ASSESSMENT OF CONCRETE PAVEMENT STRUCTURE ON URBAN HEAT ISLAND

Sushobhan Sen[1]* and Jeffery Roesler[1]

[1] Dept. of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, 205 North Mathews Ave., Urbana, IL 61801-2352

* Corresponding author: sen6@illinois.edu

ABSTRACT

The Urban Heat Island (UHI) effect is one component of the use phase in a Pavement Life Cycle Assessment (LCA). Much of UHI research has primarily focused on the role of albedo with limited effort on the other thermal properties of the pavement layers. This study explored potential UHI effects by starting with a control concrete pavement system and making independent adjustments to the layers' thermal properties for Chicago (IL) and Austin (TX) climates through application of the Enhanced Integrated Climatic Model (EICM). The analysis was done on an hourly basis for a one-year period to quantify the temporal variation of the surface temperature of the modified concrete pavement systems relative to the control. Pavements with lower density surface concrete were found to be cooler than the control case about 50% of the time, while those with a cement-treated base (CTB) were found to show significant variation in surface temperatures over both seasons. Accordingly, a concrete pavement system with a higher thermal mass was analyzed and shown to lower the surface temperature in the warm season and increase it in the cold season about 60% of the time, relative to the control case, in both cities. The analysis demonstrated that pavement layer thermal properties have an impact on the UHI and should be quantified in LCA studies besides just the albedo.

INTRODUCTION

The Urban Heat Island (UHI) effect is a phenomenon observed in built-up urban environments, where the average temperature of cities is higher than that of surrounding rural areas. One of the factors that leads to the development of a UHI is the higher thermal energy storage of building and paving materials *(1)*, which subsequently increases near surface temperatures because of their increased thermal energy content. This increased energy content is later emitted back to the atmosphere, heating up the surrounding urban environment, which can increase water consumption *(2) and energy loads (3) especially in summer.*

Understanding UHIs is a part of the larger Pavement Life cycle Assessment (LCA), which seeks to understand the impact of pavements on the environment through materials, construction, use, maintenance and end-of-life phases *(4)*. UHIs constitute one of those impacts and can be assessed in the use phase of an LCA. Several studies have shown that the albedo of roofs and pavements has a significant impact on UHI mitigation *(5,6)*. One main shortcoming of these studies is that they report the maximum decrease in surface temperature as compared to conventional pavements without examining how it varies over days, seasons, or alternative climates. Reporting the maximum peak surface temperature alone gives an incomplete view of the effect of the modification.

Limited studies have been undertaken to quantify the impact of changes to albedo on LCA *(7-9), which show that a higher albedo is beneficial to the urban environment. However, studies such as (10) contest these findings and contend that higher pavement albedo leads to higher potential heating penalty in buildings in winter while also raising cooling loads in summer because of the reflected shortwave solar radiation from pavements. Therefore, there is an ongoing debate on the true benefits of modifying albedo to mitigate the UHI.*

All the thermal properties of a pavement system – albedo, thermal conductivity, heat capacity, dry density and emissivity – have an impact on UHI and hence on pavement LCA. The impact of these properties on surface temperature was studied parametrically in *(11)* but only over three days without going into their seasonal and climatic spatial variations. Furthermore, only minimum and maximum surface temperatures were studied without analyzing the temporal variation of surface temperatures. Finally, only the properties of the surface course were varied, leaving out the impact of other support layers, which form an integral part of the pavement system. Thus, such an analysis only provides a partial understanding of the impact of the pavement system's thermal properties on Pavement LCA and at best captures an instantaneous view. The objective of this paper is to move to a more comprehensive analysis and suggest the inclusion of the thermal properties of all the pavement layers in a life cycle assessment.

METHODOLOGY

To assess the impact of changes to various thermal properties of the surface course as well as the base course, a control case was established. As shown in Figure 1, the control case is a hypothetical concrete pavement with a 4 in (100 mm) Portland Cement Concrete (PCC) surface course, a 6 in (150 mm) granular base of type A-2-4, a 12 in (300 mm) granular subbase of type A-3 and an A-6 subgrade. The control case was designated as P.

