CONCRETE PAVEMENTS AS A SOURCE OF HEATING AND COOLING

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ABSTRACT

There is great potential to use the large open space of pavement structures, equipped with an embedded pipe network, in conjunction with a heat pump, to provide heating and cooling for adjacent buildings, e.g. airport terminals, shopping centres etc, here termed a Pavement Source Heat Pump (PSHP). Due to the high thermal mass of pavement materials, seasonal temperature fluctuation under the pavement is much less than the temperature fluctuation of ambient air. Therefore, pavements can be utilised as a low grade heat source during winter and as a heat sink during summer. Airports, for example, provide a key potential application as they are very large consumers of energy, typically have very high cooling demands, have a large amount of adjacent pavement area, and are of a similar arrangement throughout the world. In this paper, the temperature distribution into pavements with different thermo-physical properties was modelled in order to evaluate their effects on depth of seasonal temperature fluctuation. The results show that there is a linear relationship between the thermal diffusivity and depth of seasonal temperature fluctuation and it decreases in relation to the thermal diffusivity of the pavement.

Keywords: Concrete pavement; heat transport; thermal diffusivity; ground source heat pump

1. INTRODUCTION

Maintaining a comfortable temperature inside a building can require a significant amount of energy which, in the UK, generally comes from fossil fuel energy resources (Figure 1). Generating energy from fossil fuels increases the net level of carbon dioxide into the upper earth atmosphere. Significant published data in peer reviewed scientific journals suggests that this can cause anthropogenic climate change; an acceleration of the ‘greenhouse effect’ (Armstrong and Blundell, 2007). In addition, the predicted short- and medium-term increases in future energy prices and increased loading of networked energy supplies suggests that there is a strong need to consider localised energy generation from renewable sources.

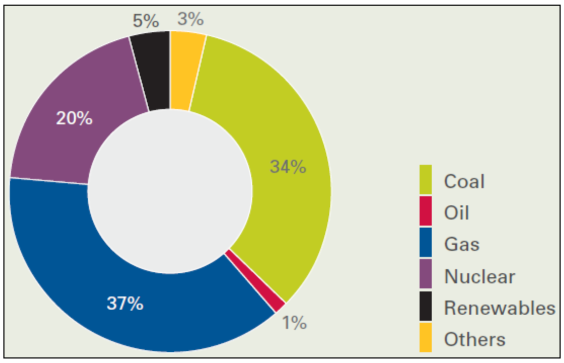

Figure 1- Renewable Contribution to Electricity Generation in the UK 2005 (Department of trade and industry, 2006)

Renewable energy combined with improved energy efficiency measures (i.e. demand-side reductions), can offer a viable solution. Almost all sources of renewable energy that are available to us rely on the sun; the mechanisms behind wind, tidal, rain, and geothermal sources ultimately depend on solar energy. Most obviously, the sun provides solar energy to our planet's surface (see Figure 2) on an annual basis at a rate of about 100, 000 TW (Armstrong and Blundell, 2007), roughly equivalent to mankind's current annual energy consumption. Incoming solar irradiation will be stored as heat energy in soils, rocks, and underground water in the subsurface. As a result, the ground can be considered as a thermal storage battery that can keep summer heat until winter. Due to the high thermal mass of the ground, seasonal temperature variations deep in the ground are much less than those near the surface (see Figure 3).

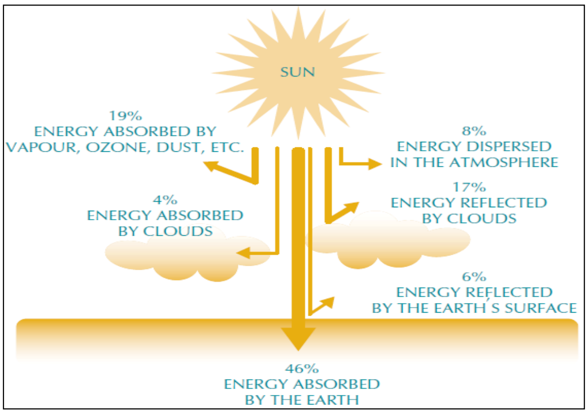

Figure 2- Solar energy distribution (Retscreen® International, 2005)

