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A Parametric Study to Investigate the Effect of Pore Size and Number on the Thermal Energy Storage Potential of a Novel Permeable Concrete Pavement#

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ABSTRACT

This study combines a novel high strength clogging resistant permeable pavement (CRP, also known as Kiacrete) with a ground source energy system GSES and numerically investigates the effect of Kiacrete's pore diameter and number on its sensible heat storage (SHS) potential. The energy storage module consists of: i) a 290 × 290 × 80 mm Kiacrete slab that is the heat storage medium; ii) a 24 mm inner diameter standard HDPE pipe that is placed underneath Kiacrete and contains the heat transfer fluid (water), flowing at a temperature of 40°C with volumetric flow rate of 18.5 litres/minute; iii) an aggregate layer (Thames Valley river gravel ≥5 mm), which is placed underneath the heating pipe, to simulate the ground conditions; and iv) a cooling plate with 8.12 mm inner diameter embedded copper pipes that has water flowing at a temperature of 10°C, and is placed at the bottom of the aggregate layer, to mimic the ground temperature conditions within the UK. Four different Kiacrete pore diameters (4 mm, 6 mm, 8 mm and 10 mm) and two different equidistant pore numbers (144 and 121) were investigated for a 12-hour heating cycle. The results showed that the lower pore number and smaller pore diameter provided more energy storage media (concrete), resulting in high sensible energy storage within the Kiacrete slab. Conversely, the effect of pore number and diameter was relatively small on the heat transfer rates inside the Kiacrete slabs.

Keywords: Permeable pavements, thermal energy storage, parametric analysis

NONMENCLATURE

Abbreviations	
CRP	Clogging Resistant permeable Pavement
GSES	Ground Source Energy System
SHTES	Sensible Heat Thermal Energy Storage
TES	Thermal Energy Storage
LHTES	Latent Heat Thermal Energy Storage
TCES	Thermo-Chemical Energy Storage
HDPE	High-Density Polyethylene
CHT	Conjugate Heat Transfer
TSP	Thermal Storage Potential

1. INTRODUCTION

Concrete pavement heating represents a cutting-edge technology designed to enhance the safety, functionality, and lifespan of roads, particularly in colder regions [1,2]. These systems work by embedding heating elements (e.g. water pipes, electric resistance heating wires) within the pavement structure [3]. The main objective of these systems is to avoid the buildup of snow and ice, thereby improving the driving conditions and minimizing reliance on conventional de-icing techniques [4]. To enhance safety for pedestrians and vehicles during the winter period, we can use some of the low to medium temperature heat that is captured in the time of availability to keep the pavement surfaces free from snow or ice. These systems are especially beneficial for busy locations like airport runways, bridges, highways and essential infrastructure [5].

Thermal energy storage (TES) is one of the techniques employed to store heat in concrete materials [6]. There are three types of TES, namely: sensible heat thermal energy storage (SHTES), latent heat thermal energy storage (LHTES), and thermo-chemical energy storage (TCES) [7, 8]. When water (acting as heat transfer fluid) in embedded pipes in concrete is heated, the hot water can create pressured forced convections in the pipes. As a result, heat transfer takes place between the hot water and the pipe wall, and the heat is then passed on through conduction and convection to a heat storage material [9, 10]. This type of heat storage is termed as SHTES in which phase of the material is unchanged throughout the heat storage process; instead, it only changes the temperature of the material [11]. The

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components of a SHTES include the: i) heat storage material; ii) heat transfer device (heat exchanger); and iii) heat containment system [12]. As the temperature of the heat storage medium increases, its energy content also rises. Once the heating ceases, the stored heat is discharged from the material and conveyed to areas with lower temperatures [13]. For concrete based thermal energy storage systems, the system's ability to store thermal energy is directly proportional to the specific heat of the concrete. Additionally, because conduction is the sole method of heat transfer within the concrete medium, the thermal conductivity of concrete is a crucial factor affecting the system's heat absorbing and releasing rate [14].

This paper presents a numerically performed parametric analysis to investigate the thermal performance of a novel high strength clogging resistant permeable pavement (CRP, also known as Kiacrete). The standard Kiacrete slab has dimensions of 290 × 290 × 80 mm. This slab has a pore structure of 144 equidistant pores of 6mm in diameter, capable of passing water through the slab (Fig. 1). In this parametric study, eight designs of Kiacrete have been investigated with four different pore diameters (4mm, 6mm, 8mm and 10 mm) and two different equidistant pore numbers (144 and 121) for a 12-hour heating cycle. The purpose of this study is to investigate the effects of changing pore size and number to investigate any significant effect on the thermal energy storage potential of Kiacrete.

