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Field and Laboratory Assessment of Different Concrete Paving Materials Thermal Behavior

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Abstract: Impervious pavement surfaces within urban areas present serious environmental problems due to waterlogging, flooding and in particular, the urban heat island (UHI) phenomenon. Another issue that has recently been highlighted is user comfort in pedestrian and cycling areas. Materials that have potential for overcoming these issues include pervious concrete (PC), a new type of construction material with improved drainage properties and thermal properties. In this study, the thermal properties and behavior of commonly used concrete paving materials in urban areas (dense concrete (DC) and concrete pavers (P)) and pervious concrete (PC) paving flags were investigated and compared in terms of their thermal properties. Material behavior under different temperature conditions was investigated within laboratory research measuring thermal conductivity (λ) and the capacity for heating and cooling using infrared lamp. Complementary to laboratory tests, field research was conducted analyzing the surrounding conditions on pavement wearing course behavior under real weather conditions. Dense concrete paving material had the highest thermal conductivity coefficient and heat absorption capacity, and slowest heating and cooling speed, compared with the other paving materials. The results also highlighted the similar thermal properties of PC and P but with potentially improved user comfort for PC due to its draining properties. The base layer and surrounding characteristics had a significant influence on the thermal behavior of pavements, and future research should consider these parameters when addressing the UHI effect for different paving materials.

Keywords: pavements; urban heat island; pervious concrete; thermal properties; paving flags

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1. Introduction

The impact of various environmental phenomena and the surrounding buildings on our daily lives and health is becoming an increasingly important topic. Attempts are being made to analyze the extent of the impact of artificially created materials and objects (buildings) on the development of mankind. Reflecting on data that more than 50% of the global population lives in cities and that this proportion will increase to ~66% by 2050 [1], questions arise regarding the consequences of high urbanization and the environment on humanity, and particularly, how to reduce the negative consequences of living in cities.

Urbanization and urban lifestyles greatly influence and change the local climate, and the effects of urban heat islands (UHIs) have been pronounced recently. The term UHI refers to a significantly higher air temperature in an urban environment compared with a rural area, caused by a large number of buildings and roads that retain more heat than parks or water surfaces. The scale of the UHI effect is influenced by several factors, including the site location, i.e., geographic location, wind characteristics, sun radiation and vegetative cover, the degree of modernization, i.e., population, population density and number and type of vehicles, and the urbanization degree, i.e., pavement type and age and height and spacing of buildings. While the site location and the degree of modernization are factors invariably depending on the geographical location and economic development, the urbanization degree set of factors has been investigated to mitigate the influence of UHIs since the 1980s, with an increasing trend in the number of laboratory experiments seeking suitable materials and new techniques [1].

The two most common urban pavement materials are asphalt mixtures and cement concrete, which can be inbuilt as monolithic slabs or as precast pavers. There is a significant difference in the thermal behavior of these materials. Therefore, to adequately address UHI mitigation, understanding the thermal properties and behavior of pavement materials is essential. Heat transfer in pavement structures is accomplished by three common modes, namely, conductivity, radiation and convection. As previously reported [2], the dominant heat transfer mode within the structure is thermal conduction, while on a pavement surface, the dominant modes are radiation and convection. Thus, UHI mitigation associated with the characteristics of pavement materials can be achieved by increasing the pavement surface reflectivity (reducing solar absorption) or by increasing the thermal conductivity (efficiently transferring heat flux toward sublayers) of the surface materials.

The high reflectivity of pavement surfaces is considered to be the most effective method for UHI mitigation by reducing the sensible heat discharge from the pavement surface [3,4]. Although reflective pavement surfaces will mitigate both the daytime and nighttime UHI effect, new findings presented in [5] state that for reducing UHI during the day, it is better to use pavement materials with higher conductivity and thermal storage and vice versa for nighttime UHI effect reduction.

Concrete pavements have a brighter surface color, resulting in a higher solar reflectivity during the daytime, which is an advantage compared with a dark asphalt surface color, particularly just after laying. An increase in asphalt surface reflectivity as a method of UHI mitigation was investigated [6], where reflective coating materials consisting of epoxy glue and different micro-TiO_2, nano-TiO_2 and nano-ZnO fillers were utilized. For concrete pavements, a potential surface reflectiveness increase was achieved by thermochromic coatings with reversible color change ability, which reflected solar energy during summer and absorbed solar energy in winter [7]. However, the main limiting factor of such materials is their high cost [8]. Brighter color can be achieved by replacing fine aggregates with lighter colored glass particles, also resulting in reduced pavement temperature [9].

