IMPACT OF FINE AGGREGATE ON HEAT STORAGE, STRENGTH AND PERMEABILITY OF PERVIOUS CONCRETE PAVEMENTS

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ABSTRACT

Pervious concrete represents a distinctive type of highly porous concrete employed in flatwork scenarios. It is designed to facilitate the passage of water from precipitation and has emerged as a viable solution for addressing urban challenges like mitigating urban heat island effects. This research focuses on exploring how different percentages of fine aggregate in the mix affect the heat storage, compressive strength, and permeability of pervious concrete. This study involves a thorough experimental investigation in which three distinct mixtures, each containing varying percentage of fine aggregate (10%, 15% and 20%), are analyzed. The effects of different percentages of fine aggregate content were evaluated by measuring layer temperatures, specific volumetric heat capacity, compressive strength, and permeability. These parameters are contingent on the proportion of voids within the pervious concrete, with this void fraction being intrinsically governed by the proportion of fine aggregate incorporated into the mixture. The results show that increasing the percentage of fine aggregate in the pervious concrete pavement slab increases the heat storage capacity and compressive strength and reduce the water permeability. This finding helps to determine the appropriate percentage of fine aggregate in the mix when designing pervious concrete pavement for specific applications.

Keywords: *Pervious concrete, heat storage capacity, permeability, compressive strength*

1.INTRODUCTION

Pervious concrete is now employed mostly in permeable pavement systems such as highways, walkways, driveways, parking lots, and other light-duty flatwork applications. While sturdy enough to sustain modest traffic, pervious concrete pavement is most commonly used as a stormwater management strategy. It readily infiltrates rainwater into the underlying layers for temporary storage before gradually infiltrating into the subsoil or sewage system. (AlShareedah & Nassiri, 2019; Rodin et al.,2019). Many cities in the United States and throughout the world are seeing an increase in the demand for permeable pavements. Pervious concrete has been utilized in Europe to minimize road noise, wet weather splashing, and to increase friction (Schaefer & Wang, 2006; Cackler et al.,2006; Caestecker, 1999). It was also employed in China's sponge city plan to alleviate the rising problem of urban floods and overburdened drainage systems (Wang et al.,2017; Zhong et al.,2018). The rapid use of this sort of pavement technology has compelled academics to focus their efforts on various areas of this technology in order to solve critical deficiencies such as inadequate strength and durability. The advantage of using pervious concrete pavement is its good water permeability. It reduces rain puddles and splashes on the pavement which are not favourable for driving. It also eliminates glare from the road surface thus improving road safety. It is increasingly used in the United States because of its various environmental benefits, such as controlling storm water runoff, restoring groundwater supplies and reducing water and soil pollution (Kajio et al. 1998; Youngs, 2005; Tennis et al., 2004). Pervious concrete is being embraced as an eco-friendly urban infrastructure solution, but the lack of standards for mixture optimization and pavement design has led to weak and less durable field installations. (AlShareedah & Nassir, 2020).

Strength and permeability are the most important parameters for evaluating the useability of pervious concrete as pavement material. Researchers are trying to co-relate some parameters with the strength and permeability of pervious concrete. The research found that a 50% replacement rate of recycled aggregate with a water–cement ratio of 0.25 results in good concrete strength (28.9 MPa) and permeability (13.26 mm/s). Incorporating 12% fly ash with a water-reducing agent enhances permeable concrete workability and frost resistance, with a frost resistance rating of F150, supporting the use of recycled aggregate in sustainable urban construction (Ruidong et al., 2022). The mechanical properties of pervious concrete can be greatly improved by using proper concrete materials and mix proportions (Sumanasooriya & Neithalath, 2011; Huang et al., 2010). The use of silica fume (SF) and superplasticizer (SP) could enhance pervious concrete strength substantially (Yang and Jiang, 2003). Another study showed that the addition of polymer (styrene butadiene rubber) could improve pervious concrete workability, strength, and permeability as well as freeze–thaw resistance (Kevern, 2008). It was found that aggregate types had a greater impact on connected porosity and compressive strength than on size (Zhong &. Wille, 2016; osic et al., 2015). When the w/c ratio is high, the permeability reduces because the paste fills the pores and draws down; however, in the case of a dry mix, the permeability increases because of the high porosity (Neamitha & Supraja, 2017; Nguyen et al., 2014).

