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Assessment of the thermal properties for the geothermal use of a permeable pavement structure for pedestrian and cycle paths

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Sustainable Drainage Systems (SuDS) have positioned themselves as one of the most widely applied Green Infrastructure (GI) techniques for sustainable stormwater management. In recent decades, new lines of research have emerged leading to the geothermal use of SuDS. The aim is to optimise available space in cities and minimise dependence on non-renewable energy sources.

Previous research has focused on determining the feasibility of combining the two technologies, both in laboratory and field studies. Other aspects such as the influence of the surface geothermal system on the quality of the water present in the SuDS were also studied. This previous research has focused mainly on permeable pavements, positioning them as one of the SuDS techniques of reference in this line of research.

This article attempts to give continuity to what has been established by other authors. It studies in depth the thermal properties of a complete section of permeable pavement under different hydraulic operating conditions. To this end, a complete section of a permeable pavement has been simulated in the laboratory using Hot-Box tests as set out in different international standards. With these tests, the values of thermal transmittance and equivalent thermal conductivity were determined.

The aim of this research is to establish a test procedure for the thermal properties of permeable floorings, based on standardised equipment. The aim is to better understand the heat transfer procedures inside SuDS. In this way, it will be possible to optimise the design of these in combination with surface geothermal elements.

Keywords: pervious paving systems, HOT-BOX TEST, surface geothermal system, SUSTAINABLE DRAINAGE SYSTEMS (SuDS), ENERGY-WATER NEXUS, GREEN INFRASTRUCTURE (GI), NATURE-BASED SOLUTIONS (NBS)

INTRODUCTION

In recent decades, cities across the globe have been facing increasingly demanding challenges [1]. In addition, the interruption of the natural hydrological cycle resulting from the waterproofing of large urban areas stresses the need for appropriate planning of stormwater management [2]. Sustainable Drainage Systems (SuDS) have established themselves as one of the most useful and widely implemented alternatives [3]. These drainage techniques fall under the umbrella of the Water Sensitive Urban Design (WSUD) ethos, as well as Low Impact Development (LID) philosophy [4].

On the other hand, there is a demand to implement renewable energy sources in urban environments, which contributes to the mitigation of energy dependence on conventional energy systems [5]. Low-enthalpy geothermal energy has become a robust renewable energy source for air conditioning and cooling in building structures [6]. The energy demand associated to buildings is equivalent to one-third of the total energy utilized in the EU [7]. This implementation is partially influenced by the availability of land within cities [8].

In order to solve these current problems, a new line of research has emerged in recent years consisting of combining SuDS and low enthalpy geothermal energy structures [8]. Hence, research on the water-energy nexus has been deepened since then [9]. To this end, a few studies have been carried out, both in the field and in the laboratory, on the geothermal potential uses of SuDS. These investigations have focused on the geothermal utilization of permeable pavements swales and green-blue roofs [10].

These preceding studies focused on the validation side of the combination of both technologies [11]. Research have been carried out on the possible effects that the introduction of a surface geothermal system would have on the water quality of the SuDS [12, 13]. Investigations have also been carried out on the thermo-hydraulic behaviour of SuDS under real operating conditions [14]. Finally, other studies targeted the assessment of the behaviour of permeable pavements with surface geothermal elements under real conditions [15].

The present research aims to continue this research line with a particular focus on the study of the thermal properties of a permeable pavement section, proposing a test procedure based on standardized equipment [16]. This investigation is one of the first attempts in the literature to characterise the thermal properties of a complete section of permeable pavement under different hydraulic operating conditions of pedestrian and cycle paths.

METHODOLOGY

A typical cross-section of a permeable pavement with a structure for pedestrian and cyclist use was developed for this study (see Fig. 1) [17, 18]. This section was made up of two layers; the lower one consisting of Atlantis Flo-Tank® drainage boxes, whilst the surface layer consists of limestone aggregate with a porosity of 35% and a bulk density of 2 690 kg/m^3. An intermediate layer was also placed between them containing a geotextile located on top of the drainage boxes, the main function of which is to acts as separation and filtering layer. The geotextile is made of short polyester fibre of 150 g/m^2, with a thickness of 1.0 ± 0.2 mm. These materials are normally used in this type of permeable paving structure [19].

