribution from daytime heating is well established (Eliasson 1996, Asaeda et al. 1996, Pomerantz 2000). Many traditional pavement types are known to be contributors to the urban heat island effect due to their bulk mass and heat absorption capacities. Previous research has shown higher albedo surfaces and shading can offset some of the impacts by reducing the solar energy absorbed in the pavements (Akbari 2001). Lighter colors and higher albedos tend to aid in the mitigation of the urban heat island by limiting solar energy absorbed into the system. The solar reflectance index (SRI) is being used as a variable to compare the 'coolness' of various traditional pavements and has been accepted by the US Green Building Council (USGBC) in its Leadership in Energy and Environmental Design (LEED™) Green Building rating system as a methodology for determining if a pavement design aids in mitigating the UHI effect (Haselbach 2008, Marceau and Van Geem 2007). This variable is used independently of any other pavement parameter with the assumption that the pavements compared have similar heat absorption and transfer characteristics below the surface, although some studies acknowledge that subsurface characteristics may be important (Gui et al. 2007).

Natural and manmade granular ground surfaces composed of soils or sands are not considered to be contributors to the urban heat island effect due to their porous nature. Of interest herein is the impact of the porosity of a pavement system on its capacity to absorb and store energy. It has been suggested that the voids within highly pervious pavements may insulate the ground, mitigating urban heat island impacts (Haselbach and Gaither 2008). Permeable surfaces may also allow for evaporation of water that infiltrates into the media, also aiding in cooling by evaporation.

There is a group of novel pavements referred to as permeable pavements which are being developed to aid in preventing stormwater related environmental problems. Permeable pavements allow stormwater to infiltrate into the ground, reducing runoff and avoiding costly additional stormwater control devices to manage flooding and pollution dissemination downstream. One such pavement is Portland Cement Pervious Concrete (PCPC), which provides a hardscape similar to traditional impermeable concrete or asphalt pavements, but also consists of a network of interconnected macro-pores which readily allow water exfiltration to the subbase below and provide some water storage for further evaporation or infiltration. A question of interest is how pervious concrete might perform due to its unique pore structure as compared to traditional concrete under very hot conditions typical for the urban heat island.

Asaeda and Ca studied several surface media during two days of extreme heat in 1994. Their results indicated that certain types of permeable pavements, particularly blocks, did not necessarily aid in abetting the urban heat island effect. Detailed information was not given for all the media used and therefore there was not a clear picture of how many of the porous pavements might react (Asaeda and Ca 2000). There are only a few published studies on the temperature impacts of using PCPC instead of other impervious pavement surfaces. From these it has been shown that the PCPC surface can have elevated temperatures as compared with traditional impervious pavements, but that temperatures decrease rapidly under the pavement (Haselbach and Gaither 2008, Kevern et al. 2009a). None of the published studies have provided overall energy balances for periods of extreme heat as compared to traditional pavements.

This study focuses on a site located at Iowa State University (ISU) where both a pervious concrete and a traditional Portland Cement Concrete (PCC) paving system were installed and temperature readings taken within the systems for extended time periods. The site was constructed as part of the Iowa Pervious Concrete Stormwater project and also contained monitors and collectors to quantify stormwater improvements observed from the pervious concrete. The analysis covers days with typical high air temperatures greater than 32°C (90°F) with negligible antecedent precipitation (no rain events in the previous 7-days), extreme conditions for urban heat island impacts.

The pervious concrete, as compared to traditional concrete, is seen to have higher mid-pavement temperatures at midday, but similar temperatures at these locations during the night/early morning. However, in order to study urban heat island effects, the fluctuations in heat storage over both of the complete systems should be evaluated to steady background soil temperatures below the pavement systems. The analysis in this paper compares the overall heat stored during several diurnal cycles in the summer throughout both of these systems. These analyses include not only the temperatures at various depths, but also the heat stored based on the bulk mass of the various layers in each system.

Although there are higher temperature readings near the surface in many of the pervious concrete systems studied, these systems appear to have significantly higher below-grade insulating capabilities than other traditional concrete systems. This may make it possible to design pervious concrete systems to mediate or reverse additional urban heat island impacts more effectively than traditional pavement surfaces.

