EVALUATION OF IN SITU TEMPERATURES, WATER INFILTRATION AND REGIONAL FEASIBILITY OF PERVIOUS CONCRETE PAVEMENTS

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ABSTRACT: Pervious Portland cement concrete has gained recent momentum in industry and local governments for being an environmentally preferred alternative to conventional impermeable pavement materials. Pervious concrete is best known for its benefits for storm water management in parking lots and low volume roads. It is also hypothesized to aid in mitigating the Urban Heat Island effect although no research has documented such a benefit in hot arid-climates. In this study, a pervious concrete parking lot constructed in the Phoenix, Arizona metropolitan area is evaluated. The facility was instrumented with temperature and soil moisture sensors, and was monitored for several months. The in situ data was used to calibrate a pavement thermal model and run several different design scenarios. The findings suggested that pervious concrete pavements can provide night time minimum surface temperatures that are lower than conventional impermeable pavements. The moisture results and regional soil analyses also indicated that these permeable materials provide an effective alternative means to capture and retain storm water runoff from parking lots and are applicable for the majority of soil types found in Arizona.

KEY WORDS: Permeable pavement, pervious concrete, heat island mitigation, pavement temperature, parking lots, storm water

1. INTRODUCTION

The land cover change associated with urbanization has many consequences to the local environment. Among the most important are interactions with natural phenomena, including precipitation and solar radiation. Most natural ground covers are permeable, capturing nearly 95% of the rainfall, leaving only 5% as runoff which supports surface water bodies. This is completely reversed in urban areas where impervious surfaces such as pavements and buildings prevent rainfall from being absorbed and the water is collected and directed into storm water collection systems leading to retention areas, water bodies or water treatment facilities. This alteration of the hydrologic cycle can result in urban flooding, decrease in infiltration that replenishes groundwater sources, high pollutant loading in sensitive water from surface runoff, and less overall moisture in the soil systems for plants [1].

Urban land cover also interacts with solar radiation much differently than natural systems. Pavements and buildings tend to be darker, denser, and devoid of moisture which is in stark contrast to the loose soils, sand, and vegetation that they replaced. These changes in material properties as well as the height and spatial design of these urban areas result in an increased rate of solar radiation absorption and retention. This alteration in the surface energy balance results in an increase of night time near-surface air temperatures in nearly all urban areas as compared to the native or agricultural areas that surround them. This phenomenon is known as the Urban Heat Island effect (UHI). The UHI has been shown to have a significant impact on the energy use, smog formation, human health and comfort in many cities around the world and particularly in the western US [2,3]. Prior works have documented the relative division of material types that form the urban land cover through the use of aerial color orthophotography, the Global Biosphere Emissions and Interactions System (GLOBEIS) model data, and Land-Use / Land-Cover (LULC) information from the United States Geological Survey (USGS). Rose et al. [4] identified that paved surfaces cover 29% of the urban land cover, while Akbari et al. [5] reported that 39% of the area seen from above the urban canopy (tree canopy) consisted of paved surfaces, including roads, parking areas, and sidewalks. Additionally, various prior works have quantified the system interactions of pavements with climate [6,7,8].

There has been a considerable amount of attention given to the consequences of storm water runoff and the UHI by organizations such as the US Environmental Protection Agency (US EPA) and the US Green Building Council (USGBC)[9]. The US EPA offers a Best Management Practices (BMP) guide for mitigating storm water runoff from urban surfaces including roofs and paved surfaces [1]. The BMP recommends using permeable pavement materials as an alternative to conventional bituminous (asphalt) and Portland cement concrete paving to reduce the amount of runoff. The permeable pavements, in concept at least, allow for water and air to penetrate the surface and allow for more natural infiltration of rainwater in to the soils beneath. There are a variety of permeable pavement designs and certain types are more suitable for different pavement applications. For local streets, parking lots, and driveways that will experience low to medium levels of traffic, pervious concrete has experienced the most publicity and use.

Pervious Portland cement concrete (PPCC) is Portland cement concrete with the sand and other small aggregates removed, and the cement and water content reduced. The resulting structure forms a series of interconnected voids – 15 to 25% air by volume in most cases [10]. These voids allow water and air to freely transfer through it while the aggregate gives it adequate strength needed to support automobile traffic. The USGBC's Leadership in Energy and Environmental Design (LEED™) Rating system for buildings and neighborhoods addresses storm water management and awards credits for using permeable surfaces such as PPCC for all hardscapes which includes parking lots, sidewalks, and driveways on the property [11]. The inclusion of permeable pavements in LEED™ has driven the interest and marketability of these products for storm water mitigation.

The US EPA also provides mitigation strategies for the UHI [12]. UHI mitigation has also been added by the US EPA as an appropriate air quality strategy for non-attainment areas to include in their State Implementation Plans (SIPs) [13]. This has sparked local and regional governments to evaluate alternative materials and designs. The US EPA recommendations focus on roofs, pavements, and urban forestry. They emphasize the need for increasing the reflectivity of these surfaces. Product terminology such as 'Cool Roofs' and 'Cool Pavements' are designed to reflect more of the sun's radiation than their conventional counterparts would. Among the 'Cool Pavements' that they recommend are permeable pavements. The reason for this is twofold – they are thought to keep cooler in direct sun light, and to support the growth of trees for shade. While permeable pavements are generally not highly reflective, they are believed to stay cooler in temperature during the day and night because of the moisture underneath and within them. In other words, they convert incoming solar energy into latent heat through the heating of water at the surface. This is similar to the way a tree leaf or grass stem avoids overheating in the sun. They are also thought to reduce night time temperatures because of their inherent void structure which reduces their density and in turn limits the total amount of energy stored within them. While both of these concepts are conceptually possible, neither have been well documented in prior research investigations. The second and more indirect benefit of permeable surfaces for UHI mitigation is their interaction with urban forestry. More specifically, permeable surfaces are believed to improve the health of shade trees that are planted near permeable pavements. The idea here is that they promote the infiltration of moisture, nutrients, and oxygen to the roots of trees that normally would be choked off by the blanket of impermeable pavements that ordinarily surround them. In addition to the moisture content, heat conduction through pavements may also elevate soil temperatures which can adversely affect the health of shade trees [14,15] Previous studies have shown that temperatures in the rhizosphere (30cm (12in)) are much higher underneath and on the perimeter of asphalt parking lots exceeded 40°C (105°F), long enough to damage tree roots growing in the parking lot medians [16]. By shading parking lots and other hardscapes from direct solar radiation the amount of energy absorbed by these surfaces can be reduced leading to an overall reduction of the UHI [17]. LEED™ and some municipal ordinances require that trees provide shade for at least 30% of all non-roof impervious surfaces, including parking lots, within 5 years of the initial construction [11].

