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Cooling the Heat Island in Compact Urban Environments: The effectiveness of Chicago's Green Alley Program

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Abstract

To build 21st century sustainable cities, officials are installing alternative infrastructure technologies to reduce atmospheric environmental problems such as the urban heat island (UHI). The purpose of this study is to further our understanding of how ground-level UHI mitigation strategies in compact urban areas impact air temperatures. The term 'cool pavement' refers to both reflective and porous pavements. While cool pavements are identified as UHI mitigation strategies, we evaluated their in-situ effectiveness on air and surface temperatures. Using a case-control research design, we measured the impact of these pavements on air temperature relative to conventional asphalt in alleys. In locations where high vertical walls constrained the release of solar radiation, reflective pavements increased air temperatures. In two neighborhoods, reflective concrete increased daytime 3-meter air temperatures by 0.9° C and 0.5° C respectively and had no influence on nighttime temperatures. Unlike reflective pavement, porous pavements permit percolation and may contribute to cooling through evaporation. However, our research illustrated that porous asphalt and porous concrete increased maximum daytime air temperatures by 0.8° C and 0.5° C and did not lower nighttime air temperatures. While porous concrete pavers had significantly warmer midday air temperatures, it was the only cool pavement strategy to yield lower early evening air temperatures relative to conventional asphalt. Even immediately after rain events, the air temperatures above the porous pavements were not significantly cooler. This research demonstrates our need to evaluate real world installations of cool pavement to determine their actual impact on decreasing summertime temperatures.

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Keywords: urban heat island; vulnerability; cool pavement; high albedo; porous pavement; mitigation

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1. Introduction

Urban heat islands (UHI) are urban and suburban areas with elevated surface and air temperatures relative to their surrounding rural or wildlands. While UHIs may increase temperatures 1° to 3°C on average, this may increase to 10°C during cloudless conditions[1]. As global climate change increases the frequency, duration, and intensity of summer heat extremes, UHIs will exacerbate these extreme temperatures and threaten residents' wellbeing[2]. Numerous researchers have pointed to pavement as a key contributor to higher surface and air temperatures [3-6]. In a study of four U.S. metropolitan areas, Rose and colleagues found that pavement covered 29.2-44.5% of the urban extents [7]. Therefore, lessening pavement's contribution to UHIs could significantly improve conditions. Yet, decision-makers lack a simple method to measure performance of cool pavement installed in compact urban canyons. As a result, planners, designers, and decision-makers are interested in strategies to reduce the UHI. The U.S. Environmental Protection Agency organizes UHI mitigation strategies into four categories: 1) increasing tree and vegetative cover, 2) installing green roofs, 3) installing cool roofs, and 4) using cooling pavements.

The Chicago Department of Transportation's (CDOT) Green Alley Program (GAP) provided us with the ability to compare installed cool pavement systems with conventional asphalt surfaces in complex, three-dimensional urban environments. Part of the aim of this research is to devise a simple method for measuring cool pavement performance in compact urban canyons. In this research, we use mobile and stationary weather data to compare air temperatures above reflective concrete, porous asphalt, porous concrete, and porous concrete pavers pavement with air temperatures over conventional asphalt in five Chicago neighborhoods. In the following literature review, we summarize the role pavement's properties play in impacting surface and air temperatures. In the methodology section, we explain how we selected 'case' and 'control' sites, set up the instrumentation, and collected data. Finally, we present our results, discuss our findings, and conclude with the implications and limitations of our study.

1.1. The role of pavement's thermophysical properties

In this review we discuss pavement's 1) thermophysical and 2) hydraulic properties. Many studies have examined pavement's thermophysical properties that contribute to elevated surface and air temperatures[3-6]. During the day, pavement surfaces are exposed to solar radiation and dissipate this heat into the air through reflectance of shortwave radiation (albedo), emittance, or convection (due to wind) [8]. Darker surfaces absorb more solar radiation than lighter surfaces. Many conventional pavements are dark and therefore have extremely low albedo values. For example, newly installed asphalt has an albedo value of 0.05, thus absorbing 95% of the incoming shortwave solar radiation; aged asphalt lightens to 0.10 – 0.18 depending upon the aggregate type. Pomerantz and colleagues measured 16 Portland cement concrete field samples in the San Francisco Bay Area and found that concrete albedo averaged 0.26 with readings ranging from 0.18 to 0.35[9].

In an effort to determine what physical properties explain pavements' thermal behavior, Gui and colleagues calibrated a one-dimensional energy-balance model with actual solar radiation, dew-point temperature, surface temperature, air temperature, and wind velocity from field sites in Phoenix, Arizona[5]. The researchers concluded that albedo and emissivity explained the greatest percentage of temperature variation. Specifically, albedo explained the largest variation in daytime surface temperature and emissivity explained the largest variation in nighttime surface temperature. Many cool pavement programs turn to increasing pavement albedo because UHIs are most extreme at night and high nighttime air temperatures are associated with increases in heat mortality [6, 10].

High albedo pavement is created by either (1) applying a thin surface treatment or (2) by incorporating light colored aggregate or pigments into the pavement material to conventional asphalt, concrete, and modular pavers. Research has found that reflective pavements lower surface temperatures. For example, Golden & Kaloush found that in Phoenix on a July day, the surface temperature of a thick asphalt rubber pavement painted white (albedo of 0.26) was 16°C cooler than a similar unpainted sample (albedo of 0.13)[4]. However, because reflective cool pavement is structurally similar to conventional pavement, they have comparable emissivity values. Like albedo, emissivity is measured on a scale of 0 to 1.0. Golden & Kaloush found conventional pavement materials had emissivity values over 0.90 and therefore effectively stored and released energy (asphalt, 0.95-0.971; concrete, 0.90-0.98; and brick, 0.94)[4]. Wider applications of high albedo pavement may substantially reduce UHIs.

Sailor simulated the impact of increasing surface albedo on air temperature in the Los Angeles basin. Throughout the basin, the average albedo was increased by 0.08 due to differences in the amount of impervious surfaces[11]. From this simulation, Sailor concluded that the modification of the albedo of impervious surface would lower summertime peak air temperatures by 1.5°C. Rosenzweig and colleagues used a computer model to estimate how different UHI mitigation strategies influenced air temperature in specific New York City neighborhoods[12]. The researchers concluded that lightening pavement may reduce 3 pm air temperatures by as much as 2.9°C [12], making it the most effective UHI mitigation strategy in their comparison. While these simulations of reflective pavement produce encouraging results, they generally failed to consider the three-dimensional character of urban environments.

