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Fluid Transport within Permeable Pavement Systems: A review of evaporation processes, moisture loss measurement and the current state of knowledge

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ABSTRACT

The purpose of this review is to give an up to date overview of the existing literature in fluid transport processes within Permeable Pavement Systems with the main focus on evaporation. The paper summarises the internal and external factors influencing evaporation rates in Permeable Pavement Systems, such as characteristics of pavement surface and sub-surface layers, presence of water barrier/treatment systems, the water availability near the surface and ambient conditions. Experimental methodologies and designs used to investigate evaporation in laboratory and field settings are discussed, as well as limitations and constraints identifying existing gaps with the potential for further research.

KEYWORDS

Evaporation; Permeable Pavement Systems; SuDS; fluid transport; porous media

1. Permeable Pavement Systems as porous media

Permeable Pavement Systems (PPS) are Sustainable Drainage Systems (SuDS) designed to control water quantity by reducing runoff volume, delaying peak flow (Andersen et al. 1999, Brattebo and Booth 2003, Fernández-Barrera et al. 2008, Gomez-Ullate et al. 2010, Sañudo-Fontaneda et al. 2014) and improve water quality by retaining and treating pollutants, such as hydrocarbons (Pratt et al. 1998, Newman et al. 2002a) by means of oil degrading microbial mixtures (Coupe et al. 2003) and heavy metals (Dierkes et al. 2002), total suspended solids, nutrients and sediments (Brattebo and Booth 2003, Bean et al. 2007 Beecham et al. 2012, Drake et al. 2014) and enhance amenity and biodiversity (Woods-Ballard et al. 2015). PPS can be associated with porous media, as by definition, a porous medium must contain pores or voids, free of solids containing some type of fluid such as water, air, oil, or a mixture of fluids (Dullien 1979). PPS are designed to consist of layers of porous or permeable materials placed in a specific way to retain water and consequently, fluid transport processes in PPS can be explained by implementing principles from the relevant fields in research on porous media. PPS hydraulic design can be classified into various categories depending on the design of the sub-layers and the type of surface material (Ferguson 2005) and can vary widely depending on factors such as the underlying soils, catchment area and weather conditions (Woods-Ballard et al. 2015). Despite this variability, PPS are very often designed as multi-layered porous media of varying porosities.

2. Fluid transport processes

2.1 Porous media

Fluid transport processes in porous media are better understood using a multi-scale approach. The flexibility of studying such phenomena on various scales has the advantage of transferring knowledge between spatial scales. Problems can be simplified by ignoring observations in micro-scale if they do not affect transport mechanisms at the observation scale, and when simplifying assumptions are not possible. Microscopic simulations and observations can provide insights for underlying mechanisms of macroscopic processes and conceptual models, upscaled to define systems at observational scale (Prat 2002).

Research on fluid flow through porous media dates back to 1856 when Henry Darcy experimentally determined the flow velocity through sand columns and introduced Darcy's law. Darcy's law is widely accepted and used in hydrology for groundwater flow modelling (Mulqueen 2005). Multi-directional flow through porous media involves various processes, depending on the phase of the transported fluid (liquid or gas). In liquid phase, fluid flow is driven by gravitational forces, capillary forces and pressure and temperature gradients, whereas, when in gas phase, the flow is diffusional and closely dependent on vapour density gradients (Philip and De Vries 1957, Bouddour et al. 1998). Despite the vast quantity of research on fluid transport processes in porous media, such processes have been rarely applied to PPS and insufficiently understood in an urban drainage context.

2.2 PPS

A survey of published research on fluid transport processes in PPS systems was conducted using Scopus and Google Scholar search engines to identify the number of publications solely on hydraulic processes and to follow the change in interest on evaporation and heat transfer in PPS in the period 1988-2019 (figure 1).

The first search was performed on published journal, press and conference papers under the terms "porous pavement", "pervious pavement", "permeable pavement", "pervious concrete", "porous concrete", "porous asphalt" and "porous paver" and was limited based on terms such as "infiltration", "hydraulic", "hydrologic", "water quantity" and "permeability". 187 publications related to the above search terms were identified. The second search, limited to "heat", "temperature", "evaporation", "thermal", "moisture", "urban heat island", "cool pavements" and "drying" generated a total of 88 publications. In figure 1, between 1988 and 2001, due to the limited number of publications, differences between the two areas of research were not significant, although looking in the period 2015-2018 the number of publications related to evaporation and heat transfer was 2-5 times lower than the number of publications on non-evaporation related hydraulic processes.