While research into the construction methods and longevity of permeable pavements have been assessed [18], and the strength and drainage properties have also been verified [19], there is a significant lack of research on the overall effectiveness of permeable pavements for storm water mitigation and UHI reduction in operational pavement systems. Of particular interest in the Desert Southwest United States is the application of permeable pavements for reducing UHI formation under normal hot arid conditions. In 2007, the National Center of Excellence on SMART Innovations for Urban Climate & Energy (www.asuSMART.org) undertook to research these various system components by monitoring a PPCC surface parking lot that was constructed on the main campus of Arizona State University in Tempe, Arizona, USA.

2. OBJECTIVE AND SCOPE

The objective of this study was to monitor the temperature and moisture changes over time of a newly constructed and fully operational PPCC parking lot located in a hot and arid climate region. The scope of the research included 1) Determination of the pavement material's thermal properties; 2) Diurnal temperature evaluations of the surface and subsurface pavement layers from January through September 2007; 3) Model the heat transfer through the PPCC structure and compare it to conventional pavement designs 4) Measure soil moisture content by depth and in conjunction with rain events over the same time period 5) Spatial analysis of Phoenix regional soils appropriate for PPCC installations.

3. EXPERIMENTAL DESIGN AND METHODOLOGY

This research project was conducted during 2007 and 2008 in Tempe, Arizona, USA. Tempe is located within the Phoenix metropolitan region in the Salt River Valley at the northeastern edge of the Sonoran Desert in the southwestern United States (33°N 112°W) at an elevation of approximately 335m (1,100ft). Phoenix has an arid, semitropical climate, with an average of 300 sunny days per year and 89 days during which the temperature reaches or exceeds 38°C (100°F) [20]. Most of these warmer days occur from early June through early September. In 2007, beginning on April 24, 2007, there were 112 days during which Phoenix reached over 38°C (100°F). During that same summer, a new record of 32 consecutive days over 43°C (110°F) was recorded in Phoenix [21]. The normal annual rainfall recorded at Phoenix Sky Harbor International Airport is 211mm (8.29in) with the wettest time of year in March [22].

3.1 Project Site

The project site is a parking lot located on the western edge of the Tempe campus at Arizona State University, directly in front of the J. Russell and Bonita Nelson Fine Arts Center. Due to storm water drainage issues, fatigue and thermal cracking of the pavement, the asphalt parking lot had to undergo rehabilitation. A project plan was presented to design, construct and monitor a PPCC pavement as a replacement pavement alternative with appropriate geotextile and subgrade preparation. The PPCC was constructed by a local general contractor (Progressive Concrete Works Inc.), and CEMEX Corporation designed and provided the PPCC mix. The construction activities took place between December 2006 through January 2007. The pavement system was designed and constructed according to the construction techniques described by the National Ready Mixed Concrete Association [23]. The lot was allowed to cure for 14 days before being opened for traffic.

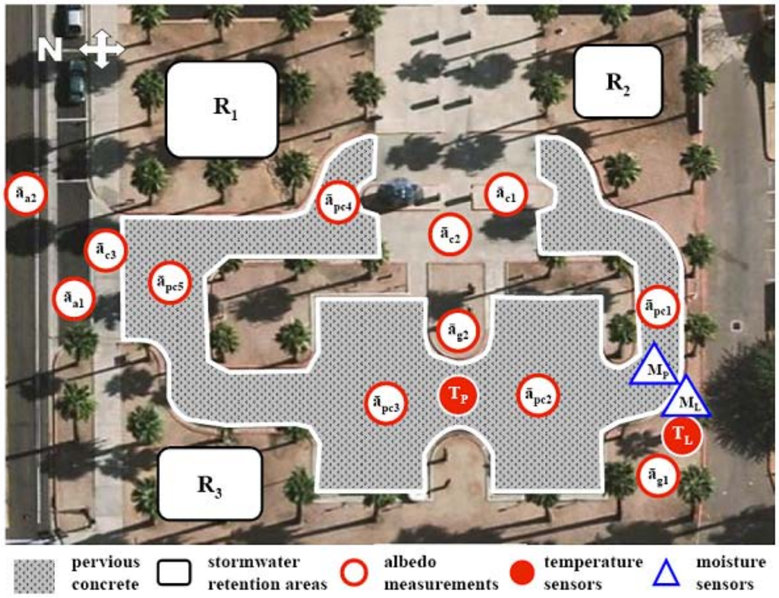


Figure 1. Map of parking lot (experimental test site) with important locations indicated

During the construction phase, multiple sensor networks were installed within the subgrade soil and pavement layers to acquire temperatures and soil moisture readings every 20 minutes. Solar reflectivity, also referred to as solar albedo, was measured at multiple locations within the parking after a few months in operation according to ASTM E 1918-06 *Standard Test Method for Measuring Solar Reflectance of Horizontal and Low-Sloped Surfaces in the Field* [24]. The experimental site diagram in Figure 1 identifies the locations of the sensors in relation to the parking lot and retention areas. The parking lot is surrounded by a concrete curb, open at storm water retention areas, followed by aggregate mulch typical of decorative desert landscaping in Arizona. The landscaped areas is also scattered with forty palm trees at an approximate height of 7.5m (25 ft) and a few 4m (13ft) saguaro cacti near the center. A fisheye image taken at opposite normal to the pavement surface indicated a large ratio of sky to non-sky, referred to as sky view factor, for the parking lot service at location Tp.