Pervious concrete pavements, as alternatives to conventional concrete, represent a sustainable paving solution in view of improved surface draining characteristics, recharging groundwater potential, reducing natural aggregate exploitation and potentially reducing the UHI effect in urban environments. The main feature of pervious concrete is its high porosity that results in an excellent drainage ability, but also reduces its strength capacity, thereby imposing the possibility of its application in low traffic pavements as opposed to structural concrete [10–12]. However, its low strength caused by lack of fine aggregate fractions makes it a sustainable solution due to its natural resource depletion reduction. In addition, sustainability is enhanced in energy and natural resource depletion reduction caused by the use of untreated subbase layers within pervious concrete pavement structure, and lower energy and CO_2 emission during its production and construction [13]. Total embodied energy and greenhouse gas emission in pervious concrete pavement with an aggregate base layer can be reduced by up to 3%, compared with Portland cement concrete pavement with similar configuration. However, recent research related to the sustainability of pervious concrete has been related to the possibility of UHI mitigation. The authors of [14] demonstrated a slower increase in surface temperature for pervious concrete compared with Portland cement concrete, with high wind influence on surface temperature reduction. Conversely, the rougher surfaces of pervious concrete pavements caused by their high porosity reflected less solar radiation and produced higher internal and surface temperatures compared with conventional concrete [6,15] in dry conditions. Furthermore, this higher porosity resulted in a decrease in thermal conductivity [16], which does not favor UHI mitigation. Thermal conductivity was improved by replacing crushed limestone aggregate with recycled concrete and coal bottom ash aggregates [17]. Similar or lower surface temperatures were recorded in wet conditions due to evaporation of the water held in pervious concrete surface pores [15]. Results presented in [18] suggested that a higher thermal conductivity of pervious concrete increased the evaporative cooling effect. Evaporative cooling performance of pervious concrete was also achieved by replacing a small quantity of cement by pulverized biochar particles [19]. A more effective method for UHI mitigation and thermal comfort improvement was achieved by sprinkling the pervious concrete surface with water [20]. Rewetting the pervious concrete kept it cooler than convectional concrete [21], suggesting an increase in water consumption to maintain user comfort. Increased need for wetting could be overcome by water-retaining paver blocks which were developed to hold water near the pavement surface in the concrete matrix by water-retentive fillers (blast furnace slags, pervious mortar, bottom ash, peat moss, hydrophilic fiber, and other) [22]. These pavements help improve ambient and human thermal conditions and comfort, and demonstrated significant surface temperature reductions compared with conventional asphalt pavement [23]. Additionally, the results presented in [24] showed that the capillary columns and an internal water storage zone formed by a high-density polyethylene liner in innovative permeable pavement enhanced evaporation and lowered pavement surface temperature compared with conventional permeable pavements. Finally, the combination of highly reflective and pervious pavement surfaces is potentially optimal [25].

While dense and pervious concrete pavements have been widely investigated for their thermophysical characteristics, there are limited data on typical and widely available and used concrete pavers. In [26], the effect of pavement texture and color on thermal performance of concrete pavers was presented. Proper selection of color and texture of pavers provided reductions in surface temperature of up to 5 °C; when considering both paver color and texture, it was shown that the red colored jagged paver could minimize pavement contribution to the UHI effect.

Thermal behavior is investigated within this research, i.e., material behavior and response to different temperature conditions, and prediction of material ability for heat transfer when inbuilt in pavement structure. The objective of the presented research was to compare different concrete paving materials in view of the manner of temperature change influencing the UHI effect. The objective was also to complement results from tests in laboratory (controlled) conditions, with real, field condition research. The aim of this research was to supplement the existing knowledge on the thermal behavior of dense and pervious concrete pavers, with an emphasis on concrete pavers typically used within urban areas. The novelty of this research lies in the analysis of the characteristics of concrete pavers that are marginalized in previous research and in supplementing laboratory research results with real condition field research. Prominent novelty is the emphasis on the need to investigate pavement thermal characteristics and UHI effect through the overall analysis of pavement structure, and not simple analyses of wearing course characteristics.

2. Materials and Methods

2.1. Materials and Sample Preparation

In this research, two types of laboratory-made paving flags were used, namely, dense concrete (DC) and pervious concrete (PC), in addition to one type of market-available concrete paver (P), as presented in Figure 1.

A dolomite aggregate with a density of 2.75 kg/dm^3 separated into fractions of 0–4 and 4–8 mm with percentages of 70% and 30%, respectively, was used for the preparation of the DC mixture. For the preparation of the PC mixture, a 4–8 mm fraction of the dolomite aggregate and a 0–2 mm fraction of river sand with a density of 2.65 kg/dm^3 were used with percentages of 90% and 10%, respectively. The cement used in both types of concrete mixtures was ordinary Portland cement (CEM II/A-M (S-V) 42.5 N) with a density of 3.0 kg/dm^3. The amount of cement in the DC mixture was 400 kg/m^3 and in the PC mixture was 300 kg/m^3. The water/cement ratio was 0.4 in the DC and 0.33 in the PC. Paving flag specimens were prepared with dimensions of 50 × 50 × 5 cm (Figure 1). During installation, both concrete mixtures were compacted with only a masonry trowel. More details on the material characteristics and drainage properties of the PC are presented in [10,12,27].