Urban climatologists have long noted the interaction of solar radiation between the ground plane and adjacent building walls [13-16]. The three-dimensional relationship of the vertical wall heights relative to the street width is referred to as the canyon aspect ratio [17]. The three-dimensional aspect of urban environments alters important heating and cooling fluxes. Masson developed a Town Energy Budget model to better describe the complicated energy budgets from roofs, walls, and pavement in complex three-dimensional urban canyons. He showed that effective canyon albedo (a combination of pavement and walls) range between ~0.10 to ~0.03 (canyon walls of 0.25 and pavement of 0.08) for urban aspect ratios between 0.5 and 1.5 during summer. During summer, when the sun is high in the sky, compact urban canyons trap incoming and outgoing radiation effectively lowering albedo. Sailor and Fan argued that by neglecting how vertical walls cast shadows as well as reflect and absorb solar radiation we may underestimate the true urban energy balance[16]. By modeling the three dimensional character of two residential neighborhoods, Sailor and Fan concluded that conventional ground surface albedo values underestimated the daily solar energy gain in three dimensional environments by 18-19%. In another study, Erell and colleagues simulated the effects of changing albedo, aspect ratio, and orientation on air temperatures in urban canyons in four different bioclimatic regions (Israel, Australia, Singapore, and Sweden)[18]. They found higher albedos (0.45 and 0.70) were associated with increased heat stress levels regardless of the canyon aspect ratio or orientation. Therefore, in confined spaces, the walls of the urban canyon may interrupt the high albedo surface's upward reflection, inadvertently decreasing thermal comfort by increasing radiant load at the pedestrian level.

1.2 The role of pavement's hydraulic properties

Porous pavement can be constructed of asphalt, concrete, or modular pavers. While reflective pavement have a comparable profile to conventional asphalt and concrete pavement, porous pavement has three important differences. The first difference is the presence of pores or voids. The pores are formed by removing the smallest aggregate and mixing in only larger aggregate with the binder in the surface, choker, and base courses. Porosity generally varies between 15 to 30% and these interconnected air-filled pores add insulation. While the pores may permit air and moisture exchange, Haselbach and colleagues noted that these pores also darken the surface thus reducing the albedo[8]. A second important difference is the strength of the surface. Adding pores reduces the compressive strength of porous pavement. This loss of strength means that porous pavement is used in lower traffic areas such as low volume residential streets, alleys, drives and parking stalls. A third difference is that porous pavement has a reservoir base. While most pavement is laid on a compacted aggregate base course, porous pavement's base course may be deeper to permit stormwater storage. Therefore water in the porous pavement or below in the reservoir base or soil may increase evaporation.

Kevern and colleagues found that conventional impervious concrete consistently stored more energy in the layered system than the porous concrete during five days in mid-summer with air temperatures over 32°C in Iowa[19]. On average over the five days, the porous concrete stored over 50 J/cm2 less energy in its system than the conventional concrete system during the daylight heating cycle. The authors explained that this difference is largely attributed to the porous system's insulating properties from the air voids, which dampened the transfer of heat into the aggregate subgrade. Asaeda and Ca found that relative to non-porous materials, the surface temperature of the porous materials increased and decreased more rapidly relative to non-porous materials[20]. Contrary to expectations, Asaeda and Ca found that both porous and non-porous materials were relatively dry. Yet after precipitation, peak latent heat was 0 W/m2 for the Hot Mix Asphalt (HMA), 20 W/m2 for the porous concrete block, 415 W/m2 for the grass, and 300 W/m2 for the porous ceramic block. The evaporative cooling effect (latent heat) from the porous concrete block pavement with consistent void size was minimal. The consistent void size in the porous block reduced the capillary pressure resulting in a faster draining material than the porous ceramic block that had voids of various sizes. By having both small and large voids, the porous ceramic block increases capillary pressure preserving water in the material longer than the porous block. This water is then evaporated during heating keeping the material cooler than the HMA or the dry porous concrete block. Subsequent research by Nakayama and Fujita provided more information about the importance of the presence of water in porous pavement[21]. Nakayama and Fujita found that quick draining infiltration pavement (porous asphalt) decreased pavement and air temperature more rapidly than the water-holding pavement, but that the effect lasted for a shorter period of time than for the water-holding pavement. By including water-holding silica in porous concrete they were able to lengthen the cooling effect, in some cases for up to three days after precipitation. The found that after a rainfall, the water-holding pavement with a high albedo (0.48) had the potential to cool pavement surface temperatures from 5-20°C over other pavement types due to a combination of the high albedo and water content in the pavement. Haselbach and colleagues recorded summertime hourly temperature data within 15.2 cm (6 inch) pavement profiles as well as in the pavement subsurface and the near-surface air temperature to compare maximum and minimum temperatures for porous concrete (porosity = 31%) with conventional concrete[8]. Consistent with Asaeda and Ca's results, the porous concrete had higher maximum temperatures but lower minimum temperatures relative to the conventional concrete[20]. In this research, Haselbach and colleagues found that after a rainfall, porous concrete cooled more rapidly than conventional concrete thus indicating that evaporative cooling was occurring. Finally, Stempihar and colleagues conducted a comparison of porous asphalt, conventional asphalt, and conventional concrete in Phoenix, Arizona[22]. The authors concluded that the, "ability of [porous asphalt] to exhibit cool temperatures at night by quickly dissipating high daytime temperatures makes it an excellent candidate to lessen the overall UHI effect. However, if daytime temperatures are of concern, another pavement material should be considered," [22]. Therefore, research has produced contradictory findings about how porous pavement affects air temperatures during dry conditions and after precipitation events.