3.2 Pervious Portland Cement Concrete Pavement Design

The pavement structure was comprised of four layers; pervious Portland cement concrete (PPCC), gravel base, filter fabric, and compacted subgrade. The pavement structure was designed to support the load of automobile traffic for visitors with the occasional heavier delivery trucks used for catering and equipment delivery at the front of the center.

Pervious Concrete Mix: The PPCC layer was 15cm (6in) thick in all areas of the lot. The mix design specified for this project used a 9mm (3/8 in) maximum aggregates size in the PPCC. This size aggregate was selected for its relative smoothness and visual appeal as compared with larger aggregate sizes. The mix was designed and manufactured by CEMEX and consisted of aggregates, cement, flyash, water, and additional proprietary admixtures.

The average voids for the material was determined to be 29%, average unit weight of 2,100 kgm^{-3}(131 $lbs\text{-}ft^{-3}$), and the compressive strength of this material ranged from 5.5 to 6.9 MPa (800 to 1000 psi) which is less than half of the strength of normal Portland cement concrete [10]. This low compressive strength is typical of pervious concrete because of the high air voids and open gradation structure. It was acceptable for the anticipated traffic loads [19]. However, several follow up projects in the Phoenix area were able to specify and achieve a minimum of 1600 psi strength values.

Gravel Base: The PPCC was supported by a 10cm (4in) layer single-grade gravel base. The gravel base consisted of washed smooth stones which were approximately 2cm (0.75in) in diameter. This layer is intended to provide storage area for water that travels through the pavement layer. Water will remain in the large voids between the gravel, while some may slowly penetrates into the subgrade, evaporates, or drained using perforated pipe. In this parking lot design, the original slope of the pavement of 2% grade was maintained in most areas. This allowed excess storm water to drain into the retention basins in case of heavy rain fall. The storage capacity of this gravel base (30% air voids) without the backup drainage is approximately 3cm (1.2in) which is greater than the maximum average monthly rain fall in the Phoenix, Arizona area; 2.9cm (1.15in).

Fabric Filter: A single layer of non-woven filter fabric, Mirafi® # 140N, produced by TenCate™ Geosynthetics was used to separate the gravel base from the subgrade soil [25]. This fabric is intended to prevent fine particles from the soil to migrate and fill the voids in the gravel base [26]. The fabric was overlapped by at least 30cm (1ft) at all joints to prevent any gaps in the layer. The fabric filter was cut in areas where temperature and moisture sensors were placed into the subgrade soil. These breaks in the fabric were sealed using an adhesive fabric tape.

Subgrade Soil: Beneath the filter fabric is the underlying silty clay soil. The soil was compacted using a plate compactor to approximately 95%. The infiltration rate was estimated to be greater than 1.2cm/hr (0.5 in/hr) according to the Natural Resources Conservation Service (NRCS) soil textural classification which is the minimum recommended for permeable pavement applications [27].

3.3 Temperature Monitoring

The temperature beneath the surface of the PPCC parking lot and the adjoining landscaping was measured to gain a better understanding of the thermal behavior of these materials. To date, there is limited information documenting the thermal transport properties and temperature profiles of PPCC. At location Tp, indicated in Figure 1, temperature tower consisting of 17 temperature sensors located at various depths were installed within the mix during construction. There were at least two sensors placed at each of the following depths; 1cm (0.5in), 2cm (1in), 10cm (4in), 15cm (6in), 20cm (8in), and 28cm (11in) below the surface. Temperature sensors were also installed at location T_L in the landscaping. There were three depths monitored in the landscaping: 2.5cm (1in), 28cm (11in) and 49cm (19in). The deepest two sensor depths corresponded with soil moisture probes, and the results are discussed later in this article.

3.4 Soil Moisture Monitoring

The variation of the moisture content of the subgrade soil with climate condition variations was monitored. Four moisture content sensors were installed in the area of study at M_L and M_P shown in Figure 1. The sensors measure the dielectric constant of the soil and were calibrated to moisture content. The two-prong design allows the measurement of high range of volumetric water content (0% to 100%) and it is suitable to all types of soil. The moisture content measurements were recorded every hour over a 3-month period during the summer of 2007 (July 6 to October 16). Moisture sensor No.1 was placed in the gravel base below the PPCC. Moisture sensor No.2 was installed in the subgrade soil below the PPCC, gravel base. Moisture sensors No.3 and No.4 were installed in the parking lot landscaped areas at 28cm and 49cm below the surface. Sensors No.2 and No.4 were purposely positions at similar depths to make a comparison between the two surface types. Sensor No.1 did not produce readings because it was dry most of the type and not embedded within soil. The results from these sensors are discussed in section 4.5 of this article.