Considering temperatures at different depths and the heat stored within various layers and below ground, the findings shows that the pervious concrete system retained 12% less energy on average than did the conventional concrete, offering potential mitigation of UHIs (Kevern et al., 2012). Only a few studies on the temperature impact of adopting pervious pavement surfaces have been reported. Research shows that the PCPC surface can have higher temperatures than standard impermeable pavements, but that temperatures drop fast beneath the pavement (Haselbach & Gaither 2008; Kevern et al. 2009. None of the available research has compared the total energy storage, permeability and compressive strength of pervious concrete pavements with changing the amount of fine aggregate used in mixing.

The primary objective of this study was to compare the amount of heat storage of three different pervious pavements through an assessment of their layer temperature, layer thickness, porosity and volumetric heat capacities. In addition, we compare and observe how to influence the strength and permeability by examining the percentage of fine aggregate in mixing of pervious concrete pavements.

2. MATERIALS AND METHODOLOGY

For all samples of pervious concrete, ordinary Portland cement (OPC) was used as the cementitious ingredient. The samples were constructed using different percentages of fine aggregates, but the other ingredients were constant. Almost uniformly graded coarse aggregate (19mm passing and 9.5mm retained) and coarser fine aggregate (4.74mm passing and 1.18mm retained) were used. Fine aggregate has a 2.4 FM value, and the gradation curve of coarse aggregate is shown in Figure 1.

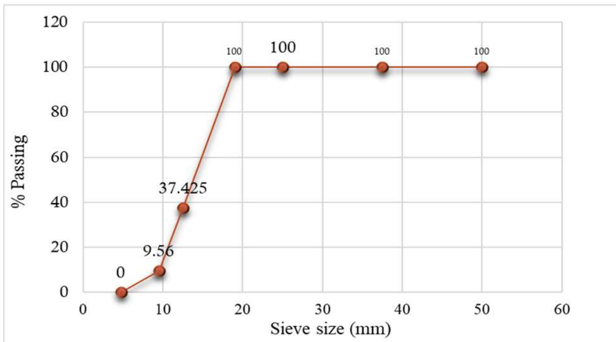

Figure 1: Gradation curve of Coarse Aggregate

The only differences in the compositions and material qualities of each form of pervious concrete are in the mixing ratios. Table 1 shows the material proportions and workability (slump test). At the sample placement location, the subgrade soil had a CBR value of 5%. The specific gravity, FM value, and unit weight of the fine aggregate were 2.62, 1631 kg/m3, and 2.4, respectively. The unit weight of the coarse aggregate is 1457 kg/m3, its specific gravity is 2.62, and its water absorption is 0.82. The cement had a normal consistency of 27.32 and a fineness of 2270 cm2/gm. Pervious Concrete-1 (PC-1) with 10% fine aggregate, Pervious Concrete-2 (PC-2) with 15% fine aggregate, and Pervious Concrete-3 (PC-3) with 20% fine aggregate.

Table 1: Mix ratio and slum of concrete

Concrete Type	**W/C**	**C:FA:CA**	**Slum (mm)**
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 Heat storage measurement

There isn't a widely recognized standard method specifically for testing the heat storage capacity of pervious concrete. A few studies have addressed the measurement of heat storage capacity in pervious concrete pavement. In this study, it leveraged insights from existing literature to quantify the heat storage capacity. In an area where sunlight is present nearly all day, three concrete samples of pavements were constructed next to the south side of KUET Civil Engineering building. Three samples of pervious concrete pavements (PC), were constructed in which the different amount of fine aggregate was used to achieve a different level of perviousness. First, the top soils were excavated to a depth of 170 mm, and a hole was made beneath the excavation base to place temperature sensors at depths of 295 mm and 420 mm from the surface of the existing soil. After inserting the sensors, the hole was correctly filled with excavated soil. Subsequently, base materials were used in a 2:1 ratio with CA and FA to fill the excavated area and provide a true sense for general pavement. To measure the base's mid-level temperature, a sensor was also installed. The samples of pavement slabs were 60x60 cm in size and 15 cm thick. A temperature sensor was placed in the middle of the slab above the base shown in figure 2.