Due to the novelty of the field, the vast majority of research on fluid transport processes in

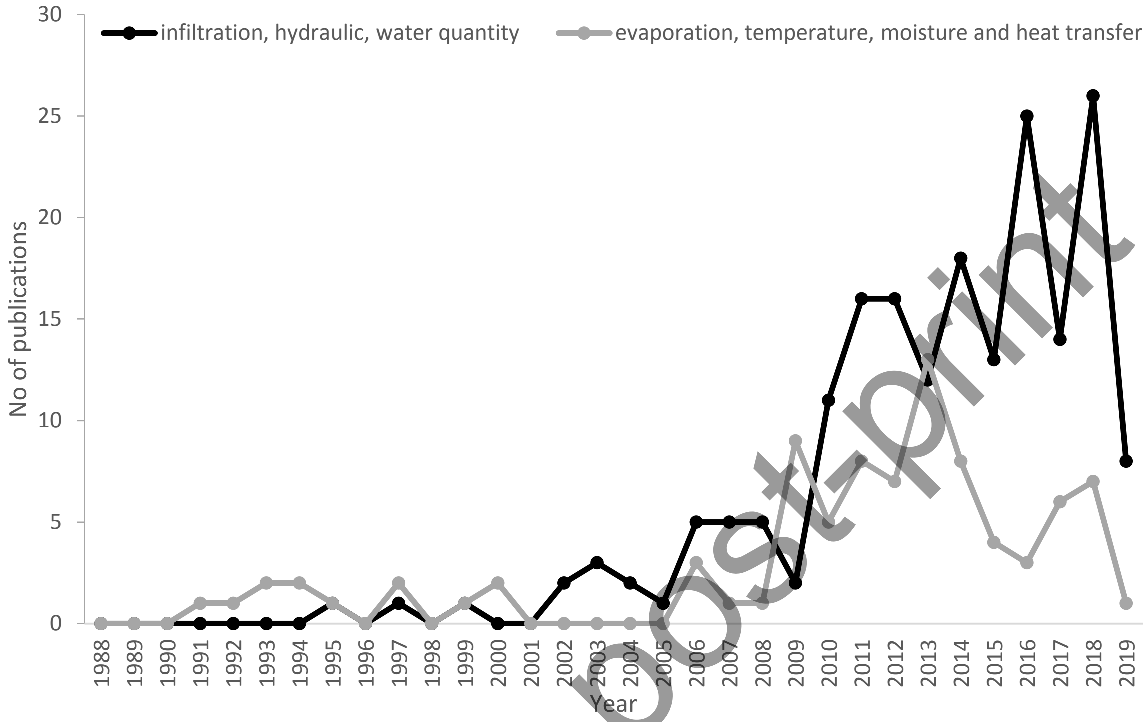

Figure 1.No of publications in the period 1988-2019

PPS is limited in a macroscale or observation scale, where transport processes are simply studied in a continuum. Amongst the 88 publications related to evaporation and heat transfer in PPS, only 28, which are presented in figure 2, were focused on measuring evaporation either through laboratory or field studies, with the first study conducted in 1999 by Andersen and colleagues at Coventry University. An increased interest in evaporation in PPS was observed in 2008 onwards (figure 2), indicating a deeper understanding of the hydraulic mechanisms within PPS and a broader interest in identifying alternative ways to improve the hydraulic capacity of such systems to respond to a variety of climatic conditions.

Figure 2.No of publications closely related to Evaporation in PPS

Whilst PPS have gained broader acceptance, the potential for wider implementation and optimisation is restricted, unless there is a broader and deeper understanding of the basic transport mechanisms within. The focus of this review paper is to investigate published research on evaporation from PPS to identify its influence on water budgets, the factors influencing evaporation in PPS, the limitations of experimental methods utilised, and existing gaps with the potential for further research.

3. Evaporation in PPS

During evaporation in porous media, the pore-filling fluid in liquid phase is gradually replaced by a fluid in gas phase creating a drying front (Yiotis et al. 2003, Lehmann et al. 2008). This process is highly dependent on medium internal and external parameters. Ambient conditions such as temperature, air current, humidity and solar radiation and porous medium structural and hydraulic characteristics such as pore space, pore size distribution, homogeneity and water availability dictate the evaporation rate from porous media (Shokri et al. 2008, Lehmann et al. 2008).

In PPS, fluid transport involves infiltration of rainwater from direct rainfall and runoff from adjacent impervious surfaces, through the surface layer into the sub-layers, where a percentage is retained to potentially either evaporate back to atmosphere or made available for reuse. The excess water will percolate into the underlying soil, or exit through a drainage pipe or a combination of the two, depending on the water holding capacity and hydraulic design of the system (figure 3) (Woods-Ballard et al. 2015).