4. RESULTS AND DISCUSSION

4.1 Temperature Results

The sensors were installed during the first week of January 2007 and data were collected until September 2007. Temperature sensors were programmed to record every 20 minutes. Due to the high volume of data points recorded during the monitoring stage and the variability that can occur hourly during the course of a day an averaging methodology was employed. This method created a generalized profile and eliminated noise from meteorological and traffic influences of specific time periods. The hourly temperature data from each sensor depth was averaged over a time period of twenty of more days at each hour for 2007. In this process, the maximum and minimum temperatures for this period were screened to ensure that there are no extreme variations, and that all the days belonged to the same seasonal period. For example, the air temperature value representing the 08:00 temperature at a depth of 1cm (0.5in) for the period from August 9 to September 5 is the mean of all 08:00 temperature values recorded during that time period of 2007 at the PPCC parking lot. This can be represented mathematically as:

$$\overline{T}_{p,h,L} = \frac{\sum_{d=1}^{n_p} \overline{T}_{d,h,L}}{n_p} \qquad (1)$$

Where $\overline{T}_{p,h,L}$ is the mean sensor temperature at hour h, at depth L, over the time period p, from the first day *d*, to n_p days later. $\overline{T}_{d,h,L}$ is the mean temperature of the multiple sensors located at a depth L below the surface at hour *h*, and day *d*. . The results for August are shown in Figure 2.

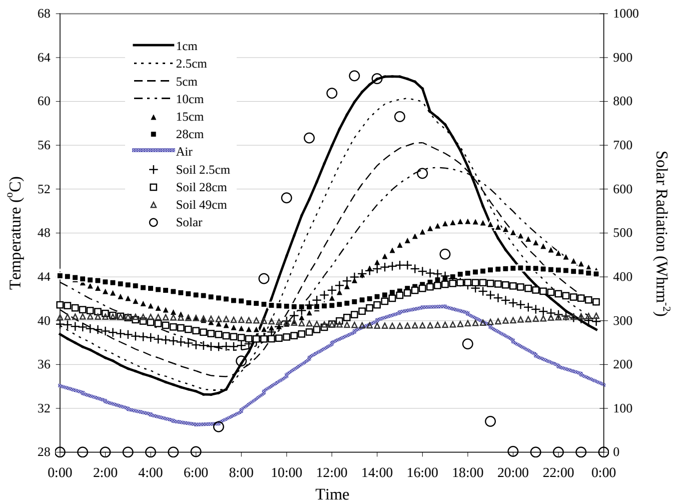


Figure 2 Averaged diurnal temperature at TP, TL, air temperature, and solar radiation for the period of August 9 to September 5 2007

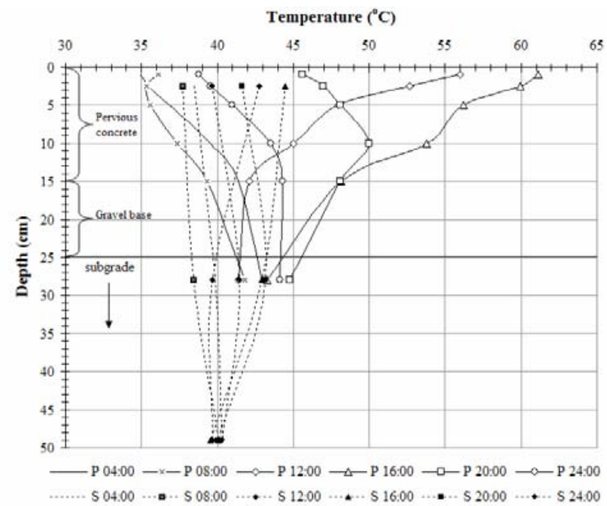


Figure 3 Average temperature with depth every 4 hours (04:00, 08:00, 12:00, 16:00, 20:00, 24:00) below the surface of the Parking lot (P) and the Landscaped soil (L) for the period of August 9 – Sept 5th, 2007

The average temperature profiles indicate that the near surface temperature (depth = 1cm (0.5in)) undergoes the greatest daily changes in temperature in direct response to the solar radiation flux. As expected the farther away from the surface the cooler the temperatures are during the day. The opposite is true once the sunset – as the surface temperature decrease the temperatures within the pavement remain elevated for several hours indicating some heat retention within the pavement structure. Temperatures at the bottom of the PPCC (15cm (6in) deep) and the soil are similar. The 28cm (11in) depth of the pavement reflects the aggregates heat retention (of a rock). This heat retention is a function of the maximum aggregate size used.

The period of from August 9 to September 5 showed the highest average temperatures with an average peak temperature of 62°C (144°F) around 14:40 in the afternoon just below the surface. The maximum near surface temperature experienced in August was 66.7°C (152°F) occurred at 15:00 on August 12, 2007. Figure 2 also includes the temperature of the subgrade soil temperatures recorded at underneath the pavement and filter fabric and outside of the lot in the landscaped area. As anticipated, the plot shows that the temperatures beneath the landscaping do not experience the magnitude of those in the pavement. In fact the temperature sensor located just 2.5 cm (1in) below the landscape aggregate layer reaches a peak average temperature of 45°C (113°F) while the same depth below the pavement peaked at 60°C (140°F). An interesting note is the behavior of the temperatures at the point where the subgrade begins, 28cm (11in) below both surfaces. The temperature profiles of these two points are similar in maximum temperature seems comparable however the time at which they reach these temperatures is shifted.

Figure 3 shows plots of depth versus temperature. Each line represents the average temperature profile below the pavement at a specific time. The plots show temperature by depth for locations within the parking lot indicated in legend at (P) and in the landscaped areas (L). The times were selected in 4 hour increments from 04:00 through 24:00. On the Y axis, the range of depths for each pavement layer is marked. This only applies to the temperature in the parking lot as the landscaping temperatures sensors were mostly in subgrade soil. The shape of the temperature curves is as expected for the pavement over the course of the day; arcing to the left during the morning hours and arcing to the right during the day as the surface layer heats up. The temperature gradient through the PPCC at 16:00 is greater than in the soil. The maximum temperature at the top of the landscaping was significantly lower. The temperatures at both locations begin to converge deeper beneath the surface.