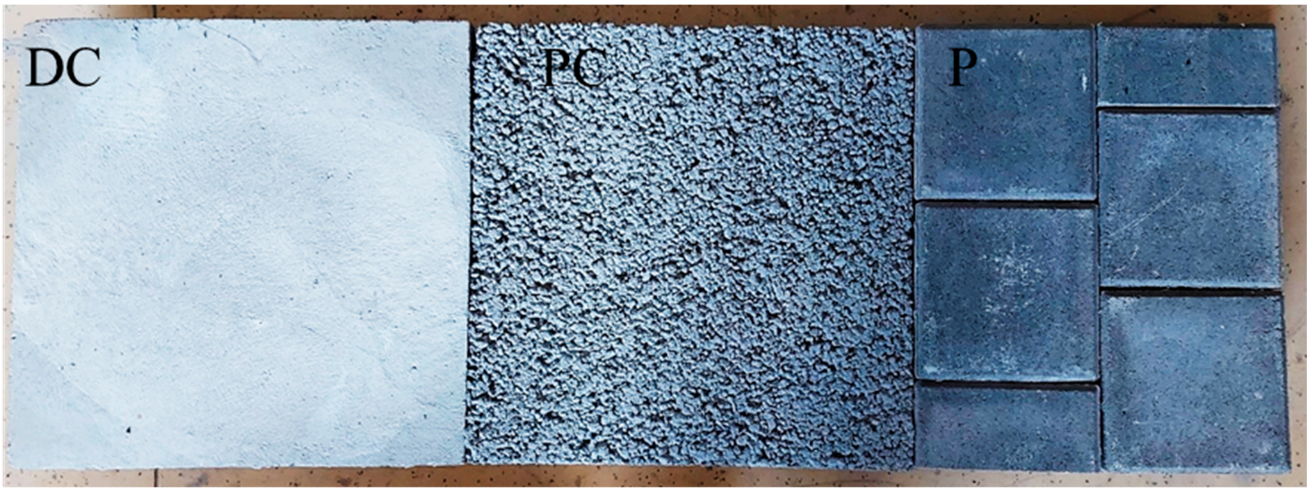


Figure 1. Concrete paving flags and pavers (DC, PC and P).

2.2. Thermal Conductivity Measurements

The thermal conductivity (λ, (W/mK)) of the material used for the paving flags was measured using a FOX 200 heat flow meter. The instrument can work with a maximum sample thickness of 51 mm and sample size of 204 × 204 mm, in a temperature range from −20 °C to 75 °C. Prior to testing, samples were conditioned to constant mass in a ventilated oven at a temperature of 105 °C for 24 h. After conditioning, samples were cooled to room temperature and stored in a sealed polyethylene bag until the testing. Samples were placed between two plates in the test stack and a temperature gradient was established over the thickness of the material. Testing instrument FOX 200 is equipped with thermocouples which were used to improve the measurement accuracy for higher thermal conductivity samples (up to 2.5 W/mK). Measurements were conducted in compliance with ISO 8301:1991 (Thermal insulation—Determination of steady-state thermal resistance and related properties—Heat flow meter apparatus). The AutoThickness function of the instrument was used, where the instrument automatically moves the lower plate after placing the test sample in the test stack, to establish contact with the sample. Three samples of each paving material type from this study were tested during this research. Thermal conductivity was determined as an average value of thermal conductivity of all three tested paving material types.

2.3. Infrared Lamp Testing

The capacity for heating and cooling of the material in time was tested using a 150 W infrared lamp. The lamp was mounted 30 cm above the sample surface. Lamp height was selected according to the light and heat flux dispersion in order to cover nearly the same sample area by lamp-directed radiation. The samples were placed on a concrete base (laboratory floor). The sample surface temperatures were recorded using two Testo 435 instruments with two sets of three thermocouples mounted on opposite sides of the sample (upper and lower surfaces), as shown in Figure 2. Testo Comfort Software was used for data processing, with temperature recorded every minute until the upper surface temperature reached 40 °C. The lamp was then turned off and the temperature drop was recorded until the upper surface temperature reached the starting (ambient) temperature.

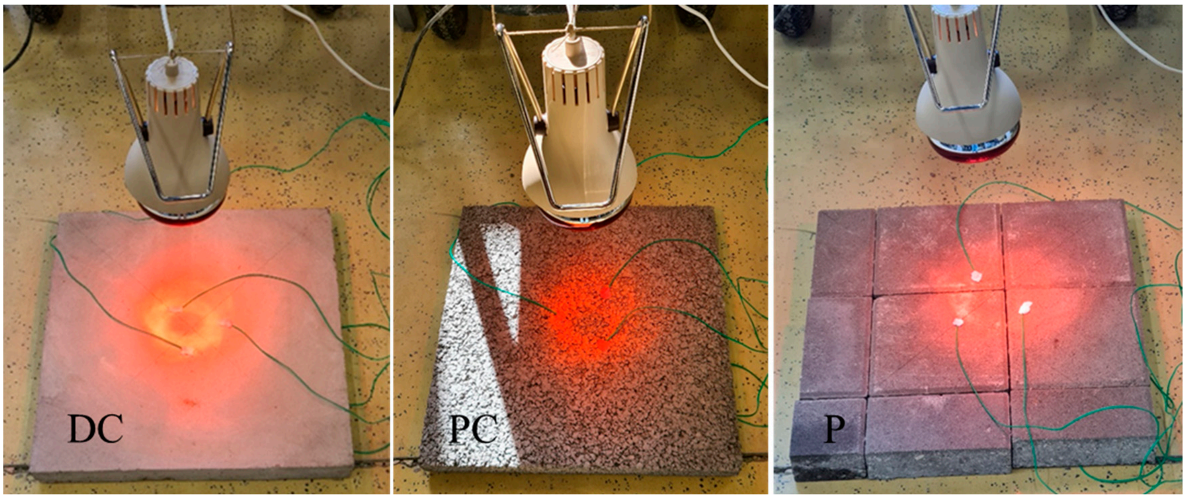


Figure 2. Infrared lamp testing setup for DC, PC and P samples.