A climatic generator and a calibrated hot box were used to calculate the steady-state thermal properties of the permeable pavement section under study. The climatic generator produces a heat flow with controlled temperature and humidity. The hot box is connected to the climatic generator, and

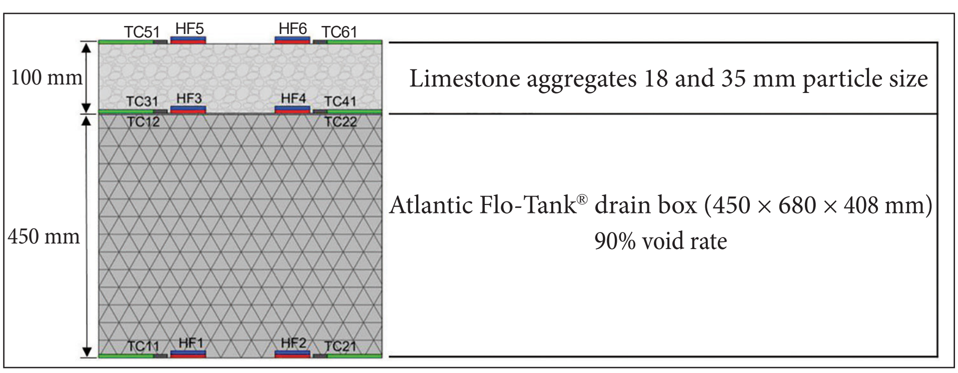

Fig. 1. Cross-section of a permeable pavement structure

the set test conditions are generated inside the 1 m^3 hot box. The test box is placed on top of the hot box. The test section was installed in the inside.

The test box was thermally insulated using a 5-cm-thick layer of extruded polystyrene ($\lambda_{polystyrene} = 0.033 \pm 0.003$ W/m·K). Data were collected using thermocouples (TC) and heat flux sensors (HF) fitted in the standard section, according to the distribution shown in Fig. 2. Measurements were taken every 10 min and collected using TRSYS equipment. The test equipment used is covered by the ISO 8990:1994 [20] and ASTM C1363-05 [21] standards.

The tests were carried out using three operating scenarios for the permeable pavement section studied: performing under wet, dry, and saturated conditions, corresponding to three of the possible hydraulic behaviours for a permeable pavement section. In dry conditions, the section described was simulated without the presence of water whatsoever. In saturated conditions, the section was simulated by filling the container completely with water, for which a total of 124.0 ± 0.5 litres was required. Finally, under wet conditions, the entire section was saturated and then as much water as possible was removed from the system.

The temperature was raised from 20°C (ambient temperature in the laboratory) up to 55°C during the test. This process was developed gradually in order to generate a steady heat flow through the section. The final test temperature was set at 55°C since the standards state that there must be a temperature difference between the lower and upper part of at least 15°C in order to be able to reliably use the measured values.

RESULTS AND DISCUSSIONS

It was possible to determine the thermal properties of the permeable pavement section studied for the different test conditions proposed with the temperature and heat flux values obtained in the laboratory tests. The following equations were used to calculate the thermal transmittance (TT) and the equivalent thermal conductivity (λ_{eq}):

$$TT\ [W/m^2\ K] = FT\ [W/m^2]\ /\ \Delta Temp\ [K], \quad (1)$$

$$\lambda_{eq}\ [W/m\ K] = TCHK\ [m]\ /\ R\ [m^2\ K/W], \quad (2)$$

where:

FT [W/m^2] is the average heat flux.

ΔTemp [K] is the temperature difference between the bottom and the top of the section.

TCHK [m] is the total thickness of the permeable pavement section under study.

R [m^2 K/W] is the thermal resistance, excluding the convection effects at the top and bottom of the test-box.