Figure 2: Construction and sensor inserting

Pavements next to each other were separated by a 2-m horizontal space to provide temperature independence and avoid moisture interaction. A larger vertical base size was employed to shield the pavement sides from the thermal effects of the surrounding soil. This common construction technique was used to construct every pavement shown in figure 2. DS18B20 sensors were used to measure the average temperature of each pavement system. Its temperature range, with a precision of ±0.5°C, is -55°C to +125°C.
A single pavement had 5 sensors installed. It should also be included in calculating the heat energy to a depth in the subgrade where there is a 1-degree-Celsius temperature difference between every pavement. The findings indicate that the temperature differences between the pavements were less than 1 degree Celsius when measured 60 cm below the surface of the pavements.
Figure 3 shows a typical cross section of various pavement layers along with the locations of the sensors in each layer. Simple coding was used to record these layer temperatures automatically, in shown in figure 4.

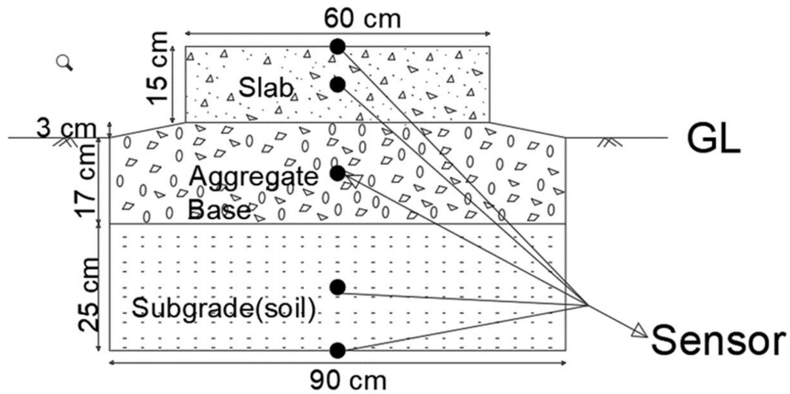

Figure 3: Layer Thickness and Sensor Position

Figure 4: Temperature Measuring

To obtain the total heat stored by a pavement system it needed to calculate how much heat energy stored in different layer. This measurement was performed at every 1-h interval and using the following equation for calculation.

$$\Delta E=C_v(slab)*\Delta T(slab)*h(slab)+C_v(aggBase)*\Delta T(agg.base)*T(agg.base)+C_v(soil)*\Delta T(soil)*h(soil) \quad (1)$$

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-^{0}C),

ΔT =change in temperature per hour at specified thermocouple depths (^{0}C /h), and

h = height of layer (cm).

Here, the porosities of the previous concrete (PC) were determined with respect traditional concrete according to the following formula by siti et al (2018). here, the porosity of Traditional concrete (TC) assumed 0%.

$C_v(PC)=C_v(T_c)*(100-Ni)$

where $C_v(PC)$ = volumetric heat capacity (J/cm^3-^{0}C) of PC

$C_v(TC)$ = volumetric heat capacity (J/ cm^3-^{0}C) of TC

N=% of voids of PC.

The first hour, such as 7 am–8 am 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 (Kevern et al, 2012). Here, three different layers were considered for heat storage calculation. To evaluate heat storage, volumetric heat capacity (C_v) is essential. The values of C_v of traditional 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 all the pervious concrete is shown in Table 2.

Table 2: %Voids and C_v of PC's

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

2.2 Permeability test

ASTM C1701, Constant head method (CHM) was used to determine the permeability of PC sample. A 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 2 cm 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, as shown in Figure 5. Upon simultaneous start of the tap and stopwatch, water evenly flowed onto the concrete. Flow was regulated to match the water inflow and tap flow. After 60 s, the tap was stopped and passed water was weighted and find out its volume. These data determined the permeability of three different pervious concretes sample.

Figure 5: Permeability test

To calculate the permeability in cm/h of the pervious concrete, the following simple equation is used

$$P=V_w/(Ac\ T) \tag{2}$$

Where,

P=Permeability of Pervious Concrete (cm/hr)

V_w= Volume of water passing through the concrete within a certain time period (cm^3)

Ac=Surface area of concrete where the water is passing (cm^2)

T=Time taken to pass V_w volume of water (hour)

2.3 Compressive strength test

To evaluate the compressive strength, cylindrical specimens of pervious concrete were constructed and cured according to ASTM C31. Compressive strength test was performed at 28 days of age of this sample that shown in figure 6.