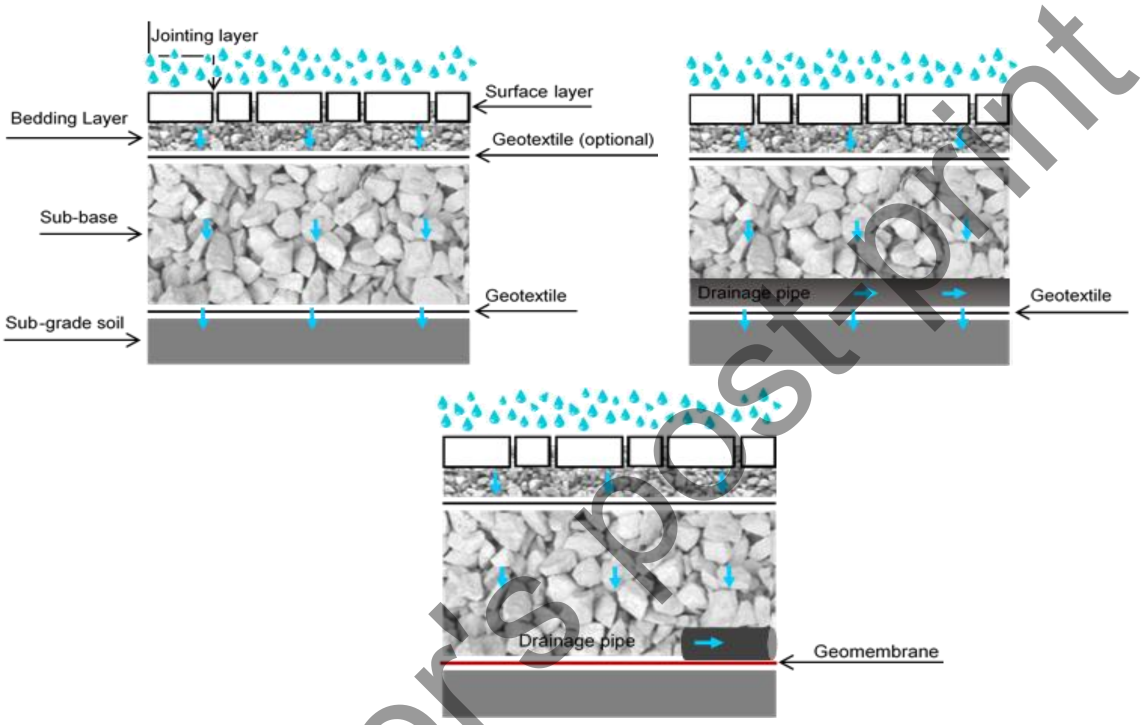

Figure 3. Total infiltration, no infiltration and partial infiltration PPS (Adapted from Interpave 2013)

The structural design of PPS varies widely depending on the traffic category, sub-grade quality and the type of surface material used (BS 7533-13:2009). According to the Construction Industry Research and Information Association (CIRIA) guidance, the grading of each aggregate layer can vary from 2/6.3 to 0/40, therefore affecting the pore space of the medium and consequently the involved fluid transport mechanisms (Prat 1993, Lehmann et al. 2008). In addition, placement of any permeable barrier (geotextiles) between aggregate layers increases the number of interfaces between layers of different hydraulic conductivities disrupting the hydraulic continuity (Zornberg et al. 2010).

3.1 Structural characteristics

3.1.1 Surface material and sub-surface layers

PPS can be designed with as many as nine different surface materials such as open jointed blocks, porous aggregate, plastic geocells, porous turf, porous concrete, open celled grids, porous asphalt, decks and “soft” pavement materials (Ferguson 2005). Despite that, research on evaporation rates from PPS is limited to specific surface materials summarised in Table 1. Out of 28 publications, porous concrete is by far the most researched surface material followed by porous asphalt and permeable blocks (table 1). Depending on the selected surface material, PPS can be classified as porous or permeable and exhibit differences in hydraulic behaviour. Generally, a porous system such as porous concrete, porous asphalt and porous concrete blocks will have a higher percentage of open surface to the atmosphere and will infiltrate water through the entire surface into the sublayers, while, permeable surfaces, such as concrete blocks, are made of impermeable pavers installed in a way to allow free flow of water through pore spaces in the joints (Woods-Ballard et al. 2015).

Surface material	Publication
Porous asphalt (PA) Including PA with water-retaining product based on a silica compound, Porous Hot-Mix Asphalt (PHMA) and Open-Graded Friction Course (OGFC)	(Asaeda and Ca 2000) (Stempihar et al. 2012) (Li et al. 2013) (Novo et al. 2013) (Poulikakos et al. 2013) (Li et al. 2014) (Brown and Borst 2015) (Jerjen et al. 2015) (Lal et al. 2017) (Aboufoul et al. 2019)
Porous Concrete (PC) Including Portland cement porous concrete (PCPC) and porous concrete with viscose fibres	(Asaeda and Ca 2000) (Haselbach et al. 2011) (Nemirovsky et al. 2011) (Nemirovsky et al. 2013) (Novo et al. 2013) (Li et al. 2013) (Syrrakou et al. 2014) (Li et al. 2014) (Brown and Borst 2015) (Teodosio et al. 2015) (Qin and Hiller 2016) (Qin et al. 2016) (Wu et al. 2017)
Porous Blocks Including porous concrete blocks, sintered ceramic porous bricks (CB) and Recycled aggregate porous brick	(Asaeda and Ca 2000) (Göbel et al. 2008) (Kevern et al. 2009) (Starke et al. 2010) (Starke et al. 2011a) (Sriravindrarajah et al. 2013) (Wang et al. 2018)
Concrete blocks Including CeePy concrete blocks, Permeable Interlocking Concrete Pavers (PICP) and Aquaflow permeable blocks	(Andersen et al. 1999) (Asaeda and Ca 2000) (Coupe et al. 2006) (Gómez-Ullate et al. 2008) (Starke et al. 2010) (Li et al. 2013) (Novo et al. 2013) (Brown and Borst 2015)
Grass Pavers Including reinforced grass with concrete grid and reinforced grass with plastic grid	(Starke et al. 2011a) (Novo et al. 2013)