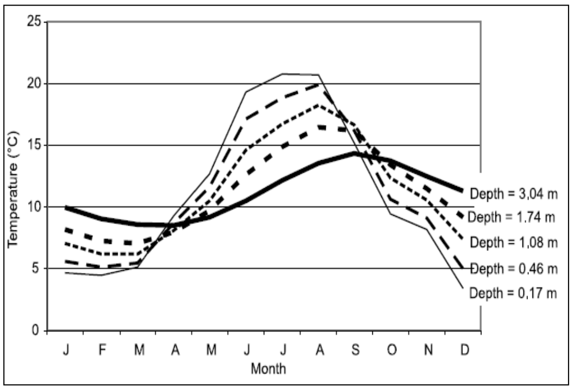

Figure 3- The seasonal temperature fluctuation in the subsurface at various depths, as observed at Radcliffe, Oxford, UK (Banks, 2008)

Ground Source Heat Pumps (GSHPs) are a highly efficient, renewable energy technology that takes advantage of stable, deep ground temperatures as a source of low grade heat. The ground temperature is often higher than ambient dry bulb air temperature in a heating season and lower in a cooling season. Therefore, by using fluid-filled pipes (known as ‘loops’) embedded in the ground, a heat pump can either upgrade low temperatures to efficiently provide heat in adjacent buildings or, in reverse, extract heat from the building and store it in the ground.

GSHP loops are usually configured either vertically or horizontally (Figure 4). Vertical loops are well suited when land surface area is limited or when minimum disruption of the landscaping is desired. The boreholes, depending on the geology and thermal properties of the ground, are normally drilled to a depth of 45m to 150m. Because the ground temperature at depth is constant year round, vertical systems are very efficient. However, they are more expensive to install due to a high drilling cost. Horizontal loops are often considered when adequate land surface is available. The pipes are placed in trenches, typically at a depth of 1.2 to 3.0 m. The advantages of horizontal systems are their lower trenching cost as well as quicker and more flexible installation. However, they are less efficient than vertical systems because of the ground’s susceptibility to the seasonal temperature variation at shallower depths.

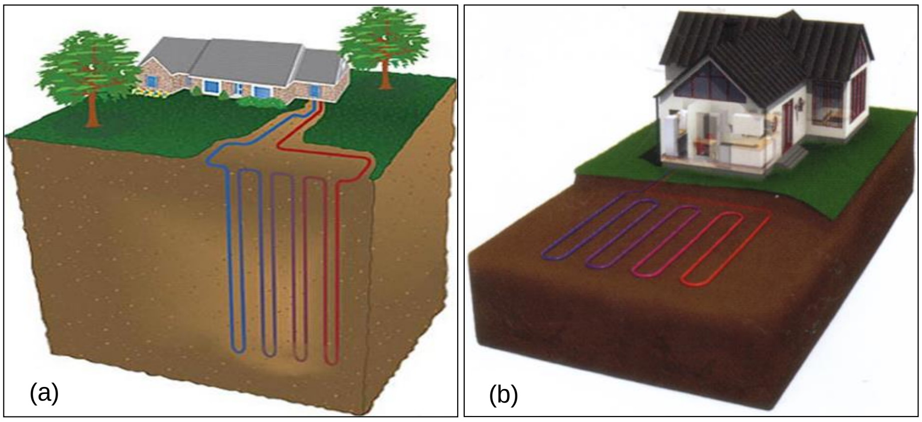

Figure 4- Vertical (left) & Horizontal (right) Ground Source Heat Pumps

There are several applications where buildings with a high heating and/or cooling load also have large adjacent pavement infrastructure, e.g. airport terminals, shopping malls, factories, warehouses, and retail outlets. The large pavement surface areas, which are already required for operational reasons and designed on the basis of their structural capacity, can potentially be optimised in order to provide a better temperature stability at shallower depth and to eliminate the need for expensive deep boreholes. Therefore, Pavement Source Heat Pumps (PSHP) as an innovative technology might be designed to operate more cost-effectively than conventional GSHP.

2. OBJECTIVE

The objective of the research presented in this paper is to determine the capacity for an optimised concrete pavement that would meet conventional pavement mechanical/structural requirements but which would also significantly decrease the minimum depth required for ground temperature stability giving comparable performance to a deep borehole system (Figure 5).