Pavement surfaces dissipate heat through convection because of wind movement. To examine wind's influence on air and surface temperatures, Morris and colleagues measured wind speed, cloud cover, and the UHI intensity in Melbourne from 1971 to 1991[23]. These researchers then divided wind speeds into six categories (0-0.6 m/s, 0.6-1.9 m/s, 2-2.9 m/s, 3-3.9 m/s, 4-4.9 m/s, ⩾ 5.0 m/s). They concluded that elevated air temperatures were most correlated with light winds (0-0.6 m/s) and clear conditions. Under the lowest wind speeds (0-0.6 m/s) they concluded that the 20-year average of the summer UHI intensity in Melbourne was 1.74° C. They also found that wind speeds over 2.0 m/s produced a statistically significant reduction in Melbourne's UHI. Therefore, it is important to measure how wind mediates the relationship between pavement surface and air temperature in specific neighborhood environments.

Building on the literature, we investigate three research questions. First, in our urban alleys, does the pavement surface temperature explain a significant proportion of air temperature at 3 meters? We suspect that pavement temperature will explain a portion of air temperature, especially under light wind conditions. Other urban surfaces (roofs, walls, and anthropogenic sources) likely provide the other contributions. The findings from this first question will then be used as the foundation to understand how changing a pavement's thermophysical properties affect air temperatures within urban canyons with complicated heating and cooling dynamics. Second, we examine when the canyon aspect ratio (wall height/street width) is greater than 0.6, how does higher albedo pavement influence air temperature at 3 meters relative to conventional asphalt? Based on the literature, we hypothesize that air temperatures in compact alleys with high albedo pavement will be higher during the day compared to alleys with conventional asphalt pavement. Finally, does air temperatures above porous pavement decline after rain events relative to conventional asphalt? Based on the literature, we hypothesize that after a rainfall air temperatures in compact alleys with porous pavement will be lower during the day due to evaporative cooling compared to alleys with conventional asphalt pavement.

2. Methods

The study was conducted in July and August of 2010. Chicago's summer of 2010 was close to average, with a mean air temperature at Midway Airport of 25.45°C (1961-1990 summer average of 25.9°C) [24]. Chicago has a mid-continental climate that makes for warm humid summers and cold snowy winters. Summer temperatures have reached as high as 40.6°C (105°F) and dipped in winter to as low as -32.8°C (-27°F) [25]. The Chicago region lies on a flat lake plain at the southwest corner of Lake Michigan. Elevations varying by only 28.6 m (94 ft.) from a low of 176.5 m (579 ft.) above sea level [26]. Paved surfaces cover 23% (13,458 hectares or 33,256 acres) of the city of Chicago proper while alleys cover approximately 2.4% of the City (1,416 hectares or 3,500 acres) [27].

For the GAP, CDOT custom designed specifications for the 1) high albedo concrete (Portland concrete cement, PCC), 2) porous asphalt (hot-mixed asphalt, HMA), 3) porous concrete (Portland concrete cement, PPCC), and 4) porous concrete pavers (modular Portland concrete cement pavers). Appendix A describes the structural properties of the four cool pavements. CDOT lightened the high albedo concrete by adding slag in the concrete at a rate of 100 pounds per cubic yard to achieve an initial albedo of 0.26 [28]. According to Attarian, CDOT substituted recycled shredded tire rubber in lieu of cellulose fibers that are typically added to the polymer modified asphalt cement in the porous HMA to prevent drain-down[28]. CDOT found that adding shredded rubber tires through the surface course resulted in better adherence of the asphalt cement to the aggregate and increased pavement durability by increasing the surface temperature range for rutting and cracking. CDOT decided a compressive strength of 11,720 kPa (1,700 psi) for the porous PCC was acceptable [28].

2.2 Case selection

We selected five neighborhoods that had green alleys installed as of December 2009 (Appendix B). Each case (green) alley was paired with a nearby control alley in the same neighborhood that had similar urban physical characteristics (percent impervious surface, percent tree canopy, canyon aspect ratio, and sky view factor) but with conventional asphalt pavement (Appendix C). Block calculations for impervious surface and tree canopy included the entire block extending out from street curb to the midpoint of each of the four bounding streets. Land cover percentages were calculated using high-resolution orthoimagery from April 9, 2010. Impervious surfaces, roofs, and pavement were calculated using a similar method to Akbari and colleagues [29]. Calculations for canyon aspect ratio and sky view factor (SVF) were measured at the HOBO weather station. Aspect ratios were calculated using orthoimagery, the Chicago Zoning Code standard building heights, and site visits. Sky view factor (SVF) or a measure of the amount of sky obstructed by surrounding elements was measured below the HOBO weather station with a Solmetric SunEye using a method similar Svensson [30]. Finally, to understand the existing reflectivity of the pavement, we measured the albedo of each pavement using an albedometer constructed of two Kipp & Zonen CMP3 Pyranometers (sensitivity between -10°C to +40°C of < 5%) to measure albedo at waist height (1.1 m; 3 ft. 7 - 5⁄16 in.) on clear, cloudless days within two hours of solar noon. Measurements were made at each of the five spot locations along each alley pair (Appendix F).

Appendix B illustrates the five selected neighborhoods. Interested in the influence of the canyon aspect ratio on high albedo pavement, we selected two different east-west alleys with different canyon aspect ratios that exceed Oke's (1988) canyon aspect ratio recommendation of 0.6. Those neighborhoods were Little Italy and Austin. For the porous pavement types we selected case and control pairs in Beverly (porous asphalt), East Side (porous concrete alley) and Bronzeville (porous concrete pavers). Overall we selected case-control pairs that had similar block characteristics (Appendix C). Percent impervious surface of the paired case-control sites were identical in Beverly, but differed by as much as 8.9% between the Austin pair. Tree canopy differences between the case-control sites were generally small (less than 8%). However, the Bronzeville pair had the largest spread with a 16.5% difference in percent tree canopy between the sites. Aspect ratio was similar between most pairs. Little Italy and Austin had case canyon aspect ratios of 1.29 and 0.68 respectively with similarly paired control alley aspect ratios of 1.07 and 0.65. The Bronzeville pair had the biggest difference with a case aspect ratio of 1.26 and the control aspect ratio of 0.67. Finally, most pairs had similar SVF. The largest difference was with the Bronzeville pairs, which had almost a 0.2 difference in SVF. .

Averaged albedo by pavement type did not vary as much as we expected (Appendix D). The porous asphalt had the lowest albedo value (0.11) and the high albedo concrete had the highest albedo value (0.22). The porous asphalt had a lower albedo value of 0.11 compared to the conventional aged asphalt (0.17). The recorded albedo value of 0.22 for the high albedo concrete was less then the 0.26 specified by CDOT. The lower measured albedo is likely due to age effects such as tire wear and dirt. The porous concrete and porous concrete pavers had comparable albedo values to aged asphalt. The lower albedo value for the porous pavement was consistent with the literature [8]..