Table 1. Publications on evaporation in PPS sorted by selected surface material

The basic concept is that the bigger the surface, the more liquid is exposed to the atmosphere and thus, the higher the evaporation potential; this has been widely discussed by studies on fluid transport in porous media (Shokri et al. 2008, 2010, Or et al. 2013). This concept is supported by the Starke et al. (2010) observation that porous concrete pavers showed a 16% higher evaporation rate compared with impermeable paving stones, mainly due to the stored water in the voids of the surface material, freely available for evaporation. In agreement with Starke et al. (2010), Brown and Borst (2015) observed that porous concrete had a significantly higher evaporation compared with Permeable Interlocking Concrete Pavers (PICP) and Porous Asphalt (PA) between which, no significant differences were observed on evaporation rates. Although, PA and PICP exhibited similar evaporation rates, it is worth noting that the sub-layers were not identical. PA surface was laid on a 10cm thick of 63/37.5mm aggregate whereas, PICP was laid on a 5cm laying course of 9.5/2.3mm aggregate and a 10cm choking layer of 25/4.75mm aggregate (Brown and Borst 2014). Despite the higher percentage of pore space in PA surface, the sub-layers of PICP were thicker and of varied hydraulic conductivities, in contrast to the single layered sub-base of PA. The coarse gravel layer in PA with limited fines, in addition to the highly porous asphalt surface might have limited evaporative drying due to the inability to provide water to the liquid/gas interface for vaporisation (Shokri et al. 2008, Lehmann et al. 2008, Shokri and Or 2011) resulting in similar evaporative drying with PICP pavement. Aboufoul et al. (2019) utilised X-Ray computed tomography and 3-d printing technology to investigate the influence of pore space topology of porous asphalt on water retention and evaporation. Due to the high porosity of the designed porous asphalt specimens' capillary forces could not facilitate water movement to the surface once the surface was dry, resulting to a disconnected drying front as shown previously by Shokri et al. (2008). The mechanism in which evaporation takes place in porous media has been classified into two stages. A constant and a falling rate stage. During the constant rate stage, mostly capillary driven evaporation is high and relatively constant, up until water films break due to inability to attract additional water (Scherer 1990, Prat 2007, Shokri et al. 2010). Aboufoul et al. (2019) observed that stage one evaporation was almost negligible compared with the long stage two evaporation, mainly controlled from pore shape and pore size distribution.

Grass pavers showed higher evaporation rates compared to all permeable and impermeable surfaces due to capillarity of the soil and transpiration from grass itself (Starke et al. 2011b) Capillary forces transfer water to the surface, increasing the volume of water readily available for evapotranspiration. As a background, Scherer (1990) observed that if a liquid evaporates in a film from a porous medium, a capillary tension develops on the drying film, drawing liquid from lower plates to create uniformity in hydrostatic pressure. Despite the importance of capillary rise in PPS, in very low temperatures this is not facilitated, due to the risk of freezing and the potential to cause cracking and stability issues when water is available in the upper layers of the pavement (Zornberg et al. 2010, Nemirovsky 2011). Göbel et al. (2008) observed that impermeable areas with seams and vegetated areas presented higher evaporation rates than permeable areas, which can only be attributed to the higher evaporation potential due to capillary rise in grass areas and due to connection of seams with the sub-layers of the pavement allowing for vapour transfer, thus explaining Starke et al. (2010) and their observed evaporative drying from impermeable surfaces, despite their dry surface.

Generally, permeable surfaces compared with impermeable surfaces show higher evaporation rates due to the open surface area and the porosity of the layers below. Fine grains have larger surface to volume ratio than coarse materials. Therefore, a higher amount of water is in contact with the material and via cohesion power, the water is retained close to the surface material, thus promoting higher evaporation rates. Studies by Li et al. (2014) showed that sand samples presented the higher evaporation rates amongst other coarser gravel types despite having low permeability and air void content, due to their ability to move moisture upwards towards the surface by capillary action. In materials with weak capillary rise action, the higher the permeability the higher the evaporation potential. (Li et al. 2014). The Li et al. (2014) study could not identify any contribution on evaporation rates from sub-layers and it rather strengthened the argument that water near the surface is subject to higher evaporation rates and underlined the significance of capillary action for increased evaporation potential, in contrast with Starke et al. (2010)

3.1.2 Water availability near the surface and levels of saturation

Andersen et al. (1999) observed that designs with the highest water retention showed the highest evaporation rates, concluding that evaporation is influenced by the water availability in the structure also supported by Göbel et al. (2008), Nemirovsky et al. (2011, 2013), Syrrakou et al. (2014), Li et al. (2014), Qin and Hiller (2016) amongst others.