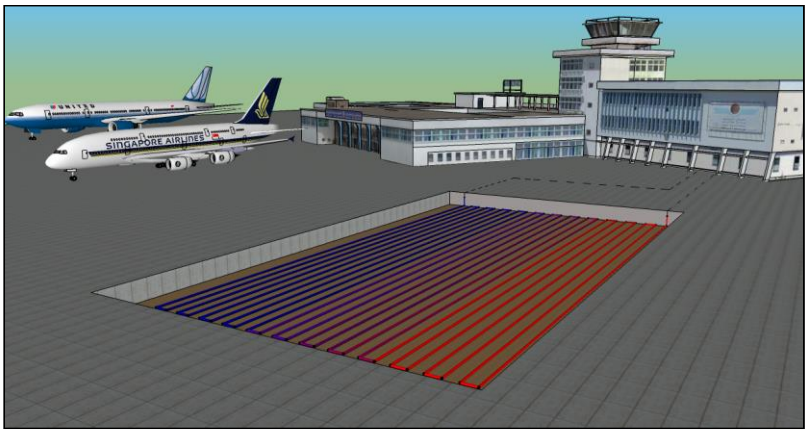

Figure 5- A PSHP under a thick concrete pavement in Airport

3. SCOPE OF WORK

The scope of work included modelling of summer and winter temperature distribution in an existing aircraft apron in East Midlands Airport (EMA), UK and compare it with pavements consisted of different thermo-physical properties. For this reason, a one-dimensional transient heat transport model, which has already been developed as part of on-going larger project, is used to calculate the temperature distributions within the pavements. The model inputs are solar radiation, dry bulb air temperature, wind velocity, and thermo-physical properties of pavement and soil materials. The thermo-physical properties of EMA's aircraft apron such as: thermal conductivity (λ), volumetric heat capacity, (ρc_p), and thermal diffusivity (α) were experimentally determined in the laboratory. The climatic data were obtained from the Sutton Bonington, Leicestershire, UK (52.58˚N, 1.38˚W) weather station, which is located about 6km to the east of EMA.

4. SUMMARY OF THE PREDICTIVE MODEL

The pavement ~~surface~~ temperature distribution~~s~~ wa~~i~~s determined using the energy balance calculation taking into account radiation, conduction and convective exchanges between the material surface and the ambient climatic conditions (Figure 6). The model is able to predict the temperature at various depths as a function of climatic variables and the thermo-physical properties of materials. It uses an explicit finite difference approach to iteration.

4.1. Solar radiation heat flux

Absorbed solar radiation on a pavement can be calculated from:

$$q_{absorbed} = \mathrm{a} \cdot q_{solar} \tag{1}$$

Where a is the absorptivity of the pavement surface and q_{solar} is incident solar radiation of the sun. Table 1 shows some typical values for absorptivity of green grass covered soil, bare soil, and concrete pavement materials.

Table 1- solar absorptivity of concrete and soil

Concrete	Bare soil	Green grass	Source
0.65-0.80	-	-	CIBSE, 1999
0.65	-	-	Bentz, 2000
0.60	-	-	Incropera et al, 2007
-	0.86-0.92	0.74	Holman, 2002
-	0.85	-	Asaeda et al, 1996

4.2. Thermal (long-wave) radiation heat flux

This heat transfer mechanism considers the radiation between pavement surface and atmosphere and can be calculated as follows:

$$q_{thermal} = \varepsilon\sigma(T_{surr}^4 - T_S^4) \tag{2}$$

Where:
ε = surface emissivity
σ = Stefan-Boltzmann constant= 5.67×10^{-8} (W/m^2 K^4)
T_{surr} = temperature of the surroundings (K)
T_s= absolute temperature of the surface (K)

T_{surr} can be assumed as 6 K below the ambient dry bulb air temperature (Underwood and Yic, 2004; Lienhard and Lienhard, 2006). The surface emissivity of a body is defined as the ratio of the energy emitted by a real body to the energy emitted by a black body. Some typical values for emissivity of concrete pavement surfaces and soil are shown in Table 2.

Table 2- emissivity of concrete and soil

Concrete pavement	Soil	source
0.88 - 0.93	0.93 - 0.96	Incropera *et al*., 2007
0.85 - 0.95	-	CIBSE, 1999

4.3. Convection heat flux at the pavement surface

This mechanism accounts for heat transfer at the pavement surface and is computed by:

$$q_{convection} = h_c\,(T_{air} - T_s) \tag{3}$$

Where h_c= convection heat transfer coefficient (W/m^2 K).

Convective heat transfer coefficient between pavement surface and air, h_c, was estimated by the following Jurges's empirical formula (Niro et al, 2009; Bentz, 2000).

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for $v_w \leq 5\,{}^{m}/_{s}$

for $v_w > 5\,{}^{m}/_{s}$

Where v_w is wind speed in m/s.

