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Investigating the Thermal Performance of Novel Permeable Concrete Pavements through Numerical Modelling[#]

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ABSTRACT

A novel high strength clogging resistant permeable pavement (CRP, also known as Kiacrete) has been developed to prevent surface flooding by absorbing stormwater runoff. Ground source energy systems (GSES) are a sustainable method to melt ice/snow on pavements. Heat energy is deposited into the ground during the summer and extracted in the winter. In this study, a numerical model has been developed, using COMSOL Multiphysics, to investigate the thermal performance of Kiacrete that is heated with a GSES. The numerical results were validated against that of the experimental values. The experimental setup consisted of i) a Kiacrete slab (290 mm × 290 mm × 80 mm) with 144 equidistant pores (each pore was 6 mm in diameter); ii) a heating water bath that pumped 40°C hot water into a standard High-Density Polyethylene (HDPE) pipe of 24 mm in diameter at a flow rate of 18.5 litres/minute. This pipe was placed underneath Kiacrete, at its centre, to mimic the ground source energy; iii) an aggregate layer (Thames Valley River gravel ⩾5 mm) to simulate the ground conditions; and iv) a cooling water bath that pumped 10°C cold water into an aluminium plate with embedded copper pipes of 8.12 mm inner diameter, spaced 18 mm apart. This cooling plate was placed underneath the aggregate layer to mimic the ground temperature conditions within the UK. K-type thermocouples were placed at different heights and locations within the Kiacrete pores and the surrounding concrete. A good agreement was observed between the numerical simulation results and the experimental values. The heat propagation inside the concrete, in lateral direction, was found to be symmetrical. Furthermore, the pores inside Kiacrete produced the effect of small chimneys supporting the convection heat transfer, with conduction heat transfer occurring inside the surrounding solid concrete. This study provides the basis for investigating the heat transfer characteristics of a new type of permeable concrete pavement, whilst providing useful insights into developing complex numerical models for simulating its efficiency in melting ice and snow.

Keywords: Numerical modelling, thermal performance, permeable pavement

NONMENCLATURE

Abbreviations	
CRP	Clogging Resistant permeable Pavement
HDPE	High Density polyethylene
GSES	Ground Source Energy Systems
CHT	Conjugate Heat Transfer

1. INTRODUCTION

For the past 150 years, societies have experienced growing urbanization, leading to larger cities that are at higher risk of flooding due to the inability of impermeable surfaces to absorb rainfall. Consequently, the likelihood of surface flooding, whether it is minor or catastrophic, has increased [1][2]. Permeable pavements have gained popularity in the effort to address urban flooding by serving as an effective sustainable drainage system [3]. Permeable pavements are capable of allowing significant amounts of water to transport through their porous structure [4][5].

Due to their ability to absorb surface water, these permeable pavements not only reduce the risk of urban flooding but can also enhance the safety of infrastructure users. Slipping and skidding of vehicles on wet or frozen pavement surfaces due to hydroplaning is a major safety concern. Certain parts of the road, such as slopes, curves, and bridges, can make the situation even more challenging. There are two common categories for snow

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and ice removal methods from road pavements namely passive and active. Mechanical snow-removal equipment and anti-icing or de-icing chemicals are mostly used by transportation authorities to handle snow and ice accumulation [6]. However, these chemicals pollute the environment along the road whilst also causing corrosion [7]. With winter seasons becoming more severe in certain areas due to climate change, the adoption of innovative de-icing technologies can enhance the resilience of vital infrastructures like airports and high-traffic zones to adapt to these changing climatic conditions [8]. One of the techniques to deice the road surfaces is to use heated pavements that utilize conventional as well as renewable energy systems for heating. Such systems involve the use of embedded pipes within the pavement through which a heat transfer fluid flows [9]. These systems are designed to prevent snow and ice accumulation, improving driving conditions and reducing the need for traditional environmentally damaging de-icing methods [10]. By utilizing captured low to medium temperature heat, when available, the pedestrian and vehicle safety is enhanced in the winter by keeping the pavement surfaces clear of snow and ice. These systems are particularly advantageous in high-traffic areas such as airport runways, bridges, highways, and critical infrastructure [11].

A novel high strength clogging resistant permeable pavement (CRP, also known as Kiacrete) has been developed that has a higher permeability, strength and durability compared with that of the conventional permeable pavement solutions [12]. Its unique pore structure allows large quantities of water to transfer through it and therefore has the potential to melt significant quantities of ice and snow once it is used with a sustainable ground source energy system (GSES). In this paper, a numerical model has been developed with its findings compared with the results from an experimental setup that replicates real-world temperature conditions in a controlled environment. The main aim of the study is to improve the basic understanding of heat transfer processes within Kiacrete, including both the engineered pore structure and the cementitious material surrounding it.