A 22-hour test was initially planned. Nevertheless, the test duration in the wet and saturated scenarios was extended since the temperature difference did not exceed 15°C during the first 22 hours. In this way, the temperature was gradually raised until the difference exceeded the 15°C established in the regulations. In

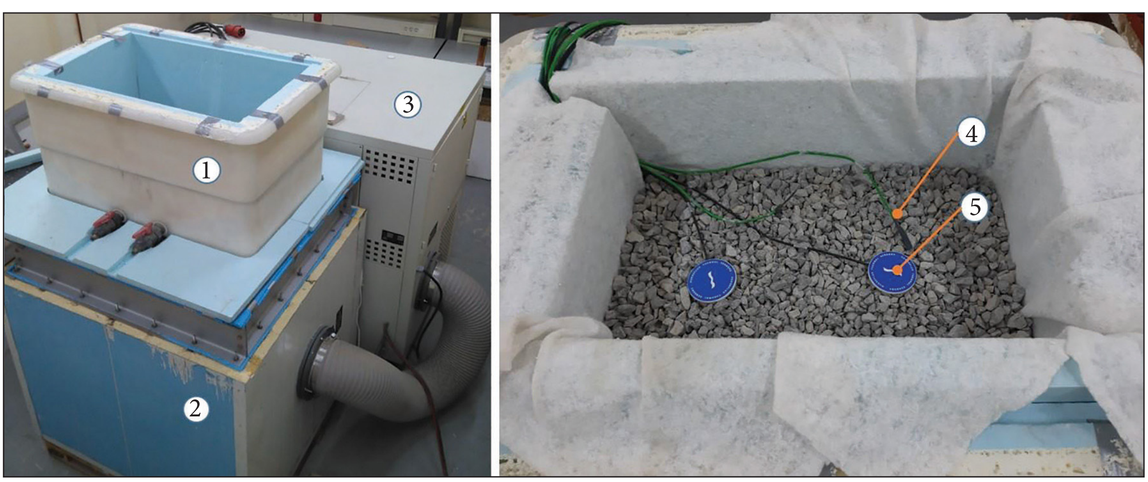

Fig. 2. Experimental set-up (1 – test-box, 2 – hot-box, 3 – climate generator equipment, 4 – temperature sensor, 5 – thermal flux sensor)

the case of the saturated test, it was observed that this temperature difference could not be reached, so the test was terminated.

The last 5 h of the tests were registered, where the stabilisation of the temperatures was observed, for the calculation of the thermal properties of the studied section. The temperature difference was constant over the last 5 h of the tests as presented in Fig. 3.

Figure 4 shows the thermal transmittance values obtained during the last 5 h of the tests. The graph depicts the three conditions tested.

Table shows the data obtained experimentally, after applying the methodological procedure described above. In general, the errors obtained were low, showing the consistency of this experimental procedure. Nevertheless, it would be convenient to increase the duration of the test,