4.4. Conduction heat flux into the pavement

This heat transport mechanism considers heat flux, in the form of transient conduction, through the semi-infinite pavement between *d* = 0 and *d* = L. Absorbed energies at the pavement surface will be exchanged within the pavement through heat conduction. The pavement layer system and the soil beneath can be considered a semi-infinite medium extending downward infinitely. Therefore, given enough depth, there are no temperature fluctuations with respect to time. This is because with increasing depth, the increasing thermal mass of the soil renders the temperature at such depths independent of the heating and cooling cycles applied at the pavement surface. For an isotropic medium and for constant thermal conductivity, heat conduction is expressed by the following equation.

Where

T = temperature (K)

d = depth (m)

ρ = dry density (kg/m^3)

c = specific heat capacity (J/kg K)

λ = thermal conductivity (W/m K)

t = time(s)

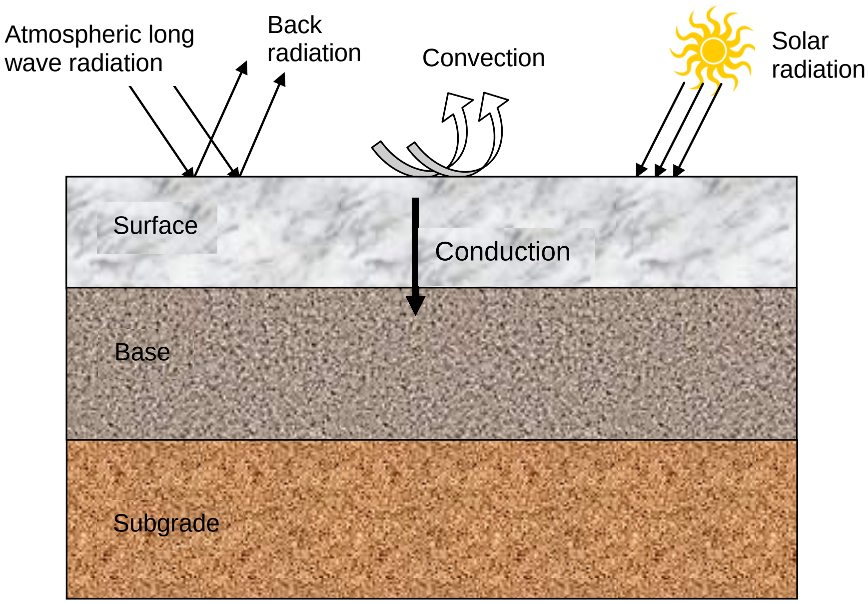

Figure 6- Heat Transfer modes between pavement and its surroundings

The initial condition at t = 0 assumes a constant uniform temperature distribution to a depth of 8 m. Previous studies show that the ground temperature in the UK remains essentially constant at around 11˚C at a depth of about 8 meters (Carder et al, 2007; Banks, 2009; Doherty et al, 2004). Therefore a uniform temperature of 11˚C was applied as the initial condition. The model has already been extensively validated against a large dataset for five different climates.

5. PREVIOUS VALIDATION OF THE MODEL

An example of the previous validation is illustrated here for a concrete pavement in North Carolina, USA (Figure 7). The climatic and physical properties of the pavement were extracted from the Seasonal Monitoring Program (SMP) conducted under the Long-Term Pavement Performance program (LTPP) which was conducted over a period of around 10 years (FHWA, 2009). Figure 7 shows the comparison of results between the field measured temperature data and the model predicted temperatures at a depth of 0.1m, over an 18-day period, with error bars of ±1.5°C and ±2.1˚C at the minimum and maximum temperature peaks, respectively. Table 3 summarises the thermal and physical characteristics of the pavement layers (from top - bottom) that are used in the model. The development of this numerical model, along with a more detailed analysis of the influence of pavement thermo-physical properties on temperature profile prediction in five different climatic regions, is being presented in a separate research paper currently in preparation by the authors.