Site Description

ISU parking lot 122 was constructed as the Department of Natural Resources Iowa Pervious Concrete Water Quality Project, with the objective to quantify the environmental impacts of pervious concrete parking areas. The site was designed to monitor both the quantity and quality of stormwater effluent from equally-sized traditional and pervious concrete parking areas. Temperature and soil moisture sensor arrays were installed in both of the pavement profiles to monitor frost line penetration and infiltration characteristics. Water level sensors in the pervious concrete aggregate bases coupled with monitoring wells allow estimation of infiltration rates and the impact on local groundwater conditions. The site was constructed during the summer and fall of 2006 and opened to traffic on December 4th, 2006. Sensors were installed to compare the stormwater characteristics and thermal behavior of the two areas. Flow meters and automated samplers were installed to measure and collect stormwater from the PCC surface and from the PCPC base. Water level sensors in the aggregate bases and monitoring wells were installed to determine actual infiltration and compare to theoretical values. Volumetric soil moisture arrays were also installed under each pavement to determine infiltration characteristics. Temperature sensor arrays (Campbell Scientific T107L) were installed into and underneath both pavements to monitor thermal behavior. Surface sensors were omitted due to concerns with winter plowing operations. The location and assigned names of the temperature sensor profiles are shown in Figure 1 for both the PCPC and PCC pavements. Table 1 provides a description of the sensors along with the depth below the pavement surface.

Figure 1. Pavement Cross Section and Sensor Placement

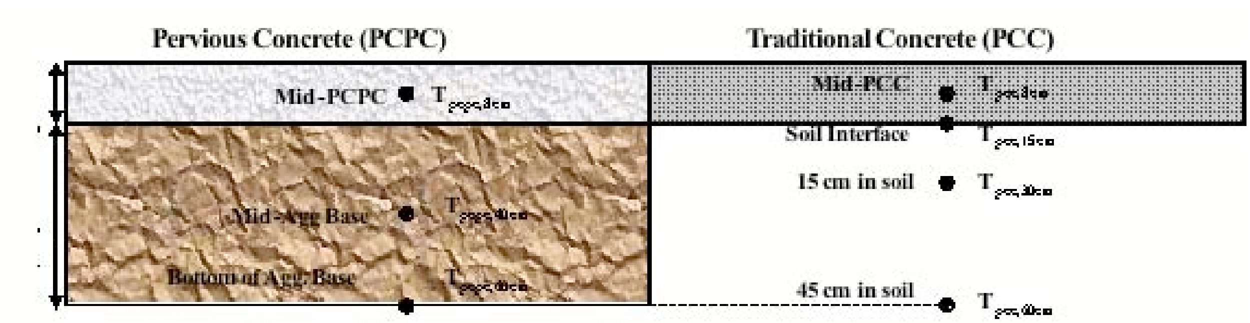


Table 1. Sensor Descriptions

Sensor	Description	Depth Below Surface (cm)
$T_{pcpc, 8cm}$	Mid-level in PCPC	8 cm
$T_{pcpc, 40cm}$	Mid-level in aggregate base	40 cm
$T_{pcpc, 60cm}$	Bottom of aggregate base	60 cm
$T_{pcc, 8cm}$	Mid-level in PCC	8 cm
$T_{pcc, 15cm}$	PCC/Soil interface	15 cm
$T_{pcc, 30cm}$	15 cm in soil	30 cm
$T_{pcc, 60cm}$	45 cm in soil	60 cm

Methodology

As the sun's energy is absorbed by the pavement, it warms. Later, the cooling cycle begins and the pavement radiates heat when the temperature of the pavement surface becomes greater than the temperature of the atmosphere above (e.g. the sun sets). The increased energy required for air conditioning caused by the urban heat island effect is directly related to the amount of energy absorbed and then released by the pavement system. A reduction in the total energy stored in a pavement system will help mitigate this effect. To accurately compare the energy stored in two systems, all energy storage calculations must be performed to a depth where the temperatures are equal. For the two pavements discussed herein, at a depth of 60 cm below the pavement surfaces the temperature difference was less than 1°C and assumed equal.