Three independent modifications were made to the control case to study changes in thermal and physical properties without changing the thicknesses of the pavement layers. To lower the thermal conductivity, lower density concrete was selected, which was designated PL. In another case, cement containing titanium dioxide (TiO_2) was used, which modified the surface albedo, and was labeled as PT. Finally, the base layer was changed from granular to a cement treated base (CTB). The base layer change modifies its thermal conductivity as well as heat capacity while maintaining the concrete surface layer. This case was designated PC.

To determine the surface temperature for each case, the Enhanced Integrated Climatic Model (EICM) embedded in the Mechanistic Empirical Pavement Design Guide (MEPDG) version 1.100 was used. The model uses hourly weather data to calculate the hourly temperature at various nodes of the pavement system. The data was analyzed from 1996 to 2005. For this preliminary study, only the surface temperatures were reported. The program outputs the surface temperature to the first decimal place.

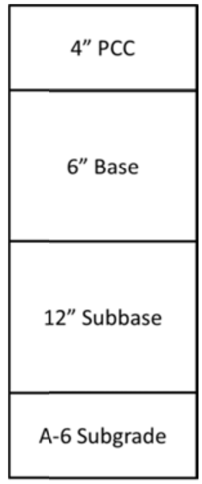


Figure 1: Concrete pavement system defined as the control case P.

In order to quantify the seasonal variation of surface temperatures, the study was divided into two periods: a warm season from April 2003 to September 2003 and a cold season from October 2002 to March 2003. Although these periods do not strictly represent summer and winter respectively, they do correspond to periods when temperatures are relatively warmer and cooler respectively. Thus, one full year of hourly data, totaling over 8000 hours, was obtained for each case. A similar analysis was done for a longer period from 1999 to 2004 but did not change the conclusions derived from the one-year analysis. Therefore, only results from the one-year analysis are discussed in this paper.

Finally, to observe climatic variation of the surface temperature, the models were analyzed in two different cities – Chicago, IL (O’Hare International Airport) and Austin, TX (Bergstrom International Airport). The former is in the northern US and experiences more severe winters but still hot summers, while the latter is in the southern US and experiences high summer temperatures and mild winter temperatures above freezing. Both are major metropolitan areas with built-up urban environments conducive to UHI formation. While neither of the two are coastal cities, Chicago is adjacent to Lake Michigan, which has an effect on its weather.

The predicted surface temperatures of the three modified cases (PL, PT and PC) are then subtracted from the corresponding surface temperature of the control case (P) at every hour of the analysis to measure the impact of the modification on surface temperature. These hourly temperature differences are designated (P-PL), (P-PT) and (P-PC) respectively for the three modified cases and are reported separately for each city and season.

MATERIAL PROPERTIES

Although the thermal properties of materials have a significant impact on the surface temperature of pavements and hence pavement performance, they have been sparingly measured without any single, comprehensive study. Table 1 summarizes the thermal properties of paving materials taken from the literature and assumed for this study.

Table 1: Thermal and Physical Properties of Paving Materials Assumed for this Study

Material	Absorptivity	Thermal Conductivity (BTU/hr-ft-˚F)	Heat Capacity (BTU/lb-˚F)	Dry Unit Weight (pcf)
PCC (JPCP)	0.70	1.25	0.28	150
A-2-4 (Base)	-	Internally calculated	Internally calculated	121.9
A-3 (Subbase)	-	Internally calculated	Internally calculated	120
A-6 (Subgrade)	-	Internally calculated	Internally calculated	100.8
Low-Density Concrete	0.70	0.35	0.25	86
Cement-Treated Base	-	1.25	0.28	150
TiO_2-incorporated concrete	0.65	1.25	0.28	150

In Table 1, the first input property is the absorptivity, which is simply one minus albedo. In general, darker materials have a lower albedo than lighter materials. Albedo varies with the time of day and even spatially over surfaces *(12)* and only a representative value can be assigned with the understanding that it is not necessarily constant. For concrete surfaces, 0.30 is such a representative value *(12)* with a corresponding absorptivity of 0.70, although it can range from 0.65 to 0.85. For the case of titanium dioxide cement (PT), albedo studies are still ongoing but *(13)* suggests that 0.33 is a reasonable value. Since no statistical analysis of the variation of the albedo was provided, a slightly higher value of 0.35 (absorptivity of 0.65) was adopted for this study.