Göbel et al. (2008) showed that although evaporation could potentially happen in the bottom layers of pavements, the highest contribution on evaporative volume comes from the upper layer and evaporation rate decreases with increasing distance from the surface, supported by Nemirovsky et al. (2011), by examining evaporation rates from laboratory pavement designs with different depths of ponded water. It was shown that the distance of ponded water from the surface is a very sensitive parameter, with the higher evaporation rates observed during saturated conditions and with a decreasing contribution to overall evaporation rate when moving downwards (Nemirovsky et al. 2011). The non-significant evaporation rates from designs with ponded water in deeper layers can be explained due to very weak capillary forces in porous media with high porosity as is the case in PPS sub - layers. Presence of water below a specific depth from the surface appeared not to influence total evaporative volume, which suggests that there is a specific zone up to where presence of free water can be of any significance. This can be attributed to an inability of capillary forces to overcome gravity and viscous forces facilitating a downwards movement, to encourage liquid movement to a vaporisation interface (Lehmann et al. 2008). In the case of Nemirovsky et al. (2011), the critical depth on which after there was no contribution was 254mm as there was no change on measured evaporation when a depth of 381mm was examined. In agreement with Nemirovsky et al. (2011) findings, studies by Syrrakou et al. (2014) and Brown and Borst (2015) obtained evaporation rates in the same order of magnitude. Laboratory relative humidity and temperature were not controlled in the Syrrakou et al. (2014) study and the designed column of the specimen was not insulated. This was in contrast with Nemirovsky et al. (2011), which had fully controlled ambient conditions and an insulated column to avoid horizontal heat transfer. Syrrakou et al. (2014) examined evaporation rates from systems with no ponded water, which in the case of PPS represent systems with an underdrain or high infiltration sub-grade. Despite the limitations of the study, Syrrakou et al. (2014) showed a non-linear decreasing trend on evaporation rates of such systems with respect to water availability, a fact that supports the argument that water availability is a governing factor on evaporation rates. The latest study on evaporation and water availability in Porous concrete by Qin and Hiller (2016), strengthened the previous argument by investigating the influence of different depths of ponded water similar to Nemirovsky et al. (2011), observing that the lowest depths contribute the least in evaporative cooling to an almost negligible rate. Enhancement of evaporative cooling through retention of water near the surface, has been the basic concept of studies on new water-holding pavements such as, the “Road cool” with fine - blast furnace powder (Takahashi and Yabuta 2009), porous asphalt pavements with water retaining fillers based on silica compounds (Nakayama and Fujita 2010), self-cooling concrete pavers with viscose fibres (Barthel et al. 2013, 2016), water retentive pavers with fly ash (Cortes et al. 2016) and interlocking paver blocks sealed with impermeable mortar (Qin et al. 2018) amongst many others.

3.1.3 Surface albedo and Urban Heat Islands (UHI*)*

Starke et al. (2010) investigated the influence of the colour of surface materials on evaporation rates by comparing a grey and an anthracite coloured pavement, concluding that a darker paving stone encourages higher evaporation rates mainly due to lower albedo. A lower albedo leads to higher energy absorption from sunlight and therefore, higher energy available for evaporation (Santamouris 2013). Zhang and Guo (2015) demonstrated that porous concrete may not be the best solution to mitigate UHI due to the observation that porous asphalt and concrete showed higher temperatures compared with dense concrete during the day and lower temperatures during the night. The concept of high reflectivity resulting in lower temperatures and therefore contributing towards limiting the near-surface heat island effect, acts against the concept of lower reflectivity, higher solar radiation absorption and thus, more evaporative cooling (Li et al. 2013). Porous pavements have lower reflectivity than conventional equivalents due to higher porosity and consequently, warmer surfaces from the absorbed solar radiation. Aida and Gotoh (1982) suggested that any contribution from evaporation in cooling the pavement surface, was insignificant as porous surfaces absorb extra heat compared to dense surfaces due to lower thermal conductivity.

3.1.4 Water barrier/ treatment systems

Geotextiles as part of PPS can be placed either between the subbase and laying course or subbase and subgrade providing separation and structural support (Woods-Ballard et al. 2015). Microbial activity is encouraged, improving water quality by enhancing biodegradation processes (Coupe et al. 2003). The need for placing a geotextile in the upper layers of PPS to improve water quality has been reported by Pratt et al. (1999), Newman et al. (2002b) and Coupe et al. (2003) while others argue that geotextiles contribution on sediment retention is not significant enough to deem necessary (Lucke and Beecham 2011). Additionally, the presence of geotextiles between pavement sub-layers could potentially act as a barrier to evaporation or enhance evaporation rates depending on the specifications of the geotextile, but little evidence is available on the hydraulic benefits from geotextiles. Gómez-Ullate et al. (2008), the only available study on evaporation rates from systems with geotextiles, compared Inbitex, a non-woven polypropylene polyethylene geotextile and one-way geotextile, a composite of Inbitex and a plastic membrane with no geotextile systems in laboratory settings. Evaporative drying took place in different stages and rates due to the nature of one-way composite. Initially, due to very slow release of water from one-way composite in the sub-base, more water was readily available and thus, the evaporation rate was higher compared with Inbitex and designs without geotextile. Once the water had reached the sub-base, Inbitex and Control rigs exhibited higher evaporation rates with the highest evaporation rate observed in the control rigs. This behaviour is to be expected because the plastic membrane of one-way geotextile acted as a barrier to evaporative losses from the sub-base (Gomez-Ullate et al. 2010) .This observation supports the argument that evaporative losses from the sub-base contribute significantly in the overall evaporative volume.