4.2 Surface Reflectance Measurements

The surface solar reflectance (also referred to as albedo) was measured at twelve different locations (refer to Figure 1) within the project areas according to ASTM E 1918-06. Three measurements of the incoming and outgoing shortwave (300-2500nm) radiation were recorded to create an average albedo at each location. Multiple locations of the landscaped aggregates (G), A nearby Hot Mix Asphalt roadway (HMA), PPCC, and PCC were measured. The PCC had the highest average albedo (0.25), followed by G (0.24), PPCC (0.18), and HMA (0.10). It is worth noting that the cement color utilized in this PPCC experiment was determined to be darker than usual, and this was reflected to some degree by the albedo measurements noted above. However, even with lighter color cement in the PPCC mix, the authors hypothesize that the lower albedo of PPCC (compared to a conventional PCC mix) may be a result of the rough texture at the surface. The voids at the surface of PPCC tend to trap light within its recesses. This trapping of light decreases the albedo and results in a warmer surface during the day. Unfortunately, there have been no studies of pervious concrete modeling the radiative effects at the surface.

4.3 Pavement Surface Thermographs

The surface temperature of the pervious lot was measured on one occasion using a FLIR® hand held infrared thermography camera. The thermographs in Figure 4 show that the pervious concrete surface in this experiment reached temperatures comparable to an HMA road surface, which is much warmer than conventional PCC during the day. This result corresponds with the albedo findings. The albedo of the aged HMA road was about (0.10) and the section of PPCC near the entrance had an albedo only slightly higher at 0.13. Again, this was attributed to the unusual darker color of the cement, especially at this location. It is expected that their peak temperatures would be similar as they are absorbing nearly the same amount of solar energy. The PCC concrete sidewalk possessed the lowest temperature at both 14:00 and 18:30 although by this time all three materials types had reached within 1^{o}C of each other which is within the uncertainty of the infrared camera and therefore no actual difference can be stated with confidence.

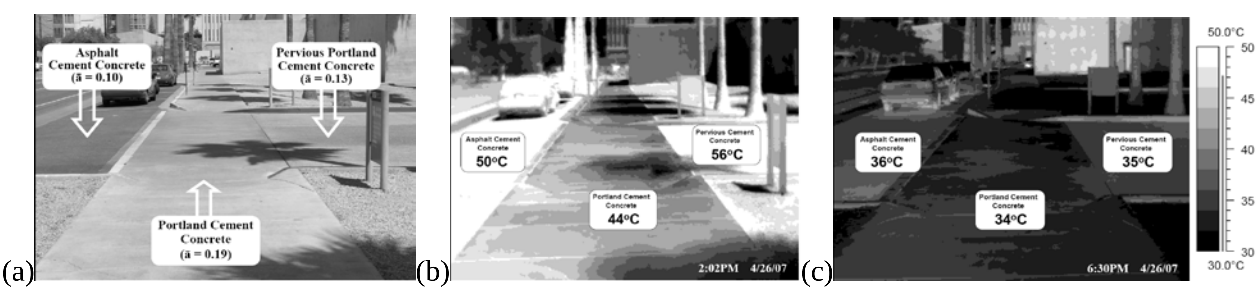
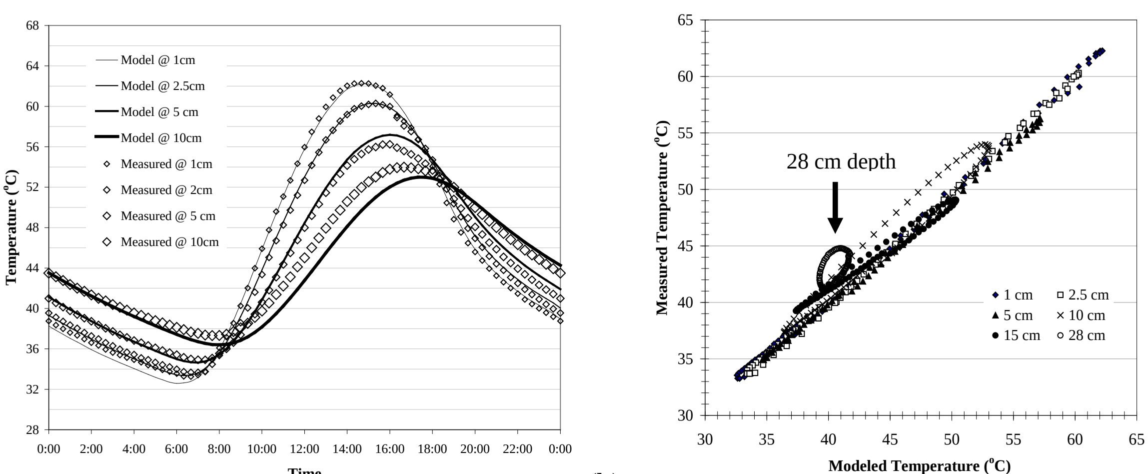


Figure 4 Comparing surface temperatures between Pervious Portland Cement Concrete (PPCC), standard Portland Cement Concrete (PCC) and Hot Mix Asphalt (HMA). (a) Digital image indicating material type and average measured albedo; (b) and (c) Infrared thermographs taken at 14:00 and 18:30 on April 26, 2007

4.4 Modeling Heat Transfer Through Pavement Structure

The temperature results from this field investigation were used to calibrate an existing pavement temperature model described in [28]. The ASU-NCE model is one dimensional and is based on fundamental heat transfer principles. The user provides the meteorological information including hourly solar radiation, wind speed and air temperature for the project location if known. In this case, the authors used data from publically available meteorological stations and averaged them over the time period of interest (mid August through mid September in this case). The user also inputs additional site specific conditions including Sky View Factor and Solar View Factor which are based on the surrounding buildings and trees that influence the amount of sun and sky the surface 'sees'. Lastly, the thickness and thermo-physical properties for each layer are entered before the model is run. The thermo-physical properties include albedo, emissivity, density, specific heat and thermal conductivity; all of which can be obtained from direct measurement or from literature values. In this case a combination of reference sources were used. The albedo, thermal conductivity, and density were measured in the lab while the other properties were obtained from literature. Once all necessary information is entered, the model is run for 40 iterations to achieve a stable result.