2. MATERIALS AND METHODS

2.1 Geometry description

Kiacrete is a novel permeable pavement that incorporates a recycled plastic-based linear pore structure within a self-compacting cementitious material shown in Fig. 1. The overall dimensions of Kiacrete in this study are 290 mm × 290 mm × 80 mm. The base plate of the standard pore structure is 3 mm thick and has 144 equally spaced pores, with each pore having a diameter of 6 mm. As described in Section 1, the number of pores and pore diameter have been varied in this study. The Kiacrete pavement slab sits on compacted aggregate (Thames Valley River gravel with a size of ≥5 mm) contained within a Perspex casing as depicted in Figure 2.

A high-density polyethylene (HDPE) pipe with a 24 mm inner diameter carries hot water and runs through the aggregate, making a contact with the Kiacrete slab at the bottom. This setup mimics the geothermal water heating used in real-world concrete pavement applications. A 190 mm × 230 mm × 15.24 mm aluminum cooling plate sits at the bottom of the arrangement, surrounded on the top and the sides by aggregates. The plate has embedded copper pipes of 8.12 mm in diameter with water of 10°C flowing through them, shown in Figure 2. This type of cooling arrangement was provided to obtain a constant temperature of 10°C for the aggregate layer to simulate the ground temperature conditions in the UK.

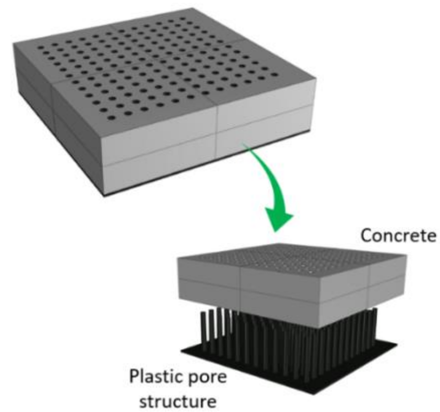


Fig. 1 Kiacrete structure

2.2 Simulation setup

The purpose of carrying out this parametric study is to investigate the effect of pore diameter on the thermal energy stored in the Kiacrete pore structure. Average temperatures of the concrete and pore structure were investigated at constant time intervals for a heating cycle of 12 hours. The heat transfer between the solid and fluid domains, specifically the concrete slab, hot water and cold water, were simulated using the conjugate heat transfer (CHT) module within the COMSOL Multiphysics software. The analysis focused on examining the effect of the diameter and number of pores on the heat storage potential of the concrete slab.

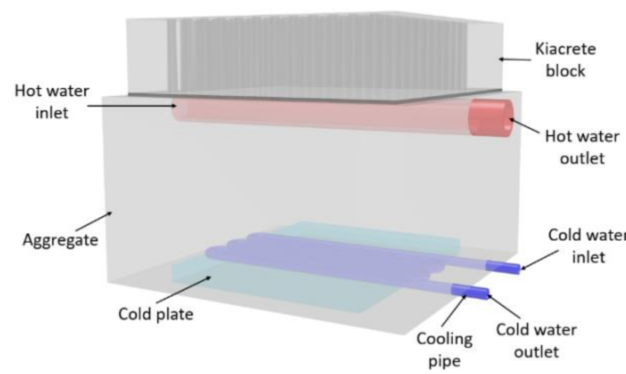


Fig. 2 Simulation model geometry

2.3 Boundary conditions

The purpose of this numerical model is to simulate the heating of a Kiacrete slab under real-life conditions. An inlet flow rate of 18.5 litres/minute was used for both hot water and cold water flows. The inlet temperatures were set to be 40°C for hot water and 10 °C for cold water, while the initial starting temperature for the whole setup was set at 22.6°C. The simulation was run in two parts. To bring the temperature of the aggregates to 10°C before the start of the heating, a simulation was run for cooling the water flowing through the cooling plate only for 24 hours. After this, both heating and cooling water flows were simulated for a physical time of 12 hours.