2.4. Thermal Camera Recording

To simulate and consider realistic parameters for the thermal property analysis of the concrete wearing course and to validate conclusions made under controlled environmental conditions on material behavior under different temperature influence (thermal behavior), field tests were conducted using infrared thermography (IRT). IRT is one of the most widely employed methods used in thermal building diagnosis and is primarily used to qualitatively evaluate buildings and detect defects. In addition, it is usually used as a nondestructive examination method of concrete pavement service condition assessment for detection of near surface delamination, in a wider spectrum and with an acceptable accuracy, compared with the visual testing method.

In this study, IRT was used to measure the temperature changes of samples and the surrounding terrain (base). A Testo 882 thermal imager was used with the accompanying IRSoft software for image processing. It has a thermal image resolution of 320 × 240 pixels with a thermal sensitivity of less than 50 mK at +30 °C and accuracy of ±2 °C. In the first field test setup (Figure 3a), concrete samples were firstly set on a grass field, and in the second test setup, they were placed on a concrete surface. The second field test with a concrete base was used to compare the influence of base characteristics on wearing course thermal characteristics, and to compare the P and PC specimen characteristics with old (darker) and dense concrete surfaces. The sample surface temperature together with air temperature were measured every 1 h for a 24 h period with a Testo 435-4 instrument. The measurements were conducted on a sunny day and at night during the summer period (July). Meteo data at test locations are presented in Table 1.

(**a**)

(**b**)

Figure 3. Field measurements: (**a**) grass setup; (**b**) concrete setup.

Table 1. Meteo data on test sites.

	Time	Wind Direction	Wind [m/s]	Air Temperature [°C]	Relative Humidity [%]		Time	Wind Direction	Wind [m/s]	Air Temperature [°C]	Relative Humidity [%]
CONCRETE SETUP	5:30	NE	1	24.4	87	GRASS SETUP	6:00	SW	1.8	21.8	90.2
	6:30	NE	1	24.6	85		7:00	SW	1.3	26.6	70.8
	7:30	E	2.2	23.8	85		8:00	NE	0.6	33	57.3
	8:30	NW	3.8	22.8	87.5		9:00	S	1.3	36.7	39.2
	9:30	NW	3.1	22.6	88.6		10:00	S	2.4	40.2	41
	10:30	NW	4.4	23.6	82.1		11:00	SW	2.3	40.8	33.8
	11:30	NW	2	22.3	82.3		12:00	SW	4.1	42.7	29
	12:30	NW	6.2	30.8	67.5		13:00	W	3.7	41.3	28.4
	13:30	NW	6.3	29.8	64.2		14:00	W	3.2	40.8	32.8
	14:30	NW	1.3	39	40		15:00	W	3.1	39.8	40.2
	15:30	E	2.8	40	42		16:00	NW	2	39.4	35.2
	16:30	NE	2.9	40.2	41		17:00	NW	1.4	34.9	41.6
	17:30	NE	3.1	39	42		18:00	NW	1.2	32.6	50.6
	18:30	NE	2.8	31	55		19:00	NE	1.2	30.4	56.5
	19:30	E	6.2	26	75		20:00	N	0.8	27.7	65.3
	20:30	N	1.5	26	72		21:00	NE	1.7	27	72.6
	21:30	NW	0.9	24.3	73		22:00	NW	1.3	25.6	81.3
	22:30	NW	1.8	23.1	80		0:00	E	0.5	23.9	86.7

3. Results and Discussion

3.1. Thermal Properties of Concrete Paving Materials

The results of the thermal conductivity measurements, as the ability of a material to conduct heat, are presented in Figure 4 as an average value of three of the sample measurement values with result variations of less than 10%. The DC had the highest thermal conductivity while the PC presented the lowest value due to its high porosity, which was in line with other literature data [15]. Pervious concrete had 42% and 28% lower thermal conductivity compared with dense concrete and concrete pavers, respectively. It is interesting to note that concrete pavers (P) had nearly 20% lower thermal conductivity compared with dense concrete, which is a significant value given their wide applicability. Finally, the highest (more effective) heat flux was obtained through the DC paving flag, while the lowest was obtained through the PC paving flag. Unlike insulating materials, for which low conductivity is preferable, for paving materials, lower thermal conductivity results in decreased heat transfer to the lower layers and soil [28], and the accumulation of heat at the pavement surface, causing thermal discomfort and contributes to the UHI effect.

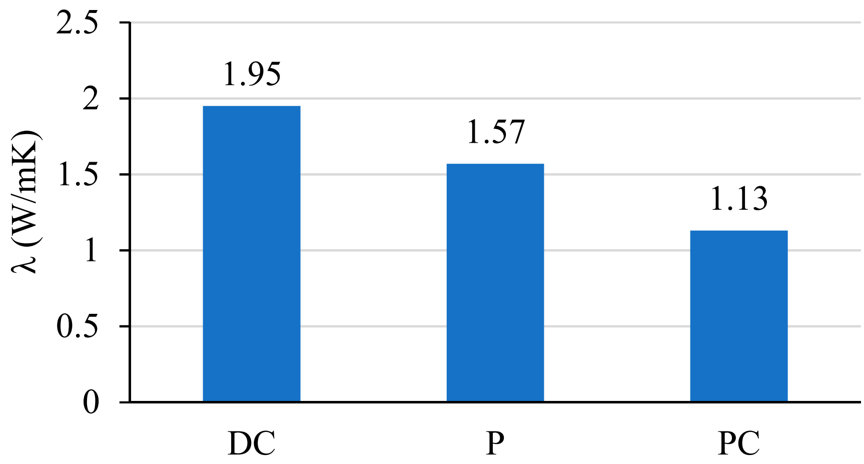


Figure 4. Thermal conductivity results.