Figure 6: Compressive Strength test

3. RESULT AND DISCUSSION

The figure 7, 8, 9, and 10 belove shows the change in temperature of different layers like top surface, mid-point of slab, base and sub-grade of three different pavements system. The average temperatures of the top surface of concrete slab of PC-1 pavements are higher than others two pavement shown in Figure 7. It also shows that the temperature is directly proportional to its previous values. This may be 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. In addition, PC-1 contains a larger interconnected voids that allow air circulation and heat retention within the concrete, further contributing to higher temperatures than PC-2 and PC-3.

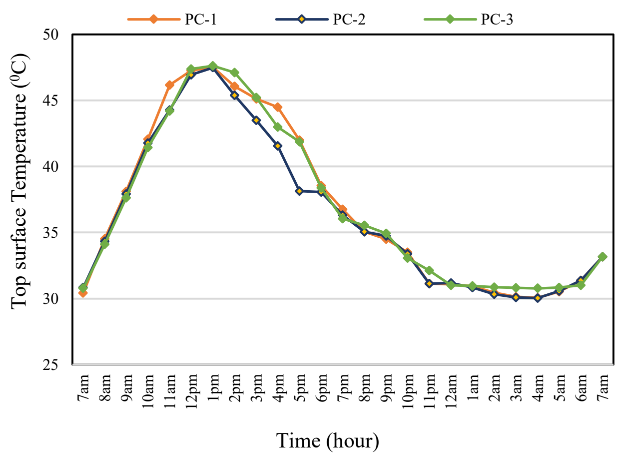

Figure 7: Top surface temperature vs Time curve

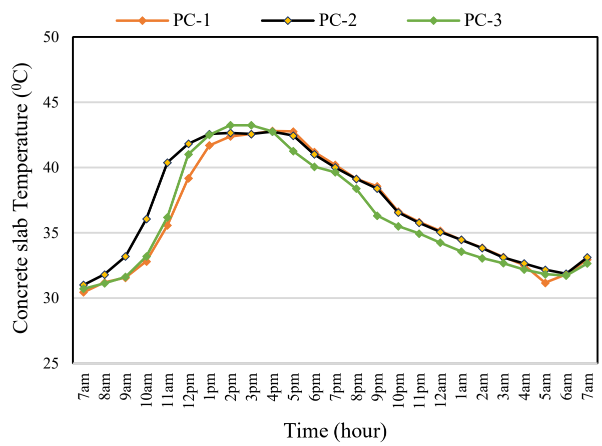

Figure 8: Average Concrete Slab Temp. vs Time Curve

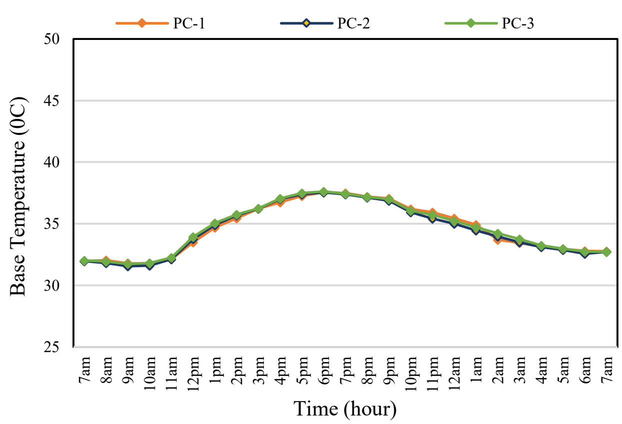

Figure 9: Average Base Temp. vs Time Curve

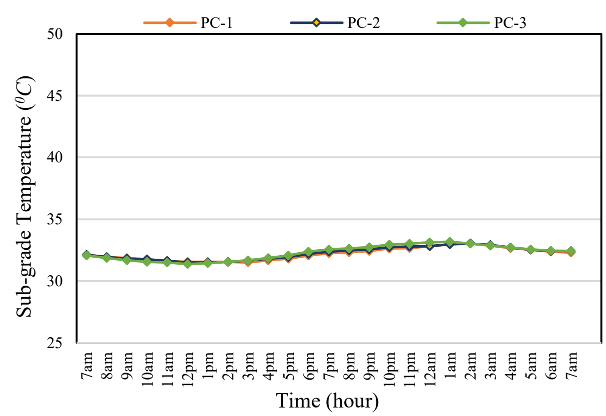

Figure 10: Average sub-grade Temp. vs Time curve

The temperature of the mid-point concrete slab of PC-2 is higher than other pavements within the heating periods of sun light (7am to 4pm), however, within the cooling periods (4pm to 7am) the PC-1 pavement showed the high temperature compared to others. This is because PC-2 has a higher surface area than PC-3 and higher conductivity than PC-1 shown in figure 8. It is shown in Figure 9 that there is a good similarity of base temperature of each pavement during heating and cooling time but the base of PC-3 is warmer fast and also fast in cooling than other pavements. PC-3 pavement, have a lower void 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 for PC-1 than for other pavements, which are typically more porous and have lower thermal conductivity and heat storage capacity.