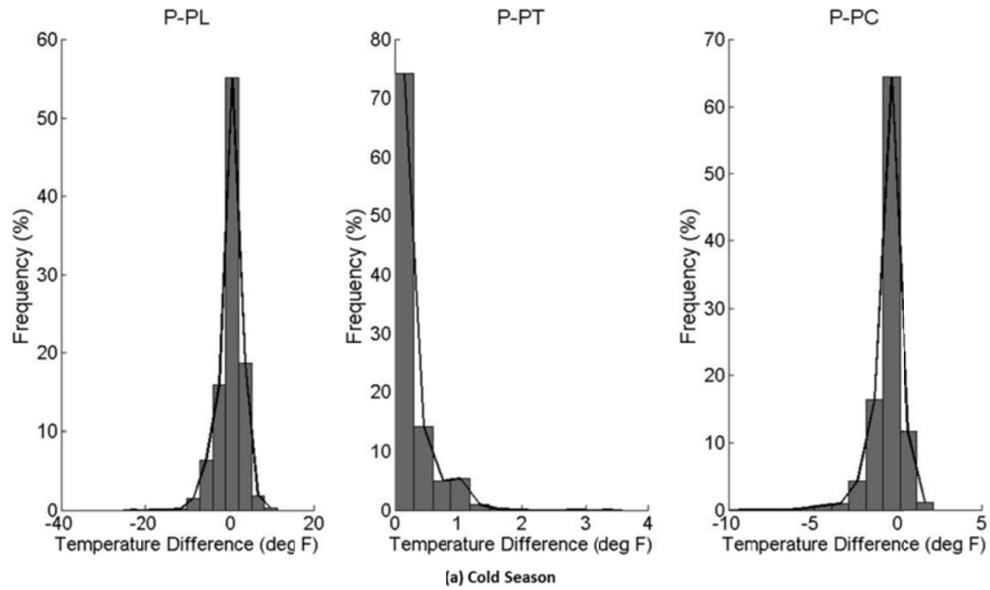
The thermal conductivity of conventional PCC was taken as the MEPDG default value *(14)* of 1.25 BTU/hr-ft-˚F (2.2 W/mK) with the same value applied for the CTB and TiO_2-incorporated concrete. The MEPDG internally calculates thermal conductivity for unbound materials. For casting lower density concrete, a variety of options are available, such as permeable concrete or lightweight aggregate concrete. For this study, the concrete contained 100% coarse and 50% fines from lightweight aggregates (expanded shale), which had a concrete compressive strength of 5,200 psi (35.8 MPa), as measured in reference *(15)*. The thermal conductivity was 0.35 BTU/hr-ft-˚F (0.61 W/mK) at a density of 86 pcf (1,380 kg/m³).

For heat capacity, the MEPDG default value for PCC and CTB is 0.28 BTU/lb-˚F (1.2 kJ/kgK) and again is internally calculated for unbound materials. Since heat capacity is primarily dependent on the morphology of the aggregates, the same value is adopted for TiO_2-incorporated concrete. For the lower density concrete, a value of 0.25 BTU/lb-˚F (1.06 kJ/kgK) was selected to correspond to the thermal conductivity from reference *(15)*.

The default unbound aggregate gradations and Soil-Water Characteristic Curve (SWCC) parameters were assumed for the EICM runs.

EICM RESULTS

The frequency distribution of the surface temperature differences (P-PL), (P-PT) and (P-PC) are shown for Chicago in Figure 2 and Austin in Figure 3 with the statistical analysis of the results presented in Table 2 and Table 3, respectively.