2.4 Analysis

The amount of thermal energy stored in the Kiacrete slab can be calculated in terms of volume, density, specific heat and temperature of its components i.e. the concrete and the recycled polypropylene pore structure. The amount of thermal energy stored in the Kiacrete slab in 12 hours of heating can be estimated by the relations given as [14,15]:

$$Q_{total} = Q_{conc} + Q_{pore} \quad (1)$$

$$Q_{conc} = \rho_{conc}\, V_{conc}\, C_{p,conc}\, \Delta T_{conc} \quad (2)$$

$$Q_{pore} = \rho_{pore}\, V_{pore}\, C_{p,pore}\, \Delta T_{pore} \quad (3)$$

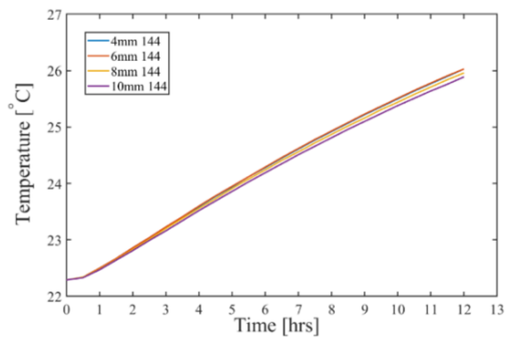
Where Q_{total} is the total amount of heat energy stored in the Kiacrete slab, Q_{conc} is the amount of heat energy stored in the concrete, Q_{pore} is the amount of heat energy stored in the pore structure, ρ_{conc} is the concrete density, V_{conc} is the total volume of concrete in the Kiacrete slab, $C_{p,conc}$ is the specific heat capacity of the Kiacrete slab, T_{conc} is the average concrete temperature, ρ_{pore} is the density of the pore structure material, V_{pore} is the volume of the pore material in the Kiacrete slab, $C_{p,pore}$ is the specific heat capacity of the pore structure material and T_{pore} is the temperature of the pore structure material.

3. RESULTS AND DISCUSSION

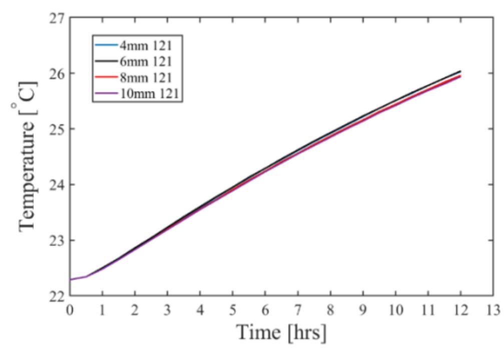
3.1 Average temperature of the Kiacrete slab

The average temperatures of different design configurations of the Kiacrete slab have been given in Figs. 3(a) and 3(b). In Fig. 3(a), the effect of pore diameter on the average temperature of the Kiacrete slab is shown for 144 pores configuration. It can be seen that the effect is very small and can be regarded as negligible. There is a maximum temperature difference of +0.15°C between the 4 mm pore diameter and the 10 mm pore diameter. Same results have been obtained for 121 pores configuration shown in Fig. 3(b).

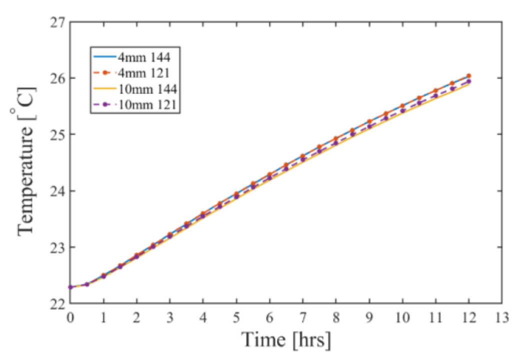
In Fig. 3(c), for the sake of simplicity, the effect of number of pores is illustrated on only two pore diameters i.e. 4 mm and 10 mm for 144 pores and 121 pore configurations. In here, the effect of the number of pores on the overall temperature of the Kiacrete slab is very small. Although a greater number of pores with larger diameters would promote convection heat transfer within the Kiacrete slab, but conduction heat transfer dominates in both 144 and 121 pore configurations because of the presence of very large volume of concrete as compared to pores.