Small adjustments to the inputs were made until the model outputs matched the field data average collected at the site. The three main parameters adjusted included Solar View Factor, the Interface Resistance Coefficient between the PPCC and gravel base, and between the gravel base and subgrade. The contact resistance values cannot be directly measured in the field and are typically determined in this processs using experimental results. The results of this model approximately fit the experimental data after these adjustments. A comparison between the measured and model temperatures at multiple depths is shown in Figure 5a. The accuracy of the model tends to decrease deeper into the pavement structure as shown in Figure 5b. This is likely due to the uncertainty of the thermo-physical properties, layer thickness, and contact resistance between layers in the field. However, the model was determined to be sufficient in simulating the temperatures within the PPCC parking lot.



(a) (b)

Figure 5 (a) Measured and Modeled temperatures at different depths for the Pervious Concrete pavement over a 24 hour period. (b) Measured vs Modeled temperatures correlations

To determine the relative temperature behavior of the PPCC layer, four additional parking lot designs with different pavement structures were used in the simulation runs of the pavement temperature model. Table 1 summarizes all input properties used for the five model runs. The first run inputs, shown in the first column uses the standard properties of the actual PPCC design that was used to correlate with the field data. The second column uses the same properties and design thicknesses as first column except for a change to the albedo from 0.18 to 0.25 to match that of the measured albedo for a lighter color cement usually found in a PCC pavement. The third column is the design of a conventional PCC having a thickness of 15cm (6in), which is placed over 10cm (4in) of a compacted aggregate base course (ABC) typical of road and parking lot designs. The fourth column consists of an Ultra Thin WhiteToping (UTW) design; The UTW design typically uses a thin conventional PCC layer placed over a dense graded Hot Mix Asphalt (HMA); both layers were kept at 7.5cm (3in) thick to be equivalent of the total top pavement layer thickness of 15cm (6 in). The thermal properties of the UTW are identical to that of the PCC in the third column. The last column in Table 1 includes the design of of a dense graded HMA with a thickness of 15cm (6 in). The albedo for each material is based on the measurements made near the project site; PPCC = 0.18, HMA = 0.10 and PCC = 0.25. These pavement designs are realistic and represent pavement structures that can carry low to medium traffic loads in the Phoenix Metropolitan area. The meteorological data, the Sky and Solar View Factors, and deep ground temperature values remained the same for all runs.

Table 1 Model input values for alternative pavement designs

		Model Input Properties				
		1	2	3	4	5
Layer 1						
Material	-	PPCC	PPCC*	PCC	UTW	HMA
Albedo	-	0.18	*0.25	0.25	0.25	0.1
Emissivity	-	0.91	0.91	0.91	0.91	0.91
Density	(kgm^{-3})	2100	2100	2350	2350	2238
Specific Heat	($Jkg^{-1}K^{-1}$)	950	950	1000	1000	921
Conductivity	($Wm^{-1}K^{-1}$)	1.1	1.1	1.5	1.5	1.2
Thickness	cm (in)	15 (6)	15 (6)	15 (6)	7.5(3) + 7.5(3) of HMA	15 (6)
Interface Resistance	-	0.001	0.001	0.001	0.001	0.001
Layer 2						
Material	-	Gravel	Gravel	ABC	ABC	ABC
Density	(kgm^{-3})	2400	2400	2000	2000	2000
Specific Heat	($Jkg^{-1}K^{-1}$)	840	840	1050	1050	1050
Conductivity	($Wm^{-1}K^{-1}$)	0.35	0.35	1.2	1.2	1.2
Thickness	cm (in)	10 (4)	10 (4)	10 (4)	10 (4)	10 (4)
Interface Resistance	-	0.01	0.01	0.001	0.001	0.001
Layer 3						
Material	-	Dry Soil	Dry Soil	Dry Soil	Dry Soil	Dry Soil
Density	(kgm^{-3})	1500	1500	1500	1500	1500
Specific Heat	($Jkg^{-1}K^{-1}$)	1900	1900	1900	1900	1900
Conductivity	($Wm^{-1}K^{-1}$)	1	1	1	1	1
Thickness	cm (in)	300	300	300 (118)	300 (118)	300 (118)
Additional Factors						
Sky View Factor	-	0.95	0.95	0.95	0.95	0.95
Solar View Factor	-	0.85	0.85	0.85	0.85	0.85

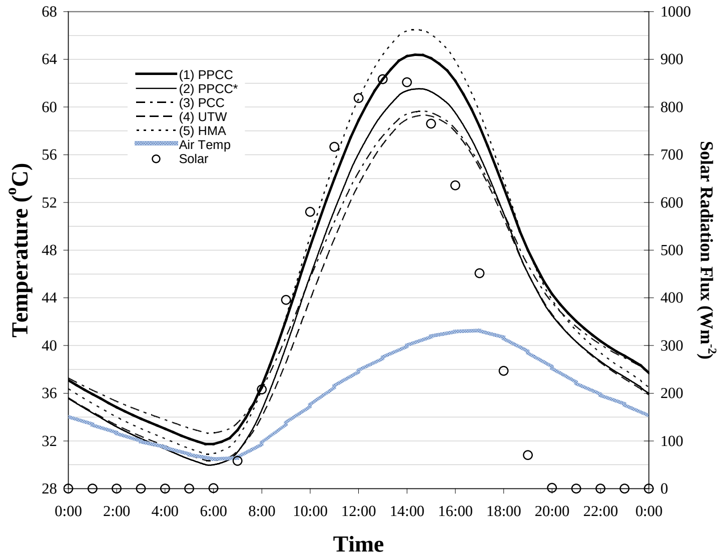


Figure 6. Model results for surface temperature of PPCC, HMA, UTW and PCC under identical conditions