2. MATERIALS AND METHODS

2.1 Geometry description

Kiacrete (Fig. 1) is a novel high strength clogging resistant permeable pavement that has an engineered recycled plastic pore structure embedded in a self-compacting cementitious material. The Kiacrete slab used in this study is 290 mm × 290 mm × 80 mm. The pore structure consists of 144 equidistant pores, with each pore being 6 mm in diameter. The simulation model geometry replicates the laboratory test setup that consists of a Kiacrete slab placed on a packed aggregate layer (Thames Valley River gravel size: ⩾ 5 mm), enclosed in a Perspex casing (see Fig. 2).

A 24 mm internal diameter high-density polyethylene (HDPE) pipe containing hot water is placed in between Kiacrete and the aggregate layer such that it touches the bottom surface of Kiacrete and the top surface of the aggregate layer. This type of heating configuration is provided to replicate heating of concrete pavements using a GSES. An aluminium cooling plate (190 mm × 230 mm × 15.24 mm) with embedded copper pipes is placed at the bottom of the test setup such that it is covered from top and sides with aggregates. This cooling plate is cooled down to 10°C by cold water flowing in the embedded copper pipes of 8.12 mm inner diameter as shown in Fig. 2.

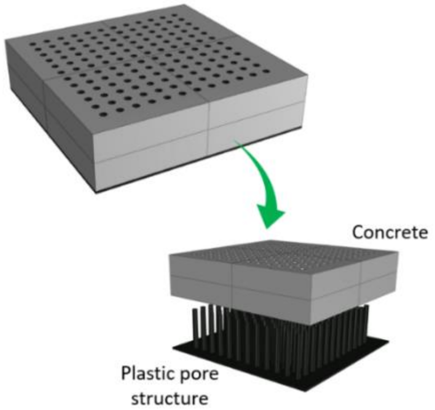


Fig. 1 Kiacrete and its engineered recycled plastic pore structure

2.2 Simulation setup

The purpose of this numerical study is to develop a robust model that is capable of investigating the temperature profile development in the system when it is exposed to both heating and cooling. To carry out this study, temperature development was investigated at several locations in Kiacrete. Two pore and two concrete locations, named C2 (pore and concrete) and F6 (pore and concrete), were chosen to monitor the temperature as indicated in Fig. 3 (circled in red). For both pore locations, two points per pore were selected; first position was at 10 mm height from the bottom of the pore and the second was at 70 mm height from the bottom of the pore located near the top of the pore. Two more sensors were positioned within the concrete (adjacent to pores C2 and F6), at the same heights as sensors in both pores, to investigate the temperature in the concrete adjacent to the pore locations. This was done to investigate the differences in the temperature profile development for both the pore structure and the concrete. To investigate the symmetry of heat transfer in Kiacrete, two more pore and concrete locations namely F8 and C11 were investigated in the numerical model as shown in Fig. 3 (locations circled in black). Both locations are at almost the same distance from centre of the heating pipe in the upper half of Kiacrete as C2 and F6 are in the lower half of Kiacrete.

A conjugate heat transfer (CHT) module in COMSOL Multiphysics software was used to simulate the heat exchanges between the solid and fluid domains, in this case the concrete slab, hot and cold water. The effect of the pores on the heating characteristics of Kiacrete was analysed.

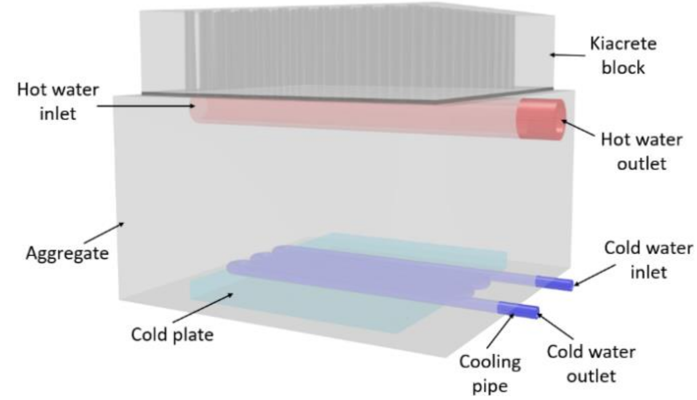


Fig. 2 The geometry used in the numerical model to simulate the experimental setup