3.2 Ambient conditions and heat transfer

There has been an overall observation that evaporation rates are always high following a rain event (Starke et al. 2010, Nemirovsky et al. 2011, Haselbach et al. 2011) complying with the observation that water availability promotes high evaporation rates (Li et al. 2013). The thermal profile of a PPS is highly correlated with ambient temperature and the heat conductivity of the medium, making it sensitive to solar radiation changes, either during the span of a day or seasonal variations (Nemirovsky et al. 2011). In 2016, Qin et al. by means of an air permeameter examined the gas permeability of porous concrete concluding that the low gas permeability cannot promote heat transport by natural convection, limiting it only to gas diffusion. Heat transfer by vapour diffusion becomes increasingly difficult moving deeper in the pavement concurring with the Nemirovsky et al. (2011) finding (Qin et al. 2016). Lal et al. (2017) using Neutron radiography, confirmed that convective drying is limited near the surface in porous asphalt and observed influence of wind speed only on that occasion. Due to the heat transfer mechanism, a lag on the thermal response may be observed depending on the depth of the pavement and thus moving downwards, a total disconnection from changes in ambient temperature is possible. Asaeda and Ca (2000) ran field tests on porous blocks, ceramic porous blocks, traditional asphalt and grass surface, indicating that temperature fluctuations on all surfaces were higher than in the sub-layers and the responsiveness to temperature fluctuations was related inversely to depth. Data taken from Kevern et al. (2009) and analysed by Nemirovsky et al. (2011) showed that depths up to 610mm were responsive to daily temperature changes, while depths of 610mm and below responded to only seasonal changes, supporting findings by Asaeda and Ca (2000). Later on, Novo et al. (2013), examined the thermal response of parking lots with reinforced grass pavers in Las Llamas parking at University of Cantabria, finding fluctuation in temperatures due to diurnal cycle higher at 15cm deep in comparison to 50cm deep, confirming the argument about thermal responsiveness by Haselbach et al. (2011). Overall, evaporation appears to follow a cyclic trend in response to diurnal cycle (Nemirovsky et al. 2011, Li et al. 2014).

Nemirovsky et al. (2011) observed that evaporation rates were higher at solar radiation peaks and not at the highest temperatures. Ambient temperature peak was two hours behind the corresponding evaporation peak. Nevertheless, surface temperatures followed solar radiation trends, with the temperatures of the sub-layers lagging behind depending on the depth (Nemirovsky et al. 2011, Novo et al. 2013). Qin and Hiller (2016) observed that porous concrete stays cooler than conventional concrete after wetting, for approximately twelve to twenty-four hours, in which then the latent heat flux becomes negligible and thus, temperature rises similar to conventional concrete, supporting the Haselbach et al. (2011) observation about similar heat balance on porous and conventional concrete during dry days but higher heat loss from porous concrete only after daytime rain events . Porous concrete lower thermal inertia, causes low resistance on temperature fluctuations and thus, at night is cooler than conventional concrete but during the day, the low thermal conductivity limits heat transfer to the sub-layers resulting in a very hot surface (Asaeda and Ca 2000, Qin and Hiller 2016) .

4. What are the methods used to investigate evaporation in PPS?

One of the limiting factors during measurements of sensitive mechanisms such as evaporation from PPS is the lack of appropriate measurement methods, as well as the challenging task of simulating realistic weather conditions which are highly correlated with evaporation rates. Considering the small number of publications on evaporation from PPS, many attempts were made to develop methodologies for both laboratory and field conditions alongside mathematical and computational models (Nemirovsky et al. 2013, Teodosio et al. 2015, Qin and Hiller 2016) to validate the methods and correlate evaporation rates with variables such as temperature, wind speed, moisture content and internal characteristics of pavements. The methods in the literature are quite limited to mass flow measurements using mass balances and load cells (Andersen et al. 1999, Gómez-Ullate et al. 2008, Nemirovsky et al. 2013, Syrrakou et al. 2014, Li et al. 2014) and to measurements of relative humidity utilising humidity sensors (Göbel et al. 2008, Starke et al. 2010, 2011b).

In 1999, Andersen et al. developed a research methodology to investigate the hydrological response of permeable pavement designs in laboratory settings and the influence of water availability on evaporation rates. A knife-edge balance was constructed to capture the changes in mass to estimate evaporative losses alongside a monitoring system to continuously capture drainage rates during and between rain events (figure 4).

Figure 4. Knife edge balance (Adapted from Andersen et al. 1999)

Attempting to investigate evaporation rates from heavy structures can be challenging in order to achieve high precision to capture small changes in mass while having the capacity to weigh heavy loads as documented by both Andersen et al. (1999) and Syrrakou et al. (2014). Andersen et al. (1999) used measuring apparatus, based on a beam balance with three knife edge points (A, B, C) to reduce friction and increase accuracy. The estimated accuracy of the device was five grams in one hundred kilos. The balance was attached on a jib arm extension which fitted a hoist with an adjustable crane arm (D). The mass measurements were taken using counterbalance weights before, immediately after the rainfall simulation and every twenty-four hours to capture evaporative losses. The actual evaporation was then compared with potential evaporation from an 'evapopan' exposed to the same ambient conditions. Measurements from 'evapopan' were taken using a micrometer connected to an AVOmeter. In the case of Brown and Borst (2015), potential evapotranspiration was computed using the Thornthwaite equation with correcting factors, using ambient temperatures readings taken from the site under investigation. Syrrakou et al. (2014) similarly to Andersen et al. (1999), made use of a counterbalance by hanging two columns of the same dimensions and weight on a balance. Column one comprised the design under investigation while column two was acting as a counterbalance filled only with crushed stone. Column two was then connected to a load cell in order to monitor the changes on the applied tension over time.