2.3 Data collection

We used 1) mobile and 2) fixed measurements. First, we measured a cross-section of each alley's air temperature, pavement surface temperature, and wind speed at 3 meters to understand if pavement surface temperature explained a significant proportion of air temperature at 3 meters. The weather tricycle contained multiple pieces of equipment located at 3 m height (Appendix E) including a model HMP45C air temperature (accuracy at 20°C of ± 0.2°C to ±0.3°C at 40°C) probe, SI-111 precision infrared radiometer (accuracy of ± 0.2°C between -10° to +65°C), and a model 014A wind speed sensor anemometer (accuracy of 0.11 m/s or 0.25 mph) [31].. These instruments measure the ambient air temperature, pavement temperature, and wind velocity respectively. These three pieces of data were collected data simultaneously only on warm days (with maximum temperatures over 26.7°C) with mostly clear or partly cloudy skies. The observations were taken at four different times of day: early morning (7am – 9am), late morning (10am – noon), early afternoon (1pm – 3pm), and late afternoon (4pm – 6pm) over a two-month period (July and August, 2010) at five discrete preselected locations along the length of each case and control alley (Appendix F).

Next, we collected longitudinal air temperature data in each neighborhood using a stationary Onset U23-002 HOBO External Temperature/RH Data Logger with sensor and a model RS3 solar radiation shield to measure air temperature (accuracy of ±0.2°C from 0 to 50°C) (Appendix G). We followed Oke's criteria to establish the locations and heights of the HOBO measurement units in each neighborhood[32]. Each HOBO station was mounted on the north or east side of a utility pole with two screws and two zip ties to secure the station at a height of 3 m (above the height of truck traffic) at the center of each neighborhood block's alley. The units were located within the urban canopy layer as residential building heights were a minimum of 9.14 meters. HOBO 5-minute weather data were used for two four-day weather periods, 1) clear/dry and 2) rainy. The clear and dry days clear days (July 1-4, 2010) were used to capture days when UHIs are most intense [33-35]. The rainy period days (July 11-14, 2010) were used to understand how porous pavement affects air temperatures after precipitation similar to Nakayama and Fujita and Asaeda and Ca [20, 21].

3. Results

First, we used cross-sectional data from the weather tricycle to understand how pavement temperature explained 3-meter air temperature under different types of wind conditions (Appendix H). We wanted to establish the influence of pavement temperature on air temperatures and to isolate that influence from other heating influences from walls and other urban surfaces. To understand the impact of wind speed on surface and air temperature during the weather tricycle rounds, we divided the recorded six-minute averaged wind speeds into quartiles at the 25th, 50th, 75th, 100th percentile, in a similar manner to Morris et al. (2001). The wind speed, air and surface temperatures were simultaneously measured using the weather tricycle. The lowest 25th percentile had six-minute averaged wind speeds from 0 to 1.21 m/s. The 50th percentile had wind speeds from 1.21 to 1.54 m/s. The 75th percentile had wind speeds from 1.55 to 2.12 m/s. Finally, the 100th percentile had winds speeds from 2.13 to 5.39 m/s. We then selected corresponding air temperatures and ran a bivariate correlation between air temperature and pavement temperature controlling for the wind category. When winds were lowest, the pavement temperatures explained 76% of the variance in air temperatures. During the highest winds, the pavement temperatures explained 50% of the air temperature's variance. Therefore, the alley's pavement temperature explained a significant proportion of the air temperature, particularly with lighter wind conditions.

3.1 Effect of cool pavement on air temperature

Next, we used stationary HOBO weather units to understand the effect of cool pavement on air temperature. We selected one contiguous four-day clear, cloudless period and one contiguous four-day rainy period to compare air temperatures. We chose July 1 – July 4 for the clear period because it had consistently clear skies with an average high temperature of 28.7°C (83.7°F) and average low of 18°C (64.4°F) at Midway Airport [36]. During this period, Midway Airport received 94.25% (100%, 100%, 100%, and 77%) of its possible sunshine [37]. Hourly wind speeds ranged from as high as 6.93 m/s at 13.51 hr to as low as 1.93 m/s at 4:51 hr. We choose July 11-14, 2010 for the four-day rainy period with a precipitation event on the first day. The only precipitation event occurred during the night of July 11 and early on the morning of July 12, 2010. Midway Airport's weather station received 19.6 mm (0.77 inches) of rain. During the rainy period, the average high temperature was 29.1°C (84.4°F) with an average low of 21°C (69.8°F) and Midway Airport received 79.5% (62%, 73%, 86%, and 97%) of its possible sunshine [36]. Hourly wind speeds ranged from as high as 5.49 m/s at 17:51 hr. to as low as 1.20 m/s at 2:51 hr.

3.1.1 High albedo pavement

Appendix G illustrates the physical conditions where the weather stations were located in the high albedo concrete case (left) alley and the matched conventional asphalt control (right) alley. Appendix I illustrates the difference in the four-day average hourly air temperatures (bold line) of the Little Italy and Austin high albedo cases relative to the asphalt pavement controls. Both the high albedo alleys in Little Italy and Austin had significantly warmer air temperatures relative to the conventional asphalt alley over the clear period. At night differences were reduced to generally less than ±0.25°C and were not significantly different. After sunrise (sunrise is 5:20 and sunset is 20:29 in early July), the two high albedo alleys are both warmer than the control alleys during the daytime hours. Little Italy's case alley is significantly warmer than the control alley from around 7:00 to 17:00 (both the lower and upper 95% confidence bands are above the zero line). Austin's case alley shows a similar pattern, but it is only significantly warmer from 7:00 to 12:00 and then again from around 16:00 to 19:00. As we would expect, the air temperatures over the highly reflective surfaces were not significantly different at night when there is no solar radiation.

