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Comparative Analysis of Heat Island Effect: Traditional versus Pervious Concrete

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Abstract

The urban heat island (UHI) effect is a very significant environmental consideration associated with urbanization and has detrimental impacts on local temperature. One effective mitigation strategy is the use of pervious concrete pavement that has a potential to mitigate the UHI effect compared to traditional concrete pavement. The primary objective of this research is to conduct an experimental work comparing the heat stored effect observed in traditional concrete and various types of pervious concrete pavements based on percentage of fine aggregate and differences in permeability and strength. The investigation is found that pervious concrete pavements stored less heat than traditional concrete pavement. When more fine aggregate is added to pervious concrete, it can hold more heat and increase its compressive strength and decrease its permeability. The research suggest that the adoption of pervious concrete pavement can help to mitigate the urban heat island effect by storing less heat energy compared to traditional concrete pavement.

Keywords: urban heat island effect; pervious and traditional concrete pavement; permeability, compressive strength

1. Introduction

One important issue of urbanization is the urban heat island (UHI) effect is noticeably observed in cities rather than in countryside (Synnefa et. al 2011, Nakayama and Fujitu 2010, Santamouris- 2015) and wide variation on temperature difference (2~15^{0}C) was observed by numerous researchers in different cities (Sen et. al. 2019; Wijieyesekera et. al. 2012; Gorsevski et al 1998, Santamouris 2013). The UHI effect is primarily caused by the modification of land surfaces through the construction of impervious structures, including roads, buildings, and traditional concrete pavements(Siti Halipah Ibrahim1, 2018). A study conducted by Akbaria and Rose (2008) in USA and found about 60% urban land was covered by manmade heat absorbent surface. Traditional concrete pavements, commonly used in urban areas, aggravate the UHI effect due to their high bulk mass,heat absorption capacities and low porosity (Haselbach et. al. 2011, Shuster et. al. 2005). These pavements absorb and retain heat from solar radiation, leading to increased ambient air temperatures. As a result, urban areas with extensive concrete pavements become "heat islands," experiencing elevated temperatures compared to their rural surroundings. One avenue of exploration involves investigating alternative pavement materials, such as pervious concrete pavement, as potential mitigation strategies.

This Pervious concrete also provides a hardscape similar to those of traditional impermeable concrete or asphalt pavements, but also consists of a network of interconnected macro-pores that readily allow water exfiltration to the subbase and provide some water storage for further evaporation or infiltration and partially protect the pavement system and soil from heat increment due to its low reflectivity (Alexandre Lorenzi , 2015).

The primary objective of this study is to compare the heat island effect of three different pervious pavement with traditional concrete pavements through an assessment of their layer temperature, layer thickness, porosity and volumetric heat capacities. The objective of this comparative analysis is to assess the efficacy of different types of pervious concrete pavements, which vary in permeability and strength, by examining the percentage of fine aggregate composition in mixing, in their ability to mitigate the heat island effect as compared to traditional impervious concrete pavements.

2. Materials and Methodology

Ordinary Portland Cement (OPC) was used as Cementitius material for all sample encompassing both pervious and traditional concrete. Uniformly graded coarse aggregates and coarser fine aggregates were used in various percentage for making traditional concrete sample (CS) and pervious concrete (PC) one. Coarse aggregate (19mm passing and 9.5mm retained), fine aggregate (4.74mm passing and 1.18mm retained) and OPC were assessed. For all concrete types, the material properties and compositions are remained consistent, differing only in mixing proportions. The material proportions and workability (slump test) were presented in Table 1. Sub-grade soil at the place of sample placement had a CBR value of 5%. Fine aggregate has a unit weight of 1631 kg/m³, specific gravity of 2.62, and FM value of 2.4. Coarse aggregate has 1457 kg/m³ of unit weight, 2.62 specific gravity, and 0.82 water absorption. Cement possessed a fineness of 2270 cm²/gm and normal consistency of 27.32.

Table 1: Mix ratio and slum of concrete

Concrete Type	W/C	C:FA:CA	Slum (mm)
CS	0.5	1:2.5:3.0	86
PC-1	0.3	1:0.16:3.16	18
PC-2	0.3	1:0.33:2.97	16.5
PC-3	0.3	1:0.49:2.80	15