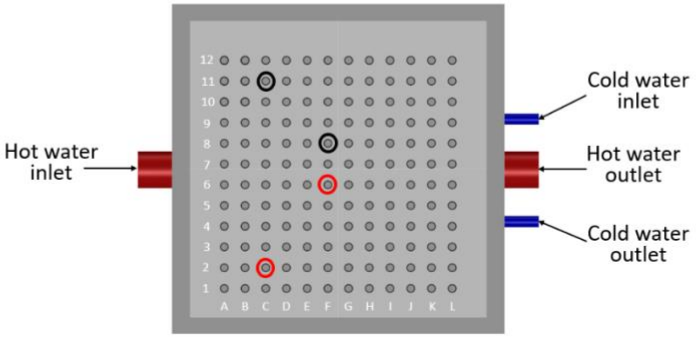


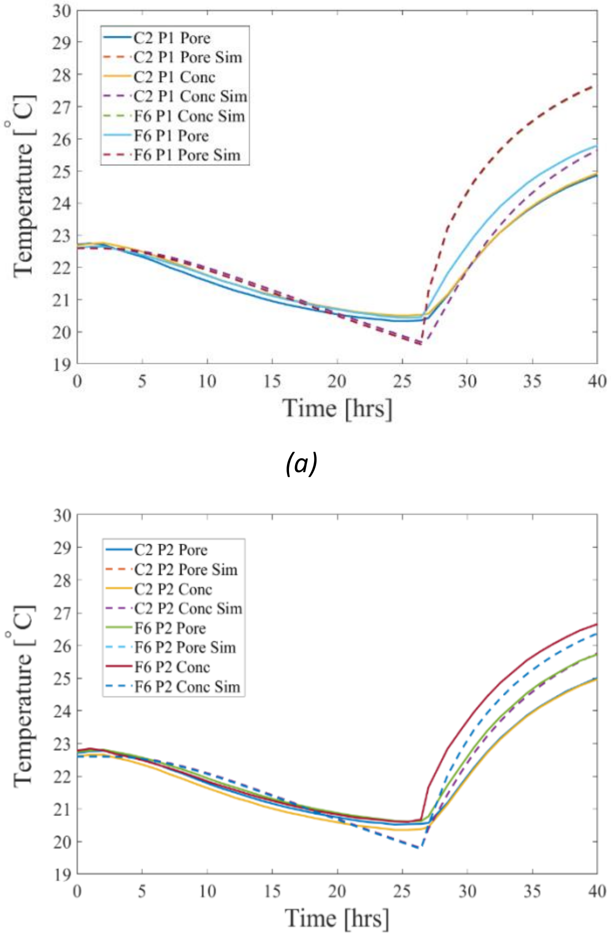
Fig. 3 The temperature measurement points in Kiacrete used in the numerical model

2.3 Boundary conditions

The numerical model in this study has been developed to simulate the real-world response of Kiacrete when exposed to the temperatures in the ground, whilst being heated using a GSES. The inlet flow rate was 18.5 litres/minute for the heated water. For the cold water that simulates the ground conditions, same flow rate of 18.5 litres/min was used. The inlet temperatures were set to be 40°C for the hot water and 10°C for the cold water respectively, while the initial starting temperature for the whole setup was at room temperature (22.6°C). The simulation was run in two parts. To bring the aggregate to 10°C before starting the heating, a simulation was run only for cooling water flow through the cooling plate for ~26.6 hours of cooling (to match the experimental results). After this, both heating and cooling water flows were simulated for a total physical time of ~14 hours to validate these results with the experimental values.

3. RESULTS AND DISCUSSION

In this study the heat transfer characteristics of a novel permeable concrete pavement when exposed to a sustainable GSES has been investigated. Fig. 3a and 3b show the temperature profiles obtained from experimental results and numerical simulations. A fair agreement was found between developed numerical model results and the experimental values except from F6 P1 location, where the deviation between simulation results and experimental values is greater than 1°C. The unique engineered pore structure of Kiacrete has facilitated heat transfer by promoting convection as well as conduction heat transfer. These pores show evidence of convection, indicated by their lower temperature at F6 sensor locations compared to the surrounding concrete, suggesting that the air inside the pores gets heated up and then transfers this heat rapidly to concrete through convection, resulting in low temperatures in the pores. This is a result of faster heat dissipation and faster convection compared to conduction, resulting in quicker heat loss from the pores to the surrounding concrete, leaving them at ~1°C lower temperature than the concrete for P2 location as shown in Fig. 3b. The pores are direct hollow channels, resulting in minimal pore pressure and allowing the air to flow continuously through them without being retained in a capillary system, which is common in traditional permeable pavements. The effect of convection occurring in the pores at sensor location C2 is quite small. This is because this location is far away from the heat source (near periphery of Kiacrete) which indicates that the effect of convection inside the pores becomes smaller as heat moves away from the centre location.