Equation 1 is used to calculate the amount of energy stored during the heating cycle of the PCC system. The specific equations include the amount of heat stored in the pavement and segregated soil layers corresponding to the temperature sensors. The first term represents the energy stored in the traditional concrete. The average temperature of the PCC was taken as the temperature recorded at mid-height in the pavement. The second term represents the energy stored in the first 15cm of soil beneath the PCC pavement. The temperature in the first 15 cm was taken as an average of the sensor located directly under the pavement and the sensor located 15 cm in the soil. The third term represents the energy stored in the soil between 15 cm and 45 cm beneath the PCC pavement. The temperature in this deeper layer was taken as the average between the temperature recorded at 15cm beneath the pavement and the sensor located at 45 cm beneath the pavement.

$$\Delta E_{pcc} = (C_{Vpcc})(\Delta T_{pcc,8cm})(h_{pcc}) + (C_{VSoil})(\frac{\Delta T_{pcc,15cm} + \Delta T_{pcc,30cm}}{2})(h_{15cm \to 30cm}) + (C_{VSoil})(\frac{\Delta T_{pcc,30cm} + \Delta T_{pcc,60cm}}{2})(h_{30cm \to 60cm}) \quad (1)$$

Equation 2 is used to calculate the amount of energy stored during the heating cycle of the PCPC system. The specific equations include the amount of heat stored in the pavement and segregated aggregate base layers corresponding to the temperature sensors. The first term represents the energy stored in the pervious concrete. The average temperature of the PCPC layer was taken as the temperature recorded at mid-height in the pavement. The second term represents the energy stored in the aggregate base beneath the PCC pavement. The temperature in the aggregate base was taken as the value recorded at mid-level in the aggregate base.

$$\Delta E_{pcpc} = (C_{Vpcpc})(\Delta T_{pcpc,8cm})(h_{pcpc}) + (C_{v:agg.base})(\Delta T_{pcpc,40cm})(h_{agg.base}) \quad (2)$$

Where:

ΔE_{pcc} is the amount of energy stored during the daily heating cycle per unit area from the PCC pavement surface to 60 cm below the surface, J/(cm^2°C).

ΔE_{pcpc} is the amount of energy stored during the daily heating cycle per unit area from the PCPC pavement surface to 60 cm below the surface, J/(cm^2°C).

C_{vi} is the volumetric heat capacity of layer 'i' such as the PCC or soil layer.

ΔT_j is the change in temperature during heating reported by the sensor at location 'j'.

h_i is the height of the particular layer 'i'.

Traditional Concrete System

The PCC system contained 15 cm of concrete pavement over a compacted soil subgrade. The volumetric heat capacity (Cv_{pcc}) of the concrete was taken as 2.1 J/cm^3°C (Asaeda et al. 1996) and a standard density (ρ) was assumed (Mehta and Monterio 1993). Soil density was tested at 12 locations under the PCC with an average value of 1.9 g/cm^3. The heat capacity of the soil was determined from the relationship between concrete heat capacity and density along with the soil actual density. A summary of values are shown in Table 2. The effects of moisture were not considered for this portion of the study. As previously noted, the data evaluated were all from time periods with negligible antecedent precipitation.

Table 2. Material Properties

Material	Cv (J/cm^3°C)	_ (g/cm^3)
PCC	2.1	2.4
Soil	1.7	1.9
PCPC	1.55	1.8
Agg. Base	1.2	1.44

Pervious Concrete System

The pervious concrete system consisted of 15 cm of pervious concrete over a 45 cm compacted limestone aggregate base storage layer. The porosity of the pervious concrete was measured as 31% (Kevern et al. 2009b). The traditional concrete was air entrained and porosity was assumed at 5%. Therefore, the volumetric heat capacity of the pervious concrete was taken as a proportion of solids versus the traditional concrete as in Equation 3.

$$Cv_{PCPC} = Cv_{PCC} \ (100\text{-}n)/100 \quad (3)$$

Where:

Cv_{PCPC} is the adjusted volumetric heat capacity of the pervious concrete

Cv_{PCC} is the selected volumetric heat capacity of the concrete (2.1 J/cm^3°C)