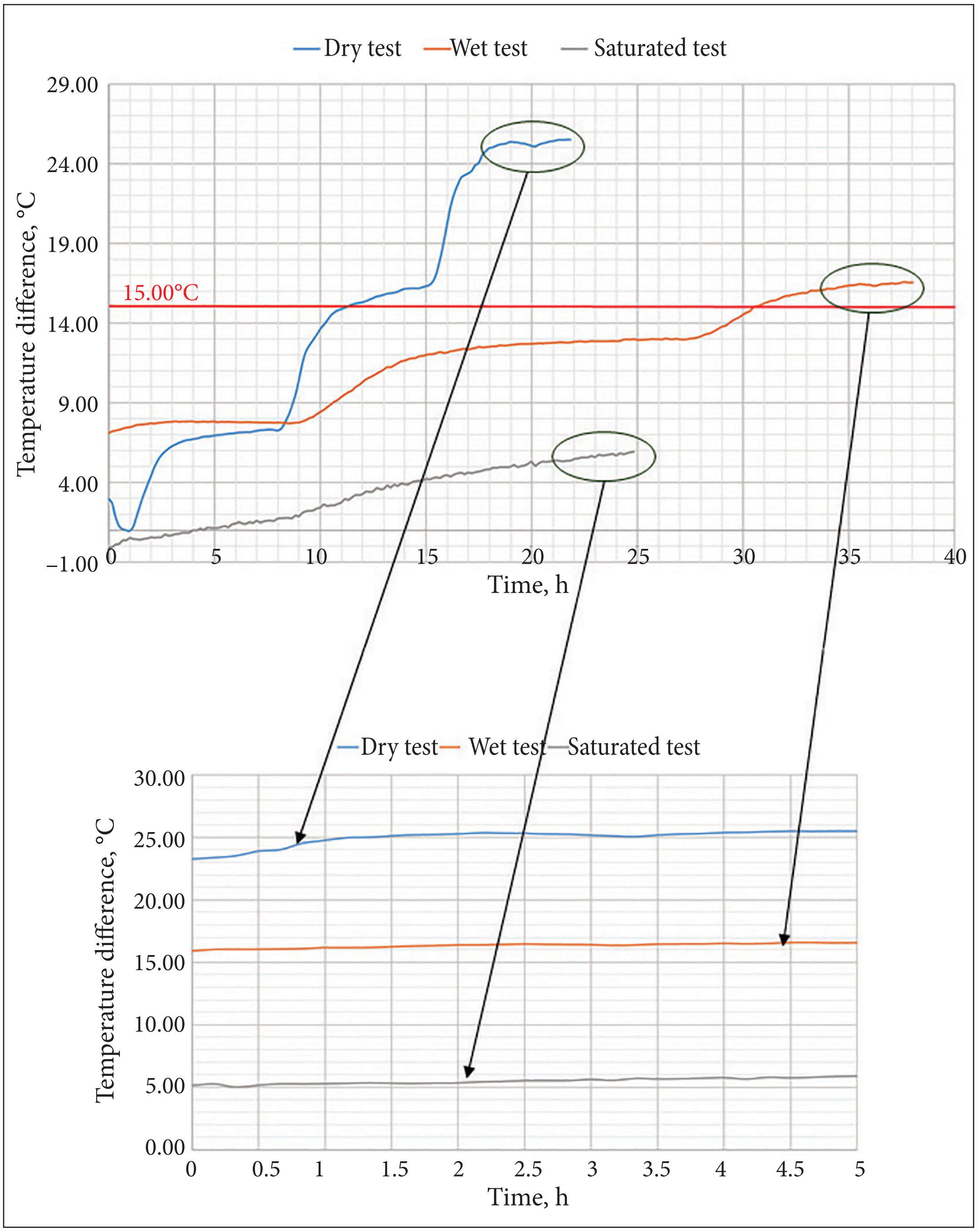

Fig. 3. Temperature difference between the lower and upper parts of the studied section