3.1.2 Porous pavement

We compared the hourly air temperature differences for the porous cases and the asphalt pavement controls for the same clear period (July 1-4, 2010) using time series analysis and again after the precipitation event Appendix J. While daytime air temperatures of porous asphalt (Beverly) were significantly higher (0.8°C), nighttime air temperatures were not significantly lower. For porous concrete (East Side), while daytime air temperatures were comparable to conventional asphalt, early evening air temperatures were significantly higher (0.5°C). Only the porous concrete pavers (Bronzeville) had significantly warmer midday air temperatures and significantly lower early evening air temperatures relative to conventional asphalt. After a rain event, the air temperature maximums and minimums decreased slightly but followed a similar temperature pattern as on dry, clear conditions.

4. Discussion

Our study examined a simple method to evaluate cool pavement performance. Yet, alleys are complex urban environments and one of our first concerns was that roofs, walls, and waste heat from vehicles and air conditioning systems might negate the relationship between the pavement's surface and air temperature at 3 meters. To address this concern we used the weather tricycle data to examine how much pavement temperature explained air temperature. From our research, we found that pavement temperature significantly correlated with air temperature in the alleys when we controlled for wind speed. Under light wind conditions, the surface temperature of the pavement explained 76% of the air temperature at 3 meters. However, under higher wind conditions, the surface temperature of the pavement only explained 50% of the air temperature. Lighter winds are more common at night and therefore, the temperature of the pavement surface will have a greater influence on 3 meter air temperatures at night relative to the day. This bivariate analysis helped us better understand the implications of our cool pavement analysis using stationary HOBO weather units.

Examining the HOBO data using time series analysis told us that relative to conventional asphalt, the air temperatures in the two alleys with the high albedo concrete were 0.5 to 1°C degrees warmer during the day. Yet, when we place this finding into context with wind speeds measured from Midway Airport, much of this difference may be hard to place solely on pavement temperatures. During the afternoon wind speeds at Midway Airport were as high as 6.93 m/s at around 2 pm. The bivariate analysis tells us that pavement temperature explains roughly 50% of the air temperature at wind speed above 2.13 m/s. This means that roof, wall, and anthropogenic heat sources likely contributed to at least half of that 0.5 to 1°C difference. During the overnight hours, when winds were lower, we found no statistically significant difference between alley air temperatures. The aim of many cool pavement programs is to reduce nighttime air temperature; we did not find evidence for this cooling benefit. While high albedo, reflective surfaces may lessen the surface temperatures on roof tops and in open parking lots, it may actually contribute little to overall cooling at night or actually create more stressful thermal environments during the day when adjacent walls reflect radiation [15].

Our research found that daytime air temperatures measured by HOBO units over porous asphalt were significantly higher (0.8°C) and this is consistent with Asaeda and Ca and Stempihar and colleagues [20, 22]. Yet again, wind speeds at Midway Airport during these times were between 3 and 6 m/s before noon during both periods. So the surface temperature of the porous asphalt likely explains roughly 50% of this difference. Nighttime air temperatures over the porous surfaces were not significantly lower and contradicts past findings. For porous concrete, while daytime air temperatures were comparable to conventional asphalt, early evening temperatures were significantly higher (0.5°C). This was also the time of highest wind speeds at Midway Airport (6 pm). Only porous concrete pavers had significantly warmer midday temperatures and significantly lower early evening temperatures relative to conventional asphalt. After a rain event (19.6 mm), the air temperature maximums and minimums over porous surfaces decreased slightly but followed a similar pattern to dry, clear conditions. Therefore, the evaporative cooling effect is relatively minimal.

Our study has several limitations because we chose to keep our methods simple and useful for city officials evaluating cool pavement in compact urban locations. First, our analysis is based on the matched sites being equivalent in all ways except for the pavement surface type, so that any difference in temperature is attributed to the pavement surface type. We attempted to account for this with our bivariate analysis of pavement temperature and air temperature. To the extent that other factors such as walls, roofs, and anthropogenic heat sources influence the air temperature at these sites, the effects of these other factors could be incorrectly attributed to the surface type. We also treated the four consecutive measurement days as replicates. If unique factors influence the temperature on different days, this heterogeneity could reduce the apparent influence of the surface type. Finally, we were limited in siting the HOBO weather units due to crowded compact alley spaces we examined. Utility poles alternate between north and south, east and west sides of the alley and may have affected air temperatures.

Despite our efforts to match the case and control alleys, it is important to note differences that may have influenced the results in the Little Italy and Bronzeville neighborhood. Little Italy's case alley had a greater canyon aspect ratio of 1.29 relative to the control alley (1.07). Also, in the case, the south facing walls were composed of red brick and likely with a much lower albedo (not measured) than the concrete pavement. Conversely, Austin's case and control alley's canyon aspect ratio were 0.68 and 0.65, respectively and the walls of the urban canyon were similarly composed of light colored garage buildings. The most mismatched case-control pair was Bronzeville. We chose to include this pair because we thought it important to include porous pavers. At the time CDOT only installed porous pavers in one alley that was located in Bronzeville. This alley was part of a HOPE VI redevelopment and the block size and urban form was more different than the other case-control pairs. The Bronzeville case block was considerably smaller (5,254 m2) than the historic control block (40,162 m2). In addition, the case alley had a canyon aspect ratio of 1.26 compared to 0.67 in the control alley.

5. Conclusion

Municipal governments require simple and effective methods to evaluate the performance of cool pavement. Weather tricycles provide fine cross-sectional detail of urban climate dynamics. Yet, they are expensive, time and labor intensive, and lack longitudinal information. On the other hand, stationary weather units provide longitudinal data at a relatively inexpensive cost and collect data simultaneously in multiple locations. Combining the two data collection techniques may provide municipalities with the information they require to adequately evaluate cool pavement in compact urban environments.

While additional research is needed in more in-situ settings, our findings suggest that increasing albedo (reflectivity) on the ground plane in a dense urban environment without consideration for the urban canyon geometry may likely have little to no cooling effect on air temperature. Pavement temperatures are only one piece of the larger contribution of other urban surfaces. Walls, roofs, and anthropogenic heat sources contribution to overall air temperature likely reduced any minor cooling effects in the alley by the high albedo concrete. This points to the limits of installing highly reflective pavement in compact urban locations. Our findings also suggest that increasing permeability on the ground plane in a dense urban environment without consideration for the urban canyon geometry may likely have little to no cooling effect on overall air temperature. Unless porous pavement is designed to store stormwater in the pavement's structure [8, 20], the cooling benefits of porous pavement is not large enough to counter other heating forces such as walls, roofs, or anthropogenic heat sources. This may put using porous pavement for both stormwater and UHI reduction at odds, because porous pavement is most commonly used to promote quick drainage for stormwater management.