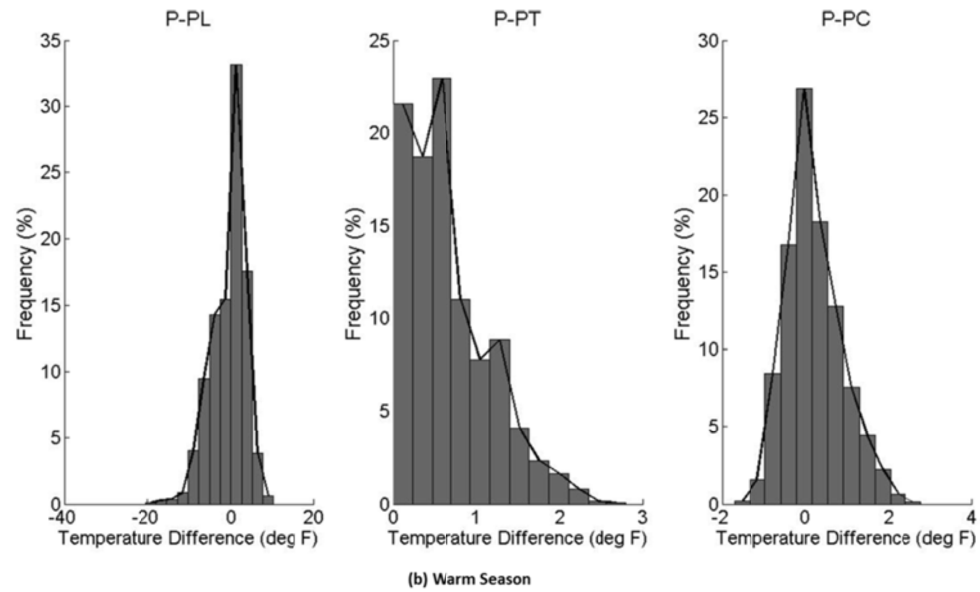


Figure 2: Frequency distribution for surface temperature differences (˚F) in Chicago.

Table 2: Results of Concrete Pavement Surface Temperature Differences (˚F) in Chicago

Chicago	Cold Season			Warm Season		
	P-PL	P-PT	P-PC	P-PL	P-PT	P-PC
Minimum	-16.1	0	-5.7	-22.9	0	-2.2
Maximum	8.8	1.9	2.6	10.5	3.5	3.1
Standard Deviation	2.53	0.29	0.78	4.33	0.52	0.73
Average	0.29	0.23	-0.55	-0.75	0.71	0.27
% Positive	47.27	59.46	17.49	46.52	90.42	52.48
% Negative	29.03	0.00	57.15	45.25	0.00	33.36
% Zero	23.70	40.54	25.36	8.22	9.58	14.16