2.1 Site Description: Four sample pavement concrete were constructed beside KUET Civil Engineering building where the Sun light is available almost full day, one is for reference sample casted as normal cement concrete (CS) and other three are pervious concrete (PC) where amount of fine aggregates are changed to achieved its different level of perviousness. Existing top soils were dug up to 170mm and a hole was formed beneath the excavation base to insert temperature sensors at 295mm and 420mm depth from the existing soil surface, shown in Figure 1 and Figure 2. The hole was filled properly with soil after the sensors had been inserted. After that, base materials (mixed with CA and FA in a 2:1 ratio) were used to fill up the dug area to form a real sense in general road construction. This base material consist CA and FA with a mixing ratio 2:1. A sensor was also inserted into the mid-level of this base to find out the temperature. Size of pavement slab samples were 60x60 cm in plan and 15 cm thick, over the base, a temperature sensor was inserted at the mid-level of the slab. A 2m horizontal gap was kept between adjacent pavements to provide temperature independence and prevent moisture interaction. To protect the pavement sides from the thermal effects of nearby soil, a greater base size was used. All pavements were built using this standard construction method (please see the figure 1). Pervious Concrete-1 (PC-1) with 10% fine aggregate, Pervious Concrete-2 (PC-2) with 15% fine aggregate, Pervious Concrete-3 (PC-3) with 20% fine aggregate, and Concrete sample (CS) were the four concrete types that were categorized. To measure the temperature of pavement, DS18B20 sensors were used. Its temperatures ranging from -55°C to +125°C with ±0.5°C accuracy.

Figure 1: Construction and sensor inserting

Total 5 number of sensors were inserted of a single pavement. And it should take the temperature such a depth of sub-grade where temperature difference among of all the pavements within 1 degree Celsius. Observation shows that at a depth of 60cm from the surface of the pavements, the temperature difference among the pavements were less than 1 degree Celsius.

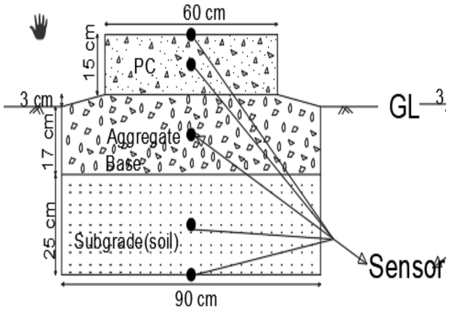

Figure 2: Cross section of PC

Figure 3: Temp. measuring

Typical cross section of different layers of pavement and the positions of sensors into each layer are shown in Figure 2. And these layer temperatures were captured in a computer shown in Figure 3.To obtain total heat stored by a pavement system it needed to calculate how much heat energy stored in different layer. This measurement was done on every one hour interval and using the following equation for calculation.

$$\Delta E_{\text{pcpc}} = C_{v(\text{slab})} * \Delta T_{(\text{slab})} * h_{(\text{slab})} + C_{v(\text{agg Base})} * \Delta T_{(\text{agg.base})} * T_{(\text{agg.base})} + C_{v(\text{soil})} * \Delta T_{(\text{soil})} * h_{(\text{soil})}$$

Where

ΔE =amount of energy stored per hour per unit area for pavement system(J/h-cm^2),
C_v=volumetric heat capacity for layer(J/cm^3-^{0C}),
ΔT =change in temperature per hour at specified thermocouple depths(^{0}C/h), and
h =height of layer (cm).

Here the porosity of CS pavement assumed 0% and the porosities of PC pavements were determined with respect CS pavement according to the following formula by siti et al (2018).

$C_{v(PCPC)}=C_{v(CS)}*(100-N_i)$

Where, $C_{v(PC)} =$ volumetric heat capacity(J/cm^3-^{0}C) of PC

$C_{v(CS)} =$ volumetric heat capacity(J/cm^3-^{0}C) of CS

N=% of voids of PC.

The first hour (7am-8am) in a daily cycle refers to the energy stored from the change in temperature from 7am to 8am, and each hour was calculated similarly up to hour 24 which was done by Kevern et al, 2012. Here, 3 layers were considered for heat energy calculation. To evaluate heat energy,v olumetric heat capacityC_v is essential. The value of C_v of normal concrete, sub-grade and base materials are 2.1, 1.7 and 1.2 J/cm^{3}respectively according to Asaeda and Wake (1996). Considering these values, the volumetric heat capacity C_v for pervious concrete is shown in Table 2.

Table 2: %Voids and C_v of concretes

Pavement Type	**%Void, N**	**C_v (J/cm^3)**
PC-1	24.2	1.6
PC-2	18.5	1.71
PC-3	13.1	1.82
CS	0	2.1

2.2 Permeability and Strength Test: A widely used technique was used to find out the permeability of PC sample, where the reference sample 'CS' considered as impermeable one. Concrete cylindrical sample was insert in a steel mold and flexible rubber pad was attached at the outside of concrete sample. The sample was secured using four bolts, with a 2cm gap between the rubber pad and the concrete's top surface, and a 6cm clearance to the mold's top. The setup was positioned beneath a water tap with a retaining pot underneath shown in Figure 4. Upon simultaneous start of the tap and stopwatch, water evenly flowed onto the concrete. Flow was regulated to match water inflow and tap flow. After 60 seconds, the tap was stopped and passed water was weighted and find out its volume. These data determined permeability for three different pervious concretes sample.