3.2. Heating and Cooling Speed Measurement Results

The thermal behavior of the three different concrete paving materials is presented in Figures 5–7. As presented in Figure 5, there is a significant difference in the thermal behavior between DC, P and PC. The infrared lamp testing showed the highest heating and cooling speed for the PC, and the lowest for the ordinary DC. One explanation of these results can be observed in Figure 1 showing a pronounced difference in color and surface texture of the different paving materials. The light, smooth surface of the DC sample resulted in the lowest heating speed due to its high reflectiveness. Its dense structure contributed to significant heat accumulation, and it took significantly longer to release all the accumulated heat. In contrast, the rough and darker color of the PC sample resulted in the highest heating speed. However, its porous structure prevented heat accumulation within the material itself (it possessed less head storage capacity compared with ordinary DC [29]), and soon after removing the source of heat (turning off the lamp), the sample rapidly cooled to room temperature. Additionally, PC had the lowest λ value, which indicated lowest heat transfer from surface to subbase (in this case concrete floor), leaving more heat accumulated on the sample top surface but not in its internal structure. Although the PC had the highest heating speed, its high cooling speed could result in improved thermal comfort during the evenings and nights.

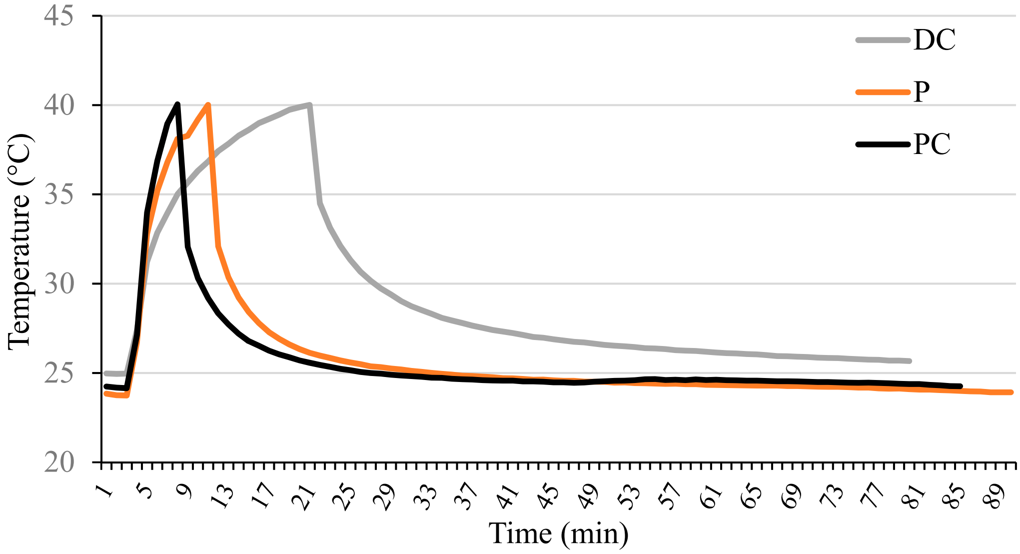
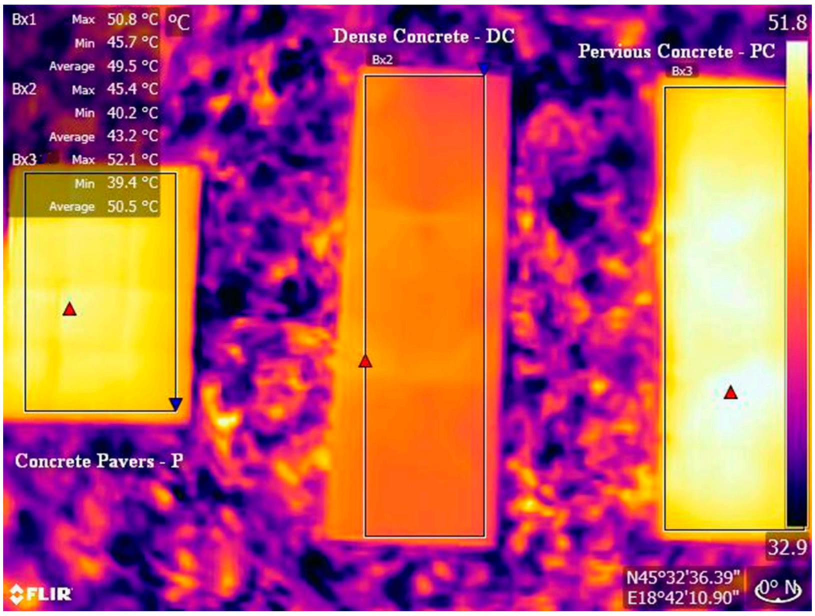
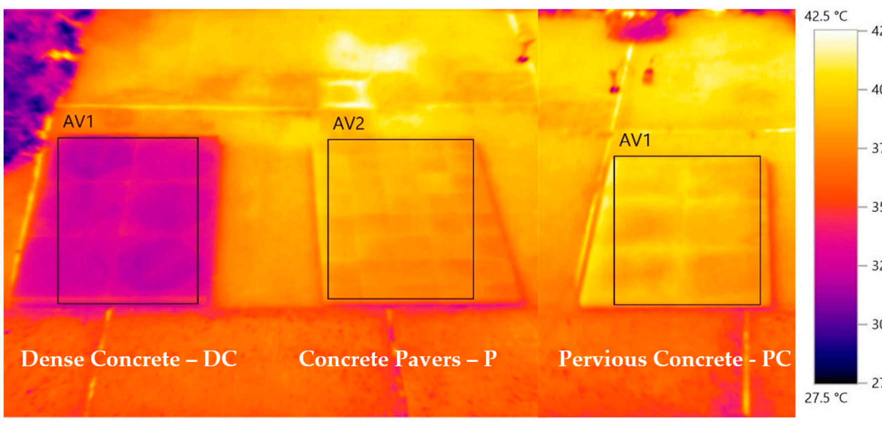