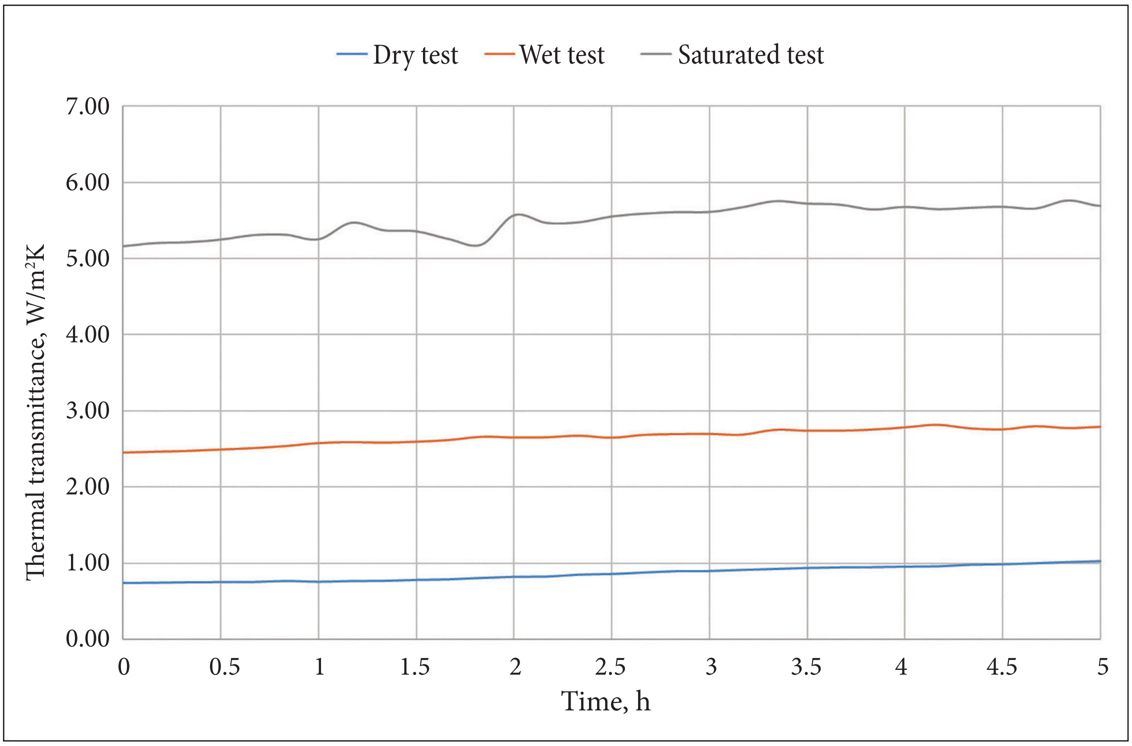

Fig. 4. Thermal transmittance during the last 5 h of the tests

Table. **Equivalent thermal conductivity and thermal transmittance values**

	TT (W/m^2K)	Absolute error (W/m^2K)	Relative error (%)	λ_{eq} (W/m·K)	Absolute error (W/m·K)	Relative error (%)
Dry test	0.87	0.09	9.98	0.39	0.04	10.01
Wet test	2.67	0.09	3.43	1.20	0.04	3.43
Saturated test	5.64	0.11	1.98	2.54	0.05	1.98

in order to have a better stabilization of the temperatures. This would improve the accuracy of the results obtained.

CONCLUSIONS

The thermal behaviour of a complete structural section of a permeable pavement was determined under different hydraulic operating conditions, becoming the first attempt in the literature to do so for the specific application of pedestrian and cycle paths. Standardised equipment was also used to study this section, introducing a new way to characterise the performance of permeable pavement sections when designed in combination with surface geothermal energy elements.

The procedure designed for this study proved to be useful for a pavement under wet and dry conditions. However, the results obtained under saturated conditions did not comply with the ASTM and ISO standards. This may be due to the fact that heat is transmitted through the water present in the section and the influence of the different materials in the section cannot be appropriately determined.

These experimental results provided positive feedback in order to improve the design of permeable pavements when designed in combination with surface geothermal elements. Thus, optimising these designs and avoiding the design problems represented in [22] such as the lack of thermal considerations suffered in a field design of a permeable pavement in combination with surface geothermal energy, representing a knowledge gap also identified by other authors [10, 23]. This research pointed out new applications which could contribute towards new developments of permeable pavement combined with renewable energy systems.

Future steps in this research line will require more laboratory tests, so that new materials and cross-sections can be fully evaluated thus determining the potential improvement of the thermal properties of the section. On the other hand, the data obtained experimentally can be used as a starting point for further numerical simulations. In these simulations, the influence of different materials in combination with surface geothermal elements can be also evaluated.

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PĖSČIŲJŲ IR DVIRAČIŲ TAKŲ PRALAIDŽIOS DANGOS KONSTRUKCIJOS ŠILUMINIŲ SAVYBIŲ ĮVERTINIMAS GEOTERMINIAM NAUDOJIMUI