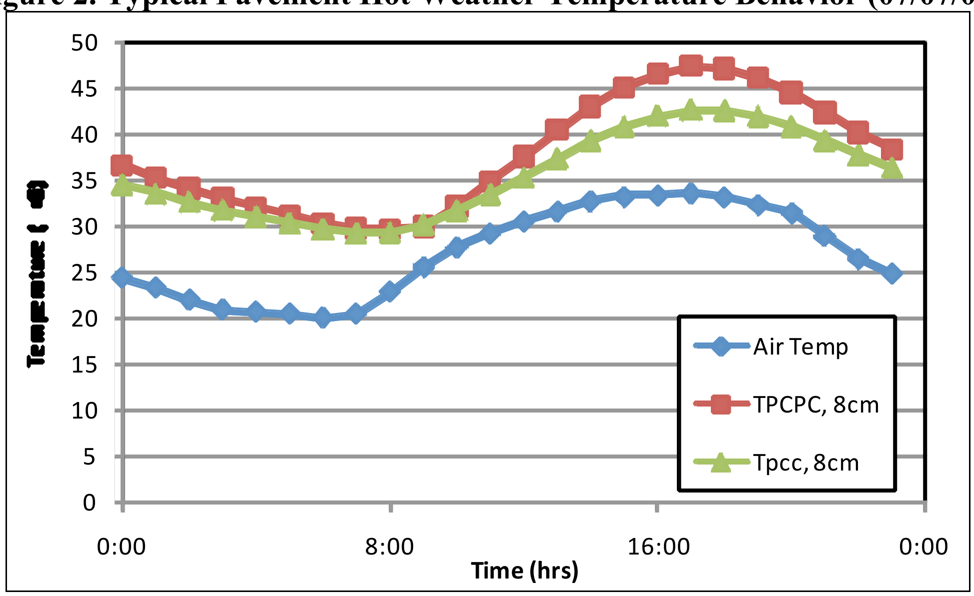
n is the difference in porosity between the PCC and PCPC (31%-5% = 26%)

The dry density of the limestone base was measured as 1.44 g/cm^3. The specific heat storage capacity of limestone was taken as 0.84 J/g°C, yielding a volumetric heat capacity of 1.2 J/cm^3°C (engineeringtoolbox 2009). A summary of the material property values used are shown in Table 2.

Results

The typical daily temperatures at the mid-heights of both pavements and the air are shown in Figure 2. During the day the temperature at mid-level in both pavements was always warmer than the air temperature, with the PCPC approximately 5°C (9°F) warmer than the PCC pavement right after the hottest period of the day. Although the PCPC was warmer during the day, both pavements cooled to similar temperatures during the night.

Figure 2. Typical Pavement Hot Weather Temperature Behavior (07/07/07)



The temperature behavior of the PCPC system with depth is shown in Figure 3 for the same time period shown in Figure 2. The changes in the PCPC temperature followed closely behind the air temperature variations, and temperatures fluctuated less with depth. The 60 cm depth fluctuated less than 1°C over the analyzed time period.

The temperature behavior of the impervious PCC system with depth is shown in Figure 4 for the same time period as Figure 2 and Figure 3. The change in PCC temperature and the upper layer of soil (15 cm below grade) are warmer than the air temperature, but follow a similar heating trend. At 30 cm below grade the temperature response is buffered with only a slight daily variation, with a significant phase lag as compared to the air temperature heating cycle. Temperature at 60 cm below grade for both pavement types remained similar and constant.

Figure 3. Typical Temperature Behavior of the Pervious Concrete System (07/07/07)