To evaluate the compressive strength, firstly cylindrical specimens of normal concrete and pervious concrete were constructed and cured according to ASTM C31. Compressive strength test was performed at 28 days age of this sample showed in Figure 5.

Figure 4: Permeability test of PC

Figure 5: Com. Strength test of PC and CS

3. Result and Discussion

The average temperatures of concrete slab of PC pavements is higher than the CS pavement in top surface and also in center of it showed in Figure 6 and Figure 9. It is showed in Figure 6 that the temperature is directly proportional to its pervious values. This may be happened due to the larger percentage of void creates a higher surface area exposed to sunlight, leading to increased absorption of solar radiation and higher heat retention, similar observation was also reported by Marceau and Geem in 2007. Additionally, PC contains interconnected voids that allow air circulation and heat retention within the concrete, further contributing to higher temperatures. It is showed in Figure 7 that there are no similarities of base temperature between PC and CS pavement during heating and cooling time. The base of CS is warmer very fast and also fast in cooling than PC pavements.CS pavement, being a dense and solid material, has higher thermal conductivity and heat storage capacity, allowing heat to transfer more efficiently through its mass. This results in faster heating and cooling rates compared to PC pavements, which are typically more porous and have lower thermal conductivity and heat storage capacity. The temperatures of sub-grade are nearly same in PC pavements and CS pavement over the time period of 1pm to 6am showed in Figure 8. The temperature of concrete slab of PC's are higher than CS pavement within the heating periods of sun light (7am to 6pm),however, within the cooling periods (6pm to 7am) the CS pavement showed the high surface temperature compared to PC. It means, the PC pavements store heat in very faster rate and also release it quickly but the CS pavement stores heat with comparatively slower rate. It means CS pavement stored the heat energy more than PC pavement, which is shown in Figure 10. However, in case of 20% addition of fine aggregate (ie. PC 3), there is no remarkable changes observed in terms of storing heat energy.

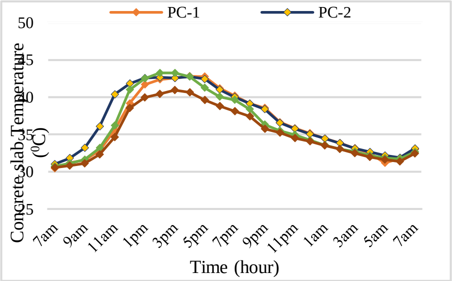

Figure 6: Average Concrete Slab Temp. vs Time Curve

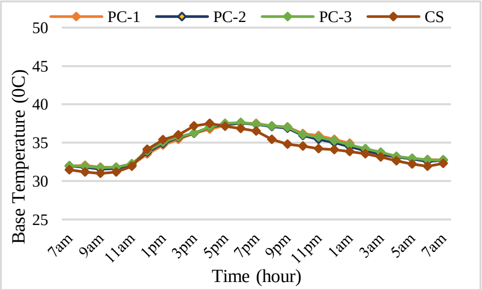

Figure 7: Average Base Temp. vs Time Curve

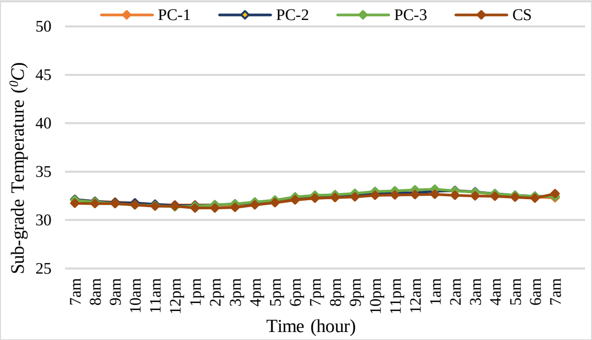

Figure 8: Average sub-grade Temp. vs Time curve

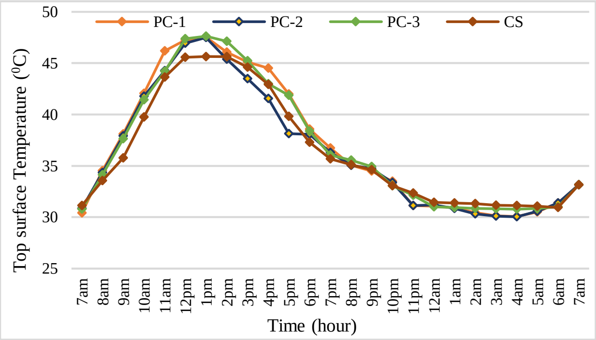

Figure 9: Top surface temperature vs Time curve

The top surface of PC, PC-3 shows the high temperature because of larger voids create a larger area to take the heat more shown in Figure 9. Similar observation was noticed by Asaeda and wake in 2000.Volumetric heat capacity of CS is greater than PC's. As a result, the ultimate heat stored capacity of CS is higher compared to PC.