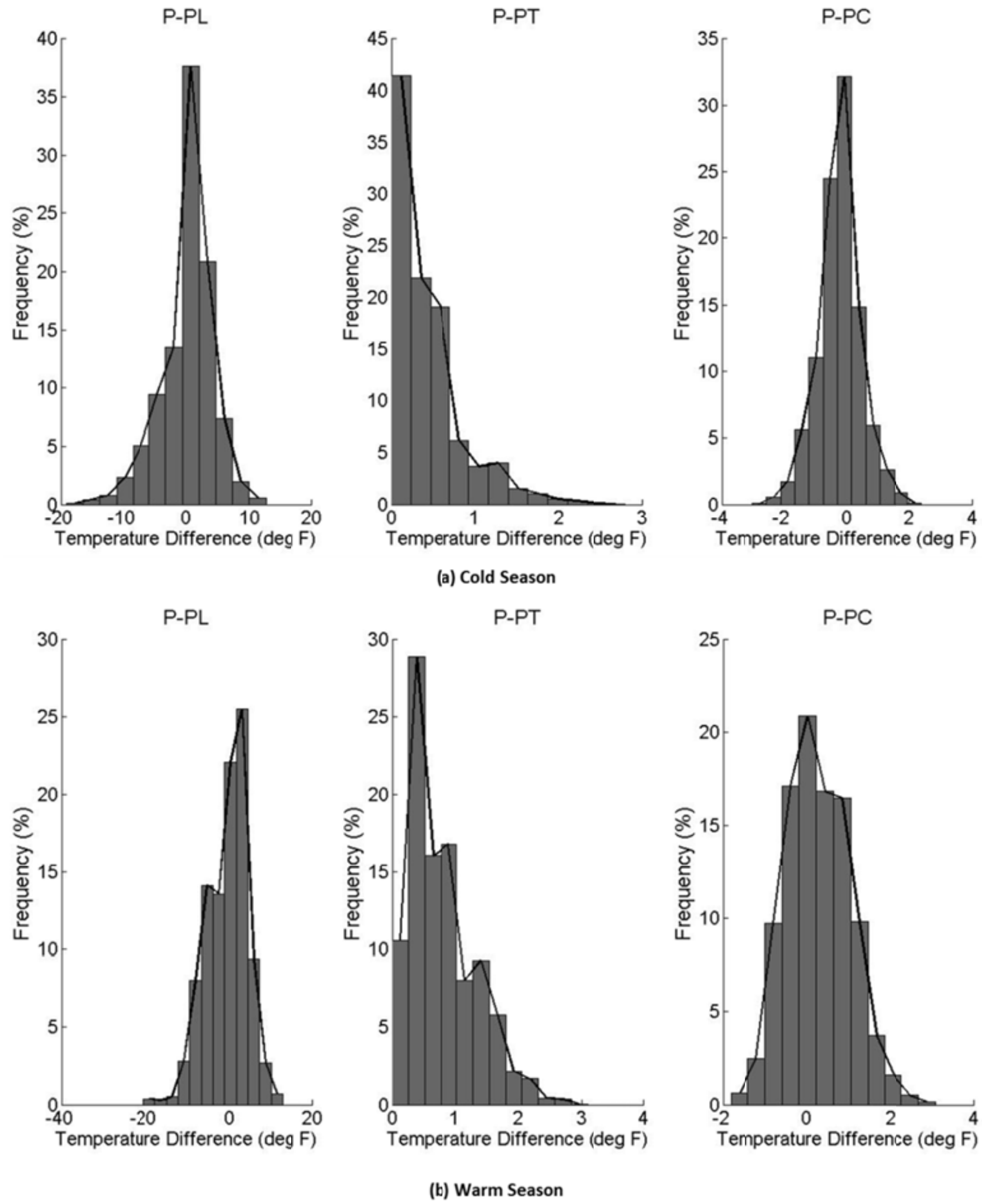


Figure 3: Frequency distribution for surface temperature differences (˚F) in Austin.

Table 3: Results of Concrete Pavement Surface Temperature Differences (˚F) in Austin

Austin	Cold Season			Warm Season		
	P-PL	P-PT	P-PC	P-PL	P-PT	P-PC
Minimum	-19.1	0	-3	-20.3	0	-1.8
Maximum	12.6	2.8	2.4	12.7	3.1	2.8
Standard Deviation	4.13	0.42	0.69	4.95	0.53	0.75
Average	0.10	0.42	-0.20	-0.55	0.84	0.28
% Positive	52.46	82.86	29.58	53.26	97.74	57.78
% Negative	34.85	0.00	52.46	44.01	0.00	35.82
% Zero	12.69	17.14	17.96	2.73	2.26	6.40

In the statistical analysis, the percentage of hours for which the deviations are positive (the control pavement has a higher surface temperature), negative (modified pavement has a higher surface temperature) and zero (the modification does not cause any difference in surface temperature to the first decimal) are also listed in Tables 2 and 3.

DISCUSSION

For the case of pavement system PL in the cold season, the modified pavement tends to be cooler than the control case in both cities. In the warm season though, the modification has a mixed impact with equal distribution of warmer and cooler surface differences (P-PL) in Chicago while in Austin, the same pavement system (PL) is cooler a higher percentage of the time. It is inferred that the lower thermal mass in pavement system PL leads to less heat storage. The behavior in the warm season in Chicago can be explained by the relatively milder season as compared to Austin. Notice also the high magnitude of the minimum and maximum differences, which shows that the change in thermal mass has a significant impact on the surface temperature.

For the case of titanium dioxide cement, PT, there is always a decrease in surface temperature over the control concrete pavement, i.e., a more positive surface temperature difference. Moreover, the surface temperature difference (P-PT) is higher in Austin relative to Chicago because of the greater incoming solar radiation for both warmer and colder seasons. The other significant observation for pavement system PT is the cooler surface temperatures it produces during the cold season, which may be detrimental in terms of energy impact in the city.

For the case of pavement system PC, a complete inversion takes place in the surface temperature difference between warm and cold seasons. The replacement of the aggregate base by a CTB leads to warmer surface temperatures in the cold season and cooler surface temperatures in the warm season for both cities. This is explained by the fact that, by increasing the thermal conductivity and heat capacity of the base layer, a CTB creates a pavement system with a higher thermal mass *(11)*.