Göbel et al. (2008), in an attempt to optimise the characteristics of water permeable pavements made use of a gauge to monitor evaporation in field conditions. The device called 'Tunnel- Verdunstungsmesser' in German and in short TUV, was developed by Professor Werner at University of Münster in Germany to measure the actual

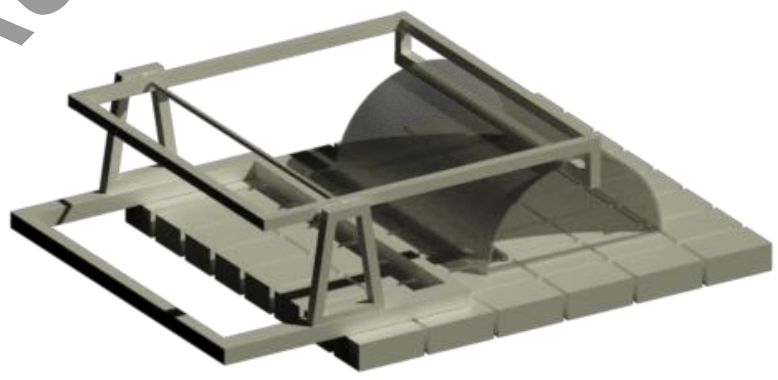

Figure 5.TUV (Adapted from Werner 2000)

evapotranspiration from vegetated and non-vegetated areas in an attempt to improve accuracy of measurement and avoid expensive previously used devices such as lysimeters and tensiometers (Werner 2000, Göbel et al. 2008).

The apparatus was made from a flexi glass halfpipe open on both ends with ventilators producing airflow on horizontal plane and a wind sensor, which controlled the wind speed in the tunnel. Furthermore, two humidity sensors captured the difference of relative humidity of inflow and outflow air in both ends of the tunnel.

The collected humidity, wind speed and temperature readings were inputted on an evapotranspiration formula for estimation. The variability of the TUV was estimated at 10% by comparing the evapotranspiration values with lysimeter reference values.

In a continuous attempt to improve the experimental method of measuring evaporation from urban surfaces, Starke et al. 2011b attempted to design a Laboratory Evaporation Measuring Device (LEMD) using the same principle as TUV (Werner 2000) used for field measurements, but with the added capacity for mass flow measurements. The device was similarly equipped with two temperature-humidity sensors (1,2) on each end of the inlet and outlet to monitor differences in relative humidity, a ventilator (3) to induce

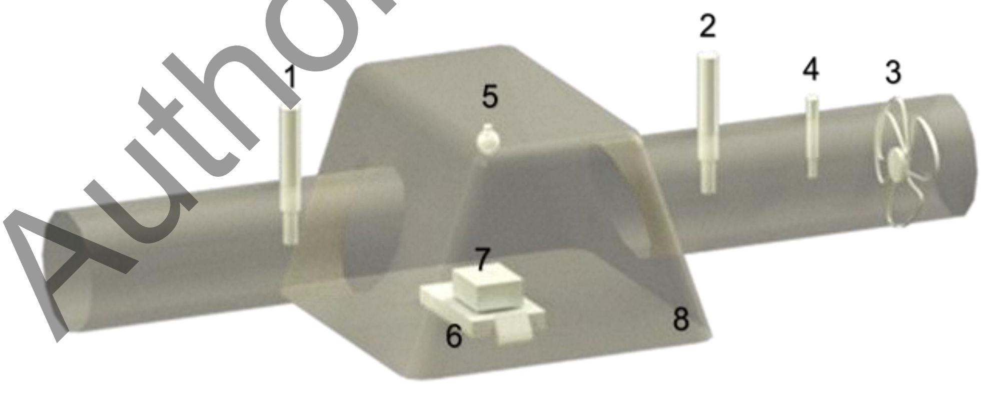

Figure 6.LEMD (Adapted from Starke et al. 2011b)

airflow and a thermocouple anemometer (4) to monitor the air speed. The LEMD was additionally equipped with a deep heat lamp (5) to simulate solar radiation and a mass balance for mass flow measurements (6). The specimens (7) were watered and placed on the mass balance in the so-called evaporation cell (8) made of polypropylene. Starke et al. (2011b) identified that the use of the vapour pressure gradient method compared to the mass flow method was over and underestimating evaporation and the error was attributed to changes in laboratory air pressure, humidity and temperature.

The LEMD was not able to simulate the differences in temperature occurring between day and night which limited the capacity to monitor changes in evaporation rate with time and could not be correlated to temperature changes. The pressure gradient method was abandoned and in later measurements only mass flow measurements were utilised as previously attempted by Göbel et al. in 2008.

Later, Poulikakos et al. (2013) and Lal et al. (2017) used apparatus similar to LEMD with the addition of a multisyringe pump for water application to investigate drying of porous asphalt under forced convection. Neutron radiography and X-ray computed tomography were utilised by Poulikakos et al. (2013), Jerjen et al. (2015) and Lal et al. (2017) to study the distribution and volume of water in porous asphalt samples. The effectiveness of Neutron radiography to measure small changes in moisture content and provide a clear image of moisture distribution was confirmed on a porous asphalt drying experiment in a micro-wind tunnel (Poulikakos et al. 2013). X-ray computed tomography was evaluated by Jerjen et al. (2015) study on porous asphalt.