This research advances our knowledge of cool paving performance. First, this study provides a real world evaluation of two cool paving strategies in complex three-dimensional urban conditions. By investigating how well the cool pavement techniques work in dense urban neighborhoods we were able to show that highly reflective pavement in urban canyons did not decrease nighttime air temperatures. We also concluded that porous pavement during dry or wet periods were not significantly cooler than the controls at night. This was contradictory to Haselbach and colleagues and Stempihar and colleagues findings[8, 22]. But consistent with the research that shows porous pavement must hold moisture in the pavement to provide cooling benefits [20]. In our Chicago alleys, the porous pavement that helps lessen stormwater problems does not appear to offer the UHI mitigation co-benefit. CDOT's porous pavement design aims to infiltrate stormwater quickly and does not aim to store water in the pavement voids. Asaeda and Ca found that to reduce pavement temperatures, porous pavement must be constructed with voids designed to store water in the surface course[20]. Specifically they found that the porous material needed to include both small and large voids to provide sufficient capillary pressure to store water in the surface course of the pavement. They found this resulted in more moisture available to cool the pavement material compared to other quick draining porous materials. Thus, maximizing porous pavement stormwater reduction goals of infiltrating water quickly may conflict with using porous pavement to reduce urban air temperatures. While lessening the UHI in urban and suburban environments is an important design goal, these findings illustrate that UHI cool pavement mitigation strategies may require more contextual understanding of the tradeoffs. Unfortunately, finding a simple method may not be sufficient to evaluate one element (pavement) out of many contributing urban factors (walls, roofs, and anthropogenic sources). Yet, city officials still need pragmatic tools to measure progress toward cooling goals. Future research should look to supplemental techniques to evaluate cool pavements in these types of environments.

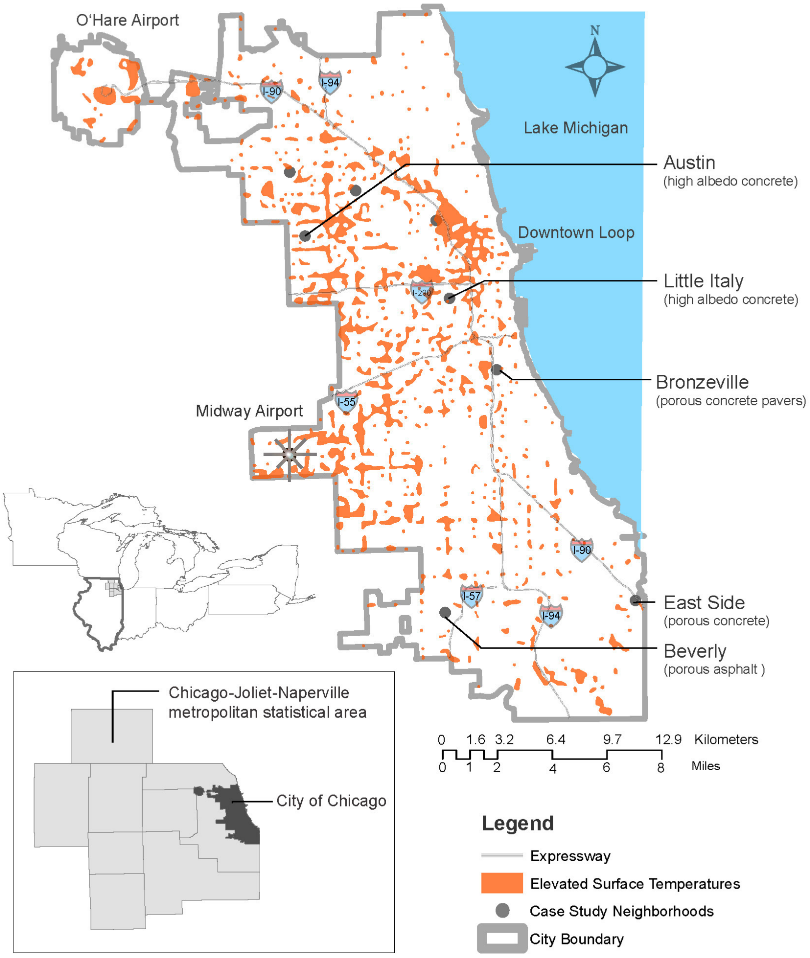
Appendix A. CDOT cool pavement properties

Structural properties of the four cool pavement systems in CDOT’s Green Alley Program

Pavement Type	Surface course thickness	Subbase thickness	Porosity
High albedo concrete	20.3 cm (8”)	30.5 cm (12”)	Porosity unknown
Porous asphalt	min. 9.525 cm (min. 3.75”)	30.5 cm (12”)	25%
Porous concrete	20.3 cm (8”)	30.5 cm (12”)	20%
Porous modular pavers	26 cm x 26 cm x 8 cm (10.2” x 10.2” x 3.2”)	30.5 cm (12”)	Porosity unknown, impervious pavers spaced 12 mm, filled with 0.6 cm open-graded aggregate

* Table information from [28]

Appendix B. Five study neighborhoods



Map illustrating the city of Chicago limits, the five study neighborhoods including the green alley treatment in each case alley, and the heterogeneous distribution of elevated surface temperatures from a City of Chicago Department of the Environment 2006 study.
Data sources:
City of Chicago map – from the City of Chicago Department of Environment GIS database, accessed February 1, 2010
Chicago-Joliet-Naperville metropolitan statistical area map – from the U.S. Department of Commerce, U.S. Census Bureau, Geography Division, 2010 Census Metropolitan Statistical Area/Micropolitan Statistical Area (CBSA), accessed February 9, 2014 from http://crystal.isgs.uiuc.edu/nsdihome/
Great Lakes region map – from the from the North American Transportation Atlas Data - 1998, prepared by the U.S. Department of Transportation, Bureau of Transportation Statistics, accessed February 9, 2014 from http://www.glin.net/gis/data/refdata.html
Illustration: by authors

Appendix C. Descriptive statistics

Descriptive statistics of case and control block land cover, variables used in the analysis for five Chicago neighborhoods in summer 2010