To understand these predicted results from an LCA perspective, there is no consensus on the metric to be used to relate surface temperatures to environmental impact, with energy consumption and CO_2-equivalent both being used *(4)*. For CO_2-equivalent as the metric, a lower surface temperature leads to a lower air temperature *(16)* and this in turn leads to a decrease in radiative forcing, which lowers the CO_2-equivalent in the atmosphere *(7)*. However, if energy consumption is the metric, then cooler temperatures in cold seasons can cause an increase in heating loads because of lower ambient air temperatures *(17)*. Greater heating loads imply higher CO_2 emissions as a result of burning fossil fuel. However, lower pavement surface temperatures in the warm seasons may actually increase cooling loads as shown in *(18)*. Because there is no generalized conclusion, a detailed, site-specific analysis is necessary. Based on the results, a higher pavement albedo may not necessarily be the only way to mitigate the impact of the urban environment especially in cooler seasons. Other thermal properties of the pavement layers can also play a significant role in reducing the negative impact of the paved surfaces on the UHI effect by altering the thermal mass of the pavement system.

ALTERNATIVE CONCRETE PAVEMENT SYSTEM FOR BALANCING SURFACE TEMPERATURE DIFFERENCE

From the preceding analysis, it can be inferred that a higher thermal mass has an impact on surface temperature. In order to increase the thermal mass of the pavement system without changing the albedo, an alternative concrete pavement system was formulated with a higher thermal conductivity at the surface and a base layer with a larger heat capacity. For the new case, the layer thicknesses were the same as the control case P (see Figure 1). To increase the thermal conductivity of the surface, steel fiber-Reinforced Concrete (FRC) was proposed. The mean thermal conductivity of 1.53 BTU/hr-ft-˚F (2.65 W/mK) for lower temperature ranges 0 to 100˚C (32-212˚F) as shown in reference *(19)* was used. The FRC density, albedo, and heat capacity was assumed to be the same as the control concrete, 150 pcf (2,400 kg/m^3), 0.30, and 0.28 BTU/lb-˚F (1.2 kJ/kgK), respectively. A CTB was used instead of a granular base with the thermal properties taken from Table 1.

The modified case was called PF and was analyzed again for both Chicago and Austin. The surface temperature differences are designated (P-PF) and their frequency distribution for the two cities and two seasons are shown in Figure 4 with the statistical analysis in Table 4. With the alternative pavement system with higher surface and base thermal conductivity leading to increased base layer thermal storage capacity, Table 4 documents that for both cities, the alternative concrete pavement has warmer surfaces in cooler seasons and cooler surfaces during warmer seasons relative to the control concrete pavement. The minimum and maximum differences vary between the two cities, indicating a dependence on climate with the minimum difference in Chicago in the cold season being -5.4˚F and -2.4˚F for the same season in Austin. On comparing the case (P-PC) from Table 2 and Table 3 with (P-PF) in Table 4, the trends are similar, as expected.

Clearly, thermal mass significantly impacts pavement surface temperature and does it in different magnitudes depending on the season and climate location.