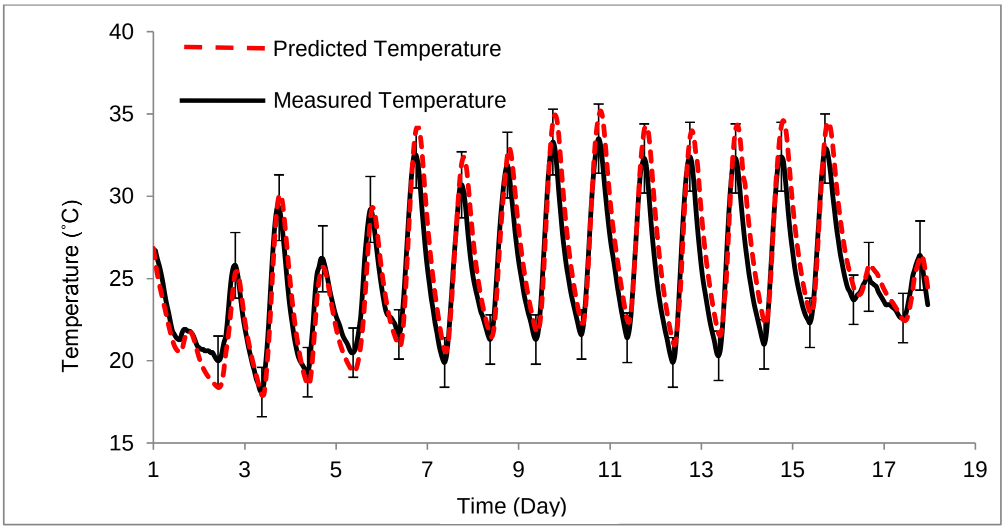

Figure 7- Comparison of measured and model-predicted temperature using North Carolina LTPP data at depths of 0.1 m

Table 3- Parameters used for model validation in North Carolina pavement

Pavement layer and Materials for North Carolina pavement	Thickness (m)	Thermo-physical properties	References
Portland Cement Concrete (PCC)	0.234	λ = 1.2 W/m K c = 1000 J/kg K ρ = 2339 kg/m^3	Mehta and Monteiro, 2006 Mehta and Monteiro, 2006 LTPP database
Crushed Gravel	0.236	λ=1.1 W/m K c=1000 J/kg K ρ=2226 kg/m^3	Coté and Konrad, 2004 Dempsey and Thompson, 1970 LTPP database
Soil-Aggregate mix	0.203	λ=1 W/m K c=960 J/kg K ρ=1650 kg/m^3	Coté and Konrad, 2004 Ashrae, 1995 LTPP database
Sandy Soil	-	λ=0.8 W/m K c=1040 J/kg K ρ=1522 kg/m^3	Ashrae, 1995 Ashrae, 1995 LTPP database

6. THERMO-PHYSICAL PROPERTY CHARACTERISATION

A guide to airfield pavement design and evaluation (PSA, 2006) was chosen as a specification for the manufacture of concrete specimens in accordance with the requirements of concrete airport pavements. The apron pavement in the EMA consisted of a 450mm Portland cement concrete slab, which normally termed Pavement Quality Concrete (PQC), on top of a 500mm base layer (Figure 6). The base layer in the EMA's apron is a low-strength concrete known as Dry Lean Concrete (DLC). Limestone, due to its low coefficient of thermal expansion, is the most preferable aggregate for concrete pavement construction. Therefore, the mix design for the PQC used is a 10/20 single sized limestone aggregate in compliance with BS EN 12620, Table 2, '4mm down' natural sand, and high strength Portland cement (CEM I, 52.*5* N/mm^2). The mix design and compressive strengths for PQC and DLC are summarised in Table 4.

Table 4-Mix design for PQC and DLC

	Aggregate (kg/m^3)		Cement (kg/m^3)	Water (kg/m^3)	Dry Density (kg/m^3)	Mean 28days compressive strength (MPa)
	fine	Coarse				
PQC	895	985	370	200	2200	43
DLC	2100		130	115	2100	22

6.1. Thermal conductivity test

The rate of heat transfer, given as heat flux , q (W/m^2), by conduction through a slab (Figure 8) of thickness, d, and temperature difference, $\Delta T = T_2 - T_1$, across the slab can be calculated using:

$$\lambda = \frac{q.d}{\Delta T} \tag{6}$$

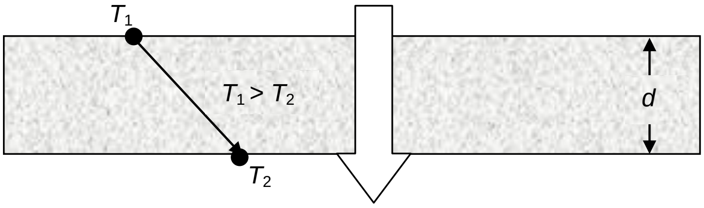

Figure 8- Rate of heat conduction through a pavement layer

The thermal conductivity testing was performed using a computer controlled P.A. Hilton B480 heat flow meter apparatus with downward vertical heat flow and which complies with ISO 8301. Two slabs each for PQC and DLC were produced from the above mix design. The slab specimens were placed inside the apparatus between a temperature-controlled hot plate and a water-cooled cold plate (Figure 9).