The model results for surface temperatures of the five different pavements are shown in Figure 6. The figure indicates that the PCC and UTW would be the coolest surface during the day, while the HMA and PPCC (both albedo values) would be warmer. This finding is consistent with the thermograph observations shown in Figure 4. The peak temperatures of all surfaces are correlated with their relative albedos. The hypothesis that the lower albedo of PPCC is also a result of other mixture factors (such as thermal conductivity) is indirectly confirmed by comparing the maximum day temperatures for cases 1, 2, and 3. The PPCC with an increased albedo of 0.25 (case 2) showed a decrease in maximum temperature by 3°C (5.4°F) as compared to actual PPCC with a measured albedo of 0.18. After the sun goes down the amount of residual heat in each surface is also indicated by their surface temperatures. After the sun sets the surface temperature of all pavement cases drop significantly but to different values. Nearly all surface temperatures remained above the average air temperature which indicates a heat transfer to the air through convection and radiation. The PPCC surface with higher albedo and UTW (cases 2 and 4) actually achieve the lowest minimum surface temperatures compared to the others. The model suggests that this high albedo PPCC would actually drop below the average air temperature at approximately 6:00am in the morning. The UTW design appears to be a winning strategy, where the both the maximum and minimum daily temperatures are among the lowest. These findings serve as initial observations of the temperature behavior of PPCC as compared to more conventional pavement designs.

4.5 Soil Moisture Results

In order to assess the suitability of the underlying soils, separate analyses are required for both the hydraulic and the structural requirements of the subgrade material. When considering the hydraulic properties, in general, the concrete permeability limitation is not a critical design criterion. However, the flow rate through the subgrade may be more restrictive. The ability to infiltrate water into the soil depends on the permeability or hydraulic conductivity of the soil. For example, clay soils can hinder the performance of pervious pavements and may need to be modified or replaced to allow proper retention and percolation of precipitation. Sands, silty sands and sandy silts with infiltration rates higher than 1cm to 2.5cm/hr (0.5 to 1 in/hr) are considered to be suitable for pervious concrete design.

Figure 7 shows the recorded precipitation and volumetric moisture content in the subgrade soil under the PPCC parking lot structure and landscaped area. An average of 36% volumetric water content was recorded during the two weeks following the installation. This value is unusually high and was probably due to the use of wet of optimum compaction conditions. Whenever a rain event was recorded, the moisture content of the subgrade, as recorded by sensor No. 2, increased accordingly. After the rain event, the subgrade showed quick decrease in moisture content indicating a good drainage condition.

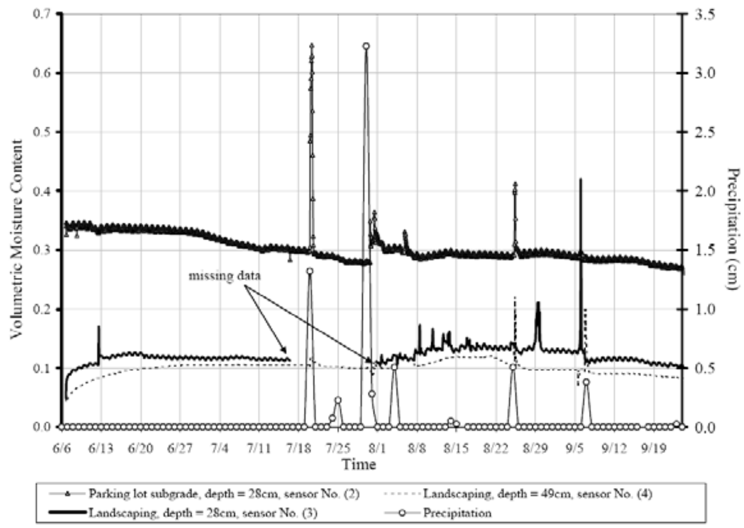


Figure 7 Recorded precipitation and volumetric moisture content in the subgrade soil under a pervious concrete parking lot structure and landscaped area

It was also observed that due to the porosity of the pervious concrete and the gravel base, the subgrade soil is slowly losing moisture due to evaporation and infiltration to lower depths. After three months of continued monitoring, the moisture content was at 25%. The moisture content of the subgrade soil showed a decreasing trend, which suggests that the moisture content is moving towards equilibrium moisture content at a rate proportional to the infiltration and the evaporation rates. The equilibrium moisture content of the subgrade soil can be assumed to be about 11% based on results obtained with sensors No. 3 and 4 as shown in Figure 6.

4.6 Subgrade Under Permeable Pavement Design Considerations

A preliminary assessment of the suitability of permeable pavement designs for the greater Phoenix, Arizona area soils was undertaken. The information presented in this section is intended as a guideline and should not replace a geotechnical analysis of the areas to be considered for PPCC pavement construction. The recommended analysis include the determination of the rate of infiltration of the subgrade soils, represented by the saturated hydraulic conductivity and the estimation of the modulus of subgrade reaction [30,31].

Soil survey area data was obtained through the Natural Resources Conservation Service's (NRCS) Soil Data Mart website. Both spatial data and tabular data were extracted. Each soil unit area was classified and grouped in the database, given a numeric label, and subsequently mapped based on the numeric map unit symbol. The database was imported into a map document and connected to spatial data downloaded from the NRCS. Nine maps were obtained for the Phoenix area, which are available from the Maricopa Department of Transportation [32].