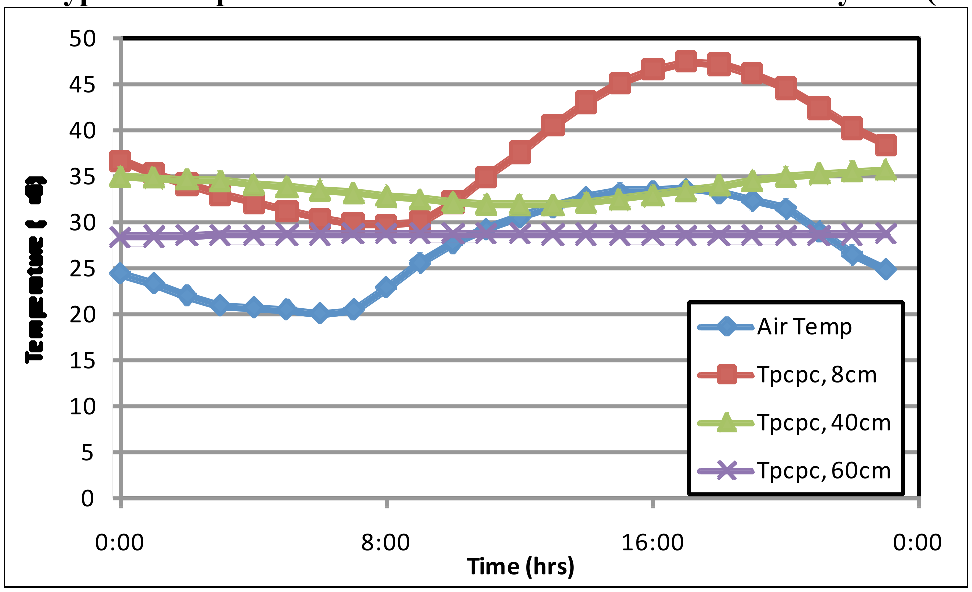
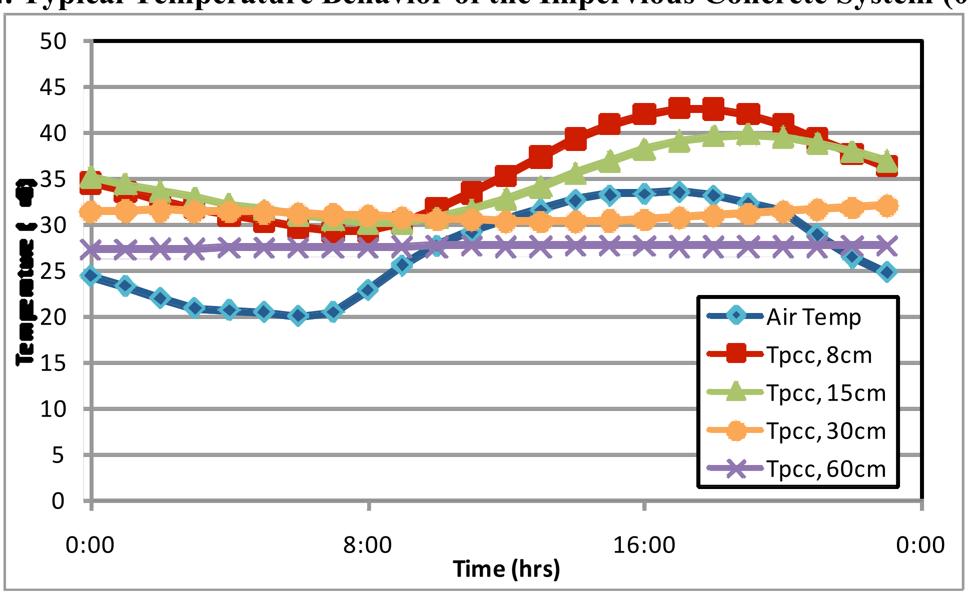


Figure 4. Typical Temperature Behavior of the Impervious Concrete System (07/07/07)



The energy storage results for the selected days are shown in Table 3. Four of the days had a heating cycle of 9 hours, while one had a heating cycle of 10 hours. For the five days analyzed, the energy stored in the PCC system was greater than the energy stored in the PCPC system, even though the PCPC pavement was warmer than the PCC pavement. This difference in heat stored is a function of the higher porosity in both the PCPC and the aggregate base as compared to the PCC and underlying soil respectively which lowered the PCPC system heat capacity for similar volumes of the systems. On average the pervious concrete system stored 12% less energy than the traditional concrete from the surface to a background temperature.