Figure 5. Surface temperature of samples under exposure to infrared lamp.



(**a**)



(**b**)

Figure 6. IRT results: (**a**) DC and P on concrete site; (**b**) PC and DC on grass site.

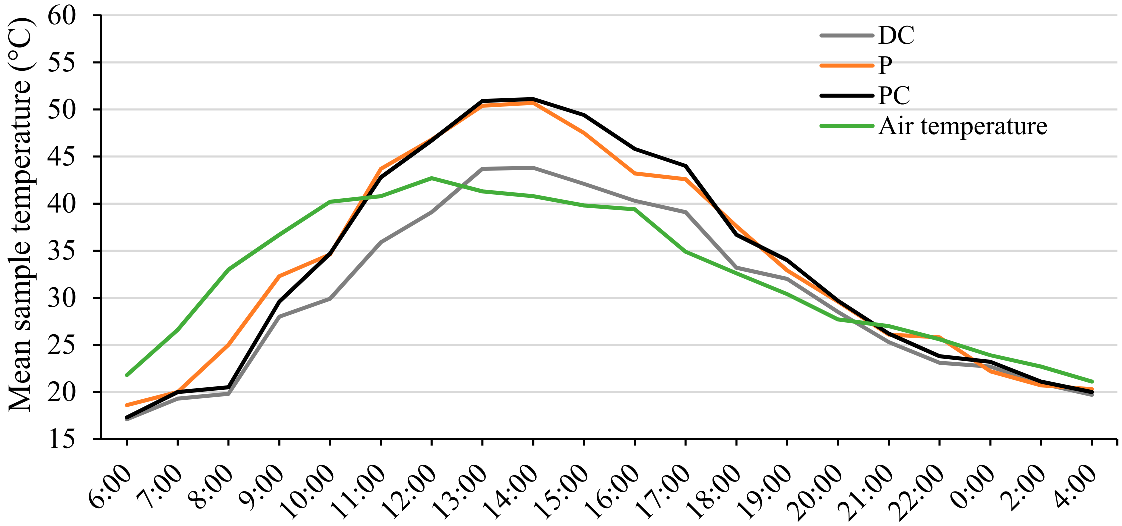


Figure 7. Concrete pavement surface temperature change on grass base.

The highest temperatures on the bottom sample surfaces for DC, P and PC were 32.14, 28.72 and 27.94 °C after 4, 7 and 10 min of turning off the infrared lamp, respectively. This meant that the highest rate of heat transfer from the heat source on the sample top surface, to the bottom surface, was obtained for the DC, while the lowest was for the PC. This was also in accordance with the results of the thermal conductivity measurements presented in Figure 3. The DC transferred more heat to the lower pavement layers, and that heat transfer occurred during a long period. The thermal conductivity of PC was 30% lower than P (Figure 3) causing 30% faster lower sample surface heating (10 min for PC compared with 7 min for P). Generally, the PC and P show similar thermal behavior (surface heating and cooling) under a controlled test regime, considering only material thermal properties. Again, very similar behavior is shown for P and PC, presenting PC to be a comparable paving material for urban areas.

3.3. Field Measurement Results

The results of the field measurements are presented in Figures 7 and 8 as a result of the applied IRT method represented by Figure 6 for one of the intervals when IRT was used. As presented in Figures 7 and 8, the highest surface temperature was recorded for PC, and lowest for DC, regardless of the test setup. This was in accordance with conducted laboratory tests, i.e., measured thermal conductivity, and heating and cooling speed, which have been discussed in previous sections.

For the grass base and surrounding surface test setup (Figure 3a), the shift in maximum temperature compared with the air temperature was for 2 h and for the concrete base and surrounding surface was for 1 h. The grass setup exhibited slower pavement surface heating compared with the concrete setup. Therefore, the pavement surrounding and base had a significant influence on the UHI effect. Figure 6 presents the infrared thermography results of the PC, DC and P on the grass and concrete sites. The minimal and maximal temperatures were observed in the selected fields on thermograms under the same weather conditions and time (air temperature of 39 °C, relative humidity of 40%, CO_2 concentration of 293 ppm and atmospheric pressure of 999 hPa at 2:00 PM) and the results are presented in Table 2. The presented results show how the type of base, grass or concrete had the highest impact on a DC sample and the lowest on a P sample. The results are presented graphically in Figures 7 and 8 with the mean sample temperatures over time for all three samples, and air temperature. The mean grass base temperature at that moment was 37.23 °C, while on a concrete base, it was 25% higher at 49.70 °C.