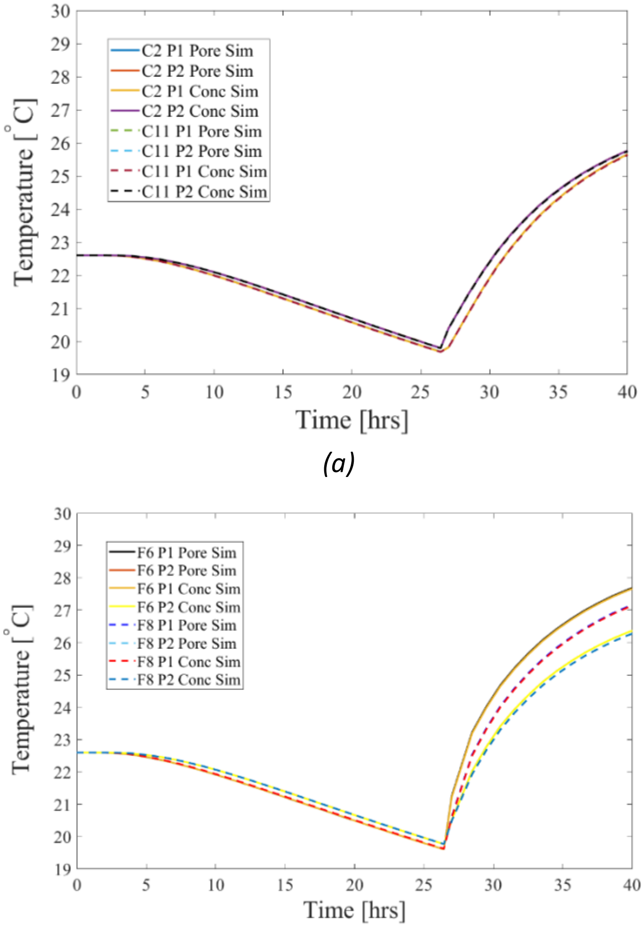


(a)

(b)

Fig. 4 Temperature distribution within Kiacrete for C2 and F6 locations

The C2 sensors are located near the edge of Kiacrete as shown in Fig. 3. The F6 sensors are positioned near the centre of Kiacrete and are close to the heating pipe that is passing through the centre of the test setup. It can be seen in Figs. 4a and 4b, that the C2 zone is cooler than the central F6 zone by ~1°C at P1 location and ~1.5°C at P2 location. This temperature difference is expected and can be explained on the fact that the F6 sensor locations are much closer to the heat source and receive consistent heat supply from the heating pipe compared to the C2 sensor locations. This is due to the uniform conduction process facilitated by the heating pipe at the centre of the setup (at F6 location), which transfers heat to the peripheral zone through the concrete slab. The pores receive heat through conduction via the pore walls and from underneath the slab. However, convection in this area (C2 location) occurs at much slower rate compared to the centre of the setup, as it is further away from the heat source. The significant temperature difference observed specifically in the central F6 zone clearly indicates the varying heat transfer rates between conductive and convective processes, attributed to the close proximity to the heat source.



(a)

(b)

Fig. 5 Symmetry of heat distribution across Kiacrete

The symmetry of heat transfer within Kiacrete is investigated and shown in Figs. 5a and 5b. Two more sensor zones (for both pore and concrete locations) named F8 and C11 were added to the numerical model to compare with the results of C2 and F6. These two locations i.e. F8 and C11 are believed to be at the same distance from the centre of Kiacrete as F6 and C2 (F6 is marginally closer to centre). It can be seen from Figs. 5a and 5b that heat is equally distributed from the centre of Kiacrete to its periphery, as both sensor locations at C2 show a perfect agreement with sensor locations at C11. While for locations F6 and F8, there is a good overall agreement between the temperature values. A temperature difference of ~0.5°C is observed between F6 P1 and F8 P1 sensor locations, which is due to both of these being very close to the heating pipe with F6 P1 being marginally closer to that of F8 P1. Overall, a heat transfer symmetry is established within Kiacrete from its centre to its periphery.

4. CONCLUSIONS

This study presents a novel approach for examining the impact of heat transfer on a new type of permeable pavement. A numerical model is developed with its results validated against the experimental test setup that simulates the real-world temperature conditions in a controlled environment. The primary goal of the research was to enhance the fundamental understanding of heat transfer mechanisms within Kiacrete (both the engineered pore structure and the surrounding cementitious material). The numerical simulation results closely matched the experimental values, indicating a good agreement. Symmetrical heat propagation was observed laterally within the concrete. The pores inside Kiacrete acted like small chimneys, facilitating convection heat transfer, while conduction heat transfer took place within the solid cementitious material surrounding the pores. This research forms the basis for exploring the heat transfer properties of Kiacrete, offering valuable insights for developing intricate numerical models to simulate Kiacrete's effectiveness in melting ice and snow.

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