5. Discussion

The key challenge to understanding evaporation in PPS comes through the inability to design a testing device to replicate real weather conditions, as they would occur in the field. Attempts were made to design devices for both field and lab conditions such as the TUV (Werner 2000) and LEMD (Nemirovsky et al. 2011) as well as utilising traditional methods using balances (Andersen et al. 1999), load cells (Syrrakou et al. 2014), humidity sensors and thermometers (Nemirovsky et al. 2011). X-ray tomography and Neutron radiography have been also utilised to understand the influence of internal characteristics of paving materials on water retention and evaporation mechanisms (Poulikakos et al. 2013, Jerjen et al. 2015, Lal et al. 2017, Aboufoul et al. 2019).

The vast majority of research on evaporation in PPS has been limited to observation scale for simplicity purposes. Internal parameters such as, type of surface material, type of sub-layers, type and placement of any water barrier and water availability and external parameters such as antecedent drying period, temperature, solar radiation and air velocity were discussed to identify limitations and potential areas for further research.

There is an overall agreement among researchers about the influence of surface water availability on evaporation rates. The higher the water availability at the surface and the bigger the surface exposed in the ambient environment, the higher the potential evaporative flux (Andersen et al. 1999, Göbel et al. 2008, Nemirovsky et al. 2011, 2013, Li et al. 2014, Syrrakou et al. 2014, Qin and Hiller 2016). Although, the previous finding leads to the conclusion that porous surfaces such as PC and PA would have higher evaporative potential than PICP owing to their high porosity, Brown and Borst (2014) did not identify any significant differences on evaporation between PA and PICP pavements. The systems under investigation did not consist of the same sub-layers which may have contributed to the result.

The influence of sub-layers on evaporation rate was not conclusive with some studies identifying a depth limit up to where water can travel from the sub-layers to the surface to evaporate (Nemirovsky et al. 2013, Syrrakou et al. 2014, Qin and Hiller 2016), others showing that evaporation from the sub-layers does not contribute significantly compared to the surface evaporative flux (Li et al. 2014) and others arguing that sub-layers contribute to the overall evaporative drying (Starke et al. 2011a, Gómez-Ullate et al. 2008).

Gómez-Ullate et al. (2008) was the only identified study focusing on the influence of water barrier/treatment presence and type on evaporation rates from PPS. The lower evaporation rate from PPS with one-way composite, could possibly indicate some contribution of sub-layers in the overall evaporation flux. Furthermore, it shifts the focus from geosynthetics' influence on water quality and opens up questions on hydraulic processes considering their many applications in engineering sectors such as capillary barriers (Zornberg et al. 2010) and soil moisture reduction (Guo et al. 2016, Wang et al. 2017).

Albedo or reflectivity of surface materials has been shown to influence evaporation rates. Starke et al. (2010) demonstrated that lower albedo means higher solar energy absorption and therefore higher evaporation rates. Porous surfaces have lower albedo than non-porous surfaces leading to the conclusion that porous surfaces are beneficial for evaporative cooling. Zhang et al. (2015) argue that porous concrete may not be the ideal option to replace conventional concrete due to very high surface temperatures present during the day. On the other hand, surface materials with high reflectivity may create a cool environment near the surface but spread intense solar radiation in the surrounding environment, resulting in higher temperatures (Zhang et al. 2015).

6. Conclusions

Evaporation in PPS is a moisture and heat removal mechanism, very beneficial in many drainage scenarios. It can be utilised in applications where drainage in the sub-grade soil is not desirable (Fire training grounds) (Knapton et al. 2006) and in applications were "cool pavements" are necessary due to UHI. This paper explored available research on evaporation in PPS with focus on laboratory and field studies. The aim was to provide a summary of the internal and external factors influencing evaporation in PPS and identify gaps and limitations in the literature. Although the first questions on evaporation in PPS were asked back in 1999, relatively early considering the novelty of PPS, the number of publications available pointed out that research on evaporation in PPS is still in the early stage and it has highlighted the need for further research.

Further research is required to:

- Identify ways of increasing water availability near the surface to enable higher evaporation potential. Water barrier/treatment systems such as Wicking geotextile or

OASIS phenolic foam could potentially act as water retaining materials based on their internal characteristics. Wicking geotextile is a commercially available geotextile used for moisture reduction from unsaturated soils. It owes its wicking ability to the large specific surface area of its hygroscopic and hydrophilic fibers (Zhang et al. 2014). Water is attracted in the fibers of the geotextile due to capillary forces and it is then transported along due to humidity gradients. The water will evaporate or drain from the exposed part (Guo et al. 2016). OASIS® phenolic foam is a novel approach in the area of water barriers. Its three dimensional highly porous structure has the advantage of storing great volumes of water. OASIS was firstly tested in 2009 at Coventry University with the potential to enhance commercially available geotextiles or totally replace them. Nnadi et al. (2014) observed that a 2cm thick specimen could store 33L of water per m^2. OASIS great water storage capacity and Wicking's water transport mechanism could potentially provide the means of achieving continuous water supply in the pavement's surface.

- Understand the contribution of sub-layers on total evaporation. Opinions are divided between those who agree that water availability near the surface is the main driver and those who show that sub-layers contribution may be significant especially in the presence of a geotextile. Further investigation on PPS with different sub-base designs e.g. aggregate size distribution, geotextile presence and type

- Understand the influence of aggregate or vegetated seams on evaporation

- Develop a surface material with a balanced combination between percentage of pore space and albedo to enhance evaporation and maintain cool temperatures.

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