The temperatures of the subgrade are nearly same in all the pavements but in PC-1 sub-grade shows the slightly lower temperature over the time period of 7am to 2pm and slightly higher temperature over the 2pm to next day 7am showed in Figure 10. This means that the PC-3 pavements store heat in very faster rate and also release it quickly but the PC-1 pavement stores heat with comparatively slower rate. This means that PC-3 pavement stored the heat energy more than other pavements, which is shown in Figure 10. Volumetric heat capacity of PC-3 is greater than PC-1 and PC-2. As a result, the ultimate heat stored capacity of PC-3 is higher than that of the other two.

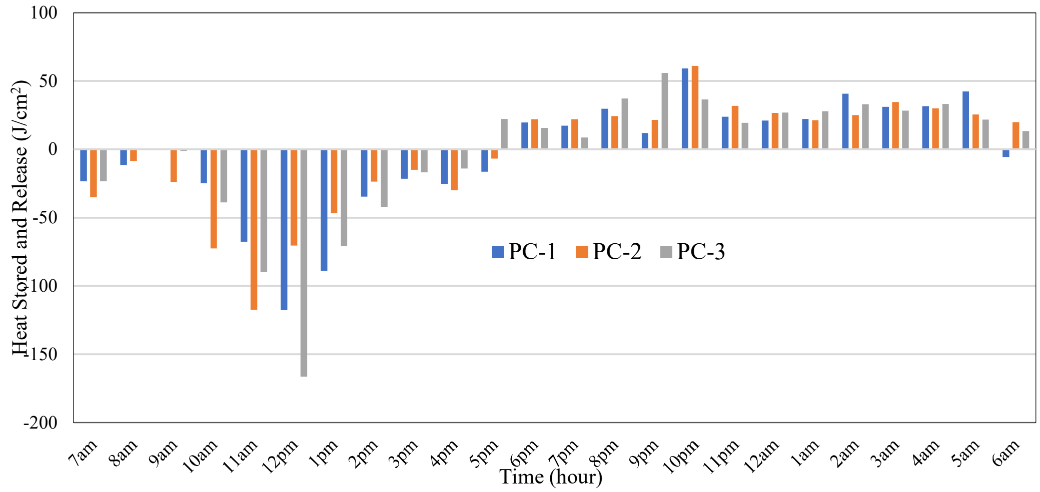

Figure 11: Hourly heat store and release vs Time curve

Hourly heat stores and releases are presented in Figure 11. The negative values of this figure show the hourly heat stored, and the positive values represent the hourly heat release. During the daytime (when sun light present), from 7am to 5pm all the pavements system stored heat energy and released at night time as showed in Figure 11 and this graph was plotted by the average data of seven days analysis. It is shown that the temperature of PC-1 pavements is higher during the heating cycle and low at cooling cycle than other pavements because PC-3 pavement stores heat and releases it slowly with respect to PC-1 and PC-2 pavements. By analyzing all the data, the heat stored by base and subgrade of all the pavements are almost same but the concrete surface of PC-3 stored more heat than others two pavements due to its high volumetric heat capacity (Cv) value and this Cv is inversely proportional to the concrete porosity. Here, PC-1 stores comparatively less 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 construction. A larger percentage of fine aggregate create lower voids in pervious concrete. While environmental factors such as season, humidity and wind speed can influence the results of heat storage capacity tests, they were not taken into consideration in this particular study.