Pavement Type/ Neighborhood	Alley	Orientation	Canyon aspect ratio[a]	SVF[b]	% tree canopy	Block area[c]	Impervious surface area[b]	Land cover of each block[b]		% roof, pavement, and alley cover of each block area[b]		
						m^2	m^2	% impervious*	% tree canopy	% roof cover	% pave**	% alley pave
High albedo concrete/	Case	East-West	1.29	0.44	21.7	19,725	17,455	88.5	21.7	38.4	50	4.4
Little Italy	Control	East-West	1.07	0.49	29.4	20,604	19,436	94.3	29.4	39.1	55.2	4.3
High albedo concrete/	Case	East-West	0.68	0.60	18.5	19,968	16,779	84	18.5	33.2	50.9	4.6
Austin	Control	East-West	0.65	0.70	19.7	19,794	14,873	75.1	19.7	28.2	46.9	4.2
Porous asphalt/	Case	East-West	0.67	0.51	54.6	23,018	12,574	54.6	54.6	20.9	33.7	4.1
Beverly	Control	East-West	0.67	0.51	60.4	22,678	12,391	54.6	60.4	22.9	31.8	4.6
Porous concrete/	Case	North-South	0.79	0.63	19.4	18,816	14,198	75.5	19.4	30.2	45.2	3.8
East Side	Control	North-South	0.75	0.69	23.1	19,468	14,325	73.6	23.1	31.9	41.7	3.8
Porous concrete pavers/	Case	North-South	1.26	0.46	2.0	5,254	4,240	80.7	2.0	33.4	47.2	6.9
Bronzeville	Control	North-South	0.67	0.65	18.5	40,162	32,086	79.9	18.5	21.8	58.1	4.4
Average	All blocks		0.85	0.57	26.7	21,505	17,159	80.4	21.2	32.6	47.7	5

* % impervious includes roof and pavement covers

** % pavement includes alley, sidewalks, and street pavement

[a] Calculated using site visits, orthoimagery, and Chicago Zoning Code Summary of standard building heights.

[b] Calculated using a Solmetric SunEye

[c] Calculated using USGS orthoimagery image from April 2010.

Appendix D. Average alley pavement albedo

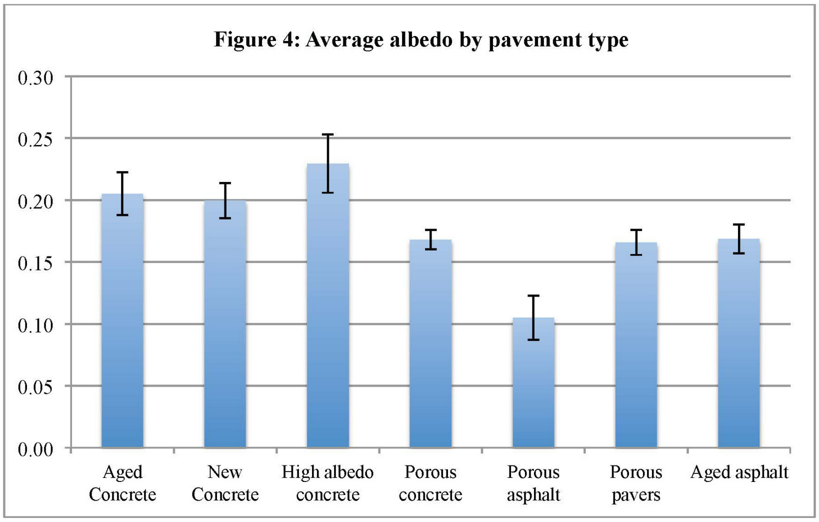
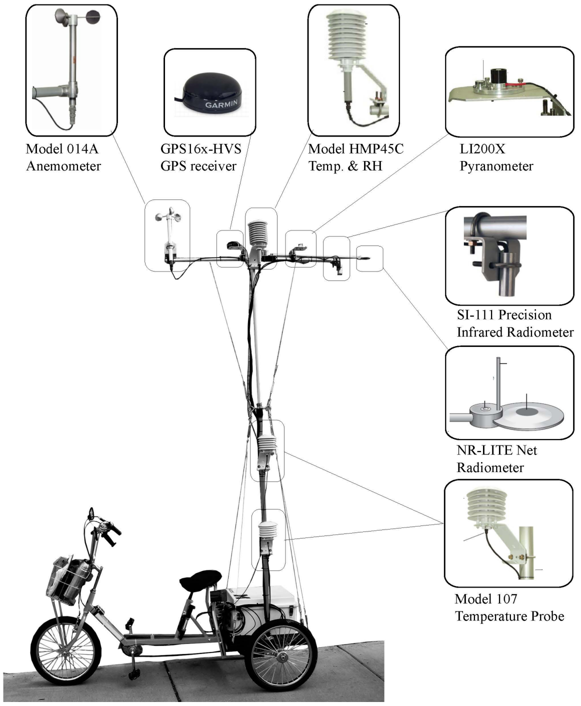


Figure 4: Average albedo by pavement type

Appendix E. Weather tricycle



Custom designed mobile weather tricycle with equipment.
Photograph and Illustration: by authors
Equipment Images: Campbell Scientific, 2012

Appendix F. Mobile weather collection sites

The location of mobile weather data collection along a north-south alley.
For east-west alleys, location #1 was on west end of case and control alleys with #5 on east end of alleys. Not to scale, for illustration only.
Source: Bing Maps
Illustration: by authors

Appendix G. Hobo weather stations located in high albedo-asphalt pairs

HOBO weather station location (*) and urban conditions in Little Italy (high albedo concrete case), Austin (high albedo concrete case), and Beverly (porous asphalt case) all east-west alleys. The north-south alleys included East Side (porous concrete case) and Bronzeville (porous pavers case). All control alleys are impervious asphalt. Not to scale, for illustration only.
Images and Illustration: by authors