Table 3. Energy Storage Results

Date	Maximum Temp ,°C (° F)	Heating Duration	Energy Stored PCC (J/cm ^{2})	Energy Stored PCPC (J/cm ^{2})
7/7/2007	33.7 (92.6)	9 hrs	560.2	492.3
7/8/2007	34.2 (93.5)	9 hrs	576.7	516.8
7/17/2007	33.9 (93.1)	9 hrs	501.6	449.5
7/18/2007	32.3 (90.1)	9 hrs	398.4	352.4
8/11/2009	32.8 (91.1)	10 hrs	486.6	449.3

Conclusions

Temperature sensors were installed at various depths in adjacent pervious concrete and traditional concrete systems. Temperature data for both systems were analyzed for five days where the maximum temperature was greater than 32°C (90°F). All the analyses were conducted for days with negligible antecedent precipitation. Bulk heat storage was calculated for the daily heating phase using known values and values common in the literature for dry conditions of the various layers in the pavement systems to a depth of a nearly constant background soil temperature. Results show that less energy was stored during heating in the pervious concrete system than the traditional concrete system. This was using similar cementitious mixtures for both pavements (similar cement colors) and where, based on previous research, the pervious concrete surface would have a lower solar reflectance and hence a higher surface temperature under similar solar radiation conditions.

A strategy for mitigating the urban heat island effect may be to employ lower energy storage pavement systems. Using pervious concrete systems with their layers of materials with higher porosity than traditional pavement systems may be an effective tool in reducing the urban heat island effect. Considerations of material characteristics below grade such as porosity are important in determining a permeable pavement's capacity for heat island mitigation. Solar reflectance should not be used independent of these other variables.

Acknowledgements

Portions of this material are based upon work supported by the Iowa Department of Natural Resources, the Iowa Ready Mixed and Concrete Paving Associations, and the National Concrete Pavement Technology Center at Iowa State University. The opinions, findings and conclusions presented here are those of the authors and do not necessarily reflect those of the research sponsors.

References

Akbari, H., M. Pomerantz, and H. Taha. Cool surfaces and shade trees to reduce the energy use and improve air quality in urban areas. *Solar Energy*, 70(3), 2001, pp. 295-310.

Asaeda, T., V. T. Ca, and A.Wake. Heat storage of pavement and its effect on the lower atmosphere. *Atmospheric Environment*, 30(3), 1996, pp. 413-427.

Asaeda, T., and V. T. Ca. Characteristics of permeable pavement during hot summer weather and impact on the thermal environment. *Building and Environment*, 35, 2000, pp. 363-375.

Eliasson, I. Urban Nocturnal Temperatures, Street Geometry and Land Use. *Atmospheric Environment,* 30(3), 1996, pp. 379-392.

Gui, J., Phelan, P.E., Kaloush, K.E. and J.S. Golden: Impact of Pavement Thermophysical Properties on Surface Temperatures. ASCE J. of Materials in Civil engineering, 19(8), 2007, 683-690

Haselbach, L. *The Engineering Guide to LEED-New Construction; Sustainable Construction for Engineers*, McGraw-Hill, 2008

Haselbach, L., and A. Gaither. Preliminary Field Testing: Urban Heat Island Impacts and Pervious Concrete. *Proceedings NRMCA 2008 Concrete Technology Forum: Focus on Sustainable Development*, Denver, CO, May 20-22, 2008 (CD-ROM).

Kevern, J.T., Schaefer, V.R., and Wang, K. "Temperature Behavior of a Pervious Concrete System," *National Transportation Research Board (TRB) Transportation Research Record* 2009a edition. (accepted, publication info pending)

Kevern, J.T., Wang, K., and Schaefer, V.R. "Test Methods for Characterizing Air Void Systems in Portland Cement Pervious Concrete," *Recent Advancements in Concrete Freezing and Thawing (FT) Durability a Journal of ASTM International special issue*, 2009b. (under review)

Marceau, M. and M. Van Geem. *Solar Reflectance of Concretes for LEED Sustainable Site Credit: Heat Island Effect.* Portland Cement Association, Skokie, IL, SN2982, 2007.

Mehta, P.K. and P.J.M. Monteiro: *Concrete Structure, Properties and Materials*, 2nd Edition, Prentice Hall, Englewood Cliffs, NJ, 1993

Pomerantz, M., B. Pon, H. Akbari, and S.-C. Chang. *The Effect of Pavements' Temperatures on Air Temperatures in Large Cities.* Lawrence Berkeley National Laboratory, LBNL-43442, Berkeley, CA, 2000.

www.engineeringtoolbox.com/**specific-heat**-solids-d_154.html Accessed March 18, 2009