Table 3: Result of heat, permeability and strength

Pavement Type	Heat Energy stored (J/cm2)	Permeability (cm/hr)	Average comp. Strength (Mpa)
PC-1	437.665	2167.89	10.88
PC-2	449.926	1576.5	11.46
PC-3	464.033	1009.52	12.36

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

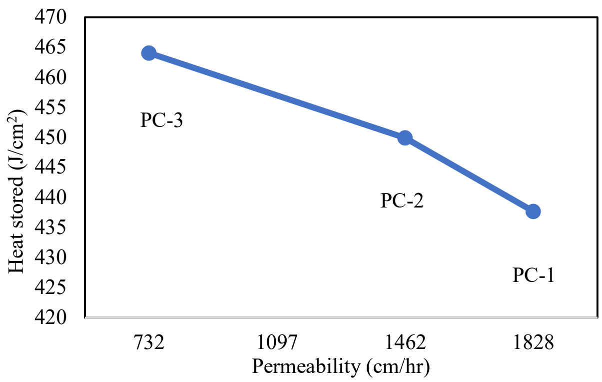

Figure 12: Permeability vs Heat capacity

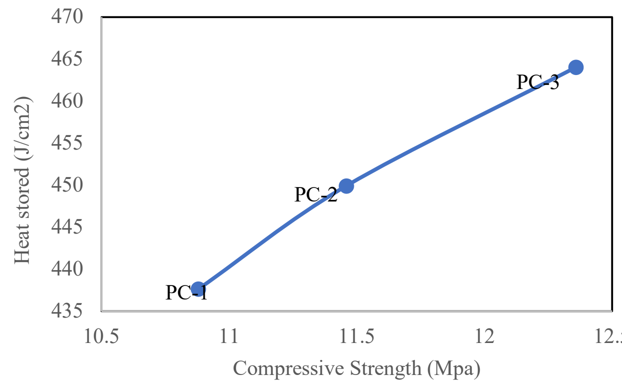

Figure 13: Compressive strength vs Heat capacity

4. CONCLUSIONS

The porous nature of pervious pavement provides many advantages like it reducing the Urban Heat Island (UHI) effect, rain water management and ground water recharge. One potential approach to address the heat consumption phenomenon is the adoption of pavement systems with lower energy storage capabilities. A practical strategy could involve the use of pervious concrete systems, which feature layers of materials with increased porosity compared to traditional pavement systems. This research aims to identify the most effective mixtures on the basis of heat storage capacity, permeability and compressive strength.

The ultimate heat-storage capacity of pervious concrete pavement is higher with respect to amount of fine aggregate used in mixed. Heat storage capacity and compressive strength are almost proportional and permeability almost inversely proportional to percentage of fine aggregate in mixing. Heat storage capacity and compressive strength increased by 3% and 5.5%, respectively, when 5% of fine aggregate. High-permeable concrete (PC-1) exhibits 6% lower heat absorbing capacity compared to low permeable concrete (PC-3). When the permeability is decreased to 53.4% then the heat absorbing capacity and compressive strength also increased by 41.7%, which is nearly inversely proportional to each other. Where the underlying soil permeability is low and need good strength in pavement, PC-3 is preferred. Conversely, where soil permeability is low, strength is less critical, and minimal heat storage is desired, PC-1 is the preferred.

REFERENCES

O. AlShareedah, S. Nassiri, Methodology for Mechanistic Design of Pervious Concrete Pavements, J. Transp. Eng. Part B Pavements. 145 (2019) 4019012.

H. Rodin III, S. Nassiri, O. AlShareedah, M. Yekkalar, L. Haselbach, Evaluation of skid resistance of pervious concrete slabs under various winter conditions for driver and pedestrian users, Road Mater. Pavement Des. (2019) 1–19.

V.R. Schaefer, K. Wang, Mix design development for pervious concrete in cold weather climates, Iowa. Dept. of Transportation. Highway Division, 2006.

E.T. Cackler, T. Ferragut, D.S. Harrington, R.O. Rasmussen, P. Wiegand, Evaluation of US and European concrete pavement noise reduction methods., (2006).

C. Caestecker, Test Sections of Noiseless Cement Concrete Pavements–Conclusions, R&T Adm. Journal Pre-proof 28 Belgium. (1999).

Y. Wang, M. Sun, B. Song, Public perceptions of and willingness to pay for sponge city initiatives in China, Resour. Conserv. Recycl. 122 (2017) 11–20.

R. Zhong, Z. Leng, C. Poon, Research and application of pervious concrete as a sustainable pavement material: A state-of-the-art and state-of-the-practice review, Constr. Build. Mater. 183 (2018) 544–553.