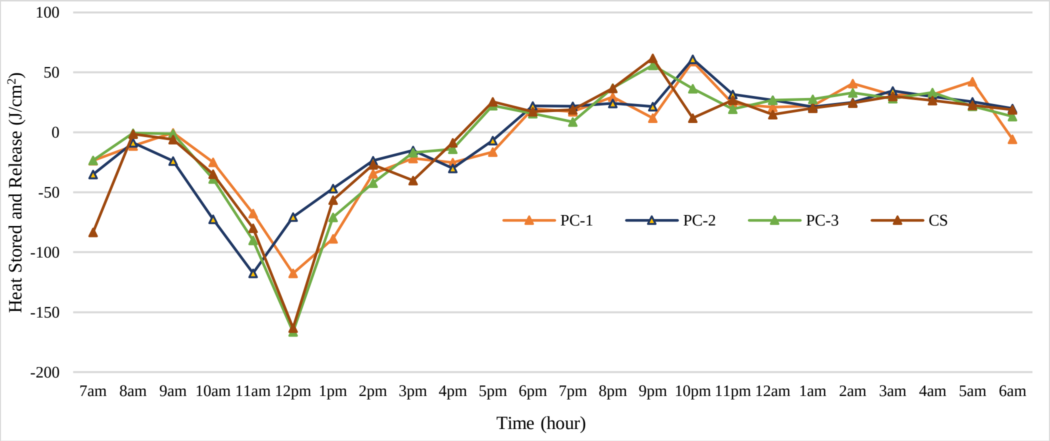

Figure 10: Hourly heat store and release vs Time curve

The hourly heat stores and releases are presented in Figure 10. The negative values of this figure show the heat stored and positive values represent the heat release in every hour interval. At the day time, from 7am to5pm all the pavements system stored heat energy and released at night time as showed in Figure 10 which was plotted by the average data of seven days history. It is shown that the temperature of PC pavements is high at heating cycle and low at cooling cycle than CS pavement because CS pavement stores heat and releases it slowly with respect to PC pavements. Analyzing all the data, the heat store by base and subgrade of CS and PC's pavements are almost same but the concrete surface of CS stored more heat than PC pavements due to its high C_v value and this C_v is inversely proportional to the concrete porosity. The pervious pavements system store overall less energy than traditional pavement system and it depends on its porosity. Here, PC-1 stores comparatively low heat energy than PC-2 and PC-3 for its high porosity and the porosity mainly depends on how much percentage of fine aggregate used in concrete production.

Table 3: Result of heat, permeability and strength

Pavement Type	**Heat Energy stored (J/cm^2)**	**% less from CS**	**Permeability (cm/hr)**	**Average comp. Strength (Mpa)**	**%Strength wrt. CS**
CS	500.775	0.0	0.0	20.53	100%
PC-1	437.665	12.6	2167.89	10.88	53.00%
PC-2	449.926	10.15	1576.50	11.46	56.10%
PC-3	464.033	7.34	1009.52	12.36	60.20%

The Permeability, strength and heat energy stored of pervious concrete (PC) and normal concrete (CS) are shown in Table 3. Study shows that the sample with larger percentage of fine aggregate have low permeability and high compressive strength and high heat stored capacity.

4. Conclusions

Pervious pavement, characterized by its porous structure, offering several benefits in reducing the Urban Heat Island (UHI) effect. One potential approach to addressing the UHI phenomenon is the adoption of pavement systems with lower energy storage capabilities. A practical strategy could involve the utilization of pervious concrete systems, which feature layers of materials with increased porosity compared to standard pavement systems. The research aims to identify the most effective mixtures for reducing the UHI effect and promoting heat dissipation. Following conclusions can be drawn from this work.

Ultimate heat stored capacity of normal concrete pavement is higher than the pervious concrete pavement. However, the internal temperature of pervious samples are higher than the normal concrete. Concrete permeability and heat absorbing capacity are directly related to each other. High permeable concrete exhibits 12.6% lower heat absorbing capacity compared to impervious concrete. When the permeability is dropped at 53.4% then the heat absorbing capacity also dropped by 41.7%, which is nearly proportional to each other.

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