Figure 9- apparatus to measure thermal conductivity of building materials

The moisture-dependent thermal conductivity (also known as thermal transmissivity) λ^*, (W/m K) of the DLC and PQC were measured. Figure 10 shows, as the moisture content increases, so does the thermal conductivity. This is attributed to changes in air voids filled with water, whose thermal conductivity is superior to that of air. In addition, thermal conductivity of PQC is higher than DLC because of higher porosity of DLC compared with PQC ~~(see Table 6)~~. Thermal conductivity of PQC is increased by about 21% from the oven dried to wet condition however, the thermal conductivity of DLC is increased by about 37%, the higher percentage of increase in thermal conductivity of DLC is due to its higher porosity & water absorption.

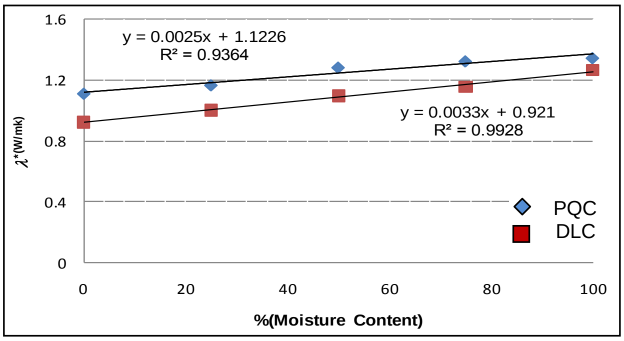

Figure 10-Moisture-dependent thermal conductivity of PQC and DLC

6.2. Specific heat capacity

Specific heat capacity can be calculated as the sum of the heat capacities of the constituent parts weighted by their relative proportions (Hall and Allinson, 2008). The specific heat capacity of PQC and DLC are summarised in Table 6. ~~The procedure for calculating the specific heat capacity of PQC is also shown in the same table.~~

Table 6 - Average specific heat capacity of PQC and DLC

Layers	Heat capacity ~~in Dry state~~ (J/kg K)	
	~~Heat capacity in saturated state (J/kg K)~~	
	Dry state	~~S~~saturated state
PQC	**858**	**1070**
DLC	**843**	**1131**

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6.3. Thermal diffusivity

Thermal diffusivity, α, can be defined as the rate of spread of absorbed heat within material and can be calculated by the following equation.

$$\alpha = \frac{\lambda}{\rho c} \quad (7)$$

Table 7 shows that the thermal diffusivity decreases for both PQC and DLC materials when they are saturated as opposed to dry, since the specific heat capacity of water is more than four times higher than that of concrete.

Table7- Average thermal diffusivity of PQC, DLC and Soil

Layer	Thermal diffusivity in dry condition, α (m^2/s)	Thermal diffusivity in wet condition, α (m^2/s)
PQC	$5.89*10^{-7}$	$5.24*10^{-7}$
DLC	$5.20*10^{-7}$	$5.08*10^{-7}$

7. SEASONAL TEMPERATURE DISTRIBUTION

Using the Sutton Bonington climatic data and experimentally determined thermo-physical properties of EMA's concrete pavement, the mean February & August temperature distribution for two cases of wet and dry pavement have been investigated (Figure 11).

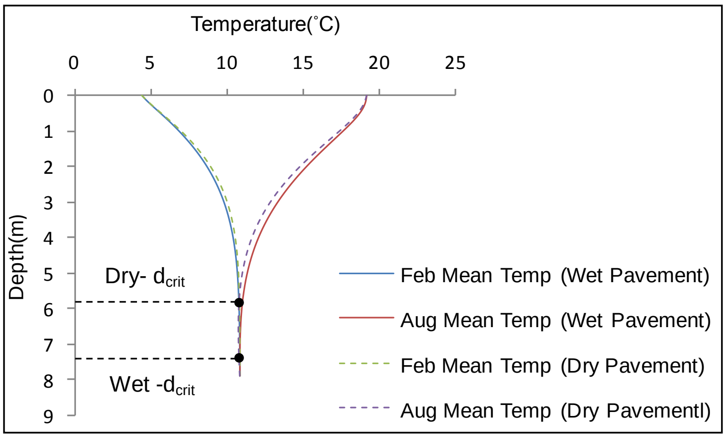

Figure11- Temperature distributions within EMA apron pavement in wet and dry conditions

The following conclusions can be drawn from Figures 10 and 11.