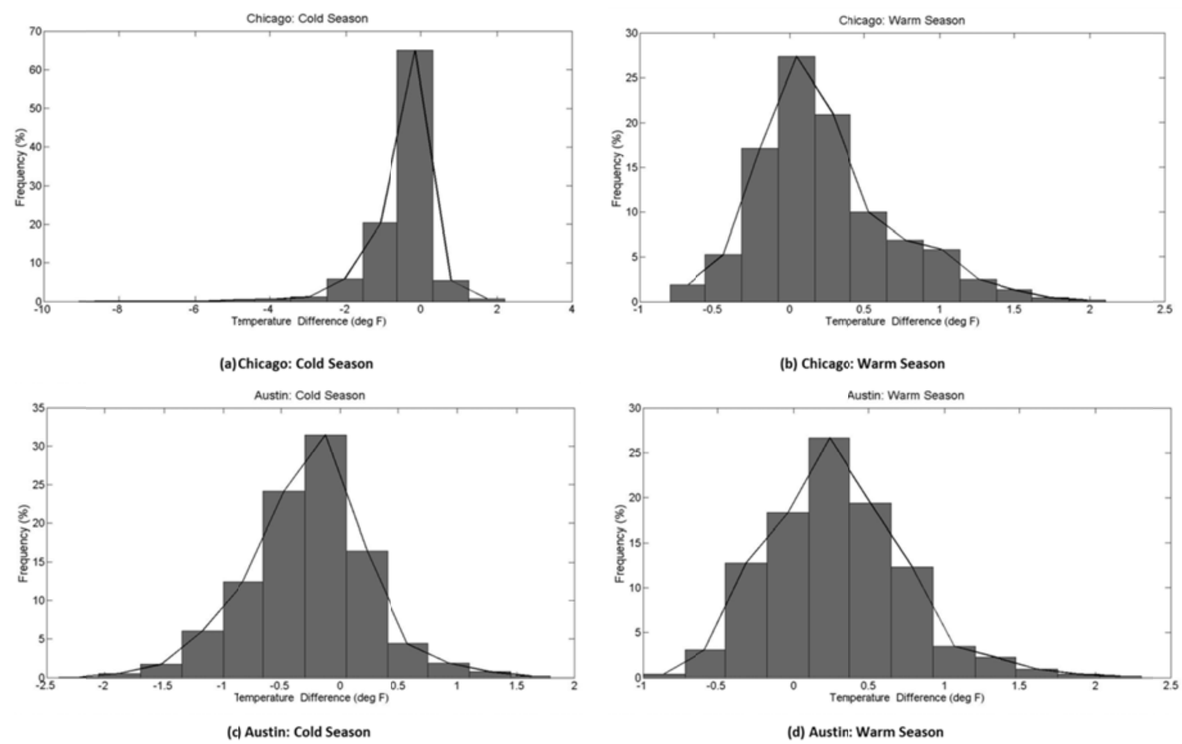


Figure 4: Frequency distributions of surface temperature differences (˚F) for the case P-PF.

Table 4: Results of a Statistical Analysis of Temperature Differences (˚F) for the case P-PF

P-PF	Chicago		Austin	
	Cold	**Warm**	**Cold**	**Warm**
Minimum	-5.4	-1.3	-2.4	-0.9
Maximum	2.4	2.5	1.8	2.2
Standard Deviation	0.73	0.49	0.53	0.45
Average	-0.35	0.26	-0.24	0.26
% Positive	16.09	59.58	24.17	63.63
% Negative	59.69	23.23	56.57	25.08
% Zero	24.23	17.19	19.26	11.29

CONCLUSION

In order to study the UHI effect with respect to pavements, it is important to understand the various factors contributing to change the pavement surface temperature including the pavement layers, materials, and local climatic condition. By using the EICM embedded within the MEDPG, the thermal properties of the entire pavement system, such as albedo, thermal conductivity and heat capacity were studied with respect to the differences in surface temperature relative to a control concrete pavement. Initially, changes were made only to one layer and from the insights gained therein, an alternative system was analyzed.

A change in a single property, such as albedo, thermal conductivity or heat capacity, while fixing the others can lead to significant change in surface temperatures from that of a control case; for example, increasing albedo from 0.30 to 0.35 can cool the surface by as much as 3.5˚F in some cases. While increasing the albedo leads to cooler surface temperatures across seasons, other modifications that change the thermal mass of the pavement system, such as using lower density concrete for the surface layer or a cement treated base or a combination of such strategies, show more variation, which was studied by hour, season, and climate. Lowering the thermal mass using lower density concrete for the surface course can decrease the surface temperature for about 50% of the time but also increase it about 35-40% of the time. Increasing the thermal mass by using a combination of FRC in the surface course and a CTB can lead to warmer surface temperatures in the cold season and cooler surface temperatures in the warm season about 60% of the time. In general, increasing the thermal mass of the system leads to it storing more thermal energy in the lower layers, which can lead to higher or lower surface temperatures depending on the season, which has a bearing on UHI. As UHI is a key component of a pavement LCA, the thermal properties impact it as well and therefore, should be considered in any pavement life cycle assessment.

The main strengths of this study are: a) the temporal resolution (one hour) for an entire year; b) coverage of different seasons and climates; and c) the use of layers and materials that could be used in pavement construction. It goes beyond previous studies in that it addresses pavement surface temperature differences on an hourly basis and as a percentage of effectiveness of a modification in properties. It also discusses effectiveness with respect to climate location. In the future, this approach can be used with a climate and building energy model to capture the estimated impact on a pavement LCA.