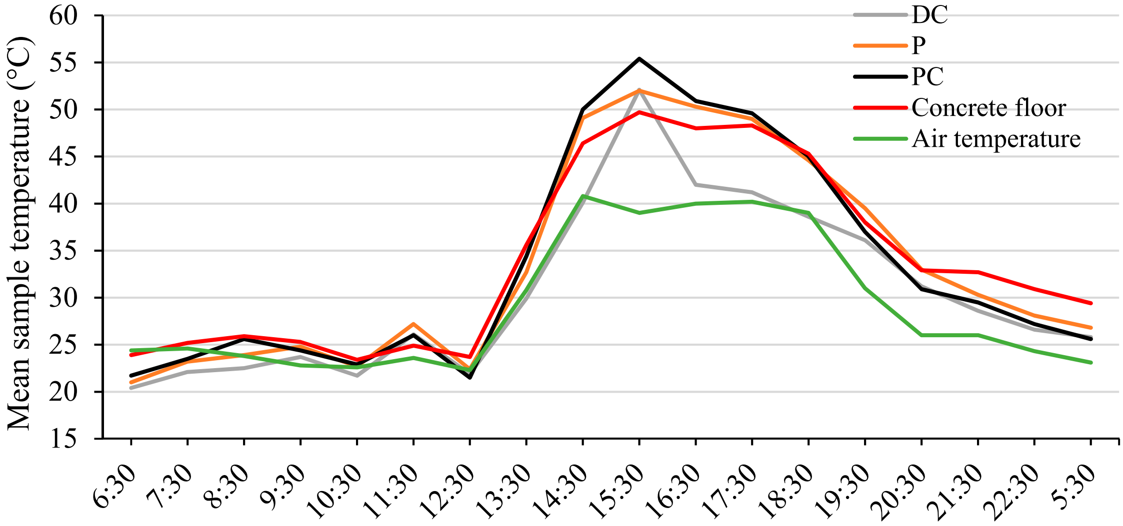


Figure 8. Concrete pavement surface temperature change on concrete base.

Table 2. Average surface temperatures of samples on grass and concrete bases.

Average Surface Temperature of Sample (°C)/Base	DC	P	PC
Grass	43.90	50.70	51.10
Concrete	52.00	52.10	55.40
Temperature difference (°C)	8.10	1.40	4.30

For the grass setup, the maximum measured temperatures for the DC, P and PC were 43.9, 50.7 and 51.1 °C, respectively, giving a maximum surface temperature difference between the samples of 7.2 °C. For the concrete setup, the maximum measured temperatures for the DC, P and PC were 52.1, 52.0 and 55.4 °C, respectively, giving a maximum surface temperature difference between the samples of only 3.5 °C. It was observed that difference in pavement maximum surface temperature was also highly influenced by its base and surroundings, with a significantly higher temperature reached for the concrete setup. The highest difference in the temperature surface due to a different field test setup was recorded for the PC samples. On the grass setup, hot air could easily transfer from the sample surface to the lower layers, while on the concrete base, hot air was "trapped" in the PC pores, resulting in a significantly higher surface temperature.

Generally, as presented in Figures 7 and 8, the temperature trends among different concrete paving materials were very similar. The large difference between the temperature movement of the new DC paving flag and the old existing concrete floor could be explained by the high color difference (Figure 3). Furthermore, the high similarity of the surface temperature trends among the P and PC samples was noted, particularly on the grass setup, where heat could easily transfer to the lower layers. This was an interesting and significant result since it highlighted the PC paving flag as a valuable alternative to standard concrete pavers. By paving pedestrian or cycling areas with PC flags, similar thermal characteristics can be achieved as when standard concrete pavers are used, but a more comfortable area can be built due to better drainage property and faster surface cooling during evenings.

For the grass setup, soon after sunset (20:19 h), the surface temperature of the samples fell below the air temperature. For the concrete setup, nearly 2 h passed after sunset (20:37 h) before the sample surface temperature fell below the air temperature. For the old concrete floor, the surface temperature did not even fall below the air temperature during the measurement.

The correlation between the pavement surface temperature and air temperature 20 cm from the ground on site is presented in Figure 9a,b for the grass and concrete setups, respectively. A strong linear correlation was observed for all concrete pavement types.

Again, high similarity was observed for the P and PC pavements, in accordance with the other presented results. The lowest linear slope coefficients (1.032 and 1.095) were found for the DC, and highest were found for the PC (1.385 and 1.513). Correspondingly, the heating and cooling speed measured by the infrared lamp (Figure 5) presents a linear slope coefficient that describes the material thermal behavior, i.e., low heating speed for DC and high heating speed for the P and PC pavement materials.