Othman AlShareedah, Somayeh Nassir, Pervious Concrete Mixture Optimization, Physical, and Mechanical Properties and Pavement Design: A Review, Journal of Cleaner Production, 2020, p:1-34

Kajio, S,, Tanaka, S., Tomita, R., Noda, E., Hashimoto, S. (1998) Properties of porous concrete with high strength. Proceeding's 8th international symposium on concrete roads, Lisbon, 171–177.

Tennis, P.D., Leming, M.L., Akers, D.J. (2004) Pervious Concrete Pavements. EB302 Portland Cement Association Skokie Illinois and National Ready Mixed Concrete Association, Maryland: Silver Spring.

Youngs, A. (2005) Pervious concrete it's for real. Presentation at pervious concrete and parking area design workshop, Omaha.

Emiko LIM , Kiang Hwee TAN, Tien Fang FWA, Effect of Mix Proportion on Strength and Permeability of Pervious Concrete for Use in Pavement, Journal of the Eastern Asia Society for Transportation Studies, Vol.10, 2013, p: 1565-1575

Kevern, J.T., Wang, K., and Schaefer, V.R. "Test Methods for Characterizing Air Void Systems in Portland Cement Pervious Concrete," Recent Advancements in Concrete Freezing and Thawing (FT) Durability a Journal of ASTM International special issue, 2009.

Haselbach, L. The Engineering Guide to LEED-New Construction; Sustainable Construction for Engineers, McGraw-Hill, 2008

Ruidong Wu, Shuning Shi, Yu Shen, Chen Hu, Mengfei Luo, Zichen Gan, Bin Xiao and Zeyu Wang, Effects of Different Factors on the Performance of Recycled Aggregate Permeable Pavement Concrete, 2022)

John T. Kevern, Liv Haselbach, Vernon R. Schaefer, Hot Weather Comparative Heat Balances in Pervious Concrete and Impervious Concrete Pavement Systems, Journal of Heat Island Institute International Vol.7-2 (2012)

R. Zhong, K. Wille, Linking pore system characteristics to the compressive behavior of pervious concrete, Cem. Concr. Compos. 70 (2016) 130–138

K. C´ osic´, L. Korat, V. Ducman, I. Netinger, Influence of aggregate type and size on properties of pervious concrete, Constr. Build. Mater. 78 (2015) 69–76

M. Neamitha, T. Supraja, Influence of Water Cement Ratio and the Size of Aggregate on The Properties of Pervious Concrete, Int. Ref. J. Eng. Sci 6 (2017) 9–16.

D.H. Nguyen, N. Sebaibi, M. Boutouil, L. Leleyter, F. Baraud, A modified method for the design of pervious concrete mix, Constr. Build. Mater. 73 (2014) 271– 282.

Sumanasooriya MS, Neithalath N. Pore structure features of pervious concretes proportioned for desired porosities and their performance prediction. Cem Concr Compos 2011;33(8):778–87.

Huang B, Wu H, Shu X, Dong Q, Burdette EG. Laboratory evaluation of permeability and strength of polymer-modified pervious concrete. Constr Build Mater 2010;24(5):818–23

Yang J, Jiang G. Experimental study on properties of pervious concrete pavement materials. Cem Concr Res 2003;33(3):381–6

Kevern JT. Advancement of pervious concrete durability. Ph.D. dissertation, Iowa State University, Ames, IA; 2008

Siti Halipah Ibrahim, N. I. (2018). THE IMPACT OF ROAD PAVEMENT ON URBAN HEAT ISLAND (UHI). International Journal of Technology, 1597-1608.

Asaeda, T., V. T. Ca, and A.Wake, (1996) "Heat storage of pavement and its effect on the lower atmosphere. Atmospheric Environment, 30(3), pp. 413-427.

John T. Kevern, Liv Haselbach, Vernon R. Schaefer, (2012) Hot Weather Comparative Heat Balances in Pervious Concrete and Impervious Concrete Pavement Systems, Journal of Heat Island Institute International Vol.7-2, p: 231-237.

Marceau, M. and M. Van Geem. (2007). Solar Reflectance of Concretes for LEED Sustainable Site Credit: Heat Island Effect. Portland Cement Association, Skokie, IL, SN2982.