1) The critical depth (d_{crit}) below the surface at which minimal Seasonal Temperature Fluctuation (STF) occurs, defined by the point of convergence between seasonal minima, is 7.4 & 5.8m for wet and dry concrete pavement, respectively. The greater depth of penetration for heat energy in wet concrete can be explained by the fact that the increased conductivity, as a result of higher moisture content (See figure 10), allows heat gains at the pavement surface to be transferred against less thermal resistance and consequently increased the summer season d_{crit} value. Conversely, the slightly higher thermal conductivity of wet concrete facilitates the removal of heat from the pavement in the winter; hence, in the winter the temperature of wet pavement at any depth is lower than that of dry pavement. From these observations it might be inferred that pavement maintenance aiming at keeping pavements dry should be prioritised, from a thermal point of view, when use of the pavement as a heat store (or heat sink) is desired.

In the next step, pavements with different thermo-physical properties (Table 8) have been replaced in the EMA's apron pavement in order to evaluate their potential on reduction of d_{crit} and increase the temperature stability at shallower depth. Figure 12 shows how d_{crit} is altered when EMA's apron (i.e. PQC and DLC) is replaced by the different layers.

Table8- Layers replaced EMA apron pavement

Layers	Mean thermal Conductivity, λ (W/m K)	Mean specific heat capacity, c (J/kg K)	Mean Density, ρ (kg/m^3)	Mean thermal diffusivity, α ($\times 10^{-7}$ m^2/s)	Source
Hematite Concrete	2.6	960	2950	9.2	Lamond and Pielert, 2006
Sandstone concrete	1.4	960	1950	7.5	
Barite concrete	1.4	630	3750	5.7	Witte and

					Backstrom, 1954
Expanded slag	0.44	960	1650	2.8	Lamond and Pielert, 2006
10% rubberised concrete	0.44	1100	2150	1.9	Sukontasukkul, 2009
Clay	1.1	900	2050	6.0	Ashrae, 1995

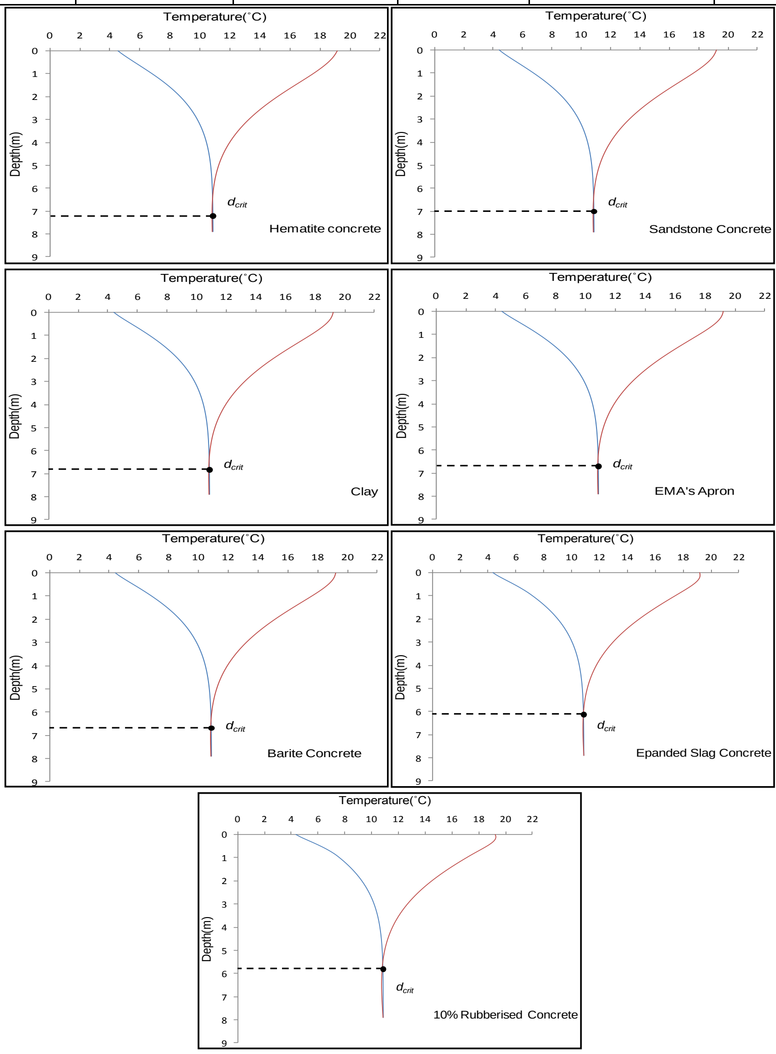

Figure12- Effect of Pavements with different thermo-physical properties on the critical depth (d_{crit})

The following conclusions can be drawn from Figure12:

1) Table 9 shows the value of d_{crit} for different pavements.