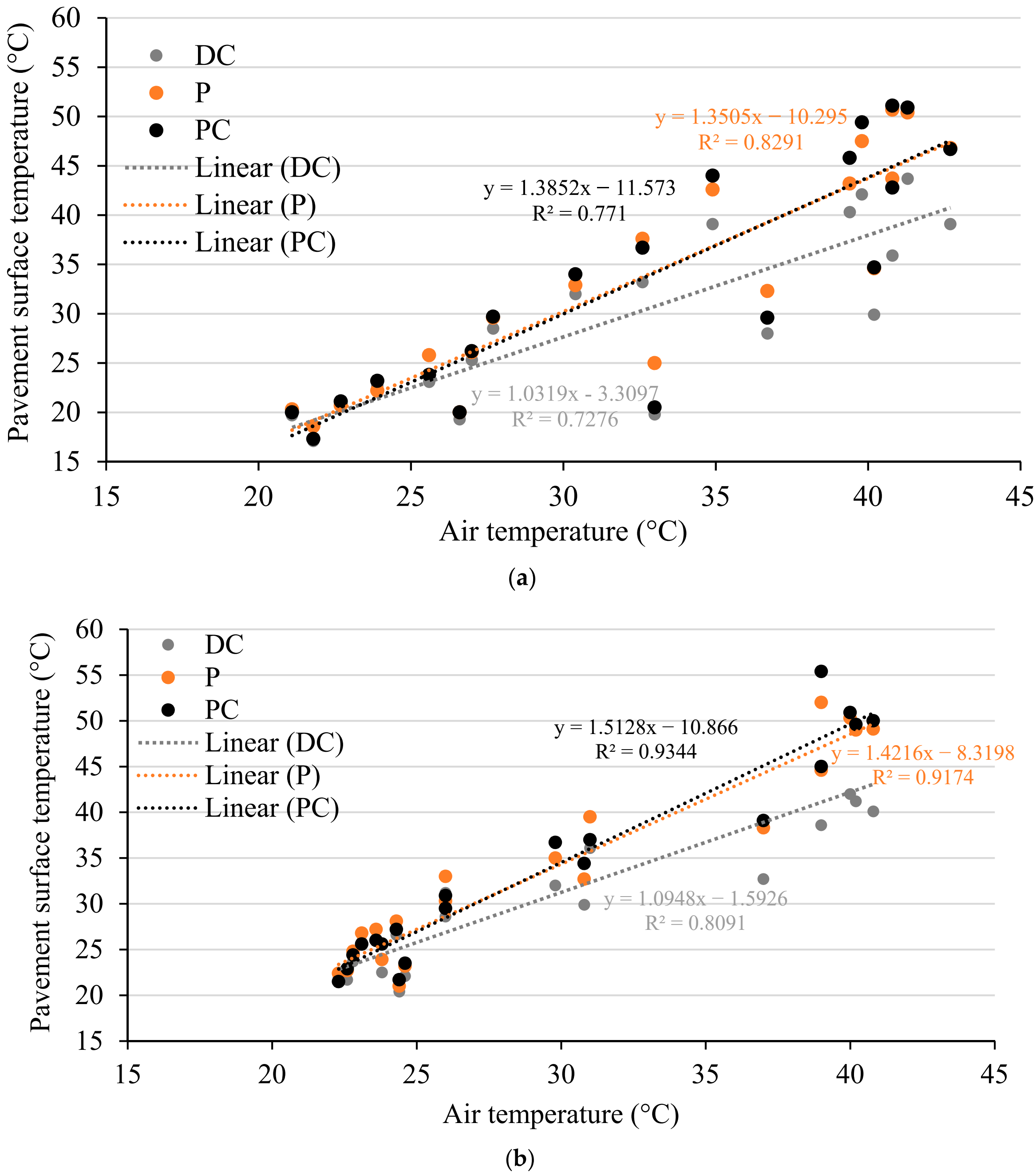


Figure 9. Air temperature to sample surface temperature correlation for (**a**) grass and (**b**) concrete setups.

4. Conclusions

In this study, three types of concrete paving materials were researched, namely, ordinary, dense concrete paving flags, concrete pavers and pervious concrete paving flags, with the aim of comparing their thermal properties and behavior. For UHI mitigation, proper paving material selection could be essential in contributing to user comfort improvement. According to all the presented research results, the following conclusions can be made:

- There is a significant difference in the thermal properties, and behavior between different concrete paving materials and proper material selection could be essential for proper UHI mitigation;
- The dense concrete paving material had the highest thermal conductivity coefficient, highest heat absorption capacity, and slowest heating and cooling speed, compared with the other paving materials;
- The thermal characteristics and behavior of the pavers and pervious concrete were similar, therefore, the pervious concrete, due to its improved drainage properties, could present a better solution for urban areas;
- There was a significant influence on the base layer and the surrounding characteristics on the pavement thermal behavior. Therefore, future laboratory and field tests should consider these parameters when addressing the UHI effect of different materials;
- A good correlation was observed between the results of thermal conductivity measurement and the results of thermal properties measurements conducted in the field. Therefore, thermal conductivity measurement as a simple laboratory method can be used for prediction of thermal behavior of paving materials in real conditions.

Finally, the added value of this research lies in its contribution to construction practice, showing the competitiveness of pervious concrete pavers with commonly used concrete pavers. The behavior in the view of UHI influence of these two materials is very similar, but the comfort of the user is increased by providing a dry pavement surface for pedestrians and cyclists, as the main users. This can help decision makers (engineers and architects) when choosing proper pavement material, depending on its purpose and expected characteristics.

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