(a)



(b)



(c)

Fig. 3 Average temperature of Kiacrete slab for different design configurations

3.2 Heat storage potential

A comparison of the TSP of different design configurations of Kiacrete is given in Fig. 4. An increase in the pore diameter is presented from left to right in Fig. 4 with respected pore number i.e., 144 and 121. For both the 144 and 121 pore designs, it can be seen from the chart that the TSP of the concrete part of the Kiacrete slab decreases as the pore diameter increases from 4 mm to 10 mm. Conversely, the TSP of the pore structure increases with increase in the pore diameter from 4 mm to 10 mm for both 144 and 121 pore configurations.

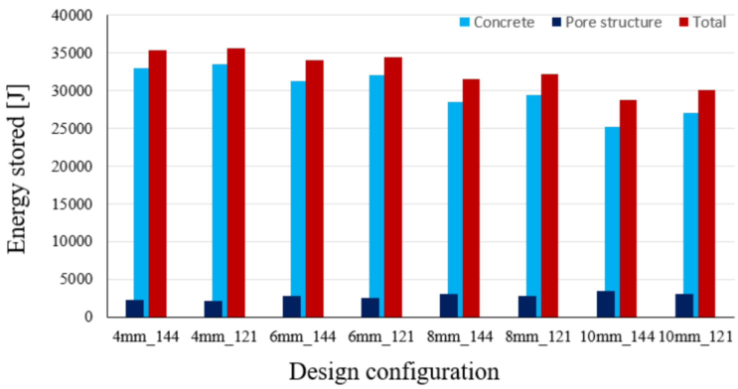


Fig. 4 Heat storage potential of different configurations

The effect of increasing the pore diameter on the TES potential of the Kiacrete slab is quite evident from Fig. 4. For the 144 pores configuration, a decrease of ~3.7% in the TES potential is observed when the pore diameter is increased from 4 mm to 6 mm. A linear decrease is found for each successive diameter increase. The highest drop of 18.7% is found in TES potential when the diameter is increased from 4 mm to 10 mm for 144 pore configuration. Likewise, 3.1% TES potential reduction is observed for the 121 pore configuration when the pore diameter is increased from 4 mm to 6 mm. This reduction in TES potential reaches to the highest value of 15.3% when the diameter is increased from 4 mm to 10 mm. If a comparison is drawn between the 121 and 144 pore configurations to investigate the effect of the number of pores in the Kiacrete slab on the TES potential, the 121 pore configuration offers slightly higher TES potential than that of the 144 pore configuration for all respective pore diameters ranging from 4 mm to 10 mm within the range of 0.71% (for 4 mm pore diameter) to 4.5% (for 10 mm pore diameter).

The main purpose of Kiacrete is to absorb stormwater to prevent surface flooding. Its added benefit is that it can also melt ice/snow using GSES and absorb this melt water, preventing it from re-icing. Therefore, both its thermal performance as well as its porous structure are of vital importance. Although, an increase in the thermal energy storage potential is evident by decreasing the number of pores and reducing the diameter size, it can decrease the water absorbing potential of Kiacrete. Clearly, we do not achieve a considerable TES potential rise for the slab when we decrease the number of pores from 144 to 121. Therefore, 144 pore structure configuration is more beneficial both in terms of its thermal performance as well as its ability to absorb more water. It is beneficial to investigate the effect of 6 mm or 8 mm pore diameter in the 144 pore configuration in future studies to further investigate the performance of the Kiacrete slab in melting ice/snow.

4. CONCLUSIONS

This study conducts a numerical parametric analysis to explore the heat efficiency of an innovative clogging-resistant permeable pavement called Kiacrete. Investigations were conducted on Kiacrete slabs with four different pore diameters (4 mm, 6 mm, 8 mm, and 10 mm) and two equidistant pore numbers (144 and 121) during a 12-hour heating cycle. The findings indicated that smaller pore diameters led to higher sensible energy storage within the Kiacrete slab, making them more effective as energy storage media. However, the impact of pore number and diameter on heat transfer rates within the Kiacrete was relatively minimal. It is evident that reducing the number of pores from 144 to 121 does not lead to a significant increase in the thermal energy storage (TES) potential for the slab. As a result, the 144 pore structure configuration proves to be more beneficial in terms of thermal efficiency and its capacity to absorb more water due to the higher number of pores. Therefore, it is more advisable to maintain medium-sized pore diameters, such as 6 mm or 8 mm, with the 144 configuration to further explore the Kiacrete slab's performance in future studies that are focused on melting snow/ice on its surface.

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