Table9- The critical depth (d_{crit}) of pavements with different thermophysical properties

pavements	Hematite concrete	Sandstone concrete	Clay	EMA's apron	Barite concrete	Expanded slag concrete	10% Rubberised concrete

d_{crit}(m)	7.1	7.0	6.8	6.7	6.7	6.1	5.8

2) In the pavements with same thermal conductivity (i.e. 10% Rubberised concrete/Expanded slag concrete and Sandstone concrete/Barite concrete) as the VHC of the pavement increases, the critical depth (d_{crit}) will decrease due to higher 'thermal mass' of the pavement materials.
3) In the pavements with similar VHC (i.e. Barite concrete/10%rubberised concrete) as thermal conductivity of the pavement materials decreases, the d_{crit} will also decrease due to the high relative insulation of the pavement.

4) From point 2 & 3, it can be concluded that the d_{crit} is a function of thermal diffusivity (See equation 7) of pavement materials. As thermal diffusivity decreases, as the result of the lower thermal conductivity and the higher VHC, the d_{crit} will also decrease. That is because the material with higher VHC and lower thermal conductivity will reduce the temperature fluctuation at lower depth. Less temperature fluctuation can improve the efficiency of the GSHPs.

5) The approximately linear relationship between the critical depth (d_{crit}) and thermal diffusivity of pavement materials can be seen in Figure 13.

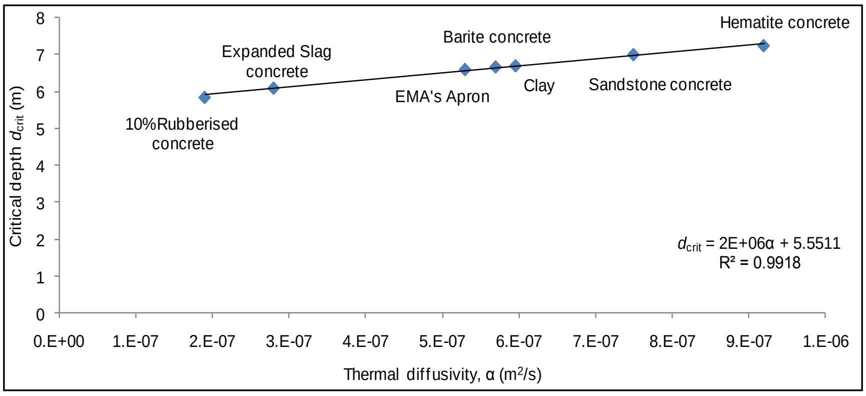

Figure13- linear relationship between the critical depth and thermal diffusivity of pavement materials

8. CONCLUSION AND FUTURE WORK

This study highlights the potential for using optimised pavement slab structures in conjunction with shallow GSHP coil networks in order to potentially raise overall system efficiency whilst negating the need for the considerably more expensive deep borehole installations. The study has successfully proven the feasibility of this approach by demonstrating that d_{crit} can be significantly reduced by installation of a low thermal diffusivity pavement slab. The predictive numerical model used for this analysis has been developed as part of a separate, more detailed study in this area and has been successfully validated to a high degree of accuracy (< ±2° C) both in this study and in more detail on separate occasions.

The potential applications of this research are when using large areas of pavement structure adjacent to large buildings with a high heating/cooling load (e.g. airport terminals). It has been shown that significantly lower values of d_{crit} could be obtained if the pavement materials are carefully selected to perform both their mechanical functions and desirable thermal responses to climatic variables. These initial results suggest that by reducing the thermal conductivity whilst increasing bulk density and specific heat capacity (within the confines of achievable pavement material properties) the resultant values for thermal diffusivity would reduce d_{crit}. The on-going project will be focused on experimentally determining the potential for intelligent thermal optimisation of concrete pavement materials whilst maintaining acceptable mechanical performance of the pavement.

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