REFERENCES

1. Kleerekoper, L.; van Esch, M.; Salcedo, T. B. How to make a city climate-proof, addressing the urban heat island effect. *Resources, Conservation and Recycling,* 2012, No. 64, 30– 38.2. Aggarwal, R. M.; Guhathakurta, S.; Grossman-Clarke, S.; Lathey, V. How do variations in Urban Heat Islands in space and time influence household water use? The case of Phoenix, Arizona. *Water Resources Research,* 2012, *48* (6), 1-13.
3. Taha, H.; Akbari, H.; Rosenfeld, A.; Huang, J. Residential Cooling Loads and the Urban Heat Island the Effects of Albedo. *Building and Environment,* 1988, *23,* 271-283.
4. Santero, N. J.; Masanet, E.; Horvath, A. Life-cycle assessment of pavements. Part I: Critical review. *Resources, Conservation and Recycling,* 2011, No. 55, 801-809.
5. Bretz, S.; Akbari, H.; Rosenfeld, A. Practical Issues for Using Solar-Reflective Materials to Mitigate Urban Heat Islands. *Atmospheric Environment,* 1998, *32* (1), 95-101.
6. Santamouris, M. Using cool pavements as a mitigation strategy to fight urban heat island — A review of the actual developments. *Renewable and Sustainable Energy Reviews,* 2013, No. 26, 224-240.
7. Munoz, I.; Campra, P.; Fernandez-Alba, A. R. Including CO_2-emission equivalence of changes in land surface albedo in life cycle assessment. Methodology and case study on greenhouse agriculture. *International Journal of Life Cycle Assessment,* 2010, No. 15, 672–681.
8. Yu, B.; Lu, Q. Estimation of albedo effect in pavement life cycle assessment. *Journal of Cleaner Production,* 2014, *64,* 1-4.
9. Susca, T. Enhancement of life cycle assessment methodology to include the effect of surface albedo on climate change: Comparing black and white roofs. *Environmental Pollution* 2012, *163,* 48-54.
10. Yang, J.; Wang, Z.; Kaloush, K. E. *Unintended Consequences: A Research Synthesis Examining the Use of Reflective Pavements to Mitigate the Urban Heat Island Effect;* Arizona State University: Tempe, 2013.
11. Gui, J.; Phelan, P. E.; Kaloush, K. E.; Golden, J. S. Impact of Pavement Thermophysical Properties on Surface Temperatures. *Journal of Materials in Civil Engineering,* 2007, *19* (8), 683-690.
12. Li, H.; Harvey, J.; Kendall, A. Field measurement of albedo for different land cover materials and effects on thermal performance. *Building and Environment,* 2013, *59,* 536-546.
13. National Concrete Pavement Technology Center. *Environmental Impact Benefits with "TX Active" Concrete Pavement in Missouri DOT Two-Lift Highway Construction Demonstration: Final Report I;* Iowa State University, 2012.
14. National Cooperative Highway Research Program Report 1-37A. *Guide for Mechanistic-Empirical Pavement Design of New and Rehabilitated Pavement Structures;* Transportation Research Board, 2004.
15. Nguyen, L. H.; Beaucour, A.-L.; Ortola, S.; Noumowé, A. Influence of the volume fraction and the nature of fine lightweight aggregates on the thermal and mechanical properties of structural concrete. *Construction and Building Materials,* 2014, *51,* 121–132.
16. Synnefa, A.; Karlessi, T.; Gaitani, N.; Santamouris, M.; Assimakopoulos, D. N.; Papakatsikas, C. Experimental testing of cool colored thin layer asphalt and estimation of its potential to improve the urban microclimate. *Building and Environment,* 2011, *46,* 38-44.
17. Akbari, H.; Konopacki, S. Calculating energy-saving potentials of heat-island reduction strategies. *Energy Policy,* 2005, *33* (6), 721-756.
18. Yaghoobian, N.; Kleissl, J. Effect of reflective pavements on building energy use. *Urban Climate* 2012, *2,* 25-42.
19. Kodur, V.; Khaliq, W. Effect of temperature on thermal properties of different types of high-strength concrete. *Journal of Materials in Civil Engineering,* 2011, *23* (6), 793-801.