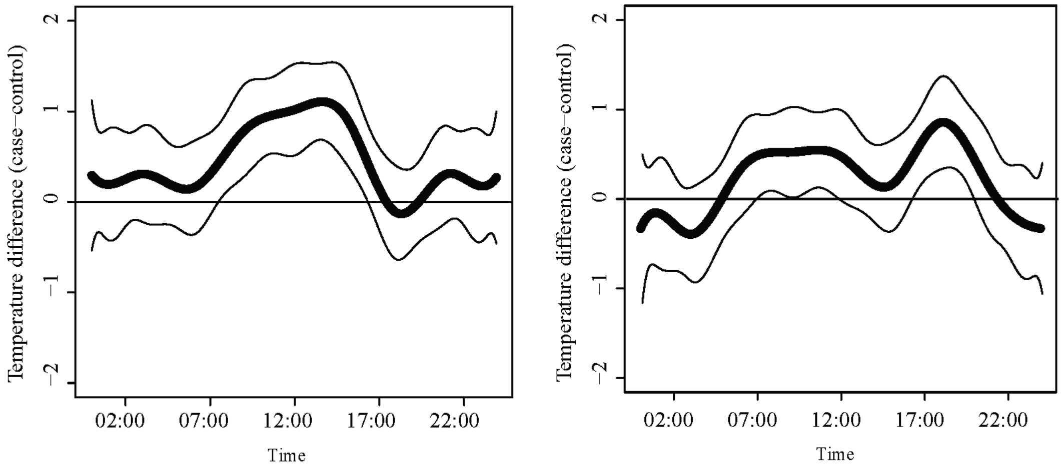
Appendix H. Bivariate analysis

Bivariate analysis of air temperature on pavement temperature at three meters with wind speeds from weather tricycle

Wind speed	*m/s*		*B*	*SE*	*Beta*
Lowest wind speeds 25% percentile	< 1.21	Pavement temperature	0.46***	0.04	0.87
		(Constant)	13.80***	1.07	
		n= 57			
		Adjusted R2 = 0.76***			
50% percentile of wind speeds	1.21 to 1.54	Pavement temperature	0.38***	0.04	0.79
		(Constant)	15.67***	1.39	
		n= 58			
		Adjusted R2 = 0.618***			
75% percentile of wind speeds	1.55 to 2.12	Pavement temperature	0.26***	0.04	0.67
		(Constant)	20.16***	1.44	
		n= 58			
		Adjusted R2 = 0.44***			
All wind speeds 100% percentile	2.13 to 5.39	Pavement temperature	0.29***	0.04	0.71
		(Constant)	19.41***	1.43	
		n = 57			
		Adjusted R2 = 0.50***			

*p < .05. **p < .01. ***p < .005 (one-tailed tests).

Appendix I. High albedo-asphalt pair average air temperature differences

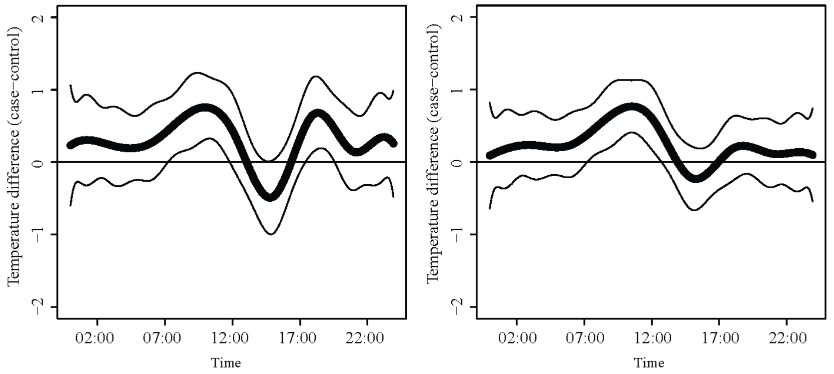


Little Italy: high albedo concrete - clear

Austin: high albedo concrete - clear

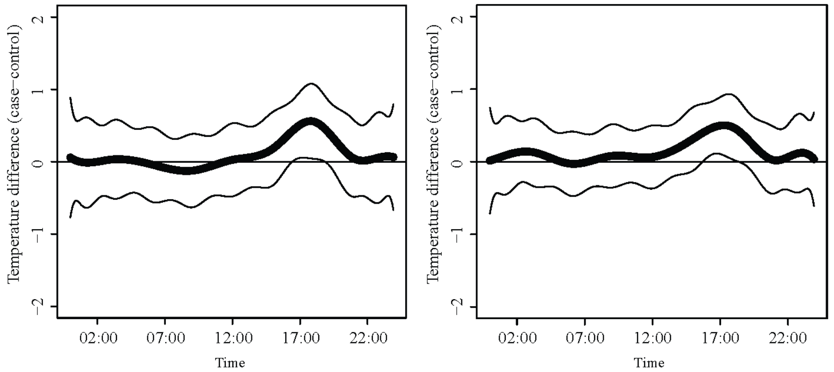
Average air temperature differences with 95% confidence bands for Little Italy and Austin case-control pairs during a four-day clear period (July 1 – July 4, 2010).

Appendix J. Porous-asphalt pair average air temperature differences



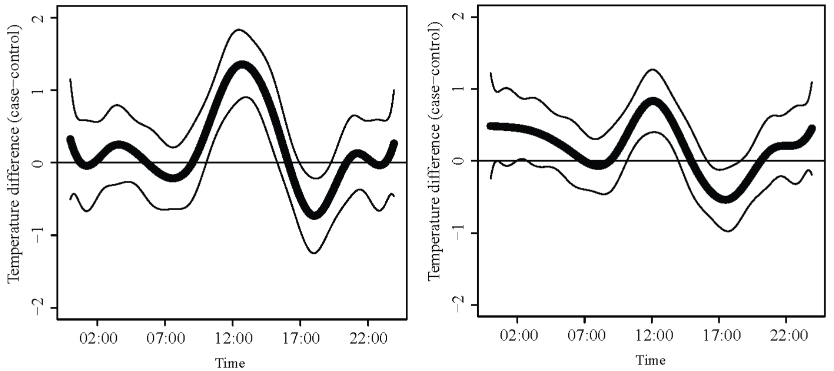
Beverly: porous asphalt – clear

Beverly: porous asphalt – rain



East Side: porous concrete – clear

East Side: porous concrete – rain



Bronzeville: porous concrete pavers – clear

Bronzeville: porous concrete pavers – rain

Average air temperature differences with 95% confidence interval bands for Beverly, East Side, and Bronzeville case-control pairs during a four-day clear (left) period (July 1 – July 4, 2010) and during four-day rainy (right) period (July 11 – July 14, 2010).

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