Soil classification according to AASHTO (American Association of State Highway and Transportation Officials), grain-size distribution, Plasticity Index, and saturated hydraulic conductivity were obtained. Based on index properties (Passing #200 and Plasticity Index), the California Bearing Ratio (CBR) was estimated. CBR results were then used to estimate the resilient modulus and modulus of subgrade reaction.

The saturated hydraulic conductivity and results of modulus of subgrade reaction were used to rate each soil unit. Three rating categories were used: Not limited (N), Some-what limited (S), and Very limited (V). The limiting criteria resulted to be the saturated hydraulic conductivity (k_{sat}) because the modulus of subgrade reaction was estimated to be greater than 68 $MPam^{-1}$ (250 pci) for all soils in the greater Phoenix area. The (N) category was given to the soils that are suitable for permeable pavement construction. The soils in this category have a hydraulic conductivity > 0.5 inches/hr. The (S) category was given to soils with hydraulic conductivity lower than 1.2cm/hr (0.5in/hr) but greater than 0.76cm/hr (0.3in/hr). The (V) category was given to soils with k_{sat} < 0.1 in/hr. Note that the soils with Very limited (V) rating are in their majority clayey soils with high percentage of fines or high Plasticity index. Of the 82 soil types analyzed, 72% were determined to be sufficiently permeable, 22% are potentially adequate and only 6% were not suitable for PPCC and other permeable pavement applications. Table 2 shows an example of these results, but it is not inclusive of all soils analyzed for brevity.

Table 2 Index properties for soils commonly found in the greater Phoenix area

USCS Classification	Passing 200 (%)	PI	k_{sat} (cm/hr)	k_{sat} (in/hr)	k (MPa/m)	k (pci)	Rating
CL	75	13	1.0	0.383	148	546	S
ML	60	3	3.4	1.32	331	1222	N
SM	37.5	2.5	10.1	3.972	374	1381	N
SM	30	2.5	10.1	3.972	427	1577	N
SC-SM	32.5	5	3.2	1.272	344	1268	N
GP-GM	7.5	5	18.0	7.068	485	1789	N
SM-SC	37.5	5	3.2	1.272	325	1201	N
GM	22.5	2.5	3.2	1.272	454	1675	N
GC	15	2.5	10.1	3.972	464	1711	N
GC	20	2.5	10.1	3.972	464	1711	N
GM-GC	15	7.5	1.1	0.425	386	1423	S
CL	60	10	2.9	1.134	189	696	N
GC	25	7.5	3.2	1.272	325	1201	N
GC	32.5	17.5	0.3	0.128	198	732	V
CH	85	30	1.0	0.383	84	309	S
CL	70	12.5	3.2	1.272	163	603	N
CL	85	25	1.0	0.383	93	345	S
CL-ML	75	5	3.2	1.272	243	897	N
SM	15	2.5	10.1	3.972	485	1789	N
CL	75	25	1.0	0.383	102	376	S
CL-ML	60	7.5	3.2	1.272	224	825	N
SM-SC	47.5	7.5	3.2	1.272	250	923	N
GC	30	15	1.1	0.425	223	824	S
GW-GM	10	2.5	10.1	3.972	508	1876	N
GM-GC	12.5	2.5	10.1	3.972	496	1830	N
SM-SC	35	7.5	3.2	1.272	285	1052	N
SM	25	2.5	10.1	3.972	446	1644	N
GC	42.5	15	1.0	0.383	187	691	S
SM	30	2	3.2	1.276	449	1655	N
GM-GC	32.5	7.5	3.2	1.272	295	1088	N
CL	57.5	16	1.0	0.383	154	567	S
CL	70	20	0.3	0.128	120	443	V
ML	67.5	2.5	3.2	1.272	338	1247	N
CL-ML	57.5	5	3.4	1.32	275	1015	N

N = Not limited; S = Somewhat limited; V = Very limited

5. CONCLUSIONS

This paper presented a documentation of the construction and design of the first PPCC parking lot constructed in the Phoenix, Arizona metropolitan area. The lot was instrumented with temperature and moisture sensors, and was monitored for several months. The albedo (reflectivity) was measured at many locations around the parking lot as well as for several types of other surfaces. The subsurface temperature profiles showed that the near surface temperature undergoes the greatest daily changes in temperature in direct response to the solar radiation flux. The farther away from the surface the cooler the temperatures were during the day. A one dimensional pavement thermal model was calibrated using the field data and resulted in a good accuracy of predicted temperature values of the PPCC pavement system. The model was used to compare the temperature responses of PPCC to conventional dense graded asphalt PCC pavements, in addition to UTW pavement design, under identical climate conditions.

The model results indicated the PCC and UTW achieve the lowest peak temperature during the day while the UTW and PPCC with an equivalent albedo (reflectivity) would have the lowest minimum temperature at night. The UTW design appears to be an effective strategy to address optimal maximum and minimum daily temperatures. The relationship between properties of PPCC, the base materials used beneath permeable pavements, and their influence on surface temperatures are worthy of further research and evaluation through field studies and modeling efforts as was demonstrated in this study. Additionally, optimal designs in relation to urban forestry, stormwater management, soil bioremediation also require further evaluation. With regards to the soil moisture results underneath the PPCC pavement, the moisture sensors placed within the subgrade showed rapid increases in soil moisture content immediately following rain events. However, the soils were quick to re-establish original moisture values in less than one day. The assessment conducted of the suitability of permeable pavement designs for the greater Phoenix, Arizona area soils revealed that 72% of the surface soil types were considered sufficient, 22% were potentially applicable and only 6% were not suitable for PPCC installations.

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